A. E. Kennelly.

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Constitution, Article VII, Sec. 2.

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TRANSACTIONS
OF THE
AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

Vol. XV. JANUARY TO DECEMBER. 1898.

New York, January 26th, 1898.

The 121st meeting of the INSTITUTE was held this date, at 12 West 31st Street, and was called to order by President Crocker at 8:30 P. M.

THE PRESIDENT:—The Secretary has some announcements to make.

THE SECRETARY:—At the meeting of Council this afternoon, it was decided to hold the General Meeting of the INSTITUTE next summer at Omaha, if satisfactory arrangements could be made. This is in accordance with the resolution passed at the General Meeting at Greenacre, favoring such action. The fixing of the exact date and the perfecting of the arrangements were left to the Executive Committee.

The following associate members were elected:

Name.	Address.	Endorsed by
Bangs, Chas. R.	Special Agent, American Telephone and Telegraph Co., 15 Dey St., New York.	F. A. Pickernell. A. N. Mansfield. J. J. Carty.
Beebe. M. C.	Ass't. in Electrical Engineering, University of Wisconsin; residence, 271 Langdon St., Madison, Wis.	D. C. Jackson. S. B. Fortenbaugh. C. F. Burgess.
Brown, Hugh Thomas	Supt. of Electrical Dept., Selma Gas and Electric Co., Selma, Ala.	Dr. E. L. Nichols. H. J. Ryan. Ernest Merritt.
Burch, Edward P.	Electrical Engineer, Twin City Rapid Transit Co., 517 6th Ave. S. E., Minneapolis, Minn.	Geo. D. Shepardson M. H. Gerry, Jr. E. W. Rice, Jr.
Crocker, Eben Clinch	Electrical Engineer, American Ordnance Co., 29 Harriet St., Bridgeport, Conn.	Jos. Wetzler. R. T. Lozier. Chas. Blizard.
Elias, Albert B.	Electrician, Davis Coal and Coke Co., Thomas, West Va.	Chas. H. Davis. A. E. Braddell. M. J. Wightman.

Garfield, Alex. Stanley	Engineer, Cie Thomson-Houston, 27 Rue de Londres, Paris, France.	E. W. Rice, Jr. C. P. Steinmetz. A. L. Rohrer
Hellick, Chauncey Graham	Electrical Engineer, The Chicago Telephone Co., residence, 193 Dearborn Ave., Chicago, Ill.	J. J. O'Connell. A. V. Abbott. F. J. Dommerque.
Morgan, Jacque L.	Electrical Inspector, Kansas City Fire Dep't.; residence, 1702 Locust St., Kansas City, Mo.	Edwin R. Weeks. Sam'l. Insull. Axel Ekstrom.
Prosser, Herman A.	Electrician, Baltimore Copper Smelting and Refining Co., Keyser Bldg.; residence, 1222 Madison Ave., Baltimore, Md.	F. B. Crocker. G. F. Sever. W. H. Freedman.
Swann, John Joseph	Assistant Editor, *Engineering News*, 220 Broadway; residence, 347 West 84th St., New York.	H. J. Ryan. Edw. L. Nichols. Ernest Merritt.
Swoope, C. Walton	Instructor, Electrical Engineering, Spring Garden Institute; residence, 12 North 38th St., Philadelphia, Pa.	Wm. S. Aldrich. A. J. Rowland. Wm C. L. Eglin.
Tachihara, Jin	General Electric Co.; residence, 106 Union St., Schenectady, N. Y.	C. P. Steinmetz. Ernst J. Berg. Eskil Berg.

I presume that many of the members have read in the daily papers the sad intelligence of the death of one of our distinguished fellow members, Mr. O. B. Shallenberger, for many years connected with the Westinghouse Electric and Manufacturing Company, as consulting engineer.

Mr. Shallenberger died at Colorado Springs, on January 23rd. His funeral will take place on Saturday next. Mr. Shallenberger was thirty-eight years of age and was a graduate of the United States Naval Academy. He became identified with the INSTITUTE in 1888, and was transferred to full membership the same year. I presume that there are many of the members present who have had the pleasure of his personal acquaintance, and as soon as particulars of his death are received a sketch of his life will be published in the TRANSACTIONS.

A Topical Discussion at the 121st Meeting of the American Institute of Electrical Engineers, New York, January 26th, 1898. President Crocker in the Chair. Chicago, Manager B. J. Arnold in the Chair.

THE STANDARDIZING OF GENERATORS, MOTORS AND TRANSFORMERS.

(A Topical Discussion.)

THE PRESIDENT:—Gentlemen, in taking up the discussion, which is the object of this meeting, it might be well to make a few statements as to what it is intended to cover, and the scope of it, as that matter has not been understood by very many of the members. The general desirability of standardizing electrical apparatus has often been spoken of and seems to be very generally believed in. The feasibility of it, or the policy of it, is another matter. If such standardizing is to be effected, this body, THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, is undoubtedly the only one which is competent to decide such a question. As to precedents, I think we have many excellent ones. I have here volume vi. of the *Transactions* of the *American Society of Mechanical Engineers*, for the year 1884, and in it is a very elaborate report of the Committee on Standard Methods of Steam Boiler Trials. This, I believe, was the first action of the *American Society of Mechanical Engineers* on this general line of work, and since then a number of other standards or standard methods of practice have been recommended by it. Other bodies, such as the *American Society of Civil Engineers*, and our sister engineering societies in England, have frequently taken such action. It is very common on both sides of the Atlantic. Therefore we should be doing nothing radical or unusual in establishing such standards provided they are found desirable. It might be said, of course, that since any hard and fast adoption or acceptance of a standard would not seem to be desirable, all these bodies, particularly the *American Society of Mechanical Engineers*, have very carefully confined their action to a recommendation of certain standards, and they have taken particular pains that it shall not appear that the absolute adoption of a certain standard is imposed upon anyone. The individual members of the INSTITUTE or any other society, are not bound, morally or legally by any such recommendation, although they would naturally follow it. It is simply left to any person to follow it, as he sees fit, whether he is a member or not, and it is merely for the convenience of the members and the public generally that any such standards would be recommended. I think those points may have been misunderstood very naturally, and might act as a very serious obstacle in carrying out any such work. Now, as to what the standards should be and how far any such action should go, that remains, of course, to be seen, and I think the desirability of such standards, what they shall be, and how far they shall go, would be the natural subject of the discussion this evening. The general question of policy and advisability is also a proper point for the members to consider.

I would call upon Mr. E. W. Rice, Jr., to open the discussion.

Mr. Rice:—Before proceeding with the few remarks that I have prepared, I wish to say that I undertook to open this discussion with considerable reluctance, seeing that I would not have time, perhaps, to do the subject justice. However, I hope that you will make proper allowance for my remarks, knowing that I have had very little time in which to prepare for this subject. I have also not had an opportunity to discuss the matter with the Executive Committee, and so do not have clearly in mind the proposed limits of the discussion.

The subject which has been selected for discussion this evening, "Standardizing of Generators, Motors and Transformers," covers in its various aspects such a large field that it would be difficult to attempt anything more than a very cursory review.

It may include the standardizing of the various types and sizes of apparatus, or the methods of rating, or of testing, or it may define such terms as regulation, efficiency, or set the limits of heating and of sparking; or again, in alternating current work, standardize the frequency.

I assume that the chief object of a meeting of this kind is to discuss the subject thoroughly, and that if as a result of such discussion it is considered that any useful purpose can be attained, the matter will be referred to a carefully selected committee with instructions to consult with the various interested parties and report its conclusions with recommendations to the Institute at some future date.

The advantages of establishing certain standard types and sizes of apparatus are apparent and have been fully recognized, particularly in this country, from the earliest days of electric lighting, which marked the beginning of the present electrical industry. Such standard lines have been arbitrarily determined by each of the different manufacturing companies, and have been built to conform to certain specifications, and tested in accordance with methods developed by experience. Competition has tended to increase the number of standard sizes and the development of the industry has added enormously to the variety of apparatus in use. I think it is generally recognized that the adoption of such standards by the manufacturers and their acceptance by the public has been one of the greatest factors in the phenomenal development of our industry in the United States, and is chiefly responsible for the present enviable position of our manufacturers of electrical apparatus as compared with other countries. It has enabled our manufacturers to produce the standard lines selected, at phenomenally low costs, and has also resulted in an equally great improvement in the quality. Large sums of money have been expended in special tools, which, while reducing the amount of labor per machine to a remarkably low figure, has, by the very means adopted for such economical production, improved the quality, because the manufacture of large quantities of duplicate apparatus has stimulated the manufacturer to spend these large amounts for tools and to organize, elaborate and perfect methods of manufacture. The history of the electrical business in this respect, of course, only parallels that of the bicycle, the typewriter, the sewing machine and other similar industries.

The importance of maintaining and extending, if possible, the policy which has enabled this country to sell apparatus in competition with other countries, frequently in the face of protective duties, is probably so thoroughly appreciated as to require no special pleading to obtain for it a hearty endorsement by those interested in the advancement of our industry.

Results such as have been mentioned are largely dependent upon the manufacture in great quantities of exactly duplicate pieces of apparatus, a condition which can only be practically realized where the apparatus is manufactured under the control of one corporation. It therefore seems evident that even if it were possible for all the interested parties to agree upon certain standards, the advantages above mentioned would not be fully realized. The chief beneficial effect of such an agreement would be to limit the demands for special apparatus which may have to be manufactured by comparatively expensive and less perfect methods, and to increase the demand for the standard apparatus.

I merely mention the above well known condition to illustrate in a general way the value of standards where they can be adopted, and to show that the manufacturer, while undoubtedly animated by selfish motives in advocating standard apparatus where possible, is at the same time advancing the best interests of the industry as a whole.

However, I think that for many reasons it would be found impracticable and probably not for the best interests of the business to establish any such standard sizes or lines of apparatus which would be equally satisfactory to the designing engineer, the consulting engineer, the manufacturer and the user.

Moreover, I do not suppose this INSTITUTE would care to attempt to introduce any standards which did not admit of definite determination or which the rapid evolution of the business would soon render useless.

There are, however, certain features of the subject under discussion which it seems to me could and should properly be considered by this INSTITUTE. These features must be considered in every commercial transaction.

I refer to the terms used to define certain characteristics of motors, generators and transformers, and the method of determining such terms. This subject has been considerably discussed of late, and was ably set forth in a recent paper by Mr. S. D. Greene, read before the New York Electrical Society; which society has in consequence invited this INSTITUTE to consider some plan for standardizing certain apparatus. I think that all of the features mentioned by Mr. Greene as requiring standardizing in practice are important, and while I am not entirely sure that all admit of such standardizing, I believe they should all be considered by this INSTITUTE. I shall therefore follow very closely Mr. Greene's list of subjects, adding one or two that have occurred to me upon a brief consideration. I shall also endeavor to give additional facts bearing upon these subjects.

1. Definition of efficiency.
2. Heating limits and methods of determining same.
3. Regulation, as applied to D. C. generators, to motors, to transformers, to A. C. generators, A. C. motors, etc.
4. Sparking in D. C. machinery.
5. Insulation—methods of testing same.
6. Rating.
7. Frequency of alternating current machinery.

1st.—*Efficiency.* The efficiency which is of practical value is the so-called commercial efficiency, that is, the ratio of the energy input to the useful energy output, thus accounting for all losses. In early days the term "electrical efficiency" was frequently confused with the term "commercial efficiency," and even at the present time the confusion sometimes occurs. Even the term "commercial efficiency" needs more exact definition as it is customary in direct coupled machinery, that is, machinery coupled directly to a prime mover, such as a steam engine, water wheel, gas engine, etc., to charge the mechanical losses, friction and windage, to the prime mover. In belted machinery the mechanical friction losses are charged against the electrical machinery. There are excellent reasons for the existing practice, but such practice at least needs standardizing.

2d.—*Heating.* While it would be obviously impracticable, even if it were desirable, to adopt any definite number of degrees increase of temperature above the air as a standard, because of the different conditions of service and design of apparatus, it would nevertheless be desirable to define the methods of determining any increase of temperature. Increase of temperature is now sometimes measured by thermometer and sometimes by increase of resistance of the copper conductors. It is evident that in some cases the first method may be better, in other cases the latter. I think that the standardizing of the proper methods in all cases would be desirable.

3d.—*Regulation.* I omit in this connection any reference to direct current machines, and select for illustration alternating current apparatus. In alternating current generators the term regulation has now several different meanings. First, the percentage of drop in pressure at the armature terminals from no load to full load with no load excitation of field. Second, the percentage increase of voltage from full load to no load with full load excitation. Third, the percentage increase in field ampere-turns required to maintain constant potential at armature terminals from no load to full load. Fourth, percentage decrease in field ampere-turns from full load to no load to maintain constant potential at armature terminal. Fifth, the relation between normal full load current delivered by the machine and the current produced on short circuit with an excitation of the field corresponding to full normal load. All of the above definitions and several others, I believe, are in use among engineers.

4th.—*Sparking*, or rather the limits between which freedom from sparking shall be demanded in commutating machines, is of importance to all parties. It is admittedly an extremely difficult matter to standardize. I doubt if any entirely satisfactory scientific definition of the terms used commonly in discussing such matters can be found. The subject is, however, worthy of consideration.

5th.—*Insulation breakdown tests.* It is becoming common to specify that the insulation of a generator or motor shall withstand certain breakdown tests by being subjected to a pressure considerably higher than that of operation. While it is possibly too early, in view of the rapid development of the art to determine definitely the limits and exact conditions of such tests, the question could very profitably be discussed and perhaps some recommendation of value made.

6th.—*Rating of alternating generators.* It is customary in this country to rate alternating current generators on the basis of volt-amperes output. Abroad in certain instances the rating is based upon the volt-amperes output multiplied by an assumed cosine of angle of lag, say .8. It may be desirable that the method adopted in this country should be standardized.

7th.—*Frequency of alternating current machinery.* Alternating current machinery is being built for frequencies of 25, 30, 33, 40, 50, 60, 66, 125 and 133 in this country. While excellent engineering reasons have presumably in every instance dictated the selection of each of the above frequencies, it is probable that the number selected for standardization need not be over three or four at most. In such event the engineer would still be able to select from the standards adopted, a frequency which would properly meet the various conditions of generation, transmission, and service, etc., which he is called upon to solve. . The net result would undoubtedly be beneficial to all parties—the engineer, the manufacturer and the consumer.

In the above remarks I have not attempted to do more than give an extremely brief review of certain phases of the subject under discussion. The subject is too large to be treated exhaustively at this evening's meeting even if one had the time and ability. In concluding, I wish to repeat the suggestion advanced in the beginning of my remarks, namely, that no practical advance is liable to be made in the consideration of these important questions unless the matter is referred to a small committee of members of this INSTITUTE. This committee should be instructed to confer with manufacturers, consulting engineers and prominent users of electrical apparatus, and report its recommendations to this INSTITUTE.

MR. W. A. MOSSCROP, (Communicated):—Mr. Chairman and gentlemen: there could hardly have been selected for discussion by the INSTITUTE's members a subject more broad in its scope.

To standardize generators, motors and transformers will require the formulation of specifications covering:

1st. The physical properties of the materials used in the construction of their several parts.

2nd. The proportions of general features that are common to the product of the different shops in each class.

3rd. The design of special details of construction for the different sizes of the different classes.

4th. Methods for testing.

The statement is axiomatic, that the formulation of specifications covering these points is the duty of the engineers.

The question that presents itself is, whose engineers—the manufacturer's or the buyer's?

The decision of this question should be governed by a determination as to who is to be held responsible for possible failures in the performance. If it is to be the engineer for the buyer, then it is his right to formulate specifications covering such features as in his opinion will ensure successful performance. If, on the contrary, it is to be the manufacturer, then he should be allowed a voice in the formulation of specifications, covering the details of design and manufacture.

When there is under consideration the construction of work of special magnitude or of special requirement, the buyer's engineer will in general make the specifications. He will best serve the interests of his employer if he gives due consideration to all the manufacturing experience he can get. When he finds conflicting statements, his is the duty of deciding so that his employer will get the best and the most for his money.

When we consider the design of details of construction of machinery for the general market, which calls for standard sizes, they are found to be matters whose choice is largely governed by shop practice, convenience and cost. Many of them are born of shop experience based upon theory. As such they are matters belonging to the manufacturer, and it will be certainly impossible for the INSTITUTE as a body to undertake the formulation of specifications covering them.

There are, perhaps, some general features of quality, design and test, for which standard specifications can be formulated, but it seems hardly possible that all the conditions governing the design of electrical machinery have yet reached the stage where one standard can be adopted for all manufacturers. It would seem that the certain way to obtain standards covering these points would be for those who are in possession of facts of interest and value in this connection to present them before the INSTITUTE by papers or by communication.

The method by communication possesses features of considerable merit, and its extension would result in bringing into closer touch with the members in New York and Chicago those who reside at a distance from these two cities. In this way standards would be obtained by virtue of a system of natural selection in which the fittest only would survive.

Some manufacturers, of course, object, and very properly too, to their engineering force presenting before the engineering societies new points within their experience, because their general publication might lower their value to a private holder.

We are, however, permitted to enjoy the fellowship of some of the brightest minds in the engineering profession who are connected with manufacturing interests. Much of their knowledge will be available to us as they find that its publication will not conflict with the interests to which they owe their first duty. And engineers who receive compensation for their services owe their first duty, in this respect, to those who employ them.

It is the manufacturer's duty to standardize his product. It is our function to help him and his employees to the attainment of the knowledge necessary for the successful manufacture of electrical machinery, and to help the buyer to make a proper selection. It is our business to bring out the facts by means of papers, communications and discussions, and it is the business of the manufacturer and the buyer to apply them. Those facts that commend themselves generally will be generally adopted, and will become standard by virtue of their fitness, and no other can be forced. If, however, there is a general belief that by formulating specifications covering some of the general requirements of the machinery under discussion we would advance the interests of the science with which we are connected, there can be most certainly no objection to our doing so. The subject needs, however, to be restricted before a plan can be outlined.

MR. ROBERT T. LOZIER:—I think the subject is an extremely broad one, but one that would be better handled in a small committee that could consider it in all its different phases. I think the general limitations are pretty well established for commercial purposes. I am speaking now only of direct current apparatus, not of alternating. I think we are doing very well at present on the existing standards. There are some details that would undoubtedly develop when the matter is placed in the hands of a committee, but any movement in that direction undoubtedly would result in a great deal of good to both manufacturers and consulting engineers—and, incidentally, of course, to purchasers.

THE PRESIDENT:—The appointment of a committee would be the natural action to be taken as the result of this meeting, but I think the committee would be very glad to have all the light possible upon the subject, and particularly the sense of the meeting, the general sentiment in favor of or against this idea, and how far it can go. I think the committee can take care of the details of such a question, but it is anxious to know the general sentiment which is very hard to get, except from a meeting. So the more light that is thrown on this subject, the more opinions expressed, the easier and more successful will be the work of the committee.

I will call upon Dr. Kennelly to speak upon this subject.

DR. A. E. KENNELLY: Mr. Chairman:—I think that the remarks we have listened to from Mr. Rice are so excellent that they require little amendment, at least on my part. I think the work of the INSTITUTE in regard to standardization should lie in the line of definitions, and not in the line of saying what should be, or should not be good apparatus, or what should or should not be good standards of apparatus. I think there are a good many phrases which are used which have different meanings, and which lead to a great many disputes, and if those phrases and definitions were formulated and standardized by the INSTITUTE, they would be of great assistance to the business and to all concerned. I think that is the proper province of an institution such as ours, in assisting and developing the business which it is our pleasure and advantage to promote. The questions of what regulation should mean, what temperature elevation should mean and how it should be measured, what efficiency should mean, etc., are eminently practical and proper technical questions which I think might save a great deal of trouble and dispute if they were settled and defined with the recommendation of the INSTITUTE. They would facilitate progress and enable people to understand each other with greater precision than they do at present. But I should be inclined to regard with disfavor any attempt made to standardize apparatus in any other way then by the process of evolution among business interests.

THE PRESIDENT:—This report that I referred to I think is of sufficient interest and application to the present case to justify me in speaking of it further. The committee that made the report consisted of Messrs. William Kent, J. C. Hoadley, R. H.

Thurston, Charles E. Emery and Charles T. Porter. The report itself is eleven pages long, and is followed by a code of rules for boiler tests, of forty pages, going into great detail and specifying just how these tests should be made; and while we have no such complicated problem as that, fortunately for us, it shows that it is common practice in that important profession and one that has produced successful results, to standardize the methods of test even to the extent of going into great detail, and our simple problem of deciding what method should be used in measuring temperature rise is a very small matter compared with the elaborate details given in this code of rules here, and it would therefore be safe for us to go into details. A general statement, and fairly specific rules as to how these tests should me made is desirable, particularly when it is remembered, as I have pointed out, that they are mere recommendations; as to whether anything more than recommendations as to methods is to be given is a point I think that ought to be considered, because I think that would be a very important one in the deliberations of the committee. If the general sense of the INSTITUTE is unfavorable to it, the committee would not have to consider that question at all; but if that question is brought in, it will be very difficult for them to decide just how far it is advisable to go. Mr. Rice suggested that three or four different frequencies would cover most ranges that were required in practice; whereas, as a matter of fact, we have many more than that. It would be interesting to know whether the various speakers would consider that a proper matter for standardizing. I think we all are somewhat hampered with the notion that this is going to be an absolute requirement from which there is no escape. There is nothing in these recommendations—if they are ever made—to prevent anyone from making another frequency. It will simply be an influence against multiplying frequencies, which in my opinion are absolutely unnecessary. Personally, I confess, I would like to see the standards adopted—not forced on the public, but simply adopted for mutual convenience, in the same way that standard screw threads are adopted—not that you cannot make another screw thread if you see fit, for certain purposes; but it is for the common convenience of all concerned that certain standards should be adopted.

MR. TOWNSEND WOLCOTT:—If I understand the situation, there are two ideas about standards—one, recognized standards in methods of testing; and the other, standard apparatus itself. Is that correct?

THE PRESIDENT:—That seems to be the way the discussion shapes itself.

MR. WOLCOTT:—I think recommending standard methods of testing is a very good idea. So far as the apparatus is concerned, I think it will eventually standardize itself, in the same sense in which you have been speaking; that is to say, we have standard voltage for constant potential continuous current. We have a so-called 110, which may be anything up to 125. If anybody wants another voltage, he gets it, but there are a great many more machines built with that, and the double voltage, 220, than there are of the intermediate ones. Dr. Kennelly remarked about the commercial conditions of the case. I think that is what determines it, and I think these odd voltages are disappearing. I know they are discouraged by manufacturers. If asked for a machine of an odd voltage for any purpose now, the manufacturer will always tell you: We can give you that machine if you want it, but it will cost more; and that is about as strong an argument with most people, to stick to standard voltages, as I can think of—they have got to pay more for the others.

THE PRESIDENT:—If there is that influence that Mr. Wolcott speaks of, that anything but standards, after they are adopted, would naturally cost more, and therefore their use discouraged, that should be the fact, but not always is the fact. I think there is a tendency on the part of a good many people to prefer something that is not standard for some reason that is entirely unintelligible to me, and it is desirable, I think, to protect ourselves against such individuals that such standards should be adopted. The general question, of course, as Mr. Wolcott says, seems to divide itself into methods of testing and the standardizing of apparatus. There seems to be a nearly unanimous approval of standard methods of testing, but considerable doubt, in fact unfavorable opinion, in regard to standardizing apparatus.

DR. CARY T. HUTCHINSON:—I think, with the other speakers, that there is no question as to the advisability of doing something in this direction. The difference of opinion seems to be how far we should go. I doubt the advisability of attempting to establish standard methods for testing different machines. Such things, I think, take care of themselves. On the other hand, I do think that standards of performance should be established, and that incident to this, the meaning of such terms as "regulation," "efficiency," "heating limit" and others should be clearly defined. As the matter now stands, many electrical manufacturers will accept any specification from engineers, hoping, in case they fail to comply with its terms, to clear themselves by some dispute on the definition of the terms employed in the specification. Hence I think we would better specify conditions of performance, and define clearly the terms involved, rather than attempt to outline standard methods of testing.

There is by no means an agreement of practice between the different electrical manufacturers, even in such old matters as the design of small direct current machines. I have recently found the greatest diversity in machines of this type made by the different manufacturers.

I agree with Mr. Rice that this work should be done by a committee. I think that this committee should be a small one, composed of members who can get together conveniently and frequently. In other words, that it should be a working committee rather than an honorary one. Moreover, I do not think that any electrical manufacturing companies should be represented on this committee. To have all of them represented would make the committee cumbersome; to have one or two represented, and exclude the others, would prejudice the work at the outset. I think the committee should cultivate the most friendly relations possible with the different manufacturers from whom, of course, it would be necessary that the committee should get much data and information. Representatives of the different companies should be invited to consult with the committee, and it is highly probable that it would be proved advisable to make various tests at some of the different factories. For all these reasons I think it would be highly inadvisable to have the different manufacturers directly represented. Not one of them, I believe, would be willing to give free access to its shops to a committee composed of members of rival companies.

THE PRESIDENT:—The matter that Dr. Hutchinson referred to, the composition of this committee—is a most important question, and it would be well, I think, if this matter were discussed as to whether manufacturers should or should not be actual members of that body.

I will call on Mr. Lieb for his views on this subject.

MR. JOHN W. LIEB, JR.:—I fear that I cannot add much to what has already been said on a rather broad subject. As to the desirability of standardizing types of apparatus, I am inclined to agree with what several of the previous speakers have said. It has been pointed out that the electrical industry bears the stamp of the general tendency of American manufacturing methods—construction, so as to secure interchangeability and duplication of parts. I think that the electrical industry, as of more recent development, has profited perhaps more largely than other industries by American manufacturing methods by using labor saving devices, working by jigs, templates and other devices for rapid duplication of parts. This is somewhat in contrast with European methods in similar industries, where, I think, a marked tendency is manifest to depart from standard types. This is the case, for instance, with direct driven dynamos, particularly if they are driven by turbines. Each turbine, practically, is designed and developed for the specific case, considering particularly the conditions of fall, discharge, etc. The result is, of course, the most efficient type of apparatus to fill each condition. It must, however, be admitted that it is rather an expensive method, each construction requiring special patterns and special development. I believe that the INSTITUTE would be doing valuable work for the industry generally, for the manufacturer and for the purchaser alike, if it could take hold of the work, and starting with certain definitions of quantity, follow on to define or recommend what should be reasonably expected from a standard piece of apparatus as regards capacity, insulation and other characteristics that have already been touched upon by previous speakers.

I would like to point out one, I might almost say insignificant, phase of this question; its relation to electricity supply companies. The tendency to-day is away from the practice that obtained at one time of basing the charge for current delivered to electric motors, on the capacity of the motor, or the charge of a flat rate per month per motor, based on its horse-power. While we have gone beyond that stage of the industry, it is still the practice of many companies to consider the rated capacity of the motor as a factor in its system of charges for current, fixing a minimum charge per month, depending upon the size of the motor installed; the horse-power capacity of the installation, its equivalent in kilowatts or 16 candle-power lamps entering as a factor in fixing the rate. I will not go too far afield in this direction, as it is comparatively one of the unimportant elements. The committee having in hand such an important piece of work should, as suggested by one of the previous speakers, be untrammelled by any direct relations with the manufacturing companies. I am sure the manufacturing companies would be most happy to place at the disposal of the committee, all the information and practical data which they have at command, but it seems to me it would be undesirable for any manufacturer to be represented on the committee. I should think they would prefer not to be directly represented. On the other hand, it would certainly be desirable that the committee should profit by consulting with those who represent the different classes of service to which the apparatus is put. It might be desirable to have apparatus which is used in an isolated plant conform to certain conditions of overload and regulation, while apparatus in a large central station should satisfy other conditions; the committee will probably find it difficult to formulate any general rules or specifications covering all conditions of service, but they would certainly do very excellent work by setting up some standard for general reference in order to minimize the questions which are constantly arising along the lines of the discussion this evening.

THE PRESIDENT:—I think Mr. Lieb is right in saying that the manufacturers would probably prefer not to be on that committee; but it is open to question, I think, whether if it were composed entirely of purchasers of the apparatus it would be as competent a committee as if it were composed entirely of manufacturers. There are three sides to the question, as Mr. Rice has pointed out in his paper—the manufacturer, the purchaser and the consulting engineer, and leaving out any one of them you do not necessarily produce any better result. I would like to have Dr. Kennelly speak on that point. In private conversation he has taken a different position and I would like to have that side of it expressed.

Dr. Kennelly:—The attitude taken by the different speakers this evening upon that point as to how the committee should be made up, is somewhat different from the manner in which I have thought about it. It seemed to me that having a committee to recommend how manufacturers should make apparatus, without having any manufacturers on that committee, was something like playing Hamlet with Hamlet left out. This is a matter which vitally interests all manufacturers. It is for their benefit, as well as for the benefit of those who purchase from the manufacturers, that such a committee would ultimately be doing this work, and in some way or other the manufacturer must be consulted, whether they are consulted by having them off the committee and asking them what they think, or whether they are consulted by having them on such a committee and assisting the lucubrations of the committee with their actual presence, is a question which admits of several considerations. I think there is one advantage of having manufacturers on the committee—it would be a safeguard against anything being recommended by the committee which could possibly give umbrage to other manufacturers, because I think that if one manufacturer saw a recommendation going into the report of the committee that would look like unfair play, he would be the very person to object to it, and I think it would be a good safeguard against any injudicious recommendations being formulated. But I think that this is a matter of opinion, because sooner or later the manufacturers must be consulted.

The President:—I will call upon Mr. Dunn to discuss this question.

Mr. Gano S. Dunn:—The problem as it has been discussed increases so greatly in magnitude that I fear our action will be discouraged. Let us not attempt to deal with the whole matter or to cover the whole field at once. I recommend the appointment of a permanent committee that shall sit through several years, and from time to time, as convenient subjects come up, shall standardize and dispose of them. For instance, the methods of measuring temperature rise could be dealt with immediately.

At present three standards of temperature increase are in vogue, and while believed by many engineers to be nearly equivalent, are different to a great degree. One requires that the rise of temperature in no part of a machine shall exceed the specification limit. Another, that the rise of temperature as measured by thermometer shall not exceed the same limit, and another that the rise of temperature as measured by increase of resistance shall not exceed the limit.

I have in my hands details of certain experiments which I will not now give, because I see the discussion has been trending in another direction, but the results show temperature measurements by thermometer differing in some cases from temperature measurements by resistance, by over 100 per cent., while in other cases the two methods reach a result different by only 20 per cent.

An immediate action that the committee could take would be to declare that in the opinion of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, the most accurate method of measuring temperature increase is by increase of resistance, and that as this method gives results considerably higher than the thermometer, the limits of rise should be newly set to be eqivalent to what has been the standard under the latter method.

This would settle the controversies arising over specifications where no method of measurement is specified, and would also direct attention to what the investigations of the INSTITUTE would have determined to be the most accurate method.

With regard to the composition of the committee, I think it would be very wrong to omit the manufacturers; as wrong as to omit the consulting engineers. I am not able to propose a solution, but my objection would be overcome by the appointment of members who are not manufacturers provided they had been at some time. The experience derived from actual contact with factory methods, is absolutely necessary to the successful determination of the questions affecting standardization of apparatus.

MR. H. B. COHO:—It seems to me that the proper way to do is to have two committees; not two committees in the INSTITUTE, but one a committee of the INSTITUTE, and the other a committee of manufacturers formed outside to consider their present standards. Of course, all manufacturers have their present standards. On the other hand, the committee of the INSTITUTE could, as Dr. Hutchinson states, suggest something that the manufacturers might work up to. Of course, if a manufacturer does not have to make new patterns, he considers himself so much better off, and naturally will not make new patterns if he can help it, whereas the committee from the INSTITUTE might suggest to the manufacturer improvements which he could from time to time adopt. There is one point, it seems to me, on which the INSTITUTE could do something, and that is in the matter of alternating current, especially with reference to motors. The great number of frequencies we have to contend with makes it almost impossible for a man to sell a motor of his own make to go on anything but his own generator. It is very seldom that a motor of one system will work on that of another, satisfactorily. Of course, I realize that this is one of the arguments used to sell complete plants of one make.

It seems to me a very good idea to have this matter taken up, but I agree with Dr. Hutchinson that manufacturers are hardly the proper persons to place on the committee, unless there is a representative from each of the manufacturers, it being, in my mind, very difficult to satisfy one manufacturer that another manufacturer is not prejudiced in his own favor.

I think the subject of alternating current, especially in regard to transformers and motors, would be a matter which could be readily brought up and discussed with a great deal of advantage.

THE PRESIDENT:—I doubt very much if the action taken will be far enough. The conservative idea that seems to prevail will prevent, I think, any action being taken which will discriminate between manufacturers. I think the action taken will be so very general that it will not fall hard on any individual. The idea at present seems to be that only a very general action should be taken, and I think it would not affect one manufacturer much more than another. It is simply the manufacturer's point of view in general, I think, that Mr. Dunn has contended for rather than any particular manufacturer's point of view.

MR. FRANK A. PATTISON:—It seems to me that we should consider why this question is brought before the INSTITUTE. There is evidently some cause that has made this question what we might call in electrical circles the living question of the day, and it seems to me it is due to the fact that we cannot understand each other. The manufacturer does not understand the engineer. The owner does not understand the engineer. The owner does not understand the manufacturer. Now, when two men start out in a discussion and want to arrive at some definite conclusion, the first thing that they reasonably agree upon is certain definitions which, if used, mean certain things and cannot mean anything else. Now all the disagreements that have come within the scope of my experience have arisen from the fact that people did not understand each other, simply because they did not understand the terms used in the same way. Therefore, it would appear that the solution of the problem is not in the standardization of the apparatus, which is an impossibility. Standardization of apparatus is a natural growth, and the minute you attempt to arbitrarily standardize anything that is going through a natural growth, you at once stint it, and it seems to me far from the right path of this INSTITUTE to attempt in any way to standardize the apparatus itself, which practically means that a 50-kilowatt machine shall be a 50-kilowatt machine "INSTITUTE standard" for example, that that means one thing, and that it cannot mean anything else; that whenever that term is used it must always mean the same thing. That is an impossibility. Standardization cannot be attained in that way. As to the committee which should take this question up, it seems to me that in a body of the standing of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS that they have no need to fear that the action of any of their committees will be questioned on account of the composition of that committee. Therefore, I am of the opinion most decidedly that that committee should be appointed by the Chair and should be composed of men who in the Chairman's opinion are best suited, regardless of whether they are manufacturers, engineers or users, and that that committee should be a permanent committee; that that committee should define terms to be used, but should not attempt in any way to define or standardize apparatus at first, and that it should deal not only with the questions that are before us to-day, but that any questions wherein definitions arise that need standardization should come within the scope of that committee, and that it should be a permanent committee of the INSTITUTE.

MR. LOZIER:—My thoughts are very much in line with what Mr. Pattison says. I would like very much to get the sense of the meeting as to whether they think the standards should be passed only on safety limitations instead of what would be desirable performance of the apparatus. I think in a great many insurance standards laid down for boiler testing, and also for steam engine testing, the terminations there are on certain fixed lines which do not necessarily call for desirable performance, but that in fixing the lines on which the tests should be made, the apparatus is restricted to certain safety factors. Now if we could determine for motors, for example, (or for dynamos) what was an exact safety limit for a 10-hour operation, that safety limit could be modified for different types and forms of machines. This is a point on which I should like to have an expression of opinion.

THE PRESIDENT:—I do not understand exactly the points you desire to bring out.

MR. LOZIER:—The point is this: Cannot the INSTITUTE lay down certain safety limits? It would seem to me that for instance the question of sparking—of course, this is rather hard to determine—but take the question of temperature alone. That has a certain safety limit that I think the INSTITUTE could determine. Of course, there are other determinations that I think would appear desirable, but at the moment I have more particularly in mind the question of temperature, and if it would not be best to have those safety limits determined by such a committee rather than what they would consider to be a desirable temperature. One man, for example, might think it would be desirable to have 35 degrees C. for a 10-hour run, while another man would want 38, while the safety limit could be used as a fixed quantity.

THE PRESIDENT:—Do I understand that you desire to have an expression of the sense of the meeting as to the actual safety limit, as to the desirability of specifying a safety limit for a rise of temperature?

MR. LOZIER:—Yes, that general feature. I think that would give us one of the quantities that should be specified within the limits of safety. I do not think that limit has ever been positively determined. We have arrived at 40 degrees C. That seems to be the generally accepted safety limit. That might be so, but it might be less than that. It might be greater. But it seems to me that we could arrive at certain fixed constants that would represent elements determined by the safety factor in distinction to what would appear to be desirable performance. I think "desirable features" is an open question.

I think this general plan of safety limits can be made to apply to more than the temperature, but I simply state that as an instance.

THE PRESIDENT:—Before putting this or any other question to vote, I think it would be well for the discussion to be completed, and it would also be well, I think, for the INSTITUTE to decide whether it cares to vote on these specific questions or not. Any question on the subject is in order.

MR. F. V. HENSHAW:—It seems to me before we go into these specific details as to what is to be standardized, and so on, it would be rather well to decide as to whether we will adopt the suggestion of a standing committee to take up these matters. I would like to say one thing in regard to the *personnel* of that committee. I do not quite understand why the INSTITUTE is so rough on the manufacturers. The standards which we have, and we have quite a number, as the result of a good many years of evolution, have all been developed by the manufacturers endeavoring to meet the demands of the public, and really to-day the best practical data we can get anywhere is from the published catalogues and tables of the various manufacturers. I furthermore agree with the recent speaker that members of the INSTITUTE ought to be like Cæsar's wife, above suspicion, in regard to furthering their own interests, and furthermore these recommendations will be submitted to the whole INSTITUTE, undoubtedly, before they are finally authorized by that body, and any member, if he has anything to object to, is always at liberty to object to it.

MR. N. M. HOPKINS:—I would like very much to hear a general opinion, not on the advisability of appointing a committee composed of manufacturing and consulting engineers, but on the probable work and decision of such a committee. I think a number of gentlemen have disfavored the appointing of a composite committee, so to speak, without thoroughly considering the question of their probable work and findings. I do not think there would be much conflict of ideas and opinions, even with such questions as efficiency of apparatus, highest permissible heating of armatures, field coils, etc. I do not think the findings of two separate committees, one composed of manufacturing engineers and the other of consulting or designing engineers would differ very materially. I do not think the manufacturing talent should be excluded from the committee.

DR. HUTCHINSON:—I see I have stirred up the meeting by my references to the electrical companies being represented on this committee. I gave my reasons for this position, and am sure that in practice the matter would turn out as I have stated. It would be necessary to have all the companies represented, or none. If you have all represented, then the factories of all would be closed to the committee for any testing work that the committee might have to do. I believe that the committee can get all the information it asks from the companies without having one of their representatives on the committee.

MR. CHARLES P. STEINMETZ:—The problem before the house to-night is undoubtedly a very important and a very difficult one. Now, as regards the question of manufacturers, there are undoubtedly some very good reasons why manufacturers should not be on the committee, and there are some very good reasons also why they should be on the committee. But it appears to me there are still very much better reasons why this question should not have been raised at all. If the INSTITUTE intends to produce something of lasting value, which will be accepted and adopted by the whole continent, then the committee doing the work must be composed of men of such standing and reputation that, regardless of whether they are connected with manufacturing concerns or not, there can be no question that they will be impartial and not influenced by the fact that they are connected with this or that company. But they must be the best men available, and then there will be no question about it whether manufacturers or not. Besides, the problem under discussion appears to me to have two different phases: one is the question of standardizing the meaning of terms, and the other is the question of standardizing the methods of tests. To arrive at a common understanding of the meaning of terms, or the constants represented by them, it is undoubtedly extremely desirable to have the terms standards. I may only mention the unfortunate term "efficiency," which used to mean in the old times the output divided by output plus C^2R, because C^2R was the only thing all people knew how to measure. But gradually it dawned upon them that there are some losses in the iron and consequently the question arose, should they be taken in the efficiency or not. After that there were other losses discovered in the brushes of the continuous current machine, etc. It is very desirable to standardize what efficiency means. Most of the discrepancies between engineers arise from the divergence in the understanding of the meaning of one of these terms. It may be quite desirable also to have standard methods of testing which is now one very great difficulty. The comparison with mechanical engineering is very nice, but we must consider that of the whole field of engineering, no branch is so much developed theoretically as electrical engineering, and if we consider the exactness of electrical engineering where you fight about a fraction of a per cent. of efficiency, with the exactness of mechanical engineering, where you make the beam that has to carry the structure of a bridge 500 per cent. stronger than calculated, you see there is great difference, and thus it may be quite desirable when making mechanical tests with the inaccuracy of mechanical engineering, to produce a standard or rather a recipe--how to make the test. But that would not do in electrical engineering. It would not do, for instance, in measuring efficiency, to say efficiency shall be tested by measuring the mechanical output by a brake, and the electrical output by an instrument. If you take a direct connected alternator of some 2,000-kilowatts capacity, you cannot get a mechanical brake to measure the input, and you cannot measure the output either, very well. From indicator diagrams of the engine you cannot get the efficiency, since the engine efficiency is so low that you cannot get any accuracy. So you see the only possibility in very many cases in determining these efficiencies is some abbreviated method. Efficiency usually is determined by measuring the losses and summing them up. Now, that is the best that can be done in many cases. But if the INSTITUTE should settle that efficiency shall be measured by adding certain losses it may be a dangerous thing, because there may be other losses coming in and there may be a difference of opinion as to whether there is loss or not. I mention, for instance, hysteresis loss, because hysteresis has always been my hobby. It is not quite agreed yet amongst all the engineers what should be charged to an alternator as hysteresis loss, whether the loss corresponding to the terminal voltage or the loss at a voltage corresponding to full load excitation at open circuit or some intermediary value. I especially gave attention to this feature and found that the nearest approach to correctness is derived by charging as loss the hysteresis loss corresponding to terminal voltage plus $C R$. It seems to me there may be other points of a similar nature where it would be liable for the INSTITUTE to settle on something that is wrong. So you see we might possibly discuss methods of testing before the INSTITUTE, or any committee, and make some recommendations, but we cannot with certainty determine these methods of tests as we should determine the meaning of terms, and that I think would be the most important work to be taken up by the committee at first namely, to decide on the meaning of terms used in electrical engineering.

MR. C. O. MAILLOUX:—I rise to a point of order and information. I think that the present Committee on Units and Standards is competent and that it is within its province to take up questions of terminology.

THE PRESIDENT:—Mr. Mailloux brings up the point that we have a standing Committee on Units and Standards, the name of which and the history of which would, I think, justify his position that the mere question of considering terms and definitions would be taken up by that committee and such questions have been considered by it in the past. This was considered to be rather a new and broader question than the one now proposed. It should be remembered that this committee would, in any case, report back to the INSTITUTE for final action. Therefore, the work of this committee would simply be preliminary and subject to revision.

Mr. Max Osterberg:—It seems to me that if we should have a committee which would determine on the general requirements of all machinery as regards temperature, different kinds of efficiency, etc., if we had a committee to determine these points, we would necessarily require a definition on the part of such a committee of what they mean by the individual terms. How, for example, they would recommend that temperature should be measured in order to satisfy the condition of what they call the requirement. It does not fully bind all the manufacturers to fulfil those, but it would certainly be one method to go by for the manufacturers in general and for the guidance of the consumer as to what he ought to require, or what he might be entitled to get. So it seems to me that since we have a Committee on Units and Standards, without treading on their toes in any way, we could have a committee to determine what the requirements of machinery should be and in that way get a direct distinct definition of the terms.

After further discussion as to the propriety of appointing a committee to consider the question, the point was raised that no quorum was present. It was then voted upon motion of Mr. Hamblet, that the whole matter be referred to Council, after which the meeting adjourned.

DISCUSSION AT CHICAGO, JANUARY 26, 1898.

THE CHAIRMAN, [MR. B. J. ARNOLD]:—Prof. Stine has read to you the letters which have been sent on here from various members of the INSTITUTE and others in New York, calling our attention to the desirability of an action or expression on the part of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS regarding the standardization of electrical machinery. This is something which those of us who are in practical work are ready to consider and see if some standard can be adopted. The electrical manufacturers of to-day, in fact, are endeavoring to find out from engineers and purchasers of electrical machinery what their ideas and desires are as to the heating limits of the machinery. In fact, one of the largest manufacturers of electrical machinery has sent a representative throughout the country, calling upon the principal engineers, and getting their ideas as to what they thought these limits should be, and I have no doubt but that others are doing the same thing. Therefore there seems to be a great desire on the part of the manufacturers and certainly on the part of the purchasers and engineers to have some such standard which will be recognized, *as a standard.*

MR. MEYER:—I think that a standard in any line of machines is certainly a very necessary thing. For instance, in machine shop practice and in electrical apparatus as well, there must be some uniformity. In dynamos it is a good thing to have all shafts of the same size and diameter, which could be used in different machines. In case of a breakdown, if there is but one shaft, it could only be used for the machine for which it was originally made. If any standard is made, it would be of great benefit. The necessity of standardizing this particular line has been recognized by many who use the apparatus and by the makers as well, for the latter have to carry a larger stock and invest heavily in machines to make apparatus, as well as in ready made parts, to supply orders on short notice. Outside of dynamos, I should think some standardization would be necessary, as well as instruments not so essential as dynamos, because instruments are usually less expensive than large dynamos. For arc lamps or incandescent lamps I should think there would not be so much standardizing required, for the lamps are now usually of the same voltage and candle power.

MR. J. R. CRAVATH:—As I understand the subject, it is to consider the subject of standardizing the rating of apparatus, not the form of the apparatus itself. We all realize that some standards are needed. The only question is, what standards? It does not make a great deal of difference what standards are adopted, so that it is perfectly understood what those standards are. At present we are all at sea as regards to what the heating limit of a machine should be, and how it should be measured, and if we can come to some conclusion or arrive at some proper definition as to what these heating limits are, we have made a great step in advance. The manufacturing concerns want it, I know. We need a standard now perhaps more in the railway field than in any other as is shown by the great frequency with which some manufacturers of electric railway motors change their methods of nomenclature in the attempt to get some way of rating more satisfactory to maker and customer. If however the INSTITUTE can formulate some standards for all to go by, the difficulty immediately disappears for it is only because of a lack of understanding as to how ratings are to be made that these differences exist.

MR. HICKOK:—Taking up the points for discussion in the order in which they are outlined on the black-board, let us first consider the proper and safe heating limits for dynamos and motors. For a machine working under normal condition, the temperature rise above the surrounding air should never exceed 80° Fah. on the armature core, 100° Fah. on the commutator, and 75° Fah. on the field coils, these temperatures being taken by applying thermometers to the outside of these parts. Standard specifications should give these heating limits after a continuous run of ten hours at the rated capacity of the machine.

Requirements for the sparkless range of the average machine should be that it should stand a change of load from no load to full load without any sparking at the brushes, they being fixed at the same position throughout the entire range.

Various engineers have their hobby as to what they consider the amount of overload a machine should stand safely, but I think that any dynamo or motor should be capable of being operated continuously for three hours at 25% overload, or for one hour at 50% overload, without causing any injurious effect.

In regard to the question of power rating, it is generally understood that dynamos should always be rated in kilowatts, and never in horse power, although the latter term does occasionally creep in.

Motors should always be rated in horse power, as that seems to be the most natural term for mechanical power, and the common formulas for work to be performed have H. P. for the unknown quantity.

If specifications are to definitely state what the insulation resistance of any machine shall be, I should think that a requirement of not less than one megohm would be sufficiently rigid for the average 110,220, or 500-volt dynamo or motor.

MR GEORGE A. DAMON:—That standard requirements for the manufacture of electrical apparatus would be desirable, is very well brought out by the tests which we recently made upon two 100 K. W. multipolar generators of the most modern types, but of different makes. One was a belted machine running at 600 turns per minute; the other was direct connected to a high speed engine. The belted machine after a run of six hours under full load had a temperature in no part higher than 104°, less than 30° above that of the surrounding atmosphere, while on the other hand the direct connected generator showed a rise in temperature of over 90° after it had been running for the same length of time. One dynamo was certainly capable of standing an overload of 25 per cent. for a number of hours, while the other generator was working at about its safe limit. Both machines were accepted, but it is plain that one purchaser got a far better machine than did the other.

In regard to the heating:—The specification which a few years ago placed a limit of 75° Fah. rise in temperature upon generators was considered severe, now it is ordinary practice, and I believe we have reached a point where we may ask the manufacturers to be liberal with their ratings. The overload requirements influence, of course, the permissible heating limits, and should be standardized as far as possible at the same time. The engineer, who recently specified a machine of a certain capacity which "should be capable of standing a continuous overload of 50 per cent." at least did something to help along this movement.

Standard specifications should not only state the requirements, but should accurately describe the tests to which it is proposed to subject the apparatus in order to ascertain whether or not it fulfils the terms of the specifications. It is fully as important a matter to modify the methods of making tests upon electrical apparatus, as it is to standardize the requirements under which it is manufactured. It is not an unusual thing for engineers to prepare long and elaborate specifications for electrical machinery and then turn around and accept it after only a few crude tests or perhaps none at all. Take the matter of efficiencies for instance. We like to write in our specifications, 94½%, 94% and 93% as the requirements for the commercial efficiency of our generators at full, three-quarter, and half load, but how many of us are ever quite sure that we get what we call for? I find the literature upon commercial efficiency tests very incomplete. Efficiency curves are published now and then by manufacturers and others, but seldom are they accompanied by any indication of the method by which they were obtained. I find that even large manufacturers are dissatisfied with the accuracy of the results of their efficiency tests, and there seems to be no unanimity of opinion in regard to the best method to be used. Besides a few laboratory methods which are not commercially practicable, we have the Hopkinson method, the stray power method, the indicator method, and now comes a new method called the Routin method. But we know most of these methods are based more or less upon certain assumptions and are therefore liable to be incorrect. In the Hopkinson method we assume that the motor and generator have the same efficiency, whereas to operate the generator at full load it is necessary to overload the other machine which is running as a motor. In the stray power method we assume that the loss in the armature when the machine is running itself as a motor with no load, is the same as when the generator is operating fully loaded, while in the indicator method we must necessarily assume that the loss by friction in both the engine and generator, as obtained in a rather uncertain way from the friction cards, remains constant at all loads. The question is, how accurate are these various methods and how will results by the different methods compare? It strikes me that a series of tests upon the same machines, under identical conditions, by the various methods, would be of value. Our Englewood and Chicago plant and the Chicago Board of Trade plant are admirably adapted for this purpose. In these plants the engines and generators are connected by means of the "Arnold system" so that it would be an easy matter to disconnect the generators from the engines and run any one as a motor, either independently or connected to another machine. As both plants are provided with storage batteries it would be comparatively easy to measure the power required to make up the losses in the manner provided for in either the Hopkinson, stray power, or Routin methods, and I hope to be able to obtain some data along this line. One of our prominent technical schools has its campus lighting plant connected by means of the "Arnold system" and a large builder of dynamo electric machinery is planning a testing table along the same lines, so that it is possible to obtain accurate information as to the relative limitations and possibilities of the various commercial systems of testing. It would be well then to accompany our standard specification efficiencies with a detailed account of at least one of the most reliable methods, if any such are found, and the same can be said of the tests which should be provided for the heating limits and the sparking, insulation and overload requirements.

PROF. STINE:—The proposition that there should be an attempt made to establish certain standards governing the drafting of specifications for the construction and operation of electrical apparatus, is meeting with such general favor that it argues a decided need for such things. The manufacturing companies have long felt that something should be done towards freeing them from burdensome, and, at times, unjust or impossible requirements which consulting engineers have imposed upon them. Recently, a set of specifications for some transformers was sent to certain manufacturers. The guarantee which they demanded from competing firms covering regulation, core aging, efficiency and temperature of operation, were incapable of being met in the present state of art, and plainly showed that the engineer who drafted them was not experimentally familiar with the subject. It is manifestly unjust to ask for bids on such a basis.

The desirability for standards governing construction, operation and testing of electrical apparatus is so generally admitted that it scarcely requires further argument. It is rather a question of agreement on a certain number of points to make a beginning. The National Electrical Code, recently adopted, shows us how to go about the matter. When first framed, it was exceedingly crude and incomplete; but anything was sufficient for a beginning, and the elaboration of the rules, as time progressed and experience widened, has been most satisfactory.

In a similar spirit let a beginning be made towards standard specifications. We know a great deal more about this subject than the insurance people did about installation in the early days of the code. We are, then, better prepared for the task and will run less chance of making errors.

No association is so representative of all interests, or contains such a wealth of experience, ability and data as the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS. The question of immediate ways and means may be left with the Council, which in turn would doubtless approach the subject through an appropriate committee.

The functions of the consulting engineer are interpreted with the widest latitude. In many instances the consulting engineer attempts the duties and responsibilities of the designing engineer. But it is not always possible to separate these. The consulting engineer may properly specify both materials and design when he endeavors to make some particular combination, and the company receiving the order is so conservative as to be behind the times. But the consulting engineer is rarely in position to specify design and materials. He has had comparatively little to do with the progress in electrical apparatus. This has come principally from the manufacturing companies, and some few testing laboratories working in co-operation with them.

As matters now stand, the consulting engineer should draw up a detailed plan of what he wishes to accomplish. This should be submitted to the manufacturing companies as the basis for bids. They in turn should then fully specify the design, construction, materials and operation of the apparatus which they tender and state the guarantees. The engineer may then gather from the competing specifications and bids the possibilities upon which he may form a final set of specifications. This ensures the competing companies the full use of their experience in construction, selection of materials and data from tests.

At the present time, there is opportunity for only a limited number of standards which shall govern the consulting engineer and manufacturer in the preliminary work.

It would be manifestly unjust and a prevention of progress to adopt standards for induction value in the iron circuits of dynamos and motors, and the cores of transformers; to specify that cast iron shall be used here, and sheet steel there, etc. Such matters as these, and practically all details of design, construction and selection of materials should be left open.

But there is still an opportunity for many standard requirements; these occur in (a) the operation; (b) the testing; and (c) the rating of apparatus. Covering the tests of apparatus I wish especially to speak. Specifications usually make quite a matter of temperature limits for different portions of electrical apparatus. The assignment of such limits would be very properly within the duties of such a committee on standards. But the manner of testing whether the machine fulfils such requirements ought to be clearly prescribed. Every one who has carefully tested the heating of transformers under load knows that a number of different temperatures may be measured about the coils and core, depending upon the manner of applying the thermometer and the part where it is inserted. Here is a real necessity for a standard direction governing the use of a thermometer in ascertaining the temperature of cores, fields, windings, and bearing and conducting surfaces.

The efficiences of apparatus at various loads is usually strongly insisted upon in specifications. Yet those who devote most attention to such tests know that with the exception of photometric tests they are the least satisfactory of all electrical measurements, on account of the uncertainties in the estimation of the power applied to a given translating device. Though specifications often designate efficiencies to a second decimal, they are rarely measured within one or two per centum, at best, and more rarely are engineers able to verify their own specifications regarding efficiency. It is very desirable that a committee on standards should formulate precise directions for a determination of efficiencies.

So far as dynamo and motor characteristics enter in specifications, their determination should also be specified. In the same connection, the rating of the output of continuous and alternating current generators needs careful definition.

Another subject of great importance is the specification of the quality of insulating materials. Common practice states this in megohms, presumably to be determined by some galvanometer method for measuring high resistances. This is unjust to the progressive manufacturer. Such ratings are practically of little value as a guide to the operation of the apparatus. No manufacturer is justified in relying on a high insulation resistance, and specifications requiring this often place the most excellent apparatus at a disadvantage. The only adequate test of an insulation is its dielectric strength. As this is usually tested with a step-up transformer, there should be some standard agreement governing the periodicity and perhaps the wave form of the E.M.F. impressed on the insulation; also an accepted agreement making mere high resistance requirements secondary to those of dielectric strength.

MR. HICKOK:—I would like to say a word in regard to the insulation and the breakdown test. I think we should also include a definite insulation resistance, for the reason that I have in mind a certain instance of a machine having its field coils wound with tape, and although it was submitted to the breakdown test, it had no injurious effect upon the machine, yet its measured insulation resistance was very low.

The customary rating of arc dynamos is in so many lamps, that is, 50, 75, 100, 125, etc. It might be better to rate them in watts.

PROF. STINE:—Do you consider it possible to-day to specify the efficiency of an arc machine.

MR. HICKOK:—Yes, it is possible to measure it within a fraction of one per cent. with a considerable degree of accuracy, but such an accurate test is necessarily an expensive one.

PROF. STINE:—Is it possible to come to any uniformity among makers on the question of efficiency of arc machines?

MR. HICKOK:—Most makers guarantee their machines, and they are frequently subjected to tests. I have several instances in mind of tests carefully made that gave very satisfactory results.

MR. ARNOLD:—If there is nothing further—no more questions to be asked, I would like to make a few statements as to what practice is followed in my office. On the question of heating limits of generators we have recently specified for some 500 kilowatt generators for light and power work, to be operated at 500 volts, 450 volts, 525 volts, for a certain station being built in this country, which is somewhat of a novelty, since the voltage is double what it ordinarily is in a direct current station. There are 440 lamps for the outside mains and 220 in the others. These generators have been specified pretty generally.

The sparking limits are such that the machines are practically sparkless all the way from no load to 50 per cent. overload, without changing the brushes. We expect to get that machine out. In fact, it is gotten out by a number of manufacturers to-day. I have seen the generator manufactured by the company Mr. Damon speaks of, stand the load from 0 to 50 per cent. overload without sparking. It is specified that the generators shall not flash when the circuit breaker is opened suddenly to 50 per cent. overload.

PROF. STINE:—In that same connection, do you put in any specification as to the self-induction of the armature?

MR. ARNOLD:—No. I am after the efficiency under different conditions of load. When we come to writing a practical specification, we have no means of determining that very closely.

These generators that I have mentioned are not to exceed these limits when operating under the following conditions at 25 per cent. overload for two hours, 33⅓ per cent. overload for one hour, or 50 per cent. overload momentarily. The efficiencies we have required are as follows:

At one quarter load	90 per cent.
At one-half load	93½ " "
At three-quarter load	94½ " "
At overload	95 " "

Such a scheme should define the limits that the generators may have, and let those limits be far enough from the drooping point on the curve so that it has a somewhat surplus path to go over the rating. The sincere manufacturers to-day are coming close to these figures which I have given here. But as we all know, the capacity of a machine, its kilowatt output capacity depends entirely upon its heating limits. It is a matter of limiting the temperature to determine the capacity of the machine.

Prof. Stine:—Would you say that that would be the only limit or would you find a droop limit?

Mr. Arnold:—There would be a slight variation of voltage when we get over the drooping point on the curve. As to how much that variation would be, I am not just at present prepared to say. I think it advisable to make such a limitation in specifications, or rather, a set of recommendations.

I also agree with one of the speakers to the effect that it is not advisable to specify sizes at all; but it is hardly within the scope of this discussion to go into the matter of sizes, as I understand it, because we wish to leave the matter of sizes to the manufacturer. Let him accomplish the result, but give us the thing we ask for in efficiency, heating limits and capacity.

Prof. Stine:—In specifications, I would specify weights, areas, and velocities, but I would not attempt to specify diameters, lengths or strengths. Possible the latter might be considered, but not the other two.

Mr. Arnold:—Another thing: The only correct way to get the temperature of the field is to measure after or during the test. It is seldom done, but I believe it should be done, instead of trying to use a thermometer when we only get an approximation. Power rating should by all means be given in kilowatts, if possible. That is the only way to do it. We certainly have got the generators in shape for that basis, and in time we will measure engines in kilowatts instead of horse-power. In measuring generators by horse-power it has to be figured up in kilowatts afterward.

In our specifications we specify mica insulation, and seldom use anything else. For a generator in which anything but mica is used, the regulations depend upon the kind of work you want the machine to do. In the machine I have mentioned the winding should maintain the voltage at 500 without the assistance of the series winding.

Prof. Stine:—You mean to say up to full load? With what range in the rheostat?

Mr. Arnold:—The rheostat controls from 400 to 500 volts. I do think this question is one of the most important which has come before the Institute since my membership in it, and it ought to be taken hold of in some kind of intelligent manner, and see if some result cannot be obtained which will bring the purchaser, the engineer and the manufacturer on some basis where they can agree, and not have the constant argument which we have to-day as to how a machine ought to be rated. If there was a plan which, in the combined judgment of the best thought in this line in the country, it would relieve a great many of the embarrassing conditions which now exist.

MR. HICKOK:—There is always a question, when the subject of efficiency comes up, as to just what the term "efficiency" means. Some engineers include with the engine losses the entire friction of the revolving parts, and also the friction of the brushes on the commutator, thus giving to the dynamo an apparently high efficiency. I think specifications should define more particularly what is meant by this word.

[Adjourned.]

[COMMUNICATED AFTER ADJOURNMENT BY CHARLES F. SCOTT.]

The desirability of uniformity in ratings and specifications of electrical apparatus to consumer, consulting engineer and manufacturer, would be obvious to anyone, but their full advantage is best appreciated by those who suffer from the difficulties and confusion which now exist.

As an example, the rating of an alternating current generator may be mentioned. Suppose a generator of 100 K. W. at 1,000 volts is to be used for operating motors which have a power factor of 90 per cent., a "100-K. W." generator may mean:

(1) One which can deliver 100 K. W. to non-inductive circuits, such as for incandescent lighting.

(2) One which can deliver 100 amperes at 1,000 volts at a power factor of 90 per cent. The true output in power is only 900 K. W., while the tax upon the machine is considerably greater for delivering this current at 1,000 volts to an inductive load, as the field current must be notably increased on account of the reaction on the field caused by the lagging armature current.

(3) One which can deliver 100 K. W. of true energy to circuits having a 90 per cent. power factor. The current required is 111 amperes, and as the power factor is 90 per cent., the tax upon the machine is considerably greater than it would be if this current were delivered to a non-inductive load.

These three performances require machines differing in capacity and represented by machines which can give approximately 100, 110 and 120 K. W. to non-inductive circuits.

The fact that these characteristics of alternators are not generally and correctly understood, makes the matter of interpretation of indefinite specifications all the more difficult.

While it is desirable, it is not as essential to have absolute scientific accuracy in all of the definitions as it is to have definite definitions of capacity and performance, and definite methods of testing which are mutually understood.

As a representative of a manufacturing concern, I urge that the INSTITUTE carry to completion the good work which it has begun.

Pittsburgh, April 2nd, 1898.

THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

New York, February 23d, 1898.

The 122nd meeting of the Institute was held this date at 12 West 31st Street, and was called to order by President Crocker at 8:20 P. M.

The Secretary announced that at the meeting of the Executive Committee in the afternoon the following associate members were elected:

Name.	Address.	Endorsed by
Broili, Frank	Electrical Engineer, California Elec. Works; residence, 828 Geary St., San Francisco, Cal.	W. F. C. Hasson. Wynn Meredith. K. G. Dunn.
Libby, Samuel Byington	Supt. N. Y. & S. I. Electric Co., West New Brighton, N. Y,	Chas. J. Bogue. W. G. Whitmore. Ralph W. Pope.
Louis, Otto T	Manager of New York Branch, Queen & Co. Inc.; residence, 840 East 119th St., New York City.	Wm. A. Anthony. James Hamblet. Samuel Sheldon.
Mortland, James A.	Prof. of Physics, Faculty State Normal School, 2502 Walnut St., Cedar Falls, Iowa.	Ralph W. Pope. Wm. J. Hammer. Wm. Maver, Jr.
Schum, Chas. H.	Electrical Engineer, Ideal Electric Corp., 216 Third Ave., New York City.	F. A. LaRoche. R. W. Pope. H. J. Ryan.
Sedgwick, C. E.	Agent at San Francisco Office, General Electric Co., 15 First St., residence, Berkeley, Cal.	J. A. Lighthipe. Wynn Meredith. F. F. Barbour.

TRANSFERRED FROM ASSOCIATE TO FULL MEMBERSHIP.

Approved by Board of Examiners, Jan. 12th, 1898.

Goltz, William	Milwaukee, Wis.

The President:—The next business is the paper of this evening, "Single Phase Induction Motor," and I will call upon the author, Mr. Charles Steinmetz, to present it.

Mr. Steinmetz read the following paper:

A paper presented at the 122d Meeting of the American Institute of Electrical Engineers, New York, February 23d, 1898, President Crocker in the Chair.

SINGLE PHASE INDUCTION MOTOR.

BY CHARLES PROTEUS STEINMETZ.

§. 1. LOAD AND SPEED CURVES OF SINGLE PHASE INDUCTION MOTOR.

In the polyphase motor a number of secondary coils displaced in position from each other, are acted upon by a number of primary coils displaced in position and excited by E. M. F.'s displaced in phase from each other by the same angle as the displacement of position of the coils.

In the single phase induction motor a system of armature circuits is acted upon by one primary coil (or a system of primary coils connected in series or in parallel) excited by a single alternating current.

A number of secondary circuits displaced in position must be used so as to offer to the primary circuit a short-circuited secondary in any position of the armature. If only one secondary coil is used, the motor is a synchronous induction motor and belongs to a different class, the reaction machines.

A single-phase induction motor will not start from rest, but when started in either direction will accelerate with increasing torque and approach synchronism.

When running at or very near synchronism, the magnetic field of the single-phase induction motor is identical with that of the polyphase motor. That is, the magnetic field has the same intensity in every direction, but is displaced in phase progressively, and can be represented by the theory of the rotating field. Thus in a turn wound at right angles to the primary winding of the single-phase induction motor, at synchronism an E. M. F. is induced equal to that induced in a turn of the primary winding, but differing therefrom by 90° in phase.

In a polyphase motor the magnetic flux in any direction is due to the resultant M. M. F. of primary and of secondary currents, in the same way as in a transformer. The same is the case in the direction of the axis of the exciting coil of the single phase induction motor. In the direction at right angles to the axis of the exciting coil, however, the magnetic flux is due to the M. M. F. of the armature currents alone, no primary E. M. F. acting in this direction.

Consequently, while in the polyphase motor running light, that is doing no work whatever, the armature becomes currentless, and the primary currents are the exciting current of the motor only, in the single-phase induction motor, even when running light, the armature still carries the exciting current of the magnetic flux in quadrature with the axis of the primary exciting coil. Since this flux has the same intensity as the flux in the direction of the axis of the primary exciting coil, the current in the armature of the single-phase induction motor running light, and therefore also the primary current corresponding thereto, has the same M. M. F., that is, the same intensity as the primary exciting current, and the total primary current of the single-phase induction motor running light is thus twice the exciting current; that is, it is the exciting current of the main magnetic flux plus the current inducing in the armature the exciting current of the cross magnetic flux. In the armature or secondary, this exciting current is a current of twice the primary frequency.

Thus, if in a quarter-phase motor running light, one phase is open circuited, the current in the other phase doubles. If in the three-phase motor two phases are open circuited, the current in the third phase trebles, since the resultant M. M. F. of a three-phase machine is 1.5 times that of one phase. In consequence hereof, the total volt-ampere input of the motor remains the same, and at the same magnetic density, or the same impressed E. M. F., all induction motors, single-phase as well as polyphase, consume approximately the same volt-ampere input, and the same power input for excitation, and give the same distribution of magnetic flux.

Since the maximum output of a single-phase motor at the same impressed E. M. F. is considerably less than that of a polyphase motor, it follows herefrom that the relative exciting current in the single-phase motor must be larger.

The cause of this cross magnetization in the single-phase induction motor near synchronism is that the induced armature currents lag 90° behind the induced magnetism, and are carried by the synchronous rotation 90° in space before reaching their maximum, thus give the same magnetic effect as a quarter-phase E. M. F. impressed upon the primary system in quadrature position with the main coil, and can be eliminated by impressing a magnetizing quadrature E. M. F. upon an auxiliary motor circuit as done in the monocyclic motor.

Below synchronism, the induced armature currents are carried less than 90°, and thus the cross-magnetization due to them is correspondingly reduced, and becomes zero at standstill.

The torque of an induction motor is proportional to the armature energy currents times the intensity of magnetic flux in quadrature position thereto. Thus in the polyphase motor, where the magnetic flux is constant in all directions at all speeds, and proportional to the counter E. M. F. e, the torque is

$$T = e\, I_1.$$

In the single-phase induction motor, the armature energy currents I_1 can flow only coaxial with the primary coil as the only position in which corresponding primary currents exist. The magnetic flux in quadrature position is proportional to the component e carried in quadrature, or approximately to $(1-s)\, e$, and the torque is thus,

$$T = (1-s)\, e\, I_1$$

thus decreases much faster with decreasing speed, and becomes zero at standstill. The power is then,

$$P = (1-s)^2\, e\, I_1.$$

Since in the single-phase motor one primary only, but a multiplicity of secondary circuits exists, all secondary circuits are to be considered as corresponding to the same primary circuit, and thus as the secondary impedance is to be used the joint impedance of all secondary circuits. Thus, if the armature has a quarter-phase winding of impedance Z_1 per circuit, the resultant secondary impedance is $\frac{Z_1}{2}$, if it contains a three-phase winding of impedance Z_1 per circuit, the resultant secondary is $\frac{Z_1}{3}$.

In consequence hereof the resultant secondary impedance of a single-phase motor is less in comparison with the primary impedance than in the polyphase motor. Since the drop of speed under load depends upon the secondary resistance, in the single-phase induction motor the drop in speed at load is generally less than in the polyphase motor. This greater constancy of speed of the single-phase induction motor has led to the erroneous opinion that such a motor operates at synchronism, while in reality even at no load whatever it cannot approach perfect synchronism.

The further calculation of the single-phase induction motor is identical with that of the polyphase induction motor, as given in my former paper on the polyphase induction motor.[1]

In general, no special motors are used for single-phase circuits, but polyphase motors adapted thereto. An induction motor with one primary winding only, could not be started by a phase-splitting device, and would necessarily be started by external means. A polyphase motor, as for instance a standard three-phase motor operating single phase, by having two of its terminals connected to the single-phase mains, is just as satisfactory a single-phase motor as one built with one primary winding only. The only difference is that in the latter case a part of the circumference of the primary structure is left without winding, while in the polyphase motor this part contains windings also, which, however, are not used, or not effective when running as single-phase motor, but are necessary when starting by means of displaced E. M. F.'s. Thus in a three-phase motor operating from single phase mains, in starting, the third terminal is connected to a phase-displacing device, giving to the motor the cross-magnetization in quadrature to the axis of the primary coil, which at speed is produced by the rotation of the induced secondary currents, and which is necessary for producing the torque by its actions upon the induced secondary energy currents.

Thus the investigation of the single-phase induction motor resolves itself into the investigation of the quarter-phase or three-phase, or in general polyphase motor operating on single-phase circuits.

If in a quarter-phase motor, or motor with two primary circuits in quadrature,

$Y^1 = g^1 + jb^1 =$ primary exciting admittance per circuit,

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[1] TRANSACTIONS, vol. xiv, p. 175, (May issue)

the same motor operating as single-phase motor on one primary circuit has the primary admittance,

$$Y = 2\,Y^1 = g + jb.$$

Since the total volt-ampere and power input when running light are the same, as seen before.

In the same way in the three-phase motor, or motor with three primary circuits if,

$Y'' = g'' + jb''$ = primary exciting admittance per circuit, the same motor operated as single-phase motor has the primary admittance:

$$Y = 3\,Y'' = g + jb.$$

The primary impedance is that of the circuits used when running single phase.

The secondary impedance is the resultant impedance of all secondary circuits, reduced to the primary by the ratio of turns, since all secondary circuits correspond to one and the same primary circuit in the single-phase motor. Thus if $Z_1^1 = r_1^1 - j\,x_1^1$ = secondary impedance per circuit of a motor with quarter-phase secondary, or secondary of two circuits in quadrature, the secondary impedance of the same motor on single-phase circuit is,

$$Z_1 = \tfrac{1}{2}\,Z_1^1 = r_1 - j\,x_1.$$

If $Z_1'' = r_1'' - j\,x_1''$ = secondary impedance per circuit, of a motor with three-phase secondary reduced to the primary, the secondary impedance of the same motor on single phase circuit is,

$$Z_1 = \tfrac{1}{3}\,Z_1'' = r_1 - j\,x_1.$$

Or in general, in a motor with quarter-phase secondary, the secondary impedance is halved; in a motor with three-phase secondary, reduced to $\tfrac{1}{3}$, since the total secondary winding corresponds to one primary winding. Thus the slip is less in the single-phase motor.

In diagrams Figs. 1, 2, 3, 4 and 5, the load curves of five typical single phase induction motors are shown.

These motors are identical with the five typical polyphase motors shown as Figs. 3, 4, 5, 6, and 7 of my previous paper[1] on the polyphase induction motor, and their constants, are abstracted on Table I. of my previous paper, under $\times_1$, $\times_2$, $\times_3$, $\times_4$, and $\times_5$ on three-phase circuit, under $\times_1^1$, $\times_2^1$, $\times_3^1$, $\times_4^1$, $\times_5^1$ of this table as single-phase motor.

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[1] TRANSACTIONS, vol. xiv, p. 175, (May issue.)

These motors are:

	THREE-PHASE, PER CIRCUIT;	SINGLE-PHASE.
1st—All around good motor:		
	$Y = .01 + .1j,$	$Y = .03 + .3j,$
	$Z = .1 - .3j,$	$Z_0 = .1 - .3j,$
	or:	$Z_1 = .033 + .1j,$
	$\vartheta = 6.36,$	$\vartheta = 12.72,$
	$\beta = 10.0$	$\beta = 10.0,$
	$\gamma = 31.6,$	$\gamma = 31.6.$
	Fig. 3.	Fig. 1.
2nd.—High resistance motor:		
	$Y = .01 + .1j,$	$Y = .03 + .3j,$
	$Z = .2 - .3j,$	$Z_0 = .2 - .3j,$
	or:	$Z_1 = .067 - .1j,$
	$\vartheta = 7.26,$	$\vartheta = 14.52,$
	$\beta = 10.0,$	$\beta = 10.0,$
	$\gamma = 55.4,$	$\gamma = 55.4.$
	Fig. 4.	Fig. 2.
3rd.—High resistance and high admittance motor:		
	$Y = .04 + .4j,$	$Y = .12 + 1.2j,$
	$Z = .3 - .3j,$	$Z_0 = .3 - .3j,$
	or:	$Z_1 = .1 - .1j,$
	$\vartheta = 34.2,$	$\vartheta = 68.4,$
	$\beta = 10.0,$	$\beta = 10.0,$
	$\gamma = 70.7,$	$\gamma = 70.7.$
	Fig. 5.	Fig. 3.
4th.—High reactance motor:		
$\left.\begin{array}{l} Y = 044 + 4j, \\ Z = 05 - .3 \end{array}\right\}$ or	$\left\{\begin{array}{l} Y = .02 + .2j, \\ Z = .1 - .6j, \end{array}\right.$	$Y = .06 + .6j,$ $Z_0 = .1 - .6j,$
	or:	$Z_1 - .033 - .2j,$
	$\vartheta = 24.44,$	$\vartheta = 48.88,$
	$\beta = 10.0,$	$\beta = 10.0,$
	$\gamma = 16.4,$	$\gamma = 16.4.$
	Fig. 6.	Fig. 4.
5th.—High susceptance motor:		
	$Y = .02 + 4j,$	$Y = .06 + 1.2j,$
	$Z = .1 - .3j.$	$Z_0 = .1 - .3j,$
	or:	$Z_1 = .033 + .1j,$
	$\vartheta = 25.35,$	$\vartheta = 50.7,$
	$\beta = 5.0,$	$\beta = .5.0,$
	$\gamma = 31.6,$	$\gamma = 31.6.$
	Fig. 7.	Fig. 5.

TABLE I.

CONSTANTS OF INDUCTION MOTORS.

$E_0 = 110.$

(The motors marked by × are typical motors.)

No of motor.	No. of diagram.	$Y = g + jb$	$Z = r - jx$	$\delta = \frac{2yz}{= y(z_0 + z_1)}$	$\beta = \frac{g}{y}$	$\gamma = \frac{r}{x} = \frac{r_0 + r_1}{x_0 + x_1}$	T_m = max. torque, synchr. kilowatt.	P_r = rated output, kw. at ½ T_m.	P_m = max. output, in per cent. of P_r.	s = slip, at P_r.	Exciting current, per cent. of current at P_r.	Power Factor at full load.	Power Factor at ½ load.	Power Factor at ¼ load.	Efficiency at full load.	Efficiency at ½ load.	Efficiency at ¼ load	Apparent efficiency at full load.	Apparent efficiency at ½ load.	Apparent efficiency at ¼ load.
		$.005 + .05j$	$.1 - .3j$	3.18	10.0	31.6	9.00	5.65	1.38	6.3	8.7	96.6	95	91	85	93	93.5	82.2	88	85
		$.01 + .1j$	$.05 - .3j$	6.12	10.0	16.4	8.90	5.75	1.42	3.2	16.7	88.7	88.7	77.8	92.4	93.5	90.8	82	83.1	70.5
×1	3	$.01 + .1j$	$.1 - .3j$	6.36	10.0	31.6	8.25	5.15	1.36	6.3	17.4	80	88.5	74	86.5	91.2	88.2	77.4	81	65
×2	4	$.01 + .1j$	$.2 - .3j$	7.36	10.0	55.4	7.10	4.90	1.25	11	19.5	91	88.4	71	76	86.5	85	69.2	76	60
		$.01 + .1j$	$.4 - .3j$	10.04	10.0	80.0	5.80	2.90	1.12	6 18	25.0	93	83	57	66	85	90	61	70	51
		$.02 + .2j$	$.1 - .3j$	12.70	10.0	31.6	7.90	4.25	1.35	6.3	32	88	74	55	84	87	80	70	64.5	44
		$.02 + .2j$	$.2 - .3j$	14·52	10.0	55.4	6.80	4.00	1.26	11	36	85	72	50,5	75.5	80.6	74	64.3	58 2	37.5
×4	6	$.04 + .4j$	$.05 - .3j$	24.44	10.0	16.4	7.90	5.10	1.42	3.2	51 4	69.4	55	37	86.4	88	73.5	60.5	45.5	27
×5	7	$.02 + .4j$	$.1 - .3j$	25.35	5.0	31.6	7.00	4.75	1.35	6.3	52	71	54	36	82	82.3	75	58.2	44.5	26
		$.04 + .4j$	$.1 - .3j$	25.40	10.0	31.6	7.80	4.55	1.35	6.3	53.5	71	54	36	79.7	79	69	56	42.5	25
×3	5	$.04 + .4j$	$.3 - .3j$	34.20	10.0	70.7	5.50	3.10	1.13	16.5	62.5	75	53	37	60.6	61.3	47	45.3	32.5	17
		Single	phase	Motors :																
1_1		$.08 + .3j$	$.1 - .3j$ $.033 - .1j$	12.72	10	31.6	9.9	6.4	1.43	2.8	36	82	73	52.5	84.5	85	78	70	61.5	40.5
2_1		$.08 + .3j$	$.2 - .3j$ $.067 - .1j$	14.52	10	55.4	7.5	4.8	1.36	4.3	44.3	85	67.5	47	74.5	78	69	62	53	33.5
4_1		$.12 + 1.2j$	$.05 - .3j$ $.0167 - .1j$	48.88	10	16.4	8.8	5.8	1.43	1.9	73	52	36	24.5	76	88	52	30.5	24.5	13
5_1		$.06 + 1.2j$	$1 - .3j$ $.033 - .1j$	50.7	5	31.6	7.75	5.0	1.41	3.4	78	52.5	35	24	69.5	62.5	47.5	37	22	11
3_1		$.12 + 1.2j$	$.3 - .3j$ $.1 - .1j$	68.4	10	70.7	4.3	2.67	1.88	6.8	98	60.5	45.7	33.5	40	28.6	.17	24.3	12.5	6.8

That is, the three-phase motors X_1, X_2, X_3, X_4, X_5 operated from a single-phase circuit give the constants shown under X_1^1, X_2^1, X_3^1, X_4^1, X_5^1. The primary admittance is increased threefold, the primary impedance remains the same, and the secondary impedance is decreased to $\frac{1}{3}$.

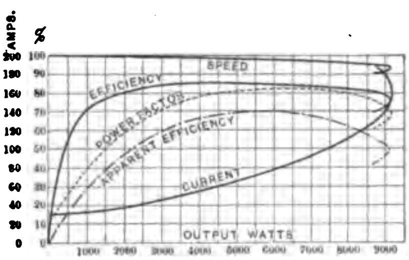

FIG. 1.—Single Phase Induction Motor. Load Curves.
$Y = .03 + .3j$. $Z = .033 - .1j$.
$Z_0 = .1 - .3j$.

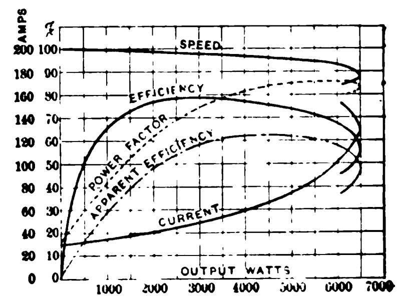

FIG. 2.—Single Phase Induction Motor. Load Curves.
$Y = .03 + .3j$. $Z_1 = .067 - .1j$.
$Z_0 = .2 - .3j$.

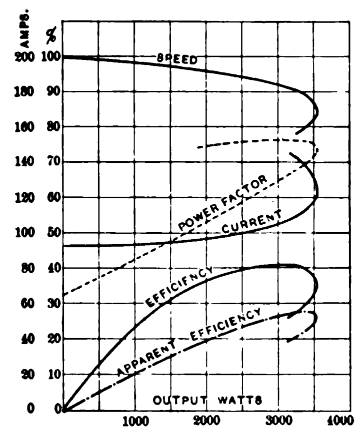

FIG. 3.—Single Phase Induction Motor. Load Curves.
$Y = .12 + 1.2j$. $Z_1 = .1 - .1j$.
$Z_0 = .3 - .3j$.

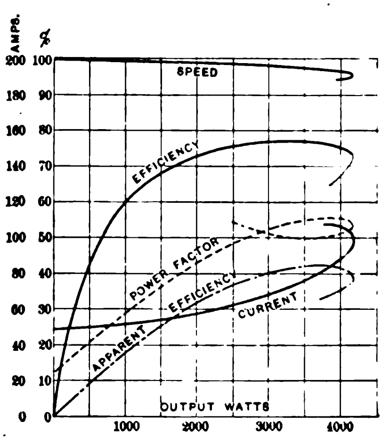

FIG. 4.—Single Phase Induction Motor. Load Curves.
$Y = .06 + 6j$. $Z_1 = 033 - .2j$.
$Z_0 = .1 - .6j$.

Since in a single-phase motor the primary impedance and the secondary impedance are generally very different, the approximation $Z_0 = Z_1$ can no longer be made, and in deriving the

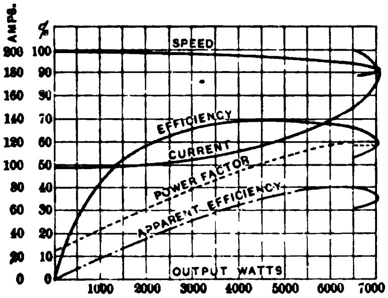

Fig. 5.—Single-Phase Induction Motor.
Load Curves.
$Y = .06 + .12j. \quad Z_1 = .033 - .1j.$
$Z_0 = .1 - .3j.$

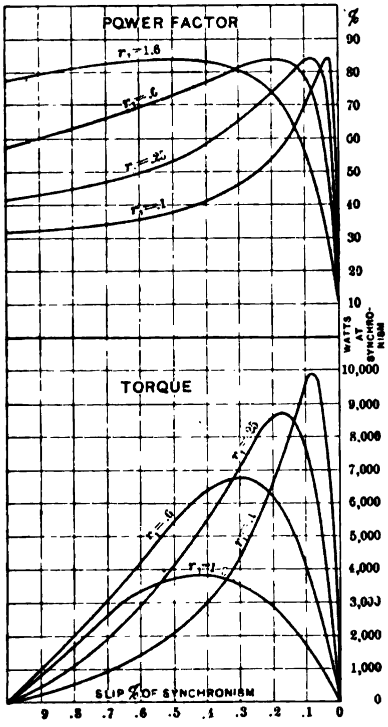

Fig. 6.—Single Phase Induction Motor.
$Y = .03 + .3j. \quad Z_1 = .033 - .1j.$
$Z_0 = .1 - .3j.$

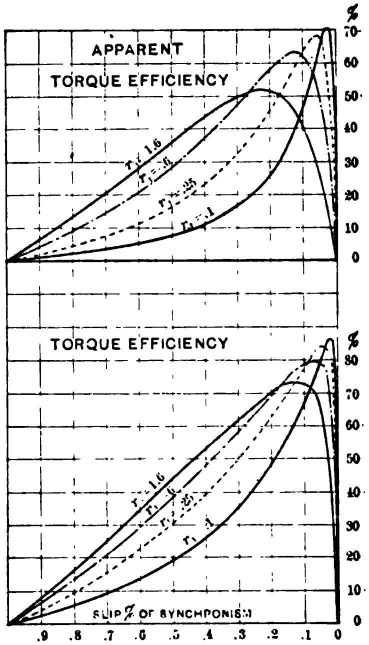

Fig. 7.—Single Phase Induction Motor.
$Y = .03 + .3j. \quad Z_1 = .033 - .1j.$
$Z_0 = .1 - .3j.$

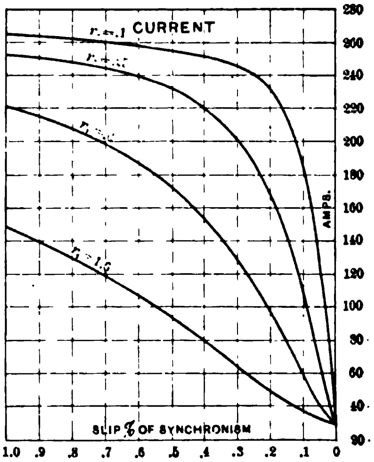

Fig. 8.—Single Phase Induction Motor.
$Y = .03 + .3j. \quad Z_1 = .033 - .1j.$
$Z_0 = .1 - .3j.$

characteristic constant ϑ and the power factor γ, the average of primary and secondary impedance is used.

$$Z = Z_0 + Z_1 = \frac{r_0 + r_1}{2} - j \; \frac{x_0 + x_1}{2}.$$

The average impedance is $\frac{2}{3}$, the primary admittance, three times that of the three-phase motor, thus the characteristic constant ϑ is doubled.

The same result applies to quarter-phase or any other polyphase motors.

That is: An induction motor operated on single-phase circuit gives twice the characteristic constant ϑ, but the same power factors β and γ as the same motor operated on polyphase circuit. The discussion in my previous paper on the effect of the constants ϑ, β, γ on the behavior of the polyphase motor essentially applies to the single-phase motor also.

Obviously, if the power factor of the secondary is different from that of the primary, the constant γ will be modified by the change to single-phase. Thus with high resistance secondary, where the power factor of the secondary is higher than that of the primary, on single phase circuit the resultant power factor γ is lower than on polyphase circuit.

The differences in the load curves of the induction motor on single-phase and on polyphase circuit, are essentially those corresponding to the doubling of the characteristic constant ϑ. Thus comparing $\times_1^1$, $\times_2^1$ with the two three-phase motors of my previous paper which have the same characteristic constant ϑ, we find very nearly the same power factors, efficiencies, apparent efficiencies and exciting currents. The values are not perfectly the same, since the slip s in the single phase motor is only about half or less of that of the three-phase motor, in consequence of the lesser secondary impedance.

Comparing, however, the single-phase motor with the same motor on polyphase circuit, we see that the former is inferior, as to be expected from the change of the characteristic constant ϑ, which, as discussed in my former paper, is the fundamental characteristic determining the quality of the motor. Especially great is the inferiority of the single-phase motor with poorer motors; less, although still very marked with good polyphase motors. The single phase motor is inferior, especially at light load, mostly due to its lower power factor.

The best insight into the changes which have taken place by operating polyphase motors on single-phase circuits, is given by comparing the load curves in the diagrams. As seen, the effect is a general decrease of the curves, especially at light loads, making them rise much slower and to lesser maximum values.

In general it can be said that a fair polyphase motor makes a poor single-phase motor. A good polyphase motor makes a fair single-phase motor, and to get a good single-phase motor an exceedingly good polyphase motor is required.

The speed is much more constant in the single-phase induction motor than in the polyphase motor.

The maximum torque and output of the single-phase motor is somewhat greater than that of the three-phase motor per circuit. Hence, since the total torque and output of the three-phase motor is three times that per circuit, the single-phase motor at the same impressed E. M. F. gives less than half the output of the polyphase motor. This is the cause of the inferiority of the single-phase motor. With the same volt-ampere excitation, the same loss of energy in the iron, and somewhat over half the loss of energy in the copper, the output is reduced to less than one-half.

Obviously by operating the single-phase motors at higher voltage, or what means the same, rewinding them for a higher density, their output can be increased, but as discussed before, their constants are not changed thereby. Limiting the output by the heating of the motor, that is the loss of energy therein, the permissible rating of a motor on single-phase circuit is about from $\frac{2}{3}$ to $\frac{3}{4}$ that of the same motor rewound for polyphase circuits. In this case, the magnetic density of the single-phase motor is from 25 to 30% higher: thus the exciting volt-amperes and the loss in the iron correspondingly higher, as represented by the constants of the motor.

The falling off of the torque and the output of the single phase motor with decreasing speed, is much more abrupt than in the polyphase motor, since the expression of the torque of the single-phase motor contains the speed $(1-s)$ as factor, while that of the polyphase motor does not.

Thus, while in the polyphase motor the insertion of resistance in the armature does not change the torque, but merely shifts all its values toward lower speeds, in the single-phase motor resistance in the armature not only shifts the values of torque towards lower speed, but also reduces the values due to the factor $(1-s)$ entering the expression of torque. In Figs. 6, 7 and 8 are shown speed curves of the motor $\times_1{}^1$ for the armature resistances,

$r_1 = .033$ (short-circuited armature),
$r_1 = .0833$,
$r_1 = .2$,
$r_1 = .533$.

corresponding to the resistances .1, .25, .6 and 1.6 in each of the three armature circuits. Thus these figures give the torque, power factor, torque efficiency, apparent torque efficiency and current as function of the speed on single-phase circuits, of the same motor and for the same armature resistances, for which the curves on three-phase circuit are shown in Figs. 10 and 11 of my previous paper. Thus these diagrams are directly comparable.

The torque curves of the single-phase motor have the same general character as those of the three phase motor; a stable branch between synchronism and maximum torque and an unstable branch between maximum torque and standstill. The difference, however, is that all the single-phase torque curves slope toward zero at standstill, while the three-phase torque curves reach definite values at standstill. With increase of armature resistance, the maximum torque point shifts towards lower speed, but at the same time decreases in the single-phase motor, while it remains the same in the three-phase motor. In the single-phase motor, the maximum torque point is nearer synchronism, that is, the speed regulation is better.

In the single-phase motor a stable and an unstable branch of the torque curve always exists. In the polyphase motor the latter disappears beyond a certain secondary resistance, and for instance no longer exists in the above discussed motor for $r_1 = .6$ and $r_1 = 1\ 6$.

The current curves in Figs. 7 and 8 on single-phase and on three-phase circuits show the same general character, with the modification due to the lesser slip of the single-phase motor, which causes the same shape to correspond to a higher resistance. For instance, $r_1 = 1.6$ in the single-phase motor gives about the same shape as $r_1 = .6$ in the three-phase motor. The power factor curves have the same character, but the single-phase curves reach a lower maximum only, at a lesser slip.

Torque efficiency and apparent torque efficiency are different in so far as these quantities in polyphase motors approach finite values at standstill, while in single-phase motors their curves slope towards zero at standstill. The torque efficiency and apparent torque efficiency reach their maxima at higher speed or lesser slip on single-phase than on polyphase circuit, and are lower.

It is obvious herefrom that the single-phase induction motor, while quite fair in the range of speed above the maximum torque point, becomes very unsatisfactory below this point, or at lower speeds. Armature resistance in the single-phase induction motor brings the maximum torque point down to lower speeds. But since the maximum torque point is lowered, the more the speed is reduced at which it takes place, single-phase motors cannot be operated on rheostatic control for variable speeds as satisfactorily as polyphase motors, and armature resistance is thus used mostly only for starting the motor.

Since the torque of the single-phase motor falls off in any case with decreasing speed, the use of variable armature resistance in starting a single-phase motor is far more necessary than in polyphase motor. For instance, the three-phase motor in Fig. 10 of my previous paper will carry one-third of full load from standstill up to synchronism with short-circuited low resistance armature, and practically full load from one-half speed. The same motor as single-phase motor will carry one-third load from one-fourth speed, or two-thirds load, from one-half speed up to synchronism, only when the armature resistance is the most favorable, $r_1 = .6$.

At standstill the single-phase motor torque is zero, and thus some starting device, electrical or otherwise, is needed. This starting device, however, while it needs not to bring the motor up to full synchronism, as necessary with a single-phase synchronous motor, has to bring it up to some speed, since only at about one-fourth speed the inherent torque of the single-phase induction motor becomes noticeable, and considerable only at about one-half speed. With short-circuited low resistance armature, the starting device has to bring the motor up fairly close to synchronism.

Concatenation or tandem control of single-phase induction motors can be used, but the result is not as satisfactory as with polyphase motors, since the magnetic field of the single-phase motor becomes uniform only when approaching synchronism, and thus at half speed the E.M.F. induced in the secondary is pulsating in intensity.

The effect of the change of frequency and change of the number of poles, etc. is the same in the single-phase motor as in the polyphase motor, and the investigation regarding hereto is directly applicable to polyphase as well as single-phase motors.

In the preceding discussion of the single-phase motor, the assumption has been made that the magnetic field of cross-magnetization produced by the armature currents is proportional to the counter E. M. F. of the motor and to the speed. In reality it varies with a more complex function of the speed, and thus the torque curves calculated with this assumption, do not show the perfect coincidence with the results of tests as is the case of the polyphase motor, although they agree fairly well.

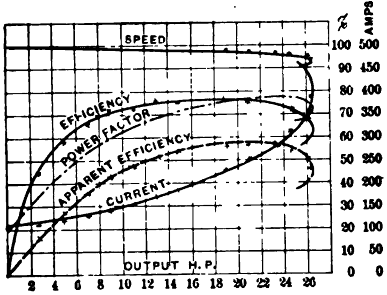

FIG. 9.
1.8-30-900-110, Form "A." 60 Cycles, 8 Poles, 110 volts. Single Phase.
Curves Calculated with $V = 135 + 1.15 j$.
$Z_0 = .045 - .124 j$. $Z_1 = .0137 - .041 j$.
Friction: 500 Watts at Synchronism.
Observed by Test: +

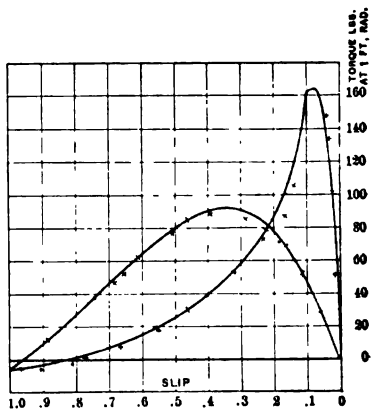

FIG. 10.
1.8-30-900-110, Form "A." 60 Cycles, 8 Poles, 110 Volts. Single Phase.
Speed Curves.
Calculated with: $V = 135 + 1.15 j$.
$Z_0 = .045 - .124 j$. $Z_1 = .0134 - .041 j$.
500 Synchronous Watts Friction.
× Observed by Test.

A further assumption has been made by representing the M. M. F. of cross-magnetization by a doubling of the primary impedance, but neglecting the effect of the armature currents producing the cross-magnetization.

In Fig. 9 are shown the load curves, and in Fig. 10 the speed curves of the 1—S—30—900—1060 cycles, form A, the same motor of which the three-phase load curves are given in Fig. 1 and the three-phase speed curves in Fig. 2 of my previous paper. These single-phase curves are calculated for the same impressed voltage, that is the same magnetic density, and with the same constants as the three-phase curves in the previous paper, with the changes discussed above; trebling the primary admittance and reducing the secondary impedance to one-third. The results of tests are marked by crosses. As seen, the coincidence between test and calculation is quite good. This motor is the first 60-cycle induction motor built, and thus does not now represent the present state of the art, but is used here, owing to the very complete investigations made with it.

§ 2. SINGLE-PHASE INDUCTION MOTOR STARTING DEVICES.

As seen in the preceding, the single-phase induction motor at standstill has no starting torque, since the line of polarization due to the armature currents coincides with the axis of magnetic flux impressed by the primary circuit. Only when revolving, torque is produced, due to the axis of armature polarization being shifted against the axis of magnetism by the rotation, until at or near synchronism it is in quadrature therewith, and the magnetic disposition thus identical with that of the polyphase induction motor.

Leaving out of consideration starting by mechanical means, and starting by converting the motor into a series or shunt motor, that is by passing the alternating current by means of commutator and brushes through both elements of the motor, as methods of starting single-phase motors are left:

1st.—Shifting of the axis of armature or secondary polarization against the axis of inducing magnetism.

2nd.—Shifting the axis of magnetism, that is producing a magnetic flux displaced in position from the flux inducing the armature currents.

The first method requires a secondary system which is unsymmetrical in regard to the primary, and thus, since the secondary is movable, requires means of changing the secondary circuit, that is commutator brushes short-circuiting secondary coils in the position of effective torque, and open-circuiting them in the position of opposing torque.

Thus this method leads to the repulsion motor, which is a commutator motor also.

With the commutatorless induction motor, or motor with permanently closed armature circuits, all starting devices consist in establishing an auxiliary magnetic flux in phase with the induced secondary currents in time, and in quadrature with the line of armature polarization in space, that is they consist in producing a component of magnetic flux in quadrature in space with the primary magnetic flux inducing the armature currents and in phase with the latter; that is in quadrature with the primary magnetic flux.

Thus if

P = polarization due to the induced or armature currents,

M = auxiliary magnetic flux,

φ = phase displacement in time between M and P, and

ω = phase displacement in space between M and P, the torque is

$$T = P\,M \sin\,\omega\,\cos\,\varphi.$$

In general the starting torque, apparent torque efficiency, etc. of the single-phase induction motor with any of these devices are given in per cent. of the corresponding values of the same motor with polyphase magnetic flux, that is, with a magnetic system consisting of two equal magnetic fluxes in quadrature in time and space.

Thus all starting devices of the commutatorless single-phase induction motor consist in the production of a component of magnetic flux displaced from the axis of polarization of the induced or armature currents.

The infinite variety of arrangements proposed for this purpose can be grouped into three classes.

1st. *Phase-Splitting Devices.*—The primary system is composed of two or more circuits displaced from each other in position, and combined with impedances of different inductance factors so as to produce a phase displacement between them.

When using two motor circuits, they can either be connected in series between the single-phase mains, and shunted with impedances of different inductance factors, as for instance, a condensance and an inductance, or they can be connected in shunt between the single-phase mains but in series with impedances of different inductance factor. Obviously the impedance used for displacing the phase of the exciting coils can either be external or internal as represented by high-resistance winding in one coil, etc.

In this class belongs the use of the transformer as phase-splitting device, by inserting a transformer primary in series to one motor circuit in the main line, and connecting the other motor circuit to the secondary of the transformer, or by feeding one of the motor circuits directly from the mains, and the other from the secondary of a transformer connected across the mains with its primary. In either case, it is the internal impedance, respectively internal admittance, of the transformer which is combined with one of the motor circuits for displacing its phase, and thus this arrangement becomes most effective by using transformers of high internal impedance or admittance, that is poor transformers.

2d. *Inductive Devices.*—The motor is excited by the combination of two or more circuits which are in inductive relation to each other. This mutual induction between the motor circuits can either take place outside of the motor in a separate phase-splitting device, or in the motor proper.

In the first case the simplest form is the divided circuit whose branches are inductively related to each other by passing around the same magnetic circuit external to the motor.

In the second case the simplest form is the combination of a primary exciting coil and a short-circuited secondary coil induced thereby on the primary member of the motor, or a secondary coil closed by an impedance.

3d. *Monocyclic Starting Device.*—An essentially wattless E. M. F. of displaced phase is produced outside of the motor, and used to energize a cross-magnetic circuit of the motor, either directly by a special teaser coil on the motor, or indirectly by combining this wattless E. M. F. with the main E. M. F. and thereby deriving a system of E. M. F.'s of approximately three-phase or any other relation. In this case the primary system of the motor is supplied essentially by a polyphase system of E. M. F. with a single-phase flow of energy, a system, which I have called "monocyclic."

A. PHASE SPLITTING DEVICES.

Parallel Connection. Let the motor contain two primary circuits of different inductance factors in parallel between the single-phase mains, and at right angles with each other in space.

Two equal primary circuits, of the apparent impedance,[1]

$$Z = r - j x,$$

---

[1] Including secondary circuit, that is, $Z = \frac{\text{impressed E. M. F.}}{\text{current}}$ in motor coil

are arranged at right angles on the motor field, and connected in series with the respective impedances:

$$Z_1 = r_1 - j\, x_1 \text{ and } Z_2 = r_2 - j\, x_2$$

in parallel across the single-phase mains of impressed E. M. F.,

$$\mathrm{E} = e$$

as shown diagrammatically in Fig. 11.

Let E_1 and I_1 = E. M. F. and current in first,

E_2 and I_2 = " " " " second motor coil.

The angle of phase displacement between the E. M. F.'s, E_1 and E_2 be:

$$(\mathrm{E}_1, \mathrm{E}_2) = \omega.$$

The torque of the motor is proportional to:

$$T_s = E_1\, E_2 \sin \omega$$ [1]

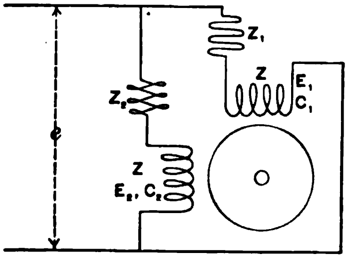

FIG. 11.

while the torque of the same motor with uniform or polyphase flux, that is as quarter-phase motor with E. M. F. e per phase, is proportional to:

$$T_p = e^2.$$

Hence, the *relative starting torque* of the single-phase motor, or the ratio:

$\frac{\text{torque single-phase}}{\text{torque polyphase}}$ at same impressed E. M. F. e, is:

$$t = \frac{T_s}{T_p} = \frac{E_1\, E_2}{e^2} \sin \omega. \qquad (1)$$

Let: $\mathrm{I} = \mathrm{I}_1 + \mathrm{I}_2$ = total current taken by the motor on single phase circuit of E. M. F. e, and I = absolute value thereof.

---

[1] E_1 I_1 etc. denoting the complex vectors, E_1, I_1 their absolute or scalar values.

The total current taken by the motor on quarter-phase circuit of E. M. F. e per phase is:

$$I_0 = \frac{2\,e}{\sqrt{r^2 + x^2}} \tag{2}$$

hence, the *ratio of currents*:

$$c = \frac{I}{I_0} = \frac{I\,\sqrt{r^2 + x^2}}{2\,e} \tag{3}$$

and consequently, the *ratio of apparent torque efficiencies* of the motor on single-phase and on polyphase circuits, or the *relative apparent torque efficiency* of the motor starting device, is:

$$\begin{aligned} \delta &= \frac{t}{c} = \frac{T_s}{T_p} \times \frac{I_0}{I} \\ &= \frac{2\,E_1\,E_2 \sin \omega}{e\,I\,\sqrt{r^2 + x^2}}. \end{aligned} \tag{4}$$

In this single-phase motor starting device, it is:

Current in first motor coil:

$$\mathrm{I}_1 = \frac{e}{Z + Z_1}, \tag{5}$$

in the second motor coil:

$$\mathrm{I}_2 = \frac{e}{Z + Z_2}, \tag{6}$$

hence, total current:

$$\mathrm{I} = \mathrm{I}_1 + \mathrm{I}_2 = \frac{e\,(2\,Z + Z_1 + Z_2)}{(Z + Z_1)\,(Z + Z_2)}, \tag{7}$$

or, absolute:

$$I = \frac{2\,e\sqrt{\left(r + \frac{r_1 + r_2}{2}\right) + \left(x + \frac{x_1 + x_2}{2}\right)^2}}{\sqrt{[(r + r_1)^2 + (x + x_1)^2]\,[(r + r_2)^2 + (x + x_2)^2]}}, \tag{8}$$

and, ratio of currents:

$$c = \frac{I}{I_0} = \frac{\sqrt{r^2 + x^2}\sqrt{\left(r + \frac{r_1 + r_2}{2}\right)^2 + \left(x + \frac{x_1 + x}{2}\right)^2}}{\sqrt{(r + r_1)^2 + (x + x_1)^2}\;\sqrt{(r + r_2)^2 + (x + x_2)^2}}. \tag{9}$$

The E. M. F. across the first motor coil is:

$$\begin{aligned} \mathrm{E}_1 = Z\,\mathrm{I}_1 &= \frac{e\,Z}{Z + Z_1}, \\ &= \frac{e\,(r - j\,x)}{(r + r_1) - j\,(x + x_1)}, \end{aligned} \tag{10}$$

or absolute:

$$E_1 = \frac{e \sqrt{r^2 + x^2}}{\sqrt{(r + r_1)^2 + (x + x_1)^2}}, \tag{11}$$

and analogously, across the second motor coil:

$$\mathrm{E}_2 = \frac{e\,(r - j\,x)}{(r + r_2) - j\,(x + x_2)}, \tag{12}$$

$$E_2 = \frac{e \sqrt{r^2 + x^2}}{\sqrt{(r + r_2)^2 + (x + x_2)^2}} \tag{13}$$

The phase displacement ω between the E. M. F.'s E_1 and E_2 is:

$$a\,(\cos a + j \sin \omega) = \frac{\mathrm{E}_1}{\mathrm{E}_2},$$

$$= \frac{(r + r_2) - j\,(x + x_2)}{(r + r_1) - j\,(x + x_1)} = \tag{14}$$

$$\frac{[(r+r_1)(r+r_2)+(x+x_1)(x+x_2)] + j\,[r(x_1-x_2)+r_2(x+x_1)-r_1(x+x_2)]}{(r+r_1)^2+(x+x_1)^2},$$

hence:

$$a = \frac{\sqrt{(r + r_2)^2 + (x + x_2)^2}}{\sqrt{(r + r_1)^2 + (x + x_1)^2}},$$

and:

$$\sin \omega = \frac{r\,(x_1 - x_2) + r_2\,(x + x_1) - r_1\,(x + x_2)}{\sqrt{(r + r_1)^2 + (x + x_1)^2}\ \sqrt{(r + r_2)^2 + (x + x_2)^2}}. \tag{15}$$

Substituting (11) (13) (15) into (1) gives the *relative torque of starting device*:

$$t = \frac{(r^2 + x^2)\,[r\,(x_1 - x_2) + r_2\,(x + x_1) - r_1\,(x + x_2)]}{[(r + r_1)^2 + (x + x_1)^2]\,[(r + r_2)^2 + (x + x_2)^2]}, \tag{16}$$

and, (9) and (16) combined, give the
relative apparent torque efficiency of the starting device:

$$\delta = \frac{t}{c} = \frac{\sqrt{r^2+x^2}\,[r(r_1-r_2)+r_2(x+x_1)-r_1(x+x_2)]}{\sqrt{(r+r_1)^2+(x+x_1)^2}\ \sqrt{(r+r_2)^2+(x+x_2)^2}\ \sqrt{(r+\frac{r_1+r_2}{2})^2+(x+\frac{x_1+x_2}{2})^2}} \tag{17}$$

SPECIAL CASES.

1. *Resistance a in series with one motor circuit:*

$$r_2 = a, \qquad r_1 = x_1 = x_2 = 0.$$

Relative torque:

$$t = \frac{a\,x}{(r + a)^2 + x^2}.$$

Relative current:

$$i = \frac{\sqrt{\left(r + \frac{a}{2}\right)^2 + x^2}}{\sqrt{(r + a)^2 + x^2}}$$

Relative apparent torque efficiency:

$$\delta = \frac{a\,x}{\sqrt{(r + a)^2 + x^2}\,\sqrt{\left(r + \frac{a}{2}\right)^2 + x^2}}.$$

2. *Reactance a in series with one motor circuit:*

$$x_1 = a, \qquad r_1 = r_2 = x_2 = 0.$$

Relative torque:

$$t = \frac{a\,r}{r^2 + (x + a)^2}.$$

Relative current:

$$i = \frac{\sqrt{r^2 + \left(x + \frac{a}{2}\right)^2}}{\sqrt{r^2 + (x + a)^2}}.$$

Relative apparent torque efficiency:

$$\delta = \frac{a\,r}{\sqrt{r^2 + (x + a)^2}\,\sqrt{r^2 + \left(x + \frac{a}{2}\right)^2}}.$$

Thus, reactance a in series with one motor circuit gives the same values, but with r and x exchanged for each other, as resistance a in one motor circuit, or: a reactance a has on a motor of impedance $Z = b - jd$ the same effect as a resistance a on a motor of impedance $Z = d - jb$.

In a motor of high reactance (permanently short-circuited armature) resistance a in series, in a motor of high resistance (variable starting resistance) reactance a in series gives better torque and apparent torque efficiency.

As instances are shown in Fig. 12, the relative apparent torque efficiency, or apparent torque efficiency $\frac{\text{single-phase}}{\text{polyphase}}$, as function of the reactance a inserted in one of the two equal primary motor circuits, for the motors with apparent impedance:

1. $Z = 1 - 3j$.
2. $Z = 3 - 1j$.

If a is resistance instead of reactance, the two curves in Fig. 12 merely exchange their position, as shown in parenthesis.

3. *Inductance and Capacity.*

$$x_2 = -(x_1 + 2x).$$

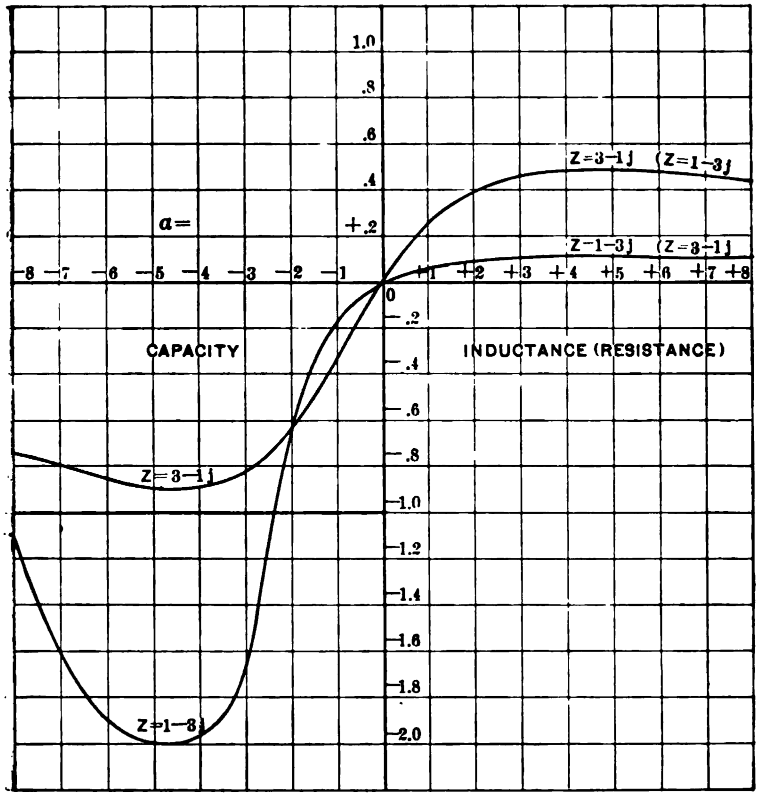

Fig. 12.

Single Phase Induction Motor. Starting Device.
Reactance $-ja$ in Circuit of one of the two Motor Primaries. Total Impedance per Motor Coil. $Z = 3 - 1j$ or $1 - 3j$.
A Phase Splitting Device.

Ratio of Apparent Torque Efficiencies. $\frac{\text{Single Phase.}}{\text{Polyphase.}}$

Relative torque:

$$t = \frac{2\,(r^2 + x^2)\,(x \times x_1)\left(r + \frac{r_1 + r_2}{2}\right)}{[(r + r_1)^2 + (x + x_1)^2]\;[(r + r_2)^2 + (x + x_1)^2]}.$$

Relative current:

$$i = \frac{\sqrt{r^2 + x^2}\left(r + \frac{r_1 + r_2}{2}\right)}{\sqrt{(r + r_1)^2 + (x + x_1)^2}\ \sqrt{(r + r_2)^2 + (x + x_1)^2}}.$$

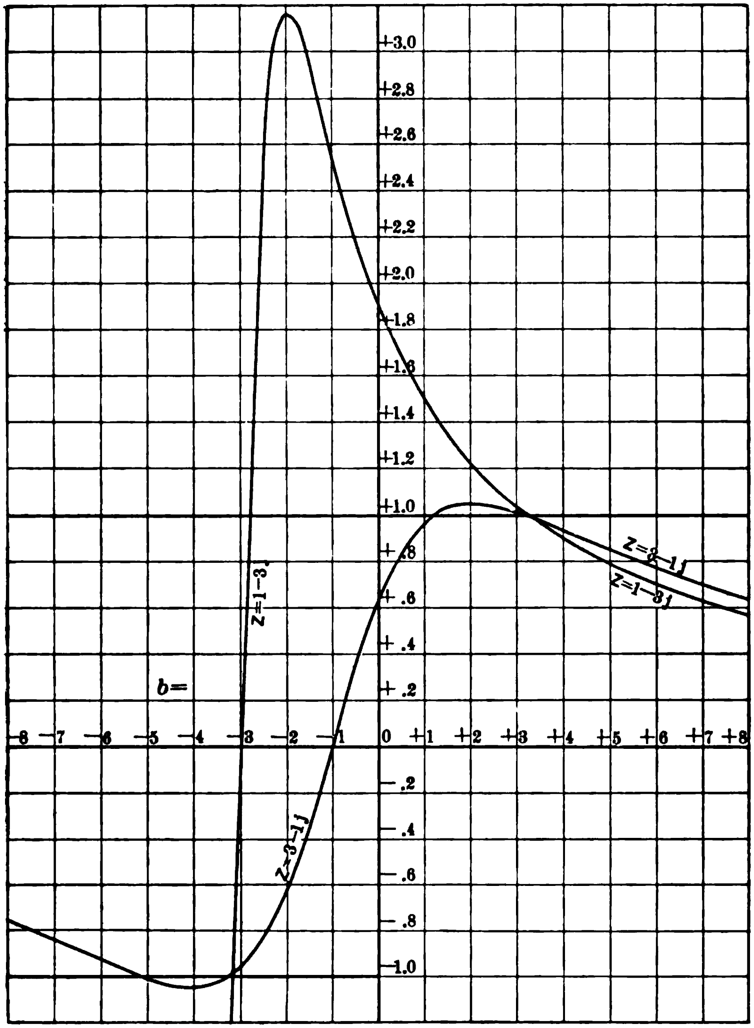

FIG. 18.—Single Phase Induction Motor. Starting Device.
Reactance $-jb$ and: $+j\,(b + 2\times)$. In Circuit of the two Motor Coils of Total Impedance.
$Z = r - jx = 3 - 1j$ or: $1 - 3j$
Ratio of Apparent Torque Efficiencies. A Phase Splitting Device.
Single Phase
Polyphase

Relative apparent torque efficiency:

$$\delta = \frac{2\sqrt{r^2 + x^2}\,(x + x_1)}{\sqrt{(r + r_1)^2 + (x + x_1)^2}\,\sqrt{(r + r_2)^2 + (x + x_1)^2}}.$$

3 *b*.—

$$x_1 = b, \qquad r_1 = r_2 = 0.$$

$$x_2 = -(b + 2x.$$

Relative torque:

$$t = \frac{2r(x + b)(r^2 + x^2)}{[r^2 + (x + b)^2]^2}.$$

Relative current:

$$i = \frac{r\sqrt{r^2 = x^2}}{r^2 + (x + b)^2}.$$

Relative apparent torque efficiency:

$$\delta = \frac{2(x + b)\sqrt{r^2 + x^2}}{r^2 + (x + b)^2}.$$

At: $b = -x$:

$$t = 0, \qquad \delta = 0,$$

as to be expected, since: $x_2 = -x = x_1$.

As instance are shown in Fig. 13, the relative apparent torque efficiency, as function of b, for a motor of apparent impedance:

1. $Z = 1 - 3j$.
2. $Z = 3 - 1j$.

As seen, very high values can be reached by two capacities in a motor with low resistance secondary; the high maximum is within a narrow range, however, and very near the point where the torque reverses.

SERIES CONNECTION.

Let the motor contain two primary circuits of different inductance factors in series, and at right angles with each other in space.

Two equal primary circuits, of the apparent admittance[1]

$$Y = g + jb$$

are arranged at right angles with each other in the motor field, connected in series with each other in the circuit of the impressed E. M. F. $E = 2e$, and shunted by the respective admittances:

$$Y_1 = g_1 + jb_1 \text{ and } Y_2 = g_2 + jb_2,$$

as shown diagrammatically in Fig. 14.

Let:

E_1 and I_1 = E. M. F. and current in the first,

E_2 and I_2 = " " " " " second motor coil,

and:

$(E_1, E_2) = \omega$ the angle of phase displacement between E_1 and E_2.

The torque of the motor is proportional to:

$$T_s = E_1 E_2 \sin \omega \qquad \text{[2]}$$

while the torque of a quarter-phase motor with the E. M. F. e per phase (or motor coil) is proportional to:

$$T_p = e^2.$$

Hence, the *relative starting torque* of the single-phase motor, or ratio.

$$\frac{\text{torque single-phase at E. M. F. } 2\,e \text{ across both motor coils,}}{\text{torque polyphase at E. M. F. } e \text{ per motor coil,}}$$

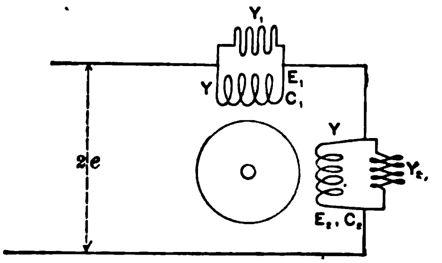

FIG. 14.

is:

$$t = \frac{T_s}{T_p} = \frac{E_1 E_2 \sin \omega}{e^2}. \qquad (1)$$

The current per motor coil at E. M. F. e and quarter-phase circuit is:

$$I_0 = e\, Y. \qquad (2)$$

or, absolute:

$$I_0 = e\, \sqrt{b^2 + g^2}, \qquad (3)$$

hence the apparent input, quarter-phase:

$$2\, e\, I_0 = 2\, e^2 \sqrt{b^2 + g^2}. \qquad (4)$$

The joint admittance of the motor coils with their shunts, on single-phase circuits is:

$$\frac{1}{\dfrac{1}{Y + Y_1} + \dfrac{1}{Y + Y_2}} = \frac{(Y + Y_1)(Y + Y_2}{2\, Y + Y_1 + Y^2},$$

---

1. and 2. see page 110.

hence the current,
at impressed E. M. F. $2e$:

$$\mathrm{I} = \frac{e\,(Y+Y_1)\,(Y+Y_2)}{Y+\frac{Y_1+Y_2}{2}}, \tag{5}$$

or absolute:

$$I = \frac{e\sqrt{(g+g_1)^2+(b+b_1)^2}\;\sqrt{(g+g_2)^2+(b+b_2)^2}}{\sqrt{\left(g+\frac{g_1+g^2}{2}\right)^2+\left(b+\frac{b_1+b}{2}\right)^2}} \tag{6}$$

and, the apparent input:

$$2\,e\,I = \frac{2\,e^2\sqrt{(g+g_1)^2+(b+b_1)^2}\;\sqrt{(g+g_2^2)+b+b_2)^2}}{\sqrt{\left(g+\frac{g_1+g^2}{2}\right)^2+\left(b+\frac{b_1+b_2}{2}\right)^2}} \tag{7}$$

hence, the ratio of apparent inputs or *relative apparent input*:

$$c = \frac{2\,e\,I}{2\,e\,I_1} = \frac{\sqrt{(g+g_1)^2+(b+b_1)^2}\sqrt{(g+g_2)^2+(b+b_2)^2}}{\sqrt{g^2+b^2}\sqrt{\left(g+\frac{g_1+g_2}{2}\right)^2+\left(b+\frac{b_1+b_2}{2}\right)^2}} \tag{8}$$

The E. M. F. across the first motor coil is:

$$\mathrm{E}_1 = \frac{\mathrm{I}}{Y+Y_1}; \tag{9}$$

hence, substituting (5) in (9):

$$\mathrm{E}_1 = \frac{e\,(Y+Y_2)}{Y+\frac{Y_1+Y_2}{2}}, \tag{10}$$

or, absolute:

$$E_1 = \frac{e\sqrt{(g+g_2)^2+(b+b_2)^2}}{\sqrt{\left(g+\frac{g_1+g_2}{2}\right)^2+\left(b+\frac{b_1+b_2}{2}\right)^2}} \tag{11}$$

and analogously, E_2.

It is:

$$\mathrm{E}_2 = \frac{\mathrm{I}}{Y+Y_2}.$$

This combined with (9) gives the angle ω between E_1 and E_2 as:

$$a\,(\cos\omega + j\sin\omega) = \frac{Y+Y_2}{Y+Y_1} = \frac{(g+g_2)+j\,(b+b_2)}{(g+g_1)+j\,(b+b_1)}, \tag{12}$$

and herefrom, analogously as on page 54:

$$\sin \omega = \frac{g\,(b_1 - b_2) + g_2\,(b + b_1) - g_1\,(b + b_2)}{\sqrt{(g + g_1)^2 + (b + b_1)^2}\;\sqrt{(g + g_2)^2 + (b + b_2)^2}} \tag{13}$$

(11) and (13) substituted in (1) gives the *relative torque:*

$$t = \frac{g\,(b_2 - b_2) + g_2\,(b + b_1) - g_1\,(b + b_2)}{\left(g + \frac{g_1 + g_2}{2}\right)^2 + \left(b + \frac{b_1 + b_2}{2}\right)^2}, \tag{14}$$

and, (14) combined with (8) gives the *relative apparent torque efficiency:*

$$\delta = \frac{t}{c} =$$

$$\frac{\sqrt{g^2+b^2}\,[g\,(b_1 - b_2) + g_2\,(b + b_1) - g_1\,(b + b_2)]}{\sqrt{(g+g_1)^2+(b+b_1)^2}\;\sqrt{(g+g_2)^2+(b+b_2)^2}\sqrt{\left(g+\frac{g_1+g_2}{2}\right)^2+\left(b+\frac{b_1+b_2}{2}\right)^2}} \tag{15}$$

As seen, the relative apparent torque efficiency of the single-phase motor starting device with series connection leads to the same expression in the admittances, as parallel connection leads in the impedances. That is, replacing in the formula for parallel connection, on page 54, the resistances and reactances by the conductances and susceptances, give the formula for series connection.

Relative torque and relative apparent input would give the same formulas in admittances in series connection, if in this case the values for constant impressed primary current had been compared with the values for constant impressed primary E. M. F. in parallel connection. The apparent torque efficiency is independent of E. M. F. or current, thus gives the same expression.

SPECIAL CASES.

1. *Conductance (or resistance) a shunting one motor coil.*

$$g_2 = a, \quad g_1 = b_1 = b_2 = 0.$$

Torque:

$$t = \frac{a\,b}{\left(g + \frac{a}{2}\right)^2 + b^2}.$$

Current:

$$i = \frac{\sqrt{(g + a)^2 + b^2}}{\sqrt{\left(g + \frac{a}{2}\right)^2 + b^2}}.$$

App. Torque Eff.

$$\delta = \frac{a\,b}{\sqrt{\left(g+a\right)^2+b^2}\sqrt{\left(g+\frac{a}{2}\right)^2+b^2}}$$

2. *Susceptance (or reactance) a shunting one motor coil.*

$$b_1 = a, \quad g_1 = g_2 = b_2 = 0.$$

Torque:

$$t = \frac{a\,g}{g^2+\left(b+\frac{a}{2}\right)^2}.$$

Current:

$$i = \frac{\sqrt{g^2+(b+a)^2}}{\sqrt{g^2+\left(b+\frac{a}{2}\right)^2}}.$$

App. Torque Eff.

$$\delta = \frac{a\,g}{\sqrt{g^2+\left(b+a\right)^2}\sqrt{g^2+\left(b+\frac{a}{2}\right)^2}}.$$

Obviously, regarding the effect and the relative advantages of conductance or susceptance, the same applies as stated on p. 4, regarding resistance and reactance.

Instance:

$$\alpha. \quad Y = 1 + 3j$$

$$\beta. \quad Y = 3 + 1j.$$

3. *Inductance and capacity.*

$$b_1 = a,$$

$$b_2 = -(a + 2b),$$

$$g_1 = g_2 = 0.$$

Torque:

$$t = \frac{2(a+b)}{g}.$$

Current:

$$i = \frac{g^2+(a+b)^2}{g\sqrt{g^2+b^2}}.$$

App. Torque. Eff:

$$\delta = \frac{2(a+b)\sqrt{g^2+b^2}}{g^2+(a+b)^2}.$$

B. INDUCTIVE DEVICES.

EXTERNAL INDUCTIVE DEVICES.

Inductively divided circuit.—In its simplest form, as shown in diagram Fig. 15, the motor contains two circuits at right angles, of the same admittance:

$$Y = g + jb.$$

The one circuit (1) is in series with the one, the other (2) with the other of two coils wound on the same magnetic circuit M.

Let:

e = E. M. F. across single-phase mains.

$Z = -j\,x$ = impedance of one turn on the magnetic circuit M.

n_1, I_1, E_1 = number of turns of M, current and E. M. F. across motor coil of circuit (1); n_2, I_2, E_2 the corresponding values of circuit (2).

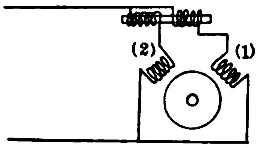

FIG. 15.

If both coils on M are wound in the same direction, n_1 and n_2 are positive; if the coils are wound in opposite direction, n_1 and n_2 are of opposite signs.

The M. M. F. acting upon magnetic circuit M is:

$$f = n_1\,I_1 + n_2\,I_2, \tag{1}$$

consequently, the E. M. F. induced per turn on M:

$$f\,Z = (n_1\,I_1 + n_2\,I_2)Z, \tag{2}$$

hence the E. M. F. across coil (1) on M:

$$E_1{}^1 = n_1 f\,Z = n_1\,(n_1\,I_1 + n_3\,I_1)\,Z, \tag{3}$$

and across coil (2):

$$E_2{}^1 = n_2 f\,Z = n_2\,(n_1\,I_1 + n_2\,I_2)\,Z. \tag{4}$$

The currents in the motor circuits (1) and (2) are:

$$I_1 = E_1\;Y, \tag{5}$$

$$I_2 = E_2\;Y. \tag{6}$$

Substituting (5) and (6) in (3) and (4), it is:

$$E_1^1 = n_1 (n_1 E_1 + n_2 E_2) Z Y, \tag{7}$$

$$E_2^1 = n_2 (n_1 E_1 + n_2 E_2) Z Y. \tag{8}$$

It is, however:

$$E_1 + E_1^1 = e = E_2 + E_2^1. \tag{9}$$

Thus, substituting (7) and (8):

$$E_1 (1 + n_1^2 Z Y) + n_1 n_2 E_2 Z Y = e, \tag{10}$$

$$n_1 n_2 E_1 Z Y + (1 + n_2^2 Z Y) E_2 = e, \tag{11}$$

hence:

$$E_1 = e \frac{1 + n_2 (n_2 - n_1) Z Y}{1 + (n_2^2 + n_1^2) Z Y}, \tag{12}$$

$$E_2 = e \frac{1 - n_1 (n_2 - n_1) Z Y}{1 + (n_2^2 + n_1^2) Z Y}, \tag{13}$$

or substituting $Z = -j x; \ Y = g + j b$:

$$E_1 = e \frac{1 + x b n_2 (n_2 - n_1) - j x g n_2 (n_2 - n_1)}{1 + x b (n_2^2 + n_1^2) - j x g (n_2^2 + n_1^2)}, \tag{14}$$

$$E_2 = e \frac{1 - x b n_1 (n_2 - n_1) + j x g n_1 (n_2 - n_1)}{1 + x b (n_2^2 - n_1^2) - j x g (n_2^2 + n_1^2)}. \tag{15}$$

The condition that the E. M. F.'s E_1 and E_2, and thus the two motor fluxes, are in quadrature, is:

$$E_2 = j a E_1, \tag{16}$$

where:

a = ratio of E. M. F.'s $\frac{E_2}{E_1}$, and thus of fluxes produced by them.

Substituting (14) and (15) in (16), it is:

$$1 - x b n_1 (n_2 - n_2) + j x g n_1 (n_2 - n_1) = j a + j a x b n_2 (n_2 - n_1)$$
$$+ a x g n_2 (n_2 - n_1).$$

thus:

$$x b n_1 (n_2 - n_1) + a x g n_2 (n_1 - n_1) = 1,$$

$$x g n_1 (n_2 - n_1) - a x b n_2 (n_2 - n_1) + a,$$

or:

$$x (n_2 - n_1) (b n_1 + a g n_2) = 1, \tag{17}$$

$$x (n_2 - n_1) (g n_1 - a b n_2) = a, \tag{18}$$

hence:

$$\frac{b n_1 + a g n_2}{g n_1 - a b n_2} = \frac{1}{a}, \tag{19}$$

herefrom:

$$a = \frac{-b\,(n_1 + n_2) \pm \sqrt{b_2\,(n_1 + n_2)^2 + 4\,g^2\,n_1\,n_2}}{2\,n_2\,g}, \tag{20}$$

or, assuming a as chosen, from (19):

$$\frac{n_1}{n_2} = a\,\frac{b + a\,g}{g - a\,b}. \tag{21}$$

Substituting (1) in (12):

$$x\,n_2^2 = \frac{(g - a\,b)^2}{a\,(b^2 + g^2)\,(g\,[1 - a^2] - 2\,a\,b)}. \tag{22}$$

$$x\,n_1 n_2 = \frac{(g - a\,b)\,(b + a\,g)}{(b^2 + g^2)\,(g\,[1 - a^2] - 2\,a\,b)}. \tag{23}$$

$$x\,n_1^2 = \frac{a\,(b + a\,g)^2}{(b^2 + g^2)\,(g\,[1 - a^2] - 2\,a\,b)} \tag{24}$$

As instance, let:

1.

$$Y = 1 + 3j,$$

$$x\,n_2^2 = \frac{(1 - 3\,a)^2}{10\,a\,(1 - 6\,a - a^2)}.$$

$$x\,n_1\,n^2 = \frac{(1 - 3\,a)\,(3 + a)}{10\,(1 - 6\,a - a^2)}.$$

$$x\,n_1^2 = \frac{a\,(3 + a)^2}{10\,(1 - 6\,a - a^2)}.$$

2.

$$Y = 3 + 1j$$

$$x\,n_2^2 = \frac{(3 - a)^2}{10\,a\,(3 - 2\,a - 3\,a^2)}.$$

$$x\,n_1\,n_2 = \frac{(3 - a)\,(1 + 3\,a)}{10\,(3 - 2\,a - 3\,a^2)}.$$

$$x\,n_1^2 = \frac{a\,(1 + 3\,a)^2}{10\,(3 - 2\,a - 3\,a^2)}.$$

$x\,n_1^2$ and $x\,n_2$ must be positive. $x\,n_1\,n_2$ is positive if the coils on M are wound in the same; negative, if in opposite direction.

It follows herefrom:

1.

$a > \sqrt{10} - 3$ $\qquad$ $x\,n_2^2 < 0,$

$> .1623$

that is, impossible.

$\sqrt{10} - 3 > a > 0$: $\qquad$ $n_1\,n_2 > 0$:

coil on M wound in same direction.

$$0 > a > -\sqrt{10} + 3: \qquad x\, n_2^2 < 0,$$

that is. impossible.

$$-(\sqrt{10} + 3) > a, \qquad n_1\, n_2 > 0:$$

coils on M in same direction.

This is the same range as above, but with E_1 and E_2 reversed.

2.

$$a > \tfrac{1}{3}(\sqrt{10} - 1), \qquad x\, n_2^2 < 0,$$

$$> .721,$$

that is, impossible.

$$\tfrac{1}{3}(\sqrt{10} - 1) > a > 0, \qquad n_1\, n^2 > 0,$$

coils on M wound in same direction.

$$0 > a > -\tfrac{1}{3}(\sqrt{10} + 1), \qquad x\, n_2^2 < 0,$$

that is, impossible.

$$-\tfrac{1}{3}(\sqrt{10} + 1) > a, \qquad n_1\, n_2 > 0,$$

coils on M in same direction.

This is the same range as above, but with E_1 and E_2 reversed.

Instance:

1.	2.
$a = .1$	$a = .5$
$x\, n_2^2 = 1.26$	$x\, n_2^2 = 1.00$
$x\, n_1\, n_2 = .555$	$x\, n_1\, n_2 = .5$
$x\, n_1^2 = .247$	$x\, n_1^2 = .25$
$n_2 = 2.25\, n_1$	$n_2 = .2\, n_1.$

Substituting in (14) (15):

$$\mathrm{E}_1 = \frac{3.1 - .7\, j}{5.5 - 1.5\, j}\, e = .56\, e\,(1 + .044\, j).$$

$$\mathrm{E}_1 = \frac{1.5\ (1 - j)}{2.25 - 3.75\, j}\, e = .48.4\,(.97 + .24\, j)\, e.$$

$$\mathrm{E}_2 = \frac{.07 + .31\, j}{5.5 - 1.5\, j}\, e = .056\, e\,(-.044 + j).$$

$$\mathrm{E}_2 = \frac{.75\,(1 + j)}{2.25 - 3.75\, j}\, e = .24.2\ (-.24 + .97\, j)\, e.$$

Substituting (22), (23) and (24) in (14) and (15) gives:

$$\mathrm{E}_1 = \frac{e\,\{(b + a\,g) - j\,(g - a\,b)\}\ \{g\,[1 - a^2] - 2\,a\,b\}}{\{(1-a^2)\,[a g^2 + b g (1-a^2) - a b^2]\} - j\,\{g^2[1 + a^4] - 2\,a b g\,[1 - a^2] + 2 a^2 b^2\}} \tag{25}$$

$$\mathrm{E}_2 = \frac{e\,a\,\{(g - a\,b) + j\,(b + a\,g)\}\ \{g\,[1 - a^2] - 2\,a\,b\}}{\text{same}}. \tag{26}$$

The current in circuit (1) is: $\mathrm{I}_1 = \mathrm{E}_1\, Y$,
The current in circuit (2) is: $\mathrm{I}_2 = \mathrm{E}_2\, Y$,
thus the total current:

$$\begin{aligned} \mathrm{I} = \mathrm{I}_1 + \mathrm{I}_2 &= (\mathrm{E}_1 + \mathrm{E}_2)\, Y, \\ &= (\mathrm{E}_1 + \mathrm{E}_2)\,(g + j\,b). \qquad (27) \end{aligned}$$

Substituting (25) and (26) in (27): (28)

$$Ie = \frac{\{2a(g^2-b^2)+j[g^2+b^2)(1-a^2)+4abg]\}\,\{g(1-a^2)-2ab\}}{\{1-a^2)(ag^2+bg[1-a^2]-ab^2)\}-j\{g^2(1+a^4)-2abg(1-a^2)+2a^2b^2\}}$$

As instance may be considered:

$$Y = g + j\,b = 3 + j. \qquad e = 100.$$

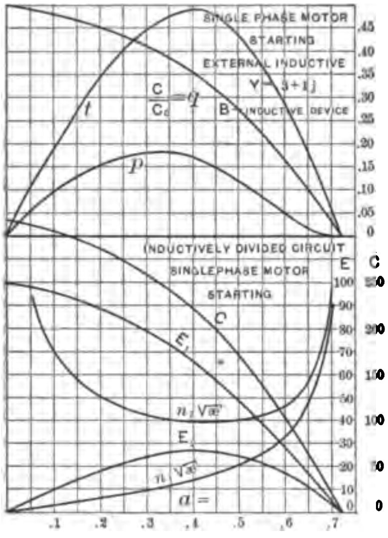

FIG. 16.

a:	$x n_2^2$ $\sqrt{x} n_2$	$x n_1 n_2$	$x n_1^2$ $\sqrt{x} n_1$	E_1	E_2	I	$q = \frac{I}{I_0}$	$p = \frac{E_1 E_2}{e^2}$	$t = \frac{p}{q}$
.721	∞ ∞	∞	∞ ∞	0	0	0	0	0	0
.7	5.8 2.408	5.48	5.18 2.276	4.7	3.3	18.3	.029	.0016	.055
.6	1.335 1.155	.933	.655 .809	27.7	16.6	102.5	.162	.046	.285
.5	1.00 1.000	.50	.25 .500	48.5	24.2	171	.270	.118	.438
.4	.98 .990	.333	.113 .336	66.0	26.4	226	.356	.174	.490
.3	1.14 1.068	.242	.051 .226	78.0	24.2	264	.406	.180	.445
.2	1.58 1.257	.181	.02 .145	89.0	17.8	287	.453	.155	.342
.1	3.03 1.741	.136	.006 .077	95.5	9.6	303	.478	.091	.190
0	∞ ∞	1.00	0 0	100	0	316	.500	0	0

where:

$I_0 = 2\,e\,\sqrt{b^2 + g^2}$ = total current input of motor on quarter-phase circuit;

$\frac{E_1 E_2}{e^2}$ = torque, and

t = apparent torque efficiency, in fraction of that of the same motor on quarter-phase circuit.

As seen before, with an inductive armature: $Y = 1 + 3j$, the conditions are much more unfavorable.

In Fig. 16 are plotted, with the values a as abscissæ, the E. M. F.'s E_1 and E_2, the current I, the relative numbers of turns $n_1\sqrt{x}$ and $n_2\sqrt{x}$, and in the upper part of the Fig. 16 the ratio of currents q, of torques p, and of apparent torque efficiencies t, of this starting device, compared with the same motor on quarter-phase circuit.

INTERNAL INDUCTIVE DEVICES.

The exciting system of the motor consists of a stationary primary coil and a stationary secondary coil, short-circuited (or closed by an impedance) upon itself, both acting upon the revolving secondary.

The stationary secondary can either cover a part of the pole face excited by the primary circuit—shading coil,—or it can have the same pitch or angular spread as the primary, but be displaced therefrom in space by an angle less than 90°—accelerating coil.

A.—SHADING COIL.

Let, in Fig. 17,

e = primary impressed E. M. F.

I_0 = " current.

I_1 = current in shading coil, reduced to primary number of turns.

E_1 = E. M. F. induced by flux through shading coil.

E_0 = " " " unshaded flux.

$Y_0 = \frac{1}{Z}$ = internal admittance of primary coil.[0]

---

[0] Flux interlinked with primary coil only, but no other circuit and effective primary resistance.

$Y_1 = \frac{1}{Z_1}$ = internal admittance of shading coil.[1]

Y = load admittance of armature.[2]

Y_{00} = magnetizing admittance, total pole.[3]

a = shaded portion of pole, as fraction of total pole,

thus: $1 - a$ = unshaded portion of pole, as fraction of total pole.

All quantities being reduced to primary number of turns.

It is, then:

Current in shading coil:

$$I_1 = E_1 \, Y_1 \qquad (1)$$

For the unshaded section of pole, it is:

Current in primary coil:

$$I_0 = E_0 \left\{ (1 - a) \, Y + \frac{Y_{00}}{1 - a} \right\} \qquad (2)$$

the first term representing the reaction of the induced armature currents, the last the exciting current of the pole arc $1 - a$.

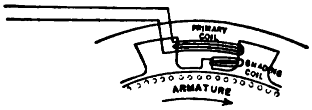

FIG. 17.

For the shaded section of pole, it is:

Current in primary coil:

$$I_0 = E_1 \left\{ a \, Y + \frac{Y_{00}}{a} + Y_1 \right\}. \qquad (3)$$

the third term $I_1 = E_1 \, Y_1$ representing the reaction of the induced shading currents, the first and second term the same as in (2).

Combining (2) and (3), it is:

$$E_0 \left\{ (1 - a) Y + \frac{Y_{00}}{1 - a} \right\} - E_1 \left\{ a \, Y + \frac{Y_{00}}{a} + Y_1 \right\} = 0. \qquad (4)$$

---

[1] Flux interlinked with shading coil only, but no other circuit, and internal resistance, together with impedance of external circuit closing shading coil, if such exists.

[2] $\frac{\text{Current in rev secondary}}{\text{E. M. F. acting upon total pole}}$ with shading coil open circuited.

[3] $\frac{\text{Current in primary of total pole}}{\text{E. M. F. at primary,}}$ with shading coil and armature open circuited.

It is, however, in primary circuit:

$$e = E_0 + E_1 + I_0 Z_0 = E_0 + E_1 + \frac{I_0}{Y_0}. \qquad (5)$$

Substituting (3) in (5):

$$e = E_0 + E_1 + E_1 \frac{Y_1 + a Y + \frac{Y_{00}}{a}}{Y_0},$$

or, transposed:

$$E_0 + E_1 \left\{ \frac{Y_0 + Y_1 + a Y + \frac{1}{a} Y_{00}}{Y_0} \right\} = e. \qquad (6)$$

(4) and (6) combined give:

$$E_0 = \frac{e Y_0 \left\{ a Y + Y_1 + \frac{1}{a} Y_{00} \right\}}{Y_0 (Y + Y_1) + (1-a)(a Y + Y_1) + \frac{Y_{00}}{a(1-a)} \left\{ Y_0 + a Y_1 + (1 - 2a + 2a^2) Y + Y_{00} \right\}} \qquad (7)$$

$$E_1 = e \frac{Y_0 \left\{ (1-a) Y + \frac{1}{1-a} Y_{00} \right\}}{\text{same denominator}}. \qquad (8)$$

Phase displacement angle $(E_1, E_0) = \omega$:

$$A (\cos \omega + j \sin \omega) = \frac{E_1}{E_0} = \frac{(1-a) Y + \frac{Y_{00}}{1-a}}{a Y + Y_1 + \frac{Y_{00}}{a}}. \qquad (9)$$

Assuming the shading coil to cover half the poleface, that is:

$$a = 1 - a = \tfrac{1}{2},$$

and neglecting the primary impedance:

$$Z_0 = \frac{1}{Y_0} = 0,$$

it is:

primary current: $I_0 = \frac{E_0}{2} (Y + 4 Y_{00}),$ (10)

and:

$$\left. \begin{aligned} E_0 &= \frac{e}{2} \frac{Y + 2 Y_1 + 4 Y_{00}}{Y + Y_1 + 4 Y_{00}}, \\ E_1 &= \frac{e}{2} \frac{Y + 4 Y_{00}}{Y + Y_1 + 4 Y_{00}}. \end{aligned} \right\} \qquad (11)$$

Phase angle: $A (\cos \omega + j \sin \omega) = \frac{Y + 4 Y_{00}}{Y + 2 Y_1 + 4 Y_{00}}$ (10)

Substituting: $Y + Y_1 + 4\,Y_{00} = Y^1$ (13)

it is:

$$I_0 = \frac{E_0}{2}\,(Y^1 - Y_1), \tag{14}$$

$$\left.\begin{aligned} E_0 &= \frac{e}{2}\,\frac{Y^1 + Y_1}{Y_1} = \frac{e}{2}\left(1 + \frac{Y_1}{Y^1}\right), \\ E_1 &= \frac{e}{2}\,\frac{Y^1 - Y_1}{Y^1} = \frac{e}{2}\left(1 - \frac{Y_1}{Y^1}\right), \end{aligned}\right\} \tag{15}$$

$$I_0 = \frac{e}{4}\,\frac{Y^{1\,2} - Y_1^2}{Y^1}. \tag{16}$$

$$A\,(\cos\omega + j\sin\omega) = \frac{Y^1 - Y_1}{Y^1 + Y_1}. \tag{17}$$

Substituting now $Y = g + j\,b$ etc., and eliminating imaginary quantities, gives:

$$\left.\begin{aligned} E_0 &= \frac{e}{2\,y^1}\sqrt{\left(g^1 + g_1\right)^2 + \left(b^1 + b_1\right)^2}, \\ E_1 &= \frac{e}{2\,y^1}\sqrt{\left(g^1 - g_1\right)^2 + \left(b^1 - b_1\right)^2}. \end{aligned}\right\} \tag{18}$$

$$I_0 = \frac{e}{4\,y^1}\sqrt{\left[\left(g^1 + g_1\right)^2 + \left(b^1 + b_1\right)^2\right]\left[\left(g^1 - g_1\right)^2 + \left(b^1 - b_1\right)^2\right]} \tag{19}$$

$$A\,(\cos\omega + j\sin\omega) = \frac{(g^1 - g_1) + j\,(b^1 - b_1)}{(g_1 + g_1) + j\,(b^1 + b_1)}, \tag{20}$$

hence:

$$\tan\omega = 2\,\frac{g_1\,b^1 - g^1\,b_1}{y^{1\,2} + y_1^2}. \tag{21}$$

Since the denominator in (21) can never $= 0$, ω can never $= 90°$. That is:

It is not possible to produce exact quadrature flux by means of this shading coil.

$$\omega = 0, \text{ for: } g_1\,b^1 - g^1\,b_1 = 0, \text{ or:}$$

$$\frac{g_1}{b_1} = \frac{g^1}{b^1}, \text{ or } \frac{g_1}{y_1} = \frac{g^1}{y^1}. \tag{22}$$

That is:

If the power factor of the shading coil: $\frac{g_1}{y_1}$, equals the power factor $\frac{g^1}{y^1}$ of the term: $Y + Y_1 + 4\,Y_{00}$, the shaded flux comes in phase with the unshaded flux, and the torque becomes $= 0$.

If: $\frac{g_1}{y_1} > \frac{g^1}{y^1}$, $\omega > 0$, that is, the torque of the motor is from the direction of the unshaded portion, towards the shaded portion of the pole, and the shading coil is a lagging coil.

If: $\frac{g_1}{y_1} > \frac{g^1}{y}$, $\omega > 0$, that is, the torque is from the shaded towards the unshaded portion of the motor pole, and the shading coil is an accelerating coil.

Hence, with a high resistance low reactance shading coil the motor armature turns towards the shading coil, as shown by the arrow in Fig 17, with a high reactance low resistance shading coil it turns in the opposite direction.

The torque of an induction motor is the sum of the vector products of primary counter E. M. F.'s times secondary currents induced by their quadrature E. M. F.'s, thus in the present instance.

$$T = /\mathrm{E}_0 \, \mathrm{I}_1^0/ + /\mathrm{E}_1 \, \mathrm{I}_0^0/, \tag{23}$$

where:

I_0^0 = current induced in the armature section covered by unshaded,

I_1^0 = current induced in the armature section covered by shaded portion of pole, reduced to primary number of turns.

It is however:

$$\left.\begin{aligned} \mathrm{I}_0^0 &= \mathrm{E}_0 \, Y (1 - a) \\ \mathrm{I}_1^0 &= \mathrm{E}_1 \, Y a, \end{aligned}\right\} \tag{24}$$

or, at $a = \frac{1}{2}$:

$$\left.\begin{aligned} \mathrm{I}_0^0 &= \frac{\mathrm{E}_0 \, Y}{2}, \\ \mathrm{I}_1^0 &= \frac{\mathrm{E}_1 \, Y}{2}. \end{aligned}\right\} \tag{25}$$

Substituting:

$$\tan a = \frac{b}{g}, \tag{26}$$

where a = lag angle of induced armature currents I_0^0 and I_0^1 behind their inducing E. M. F.'s E_0 and E_1,

since ω = phase displacement between E_0 and E_1,

the phase displacement between E_0 and I_1^0 is $\omega + a$,

" " " " E_1 and I_0^0 is $\omega - a$,

hence, substituting the real values in (23), with (25):

$$T = \frac{E_0 E_1 y}{2} \left\{ \sin(\omega + a) + \sin(\omega - a) \right\}$$

$$= E_0 E_1 y \cos a \sin \omega, \qquad (27)$$

since, from (26):

$$\cos a = \frac{g}{y},$$

it is:

$$T = E_0 E_1 g \sin \omega. \qquad (28)$$

the torque of the motor.

Substituting (18) and (21) in (28), it is:

$$T = \frac{e^2 g}{4 y^{1\,2}} \sqrt{[(g^1 + g_1)^2 + (b^1 + b_1)^2]\,[(g^1 - g_1)^2 + (b^1 - b_1)^2]}$$

$$\times \frac{2 (g_1 b^1 - g^1 b_1)}{\sqrt{(y^{1\,2} + y_1^2)^2 + 4 (g_1 b^1 - g^1 b_1)^2}}. \qquad (29)$$

$$= \frac{e^2 g (g_1 b^1 - g^1 b_1) R}{2 y^{1\,2} \sqrt{(y^{1\,2} + y_1^2)^2 + 4 (g_1 b^1 - g^1 b_1)^2}}.$$

Since:

$$R^2 = [(g^1 + g_1)^2 + (b^1 + b_1)^2]\ [g^1 - g_1)^2 + (b^1 - b_1)^2]$$

$$= (y^{12} + y_1^2)^2 - 2 [(g^1 g_1 + b^1 b_1)^2 - (g^1 b_1 - g_1 b^1)^2],$$

it is, substituted in (29):

$$T = \frac{e^2 g (g_1 b^1 - g^1 b_1)}{2 g^{1\,2}} \times$$

$$\sqrt{\frac{1 - \dfrac{2 [(g^1 g_1 + b^1 b_1)^2 - (g^1 b_1 - g_1 b^1)^2]}{y^1 + y_1^2)^2}}{1 + \dfrac{4 (g_1 b^1 - g^1 b_1)^2}{(y^{12} + y_1^2)^2}}} \qquad (30)$$

Thus, approximately:

$$T = \frac{e^2 g (g_1 b^1 - g^1 b_1)}{2 y^{12}}. \qquad (31)$$

The apparent input of the motor is:

$$Q = e I_0 \qquad (32)$$

Substituting (19), in (32), it is:

$$Q = \frac{e^2 R}{4 y^1}. \qquad (33)$$

Thus, the apparent torque efficiency, by substituting (29):

$$t = \frac{T}{Q} = \frac{2 g (g_1 b^1 - g^1 b_1)}{y^1 \sqrt{(y^{1\,2} + y_1^2)^2 + 4 (g_1 b^1 - g^1 b_1)^2}} \qquad (34)$$

or:

$$t = \frac{g_1}{y} \frac{1}{\sqrt{1 + \left(\frac{{y^1}^2 + y_1^2}{2\,(g_1 b^1 - g^1 b_1)}\right)^2}}. \tag{35}$$

Neglecting the second term in the denominator of (34), it is:

$$t = \frac{2\,g\,(g_1 b^1 - g^1 b_1)}{y^1\,({y^1}^2 + y_1^2)}. \tag{36}$$

As seen, the apparent torque efficiency is very small under any circumstance, except when $b_1 < 0$, that is, the shading coil is closed by capacity.

As instances may be considered the following conditions:

APPARENT TORQUE EFFICIENCY.

	Shading Coil: Y_1	Secondary: Y	Primary Excitation: Y_{00}	Hence:	Resultant: Y^1	t		$\frac{t}{g}$
						in Approx: (36)	%, exact: (35)	
0	.5	1.0	.05+.2j		1.7+.8j	+11.3	+11.0	11.0
		.8+.6j	......		1.5+1.4j	+12.2	+11.7	14.6
		.6+.8j	......		1.3+1.6j	+10.3	+9.7	16.2
		.1+1.0j	......		.8+1.8j	+2.2	+2.0	20.0
37	.4+.3j	1.0	......		1.6+1.1j	−1.03	−1.03	.....
		.8+.6j	......		1.4+1.7j	+3.7	+3.7	......
		.6+.8j	......		1.2+1.9j	+4.0	+4.0	......
		.1+1.0j	...		.7+2.1j	+1.16	+1.15	......
53	.3+.4j	1.0	......		1.5+1.2j	−6.3	−6.3	.....
		.8+.6j	......		1.3+1.8j	+.28	+.28	......
		.6+.8j	......		1.1+2.0j	+1.53	+1.53	.....
		.1+1.0j	......		.6+2.2j	+.74	+.73	.....
90	.5j	1.0	......		1.2+1.3j	−20.0	−18.9	−18.9
		.8+.6j	......		1.0+1.9j	−7.6	−7.5	−9.4
		.6+.8j	......		.8+2.1j	−4.0	−4.0	−6.7
		.1+1.0j	......		.3+2.3j	−.15	−.15	−1.5
−37	.4−.3j	1.0	......		1.6+.5j	+26.5	+24.3	Capacity in Shading Circuit.
		.8+.6j	......		1.4+1.1j	+22.7	+20.2	
		.6+.8j	.....		1.2+1.3j	+17.7	+15.8	
−53	.3−.4j	1.0	......		1.5+.4j	+34.8	+30.6	
		.8+.6j	.....		1.3+1.1j	+27.2	+23.8	
		.6+.8j	......		1.1+1.2j	+20.3	+18.0	

These values are recorded as curves in Fig. 18. As seen, they are extremely small, and somewhat better, although still low, by the use of capacity in the shading circuit.

The torque is in some instances in the one, in others in the other direction, according to the relative power factors of admittances Y_1 and Y^1.

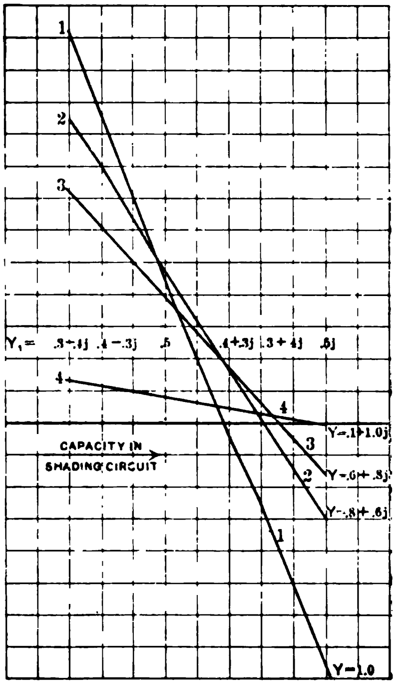

Fig. 18.—Single Phase Induction Motor.
Starting Shading Coil.
Magnetizing Admittance of Motor: $Y = .c5 + 2j$.

		CURVE
Load Admittance of Armature:	$Y = 1.0$	(1)
	$.8 + .6j$	(2)
	$.6 + .8j$	(3)
	$.1 + 1.0j$	(4)
Shading Coil Admittance	$Y_1 = .3 - .4j$	
	$.4 - .3j$	
	$.5$	
	$.4 + .3j$	
	$.3 + .4j$	
	$.5j$	

B Inductive Device.

B. Accelerating Coil.

Let, in Fig. 19,

e = primary impressed E. M. F.,

I_0 = primary current,

I_1 = current in accelerating coil,

$\frac{1}{Y_0} = Z_0$ = impedance of primary coil,[1]

Z_1 = " " accelerating coil,[1]

Y_{00}= magnetic admittance per coil, primary or accelerat. coil,[1]

Y = load admittance of armature,[1]

a = ratio of widths of sections of primary coil ($2 \div 1$ in Fig. 19),

E_1 = E. M. F. induced per coil by the one $(1 - a)$,

E_2 = " " " " " " other (a) section of primary coil, all these values being reduced to the primary coil by the ratio of turns.

It is then:

$$\left.\begin{array}{ll} \text{Accelerating coil:} & I_1 Z_1 = E_1 - E_2 \\ \text{Primary coil:} & e_0 - I_0 Z_0 = E_1 + E_2 \end{array}\right\} \text{E. M. F.} \qquad \begin{array}{r} (1) \\ (2) \end{array}$$

$$\left.\begin{array}{ll} \text{Section 1:} & E_1 \left\{ \frac{Y_{00}}{1-a} + (1-a) Y \right\} + I_1 = I_0 \\ \text{" 2:} & E_2 \left\{ \frac{Y_{00}}{a} + a Y \right\} - I_1 = I_0 \end{array}\right\} \text{M. M. F.} \qquad \begin{array}{r} (3) \\ (4) \end{array}$$

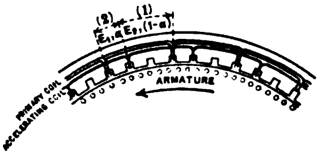

FIG. 19.

the first terms representing the magnetizing current, the second the armature reaction, and the third the accelerating coil.

(3) and (4) combined gives:

$$2 I_0 = E_2 \left\{ \frac{Y_{00}}{a} + a Y \right\} + E_1 \left\{ \frac{Y_{00}}{1-a} + (1-a) Y \right\} \tag{5}$$

$$2 I_1 = E_2 \left\{ \frac{Y_{00}}{a} + a Y \right\} - E_1 \left\{ \frac{Y_{00}}{1-a} + (1-a) Y \right\} \tag{6}$$

(5) and (6) substituted in (1) and (2), and transposed, gives after some transformations:

$$E_1 = 2 e \frac{2 + Z_1 \left\{ \frac{Y_{00}}{a} + a Y \right\}}{\left\{ 2 + Z_0 \left[\frac{Y_{00}}{1-a} + (1-a) Y \right] \right\} \left\{ 2 + Z_1 \left[\frac{Y_{00}}{a} + a Y \right] \right\} + \left\{ 2 + Z_0 \left[\frac{Y_{00}}{a} + a Y \right] \right\} \left\{ 2 + Z_1 \left[\frac{Y_{00}}{1-a} + (1-a) Y \right] \right\}} \tag{7}$$

---

[1] See footnotes 0 to 3 under "Shading Coil."

$$\mathbf{E}_2 = 2\,e\,\frac{2 + Z_1\left\{\frac{Y_{00}}{1-a} + (1-a)\,Y\right\}}{\text{same denominator}}. \tag{8}$$

Assuming the accelerating coil of the same impedance as the primary coil:

$$Z_1 = Z_0 = Z,$$

and $a = \frac{1}{3}$, or 60° space displacement, it is:

$$\mathbf{E}_1 = \frac{e}{2 + Z\left\{\frac{Y_{00}}{1-a} + (1-a)\,Y\right\}}, \tag{9}$$

$$\mathbf{E}_2 = \frac{e}{2 + Z\left\{\frac{Y^{00}}{a} + a\;Y\right\}}, \tag{10}$$

and $a = \frac{1}{3}$:

$$\mathbf{E}_1 = \frac{6\,e}{12 + Z\,[9\;Y_{00} + 4\;Y]}, \tag{11}$$

$$\mathbf{E}_2 = \frac{3\,e}{6 + Z\,[9\;Y_{00} + Y]}. \tag{12}$$

Phase displacement between $\mathbf{E}_1$ and $\mathbf{E}_2$: $(\mathbf{E}_2, \mathbf{E}_1) = \omega$:

$$A\,(\cos\omega + j\sin\omega) = \frac{12 + Z\,(9\;Y_{00} + 4\;Y)}{12 + 2\,Z\,(9_{00} + Y)}, \tag{13}$$

substituting for $Z_1\;Y_1\;Y_{00}$:

$$A\,(\cos\omega + j\sin\omega) = \frac{12+(r-j\,x)\,[(4\,g+9\,g_{00})+j(4\,b+9\,b_{00})]}{12+2\,(r-j\,x)\,[(g+9\,g_{00})+j\,(b+9\,b_{00})]},$$

$$= \frac{[12+r(4g+9g_{00})+x(4b+9b_{00})]+j[r(4b+9b_{00})-x(4g+9g_{00})]}{[12+2r(g+9g_{00})+2x(b+9b_{00})]+2j[r(b+9b_{00})-x(g+9g_{00})]} \tag{14}$$

Substituting:

$$\left.\begin{aligned} 4\,g + 9\,g_{00} &= g_1, & 4\,b + 9\,b_{00} &= b_1, \\ 2\,(g + 9\,g_{00}) &= g_2, & 2\,(b + 9\,b_{00}) &= b_2, \end{aligned}\right\} \tag{14}$$

it is:

$$A\,(\cos\omega + j\sin\omega) = \frac{(12 + r\,g_1 + x\,b_1) + j\,(r\,b_1 - x\,g_1)}{(12 + r\,g_2 + x\,b_2) + j\,(r\,b_2 - x\,g_2)}$$

$$= \frac{[(12+rg_1+xb_1)(12+rg_2+xb_2)+(rb_1-xg_1)(rb_2-xg_2)]+j\,[(rb_1-xg_1)(12+rg_2+xb_2)-(rb_2-xg_2)(12+rg_1+xb_1)]}{(12+rg_2+xb_2)^2+(rb_2-xg_2)^2},$$

hence:

$$\tan = \frac{(rb_1 - xg_1)(12 + rg_2 + xb_2) - (rb_2 - xg_2)(12 + rg_1 + xb_1}{(12 + rg_1 + b_1)(12 + rg_2 + xb_2) + (rb_1 - xg_1)(rb_2 - xg_2)}$$

$$= \frac{12r(b_1 - b_2) - 12x(g_1 - g_2) + (r^2 + x^2)(b_1 g_2 - g_1 b_2)}{144 + 12r(g_1 + g_2) + 12x(b_1 + b_2) + g_1 g_2 + b_1 b_2)(r^2 + x^2)}.$$

That is:

$$\tan \omega = \frac{12r(b_1 - b_2) - 12x(g_1 - g_2) + Z^2(b_1 g_2 - g_1 b_2)}{144 + 12r(g_1 + g_2) + 12x(b_1 + b_2) + Z^2(g_1 g_2 + b_1 b_2)}. \qquad (15)$$

Since the denominator can never $= 0$, it is not possible to produce exact quadrature flux:

$$\omega = 90^\circ.$$

$$\omega = 0$$

for:

$$12\,r\,(b_1 - b_2) - 12\,x\,(g_1 - g_2) + z^2\,(b_1\,g_2 - g_1\,b_2) = 0, \qquad (16)$$

or approximately:

$$12\,r\,(b_1 - b_2) - 12\,x\,(g_1 - g_2) = 0,$$

$$\frac{x}{r} = \frac{b_1 - b_2}{g_1 - g_2},$$

substituting (14):

$$\frac{x}{r} = \frac{2\,b - 9\,b_{00}}{2\,g - 9\,g_{00}} = \frac{b + 4.5\,b_{00}}{g + 4.5\,g_{00}}. \qquad (17)$$

That is, if the displacement angle of the accelerating coil:

$$\tan x_1 = \frac{x}{r},$$

equals the displacement angle of the armature plus 4.5 times the magnetizing current, the torque $= 0$. On one side of this point the torque is in the one, on the other side in the opposite direction.

This condition is essentially the same as found in "A, Shading Coil," thus the further discussion can be omitted.

C.—MONOCYCLIC STARTING DEVICES.

The monocyclic starting devices consist in producing externally to the motor a system of polyphase E. M. F.'s with single-phase flow of energy, and impressing it upon the motor, which is wound as polyphase motor.

Such a polyphase system of E. M. F.'s with single-phase flow of energy has been called a monocyclic system. It essentially consists, or can be resolved into, a main or energy E. M. F., in phase with the flow of energy, and a teaser or wattless E. M. F., in quadrature with the flow of energy and thus with the main E. M. F.

By combining these E. M. F.'s, compound systems of polyphase E. M. F.'s can be produced, as for instance a three-phase triangle with one side as teaser, and the other two sides as resultants of teaser and main (Fig. 20, the direction of the main E. M. F. being given by the arrow), or a three-phase triangle with one side as main, and the other two sides as resultants of main and teaser (Fig. 21), or a quarter-phase system of E. M. F.'s with the diagonal as main, and the sides as resultants of main and teaser (Fig. 22):

When derived from a monocyclic generator, the wattless feature of the teaser voltage is secured by its internal reactions, thus not as complete as when the teaser voltage is derived from the main voltage by phase displacing devices. Thus only the latter case will be discussed.

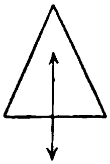

Fig. 20.

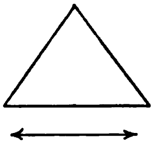

Fig. 21.

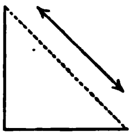

Fig. 22.

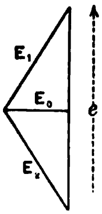

Fig. 23.

If across the single-phase mains of E. M. F. e, two impedances of different inductance factors are connected, the E. M. F.'s across these two impedances, E_1 and E_2, are displaced from each other, thus forming with the main E. M. F. e on E. M. F. triangle, (Fig. 23.)

The altitude of this triangle, or the E. M. F. E_0 between the common connection of the two impedances and a point inside of the main E. M. F. e (its middle, if the impedances are equal), is as E. M. F. in quadrature with e, and a teaser voltage, that is, when current is derived from this E. M. F., it droops.

Such an E. M. F. triangle thus constitutes a monocyclic system, or a polyphase system of E. M. F.'s with single-phase flow of power, and can be used for starting a suitable induction motor, as for instance a motor with main and teaser winding, or a motor with three-phase winding.

Let, in Fig. 24:

e = E. M. F. between single-phase lines,

I = current in single-phase lines,

Y = admittance of motor between single-phase lines 1 and 2,

I^1 = current flowing through this admittance between 1 and 2,

Y_1, E_1, I_1 = admittance, E. M. F. and current in impedance 1,

Y_2, E_2, I_2 = admittance, E. M. F. and current in impedance 2,

Y_0, E_0, I_0 = admittance, E. M. F. and current of motor circuit in quadrature to the main motor circuit, or from 3 towards (1, 2),

$E_0 = e_0' + j e_0''$,

I_1^1 = current entering terminal 1 of motor,

I_2^1 = current leaving terminal 2 of motor,

I_{31} and I_{32} = current flowing from 3 to 1 and 2 respectively.

The directions in which these E. M. F.'s and currents are counted, as shown by the arrows in Fig. 24, the E. M. F. triangle shown in Fig. 25.

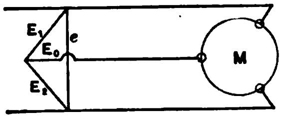

FIG. 25.

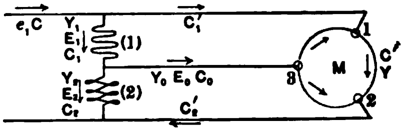

FIG. 24.

It is then:

$$\left.\begin{aligned} E_1 + E_2 &= e, \\ E_2 - E_1 &= 2\,E_0, \end{aligned}\right\} \qquad (1)$$

$$I_1 - I_2 = I_0, \qquad (2)$$

$$\left.\begin{aligned} I_1 &= Y_1\,E_1, \\ I_2 &= Y_2\,E_2, \end{aligned}\right\} \qquad (3)$$

$$I_0 = Y_0\,E_0, \qquad (4)$$

Substituting (3) and (4) in (2):

$$Y_1\,E_1 = Y_2\,E_2 = Y_0\,E_0, \qquad (5)$$

From (1) we get:

$$\left.\begin{aligned} E_1 &= \frac{e}{2} - E_0, \\ E_2 &= \frac{e}{2} + E_0, \end{aligned}\right\} \qquad (6)$$

Substituting (6) in (5), and transposing:

$$E_0 = \frac{e}{2} \frac{Y_1 - Y_2}{Y_1 + Y_2 + Y_0} \Bigg\} \qquad (7)$$

Substituting (7) in (6):

$$\left. \begin{aligned} E_1 &= \frac{e}{2} \frac{2\, Y_2 + Y_0}{Y_1 + Y_2 + Y_0} \\ E_2 &= \frac{e}{2} \frac{2\, Y_1 + Y_0}{Y_1 + Y_2 + Y_0} \end{aligned} \right\} \qquad (8)$$

Substituting (7) and (8) in (3) and (4):

$$\left. \begin{aligned} I_1 &= \frac{e}{2} \frac{Y_1 (2\, Y_2 + Y_0)}{Y_1 + Y_2 + Y_0} \\ I_2 &= \frac{e}{2} \frac{Y_2 (2\, Y_1 + Y_0)}{Y_1 + Y_2 + Y_0} \end{aligned} \right\} \qquad (9)$$

$$I_0 = \frac{e}{2} \frac{Y_0 (Y_1 - Y_2)}{Y_1 + Y_2 + Y_0} \Bigg\} \qquad (10)$$

It is, from diagram:

$$I_1 = e\, Y, \qquad (11)$$

$$\left. \begin{aligned} I_1^1 &= I^1 - \frac{I_0}{2} \\ I_2^1 &= I^1 + \frac{I_0}{2} \end{aligned} \right\} \qquad (11)$$

$$I = I_1^1 + I_1 = I_2^1 + I_2. \qquad (13)$$

Substituting in these equations (12, 13) the equations (9, 10, 11) gives:

$$\left. \begin{aligned} I_1^1 &= \frac{e}{4} \left\{ 4\, Y - \frac{Y_0 (Y_1 - Y_2)}{Y_1 + Y_2 + Y_0} \right\} \\ I_2^1 &= \frac{e}{4} \left\{ 4\, Y + \frac{Y\, (Y_1 - Y_2)}{Y_1 + Y_2 + Y_0} \right\} \end{aligned} \right\} \qquad (14)$$

$$I = \frac{e}{4} \left\{ 4\, Y + \frac{4\, Y_1\, Y_2 + Y_1\, Y_0 + Y_2\, Y_0}{Y_1 + Y_2 + Y_0} \right\} \qquad (15)$$

The total volt-ampere input of motor and starting device is:

$$\begin{aligned} Q &= e\, I, \\ &= \frac{e^2}{4} \left[4\, Y = \frac{4\, Y_1\, Y_2 + Y_1\, Y_0 + Y_2\, Y_0}{Y_1 + Y_2 + Y_0} \right] \end{aligned} \qquad (16)$$

that of the motor alone:

$$Q^1 = e\, I^1 + E_0\, I_0. \qquad (17)$$

In a polyphase motor, the volt-ampere input of the two quadrature fluxes is equal, thus in the motor M on polyphase circuit it is:

$$Q_0 = 2\, e\, I^1 = 2\, e^2\, y. \qquad (18)$$

Thus the ratio of apparent inputs:

$$\mathrm{I} = \frac{Q}{Q_0} = \frac{1}{8}\, y \left[4\, Y + \frac{4\, Y_1\, Y_2 + Y_1\, Y_0 + Y_2\, Y_0}{Y_1 + Y_2 + Y_0}. \right. \qquad (19)$$

The ratio of torque of this motor M with monocyclic starting device to the torque of the same motor on polyphase circuits is obviously the ratio of the quadrature flux produced by the teaser voltage E_0 to the quadrature flux in the polyphase motor, that is the main flux produced by e.

Hence, if q = ratio of number of effective turns of the cross circuit Y_0 to the main circuit Y, a polyphase flux would require in this cross circuit the impressed E. M. F. $q\, e$, and thus, if e_0 = imaginary or quadrature component of the cross E. M. F. $E_0 = e_0 + j\, e_0''$, the ratio of torque by monocyclic starting device, T, to polyphase torque T_0, is:

$$\frac{T}{T_0} = \frac{e_0''}{q\, e}. \qquad (20)$$

Hence the relative apparent torque efficiency, or ratio of apparent torque efficiencies:

$$t = \frac{T}{T_0} \times \frac{Q_0}{Q}. \qquad (21)$$

If the motor M is wound with main circuit and teaser circuit of one quarter as many turns of the same size as those of the main circuit, $q = \frac{1}{4}$,
if it is wound with two equal circuits, as quarter-phase motor, it is: $q = 1$ or: $q\ \frac{1}{2}$,
if it is wound as three-phase motor, it is: $q = \frac{1}{2}\ \sqrt{3} = .866$.

These three are the most important arrangements.

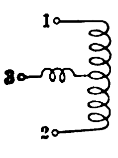

FIG. 26.

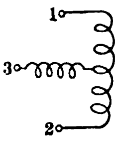

FIG. 27.

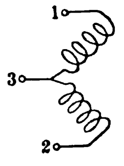

FIG. 28.

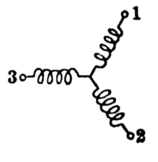

FIG. 29.

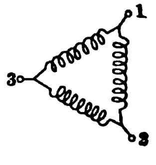

FIG. 30.

FIG. 26. Monocyclic Motor : $q = \frac{1}{4}$. $Y_0 = 4\ Y$,
FIG. 27. Quarter-phase Motor: $q = 1$. $Y_0 = Y$
FIG. 28. " " $q = \frac{1}{2}$. $Y_0 = 4\ Y$,
FIGS. 26 to 30. Three-phase Motor : $q = \frac{1}{2}\ \sqrt{3}$. $Y_0 = 4/3\ Y$.

Substituting these values in equations (7) (10) (15), it is:

1. **Monocyclic Motor:** $q = .25, \quad Y_0 = 4\ Y.$

$$E_0 = \frac{e}{2} \frac{Y_1 - Y_2}{Y_1 + Y_2 + 4\ Y},$$

$$I_0 = 2\ e\ \frac{Y\,(Y_1 - Y_2)}{Y_1 + Y_2 + 4\ Y}. \tag{22}$$

$$I = e\frac{4\ Y^2 + 2\ Y\ Y_1 + 2\ Y\ Y_2 + Y_1\ Y_2}{Y_1 + Y_2 + 4\ Y}.$$

2. **Quarter-phase Motor, connected for** $q = 1, \ Y_0 = Y$:

$$E_0 = \frac{e}{2} \frac{Y_1 - Y_2}{Y_1\ Y_2 + Y},$$

$$I_1 = \frac{e}{2} \frac{Y\,(Y_1 - Y_2)}{Y_1 + Y_2\ Y}. \tag{23}$$

$$I = \frac{e}{4} \frac{4\ Y^2 + 5\ Y\ Y_1 + 5\ Y\ Y_2 + 4\ Y_1\ Y_2}{Y_1 + Y_2 + Y}.$$

3. **Quarter-phase Motor, connected for** $q = .5, \quad Y_0 = 4\ Y$:

$$E_0 = \frac{e}{2} \frac{Y_1 - Y_2}{Y_1 + Y_2 + 4\ Y},$$

$$I_0 = 2\ e\ \frac{Y\,(Y_1 - Y_2)}{Y_1 + Y_2 + 4\ Y}, \tag{24}$$

$$I = e\ \frac{Y^2 + 2\ Y\ Y_1 + 2\ Y\ Y_2 + Y\ Y_2}{Y_1 + Y_2 + 4\ Y}.$$

4. **Three-phase Motor:** $q = \frac{1}{2}\ \sqrt{3}, \quad Y_0 = 4/3\ Y.$

$$E_0 = \frac{e}{2} \frac{Y_1 - Y_2}{Y_1 + Y_2 + 4/3\ Y} = \frac{3\ e}{2} \frac{Y_1 - Y_2}{3\ Y_1 + Y_2 + 4\ Y},$$

$$I_0 = \frac{2\ e}{3} \frac{Y\,(Y_1 - Y_2)}{Y_1 + Y_2 + 4/3\ Y} = 2\ e\ \frac{Y\,(Y_1 - Y_2}{3\ Y_1 + 3\ Y_2 + 4\ Y}$$

$$\tag{25}$$

$$I = \frac{e}{4}\left\{4\ Y + \frac{4\ Y_1\ Y_2 + 4/3\ Y\ Y_1 + 4/3\ Y\ Y_2}{2\ Y_1 + Y_2 + 4/3\ Y}\right. =$$

$$e\ \frac{4\ Y^2 + 4\ Y\ Y_1 + 4\ Y\ Y_2 + 3\ Y_1\ Y_2}{3\ Y_1 + 3\ Y_2 + 4\ Y}$$

The most important combinations of impedances are:
Resistance — inductance, as the simplest device.

Capacity — inductance, as giving the highest cross E. M. F. E_0 and thus best starting torque and torque efficiencies, and

Combinations of both, as:

Non-inductive resistance — reactive coil,

Electrolytic condenser — reactive coil, etc.

The three-phase motor with monocyclic starting device, consisting of resistance — inductance, is the only type of single-phase induction motor which has found an extensive commercial application, in sizes from $\frac{1}{4}$ H. P. to 100 H. P., and thus will be more fully discussed.

(a). *Resistance — Inductance.*

Let, in a three-phase $\triangle$ connected motor, $Y^1 = g^1 + j\, b^1 =$ admittance per motor circuit. (In a Y connected motor with admittance Y^{11} per circuit, the $\triangle$ admittance, or admittance reduced to $\triangle$ connection, would be: $Y^1 = \frac{1}{3}\, Y^{11}$.)

Let $Y_1 = r, \quad Y_2 = + j\, a.$

Introducing the substitution:

$$Y^1 = a\, A = a\, (\gamma + j\, \beta), \qquad \vartheta = \sqrt{\gamma^2 + \beta^2},$$

where ϑ is the ratio of the absolute admittance per motor circuit to that of the resistance or inductance of the starting device.

In the three-phase motor with $\triangle$ admittance Y^1 it is:

$Y = 1.5\, Y^1 = 1.5\, a\, A =$ admittance between single-phase mains,

$Y_0 = 2\, Y^1 = 2\, a\, A =$ admittance of cross circuit, and

$a = \frac{1}{2}\sqrt{3} =$ ratio of effective turns of teaser or cross circuit to main circuit.

Substituting these values in the preceding equations, it is:

$$E_0 = \frac{e}{2}\, \frac{1 - j}{1 + j + 2\, A},$$

$$E_1 = e\, \frac{j + A}{1 + j + 2\, A},$$

$$E_2 = e\, \frac{1 + A}{1 + j + 2\, A},$$

$$I_1 = e\, a\, \frac{j + A}{1 + j + 2\, A},$$

$$I_1 = j\, e\, a\, \frac{1 + A}{1 + j + 2\, A},$$

$$I_0 = e\, a\, A\, \frac{1 - j}{1 + j + 2\, A},$$

$$I^1 = 1.5\, e\, a\, A,$$

$$I_1^1 = e\, a\, A\, \frac{1 + 2j + 3A}{1 + j + 2A},$$

$$I_2^1 = e\, a\, A\, \frac{2 + j + 3A}{1 + j + 2A},$$

$$I = e\, a \frac{j + 2A + 2jA + 3A^2}{1 + j + 2A}.$$

$$avg\ I_1, I_2 = \frac{I_1 + I_2}{2} = \frac{e\, a}{2}\, \frac{2j + A\,(1 + j)}{1 + j + 2A}.$$

Quadrature component of E_0:

$$e_0^j = \frac{e}{2}\left[\frac{1 - j}{1 + j + 2A}\right]^j.$$

Relative torque:

$$t = \frac{T}{T\triangle} = \frac{e_0^j}{q\, e} = \frac{1}{\sqrt{3}}\left[\frac{1 - j}{1 + j + 2A}\right]^j,$$

where $T\triangle$ = three-phase torque.

In the following Table II. are calculated the relative torque,

TABLE II.

RESISTANCE — INDUCTANCE.

$Z = .1 - .3j$. $Y = .01 + .1j$. $e = 110$.

R:	$T\triangle$:	$I\triangle$:	$PF\triangle$:	$IF\triangle$:	$ATE\triangle$:	y^1:	Y^1:	e_0^j:			
								$a=.5$:	$a=1$:	$a=2$:	$a=4$:
0	8.80	176	.315	.948	.153	1.60	.505+1.515 j	9.4	16.4	25.8	52.3
.15	18.15	160	.490	.870	.341	1.46	.715+1.27 j	10.6	17.8	27.0	52.6
.5	24.75	124	.740	.670	.615	1.13	.836+.757 j	13.1	21.2	30.6	53.5
1.0	21.90	85	.870	.495	785	773	.670+.38 j	....	26.6	....	...
1.5	16.90	64	.890	.455	815	.580	.516+.26 j	20.7	30.3	39.0	54.6

	t				T			
R:	$a=.5$:	$a=1$:	$a=2$:	$a=4$:	$a=.5$:	$a=1$:	$a=2$:	$a=4$:
0	.099	.172	.272	.548	.87	1.51	2.40	4.02
.15	.111	.188	.283	.551	2.02	3.41	5.15	10.00
.5	.134	.223	.322	.561	3.40	5.52	7.95	13.90
1.0		.273				6.05		
1.5	.217	.318	41	.573	3.67	5.40	6.92	9.70

	I				I			
R:	$a=.5$:	$a=1$:	$a=2$:	$a=4$:	$a=.5$:	$a=1$:	$a=2$:	$a=4$:
0	$100+265j$	$121+283j$	$170+323j$	$314+445j$	283	308	365	545
.15	$135+225j$	$156+244j$	$203+287j$	$343+415j$	262	290	352	538
.5	$154+142j$	$175+163j$	$223+211j$	$353+343j$	210	240	307	492
1.0		$149+105j$				182		
1.5	$103+63j$	$126+88j$	$176+140j$	$298+268j$	121	154	229	401

	p				t/p			
R:	$a=.5$:	$a=1$:	$a=2$:	$a=4$:	$a=.5$:	$a=1$:	$a=2$:	$a=4$:
0	.537	.538	.692	1.03	.184	.293	.394	.532
.15	.545	.606	732	1.12	.203	.310	.386	.493
.5	.565	.646	.827	1.32	.343	.345	.390	.425
1.0		.713				.390		
1.5	.930	.803	1.17	2.09	.344	.397	.350	.273

in fraction of the polyphase motor torque t,

Torque, in synchronous K. W., T,

Total current input, I, inclusive starting device,

for the motor:

$$Z = .1 - .3j, \qquad Y = .01 + .1j, \qquad e = 110;$$

for the additional armature resistances:

$$R = 0, \quad .15, \quad .5, \quad 1.0, \quad 1.5,$$

and the constants of the starting device:

$$a = .5, \quad 1, \quad 2, \quad 4.$$

Since a single-phase motor is generally operated at 30 per cent. higher density than the same motor as polyphase motor, and is rated, at this higher density, at $\frac{3}{4}$ the output of the polyphase motor, in Table III. the corresponding values are given, and plotted in Figs. 31, 32 and 33 for this motor as three-phase motor, and as single-phase motor at 30 per cent. higher magnetic density, that is rewound with $\frac{1}{1.3}$ times as many turns of 1.3 times the cross section, or of constants:

$$Z = .059 - .177j, \qquad Y = .0169 + .169j, \qquad e = 110.$$

$$R = 0, \quad .2535, \quad .845, \quad 1.69, \quad 2.535.$$

$$a = .845, \quad 1.69, \quad 3.38, \quad 6.76.$$

TABLE III.

	$P F$					$A T E$					$T E$				
R:	$a=.5$:	$a=1$:	$a=2$:	$a=4$:	Δ:	$a=.5$:	$a=1$:	$a=2$:	$a=4$:	Δ:	$a=.5$:	$a=1$:	$a=2$:	$a=4$:	Δ:
0	35.2	29.3	46.5	58.0	31.5	2.8	4.5	6.0	8.15	15.3	7.9	11.4	12.9	14.1	51.5
.15	51.5	54.0	57.6	62.0	49.0	6.9	10.6	13.1	16.8	34.0	13.4	19.6	22.8	27.0	69.5
.5	73.5	73.5	72.7	72.0	74.0	15.0	21.2	24.0	26.2	61.5	20.4	28.8	33.0	36.4	83.0
1.0		82.0			87.0		30.6			78.5		37.3			90.4
1.5	85.0	82.0	78.3	74.5	89.0	28.0	32.4	28.5	22.3	15.8	33.0	39.6	36.4	29.9	91.6

	T					C				
R:	$a=.5$:	$a=1$:	$a=2$:	$a=4$:	Δ:	$a=.5$:	$a=1$:	$a=2$:	$a=4$:	Δ:
0	1.47	2.55	4.05	8.14	8.80	478	520	617	920	528
.15	3.40	5.75	8.7	16.9	18.15	441	400	593	910	480
.5	5.74	9.33	13.4	23.5	24.75	355	405	518	830	372
1.0		10.2			21.90		307			255
1.5	6.20	9.1	11.7	16.4	16.90	204	260	380	676	192

	The three-phase motor is rated at:	The single-phase motor is rated at:
Output, full load	15.45 K. W.	10.8 K. W.
Full load current, total	184 amps	142 amps.
No load current, total	32 "	51 "
Maximum output	21.0 K. W.	15.4 K. W.
Full load torque	16.5 "	11.1 "
Maximum torque	24.75 "	16.7 "
Maximum torque with starting device	$a=.5$:	6.4 "
	1:	10.3 "
	2:	13.8 "
	3:	23.5 "
Current with starting device at full load torque	$a=1.2$:	305 amps.

From Figs. 10, 11 and 12 of my previous paper on the polyphase induction motor are taken the values of the first columns of Table II:

T_d = three-phase torque, or three times torque per circuit, as given in Fig. 2 of previous paper,

I_d = three-phase current per circuit, absolute, from previous paper,

$P F_d$ = three-phase power factor, from previous paper,

$I F_d$ = three-phase induction factor, calculated from power factor, $= \sqrt{1 - P F_d^2}$,

$A T E_d$ = three-phase apparent torque efficiency, from previous paper.

Therefore:

y^1 = absolute admittance per three-phase $\triangle$ circuit $= \frac{I_d}{e}$,

Y^1= vector admittance per three-phase $\triangle$ circuit

$$= y^1 (P\,F_d + j\,I\,F_d),$$

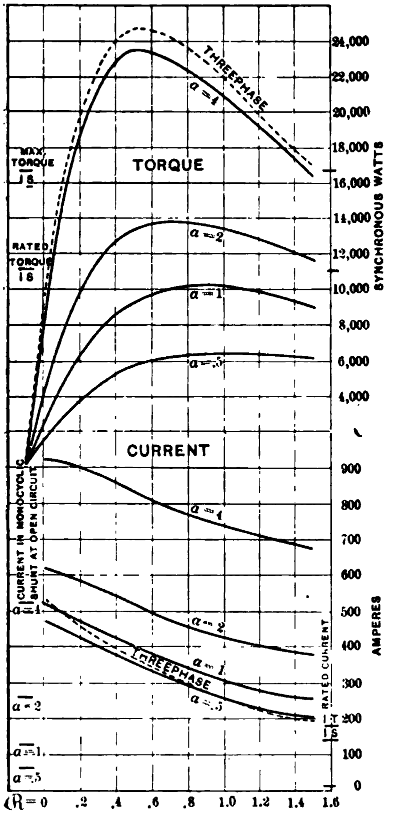

FIG. 31.—Single Phase Induction Motor.
Monocyclic Starting Device.
Resistance — Inductance
$Y_1 = a$. $Y_2 = j\,a$
Three Phase Motor
$Y = .01 + .1\,j$. $Z = .1 - .3\,j$. 110 Volts.

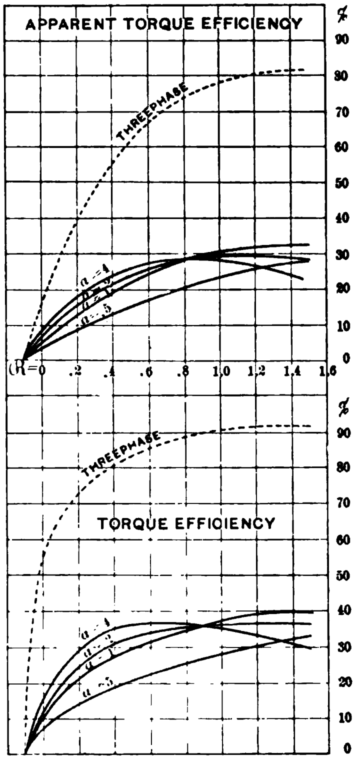

FIG. 32.—Single Phase Induction Motor.
Monocyclic Starting Device.
Resistance — Inductance
$Y = a$. $Y_2 = j\,a$.
Three Phase Motor.
$Y = .01 + .1\,j$. $Z = .1 - .3\,j$. 110 Volts.

e_0^1 = cross E. M. F.

$$t = \frac{1}{\sqrt{3}} \left[\frac{1 - j}{1 + j + 2\,A} \right]^1$$

$$T = t\,T_d,$$

$$I = e\,a\,A \,\frac{1 - j}{1 + j + 2\,A},$$

$$I = /I/,$$

$$p = \frac{I}{3\,I_d} =$$ ratio of single-phase and of three-phase current,

$\frac{t}{p} =$ ratio of single-phase and of three-phase apparent torque efficiency.

Herefrom, in Table III, for this motor as three-phase motor, and as single-phase motor at 30% higher magnetic density, and $e = 110$:

$P.\ F.$, = power factor, from I, for $a = .5, 1, 2, 4$, or rather: $a = .845, 1.69, 3.38$ and 6.76, and for three-phase, $\triangle$:

$A.\ T.\ E. = \frac{t}{p}\ A.\ T.\ E._{\triangle}$, for $a = .5, 1, 2, 4$, or rather: $a = .845, 1.69, 3.38$ and 6.76, and for three-phase, $\triangle$:

$T.\ E. = \frac{A.\ T.\ E.}{P.\ F.}$; for $a = .5, 1, 2, 4$, or rather: $a = .845, 1.69, 3.38$ and $6\ 76$, and for three-phase, $\triangle$:

Total current, I, for $a = .5, 1, 2, 4$, or rather: $a = .845, 1.69, 3.38$ and 6.76, and for three-phase, $\triangle$: $= 3\ I_d$.

Torque T, Power input P, Volt-ampere input Q.

These values are plotted in Figs. 31, 32 and 33 with the external secondary resistance R as abscissæ The resistance R refers to the three-phase motor, and thus in the single-phase motor is $\frac{1}{1.3}$ as high, due to the higher density.

As seen from these tables and diagrams, the torque and current curves, as function of the secondary resistance, have with the monocyclic starting device $b\ e\ j$ resistance—inductance the same general shape as with the polyphase motor.

Choosing in the single-phase motor a 30% higher density, the maximum available starting torque is about the same as with the three-phase motor (thus, when rating the single-phase motor at about ¾ the capacity of the same motor as polyphase motor, a larger percentage of full lead torque than on polyphase circuit.) This starting torque however requires a very much larger current than with the polyphase motor, from two to three times as much at $a = 4$.

The single phase motor can start with about the same current as the polyphase motor, but gives in this case only about one third the torque, at $a = .5$.

In the diagram (Fig. 31) are marked, also the current consumed in the monocyclic starting device (at 45° lag) with the motor disconnected therefrom, and the full load currents of the motor without starting device, the motors being rated at $\frac{2}{3}$ their maximum torque as full load torque.

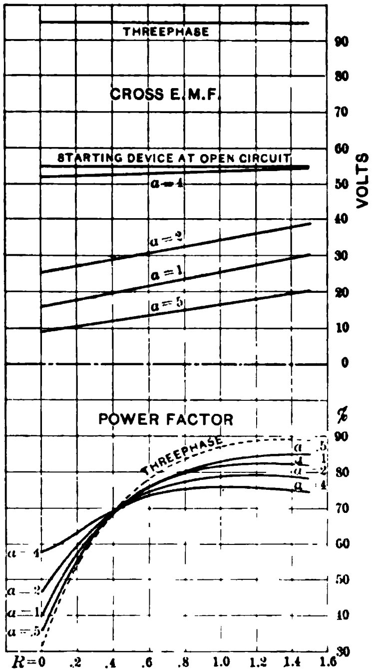

FIG. 33.—Single Phase Induction Motor.
Starting Device.
Resistance — Inductance
$Y_1 = a. \quad Y_2 = j\,a.$
Three Phase Motor.
$Y = .01 + .1j. \quad Z = .1 - 3j.$ 110 Volts.

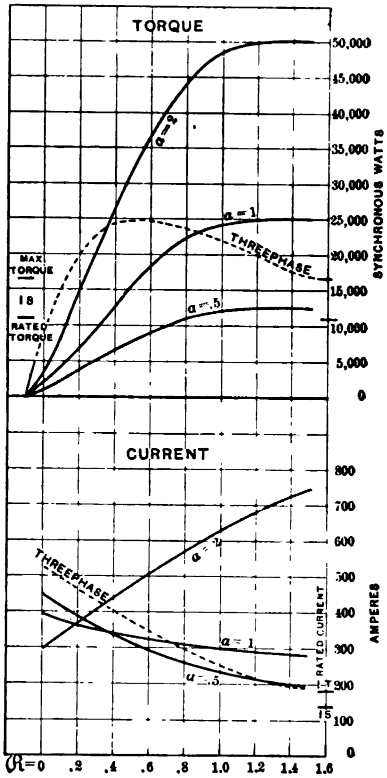

FIG. 34.—Single Phase Induction Motor.
Monocyclic Starting Device.
Condensance — Inductance
$Y_1 = j\,a. \quad Y_1 = -j\,a.$
Three Phase Motors
$Y = .01 + .1j. \quad Z = .1 - 3j.$ 110 Volts.

b.—CAPACITY.—INDUCTANCE.

Let, in a three-phase motor, $Y^1 = g^1 + j\,b^1$ = admittance per motor circuit, reduced to Δ connection.

Let:

$$Y_1 = + j\, a,$$
$$Y_2 = - j\, a.$$

Substituting:

$Y^1 = a\, \Delta = a\,(\gamma + j\, \beta)$, $\vartheta = \sqrt{\gamma^2 + \beta^2}$, it is, in the three-phase motor:

$$Y = 1.5\, Y^1 = 1.5\, a\, \Delta,$$
$$Y_0 = 2\, Y^1 = 2\, a\, \Delta,$$
$$q = \tfrac{1}{2} \sqrt{3}.$$

Hence, substituting these values in the general equation, it is:

$$E_0 = \frac{e}{2} \frac{j}{\Delta},$$
$$E_1 = \frac{e}{2} \frac{\Delta - j}{\Delta},$$
$$E_2 = \frac{e}{2} \frac{\Delta + j}{\Delta},$$
$$I_1 = \frac{e\, a}{2} \frac{1 + j\, \Delta}{\Delta},$$
$$I_2 = \frac{e\, a}{2} \frac{1 - j\, \Delta}{\Delta},$$
$$I_0 = j\, e\, a,$$
$$a\, v\, g\, I_1, I_2 = \frac{I_1 + I_2}{2} = \frac{e\, a}{2\, \Delta},$$
$$e_0 j = \frac{e}{2} \left[\frac{j}{\Delta}\right]^1 = \frac{e\, \gamma}{2\, \vartheta^2},$$
$$I^1 = 1.5\, e\, a\, \Delta,$$
$$I_1^1 = \frac{e\, a}{2} (3\, \Delta - j),$$
$$I_2^1 = \frac{e\, a}{2} (3\, \Delta + j),$$
$$I = \frac{e\, a}{2} \frac{1 + 3\, \Delta^2}{\Delta}.$$

Relative torque:

$$t = \frac{T}{T_d} = \frac{e_0^1}{q\, e} = \frac{\gamma}{\vartheta^2 \sqrt{3}}.$$

Relative current or volt-ampere input:

$$p\,\frac{e\,I}{3\,e\,I_d}=\frac{\frac{e^2\,a}{2\,\vartheta}\left[1+3\,\Delta^2\right]}{3\,e^2\,a\,\vartheta}=\frac{1}{6\,\vartheta^2}\left[1+3\,\Delta^2\right]$$

$$=\frac{1}{6}\sqrt{1+\frac{1}{\vartheta^4}+2\,\frac{\gamma^2-\beta^2}{\vartheta^4}}.$$

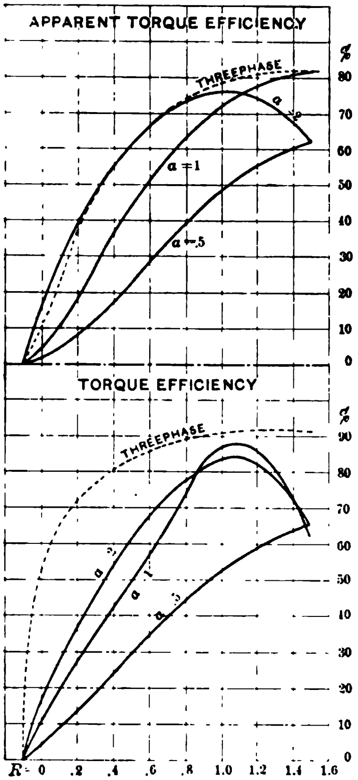

FIG. 35.—Single Phase Induction Motor.
Monocyclic Starting Device.
Condensance — Inductance
$Y_1 = j\,a$. $Y_2 = -j\,a$.
Three Phase Motor
$Y = .01 + .1j$. $Z = .1 - .3j$. 110 Volts.

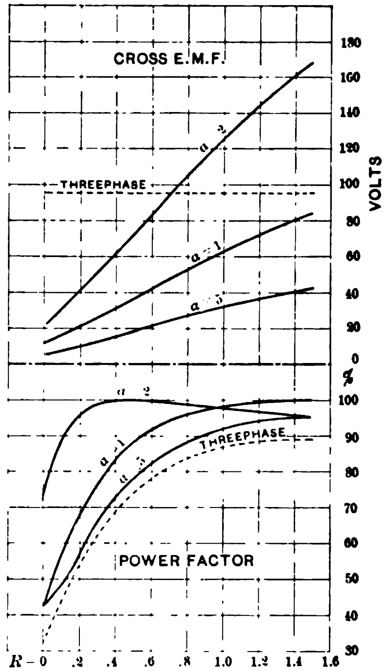

FIG. 36.—Single Phase Induction Motor.
Starting Device.
Condensance — Inductance
$Y_1 = j\,a$. $Y_2 = -j\,a$.
Three Phase Motor
$Y = .01 + .1j$. $Z = .1 - .3j$. 110 Volts.

In Table IV. are calculated, and plotted on Figs. 34, 35 and 36, the values of:

Relative Torque: t.

Vector Current: I.

Relative Current: p.

Relative apparent torque efficiency: $\frac{t}{p}$

Power Factor.

Apparent torque efficiency.

TABLE IV.

CAPACITY — INDUCTANCE.

$Z = .1 - .3j. \qquad Y = .01 + .1j. \qquad e = 110.$

	t			I		
R:	$a = .5$:	$a = 1$:	$a = 2$.	$a = .5$:	$a = 1$:	$a = 2$:
0	.057	.125	.228	$111 + 242j$	$94 + 217j$	$126 + 120j$
.15	.097	.194	.388	$123 + 205j$	$137 + 171j$	$192 + 76j$
5	.189	.378	.760	$147 + 117j$	$174 + 92j$	$282 - 6.6j$
1.0	.330	.660	1.315	$126 + 54j$	$173 + 27j$	$362 - 77j$
1.5	.441	.892	1.760	$106 + 33j$	$169 + .6j$	$423 - 128j$

	p			t/p		
R:	$a = .5$:	$a = 1$:	$a = 2$:	$a = .5$:	$a = 1$:	$a = 2$:
0	.500	.445	.33	.113	.282	.690
.15	.500	.457	.435	.194	.425	.893
.5	.506	.530	.76	.365	.716	1.00
1.0	.538	.688	1.45	.614	.962	.910
1.5	.580	.880	2.31	.762	1.00	.765

	PF				ATE				TE			
R:	$a = .5$:	$a = 1$:	$a = 2$:	Δ:	$a = .5$:	$a = 1$:	$a = 2$:	Δ:	$a = .5$:	$a = 1$:	$a = 2$:	Δ:
0	41.8	40.0	72.4	31.5	1.72	4.3	10.4	15.3	4.1	10.5	14.5	51.5
.15	51.4	62.5	92.3	49.0	6.6	14.4	30.3	34.0	12.8	23.1	32.8	69.5
.5	78.0	88.4	100	74.0	22.4	44.0	61.5	61.5	28.7	49.8	61.5	83.0
1.0	92.0	98.6	97.8	87.0	48.2	75.5	71.4	78.5	52.5	76.7	73.0	90.4
1.5	95.5	100	95.7	89.0	62.0	81.5	62.3	81.5	65.0	62	65.2	91.6

	T				*I*			
	at 30 per cent. higher density:				at 30 per cent. higher density:			
R:	$a = .5$:	$a = 1$:	$a = 2$:	Δ:	$a = .5$:	$a = 1$:	$a = 2$:	Δ:
0	.85	1.9	3.4	8.8	450	397	293	528
.15	3.0	5.6	11.9	18 15	403	370	351	480
.5	7.8	15.8	31.8	24.75	317	333	476	372
1.0	12.1	24.3	48.6	21.90	232	296	625	255
1.5	12.6	25.2	50.2	16.90	188	285	745	192

Torque efficiency of the three-phase motor:

$$Z = .1 - 3j,\ Y = .01 + 1j,\ e = 110,$$

with single-phase, capacity-inductance monocyclic starting devise of admittance: $a = .5$, $a = 1$, $a = 2$, and the values of torque.

Total current input of the motor as three-phase motor, and as single-phase motor at 30 per cent. higher density (that is, of the constants:

$$Z = .059 - .177j,\ Y = .0169 + .169j,\ e = 110,$$
$$a = .845,\ 1.69,\ 3.38.$$

As seen herefrom, by means of condensance-inductance as monocyclic starting device, the motor can be started with a torque far in excess to its maximum torque as three-phase motor; its power factor is higher than on three-phase circuit, its torque efficiency lower, and its apparent torque efficiency about equal to that of the three-phase motor.

While, however, with the resistance-inductance starting device, the general shape of the curves, as the change of torque, current, etc., with the secondary resistance of the motor, is of the same character as with the three-phase, showing a gradual approach from the single-phase shape towards that of the three-phase motor, with increasing a, it is in the capacity-inductance device essentially different, the more, the larger the capacity admittance a is. For instance, with $a = 2$, the current is a minimum with short-circuited secondary, and rises very greatly with increasing secondary resistance—just the reverse of the three-phase motor. In general, by the use of capacity, the high range of the curves is short, that is, the curves are steeper.

A more complete discussion of the effect of capacity must, however be reserved for a separate paper.

c). *Polarization-Inductance.*—As further instance of the monocyclic starting device of single-phase motors are shown in Fig. 37, the curves of the three-phase motor,

$$Z = .1 - .3j,\ Y = .01 + .1j,\ e = 110,$$

or, as single-phase motor rewound for 1.30 times the magnetic density, as:

$$Z = .059 - .177j,\ Y = .0169 + .169j,\ e = 110,$$

with an inductance of .10 power factor and an electrolytic condenser, or series of polarization cells (which, as known, act like a leaky condenser, or condenser of high power factor) of .707 power factor (45° lead), corresponding to $a = 1$ in the previous instances.

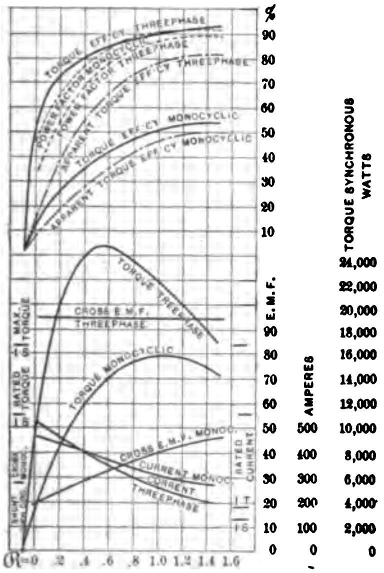

FIG. 37.—Single Phase Induction Motor.
Monocyclic Starting Device.
Electrolytic Condenser and Inductance.
$Y_1 = .17 + 1.52j.$ $Y_2 = 1.18 - 1.18j.$
Three Phase Motor
$Y = .01 + .1j.$ $Z = .1 - .3j.$

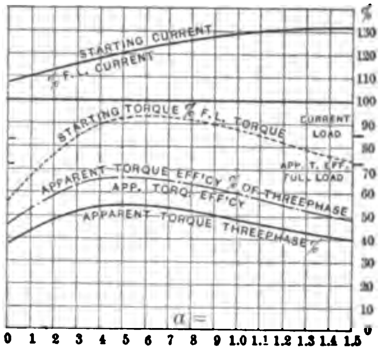

FIG. 88.—Single Phase Induction Motor. Starting.
Condenser of $-.375j$ Admittance in Shunt of Second. Self Induct of $+aj$ Admittance in Shunt of Third Phase. Condenser Adjusted for 100 per cent. P. F. at ¼ Load. Total Admittance per △ Circuit: $Y_0 = .49 + .25j.$
Three-Phase Motor
$Y = .01 + .1j.$ $Z = .1 - .3j.$

It is thus:

$$Y_1 = .1 + .9j,\ Y_2 = .707 - .707j,$$

or, reduced to the motor of 30 per cent. higher density.

$$Y_1 = .17 + .152j,\ Y_2 = 1.18 - 1.18j.$$

As seen, the curves show the same characteristics as the three-phase, and the resistance-inductance curves, being intermediate between them.

That is, torque, torque efficiencies, etc. are higher than with the resistance-inductance device, but lower than on three-phase circuit, except the power factor, which is higher.

These curves do not show any of the peculiarities of the condensance-inductance curves. That is, due to the high power factor of the electrolytic condenser, all resonance phenomena have disappeared.

In the preceding instances the absolute values of admittances Y_1 and Y_2 have been assumed as equal.

To investigate the effect of a change of one of these values, in Fig. 38 are plotted for:

$$Y_1 = + j\, a,$$
$$Y_2 = - .375 j,$$

that is, constant condensance, and varied inductance, with the inductive reactance a as abscissæ, and the total admittance per Δ circuit of the motor, of $Y^1 = .49 + .25 j$, the values:

Starting current, in per cent. of full load current;

Starting torque, in per cent. of full load torque;

Apparent torque efficiency, in per cent., and

Apparent torque efficiency, in per cent. of that of the three-phase motor or relative apparent torque efficiency.

The admittance of the motor, $Y^1 = .49 + .25 j$, corresponds to ¾ load.

The condensance, $Y_2 = - .375\, a$, is such as would make the power factor at ¾ load 100 per cent., when connected across the main circuit.

As seen, the changes with varying a are comparatively small over a wide range.

The starting torque is a maximum at: $a = .65$.

The apparent torque efficiency is a maximum at: $a = .55$.

The relative apparent torque efficiency is a maximum at: $a = .5$.

The starting current increases

from 1.08 times three-phase current, at $a = 0$,
to 1.32 times three-phase current, at $a = 1.5$.

§3. ACCELERATION WITH STARTING DEVICE.

The torque of the single-phase induction motor (without starting device) is proportional to the product of main flux or magnetic flux produced by the primary impressed E. M. F. and the speed. Thus it is the same as in the polyphase motor at or very near synchronism, but falls off with decreasing speed and becomes zero at standstill.

To produce a starting torque, a device has to be used to impress an auxiliary magnetic flux upon the motor, in quadrature with the main flux in time and in space, and the starting torque is proportional to this auxiliary or quadrature flux. During acceleration or at intermediate speeds, the torque of the motor is the resultant of the main torque or torque produced by the primary main flux, and the auxiliary quadrature or starting flux. In general this resultant torque is not the sum of main and auxiliary torque, but less, due to the interaction between the motor and the starting device.

All the starting devices depend more or less upon the total admittance of the motor and its power factor. With increasing speed, however, the total admittance of the motor decreases and its power factor increases, and an auxiliary torque device suited for the admittance of the motor at standstill will not be suited any more for the changed admittance at speed.

The currents induced in the secondary by the main or primary magnetic flux are carried by the rotation of the motor more or less in quadrature position and thus produce the quadrature flux, giving the main torque as discussed in the first paragraph.

This quadrature component of the main flux induces an E. M. F. in the auxiliary circuit of the starting device and thus changes the distribution of currents and E. M. F.'s. in the starting device. The circuits of the starting device then contain besides the motor admittance and external admittance an active counter E. M. F., changing with the speed. Inversely the currents produced by the counter E. M. F. of the motor in the auxiliary circuits react upon the counter E. M. F., that is upon the quadrature component of main flux and change it.

Thus during acceleration we have to consider:

1st. The effect of the change of total motor admittance, and its power factor, upon the starting device.

2nd. The effect of the counter E. M. F. of the motor upon the starting device, and the effect of the starting device upon the counter E. M. F. of the motor.

1st. The total motor admittance and its power factor change very much during acceleration in motors with short-circuited low resistance secondary. In such motors the admittance at rest is very large and its power factor low, and with increasing speed the admittance decreases and its power factor increases greatly. In motors with short-circuited high resistance secondary, the admittance also decreases greatly during acceleration, but its power factor changes less, being already high at standstill. Thus the starting device will be affected less. Such motors, however, are inefficient at speed. In motors with variable secondary resistance the admittance and its power factor are maintained constant during acceleration by decreasing the resistance of the secondary circuit in correspondence with the increasing counter E. M. F. Hence in such motors the starting device is not thrown out of adjustment by the changing admittance during acceleration, and they are thus preferable.

The investigation of the phenomena taking place during acceleration can be carried out in a similar manner as the investigation of the starting in paragraph 2, by considering, however, in the circuits besides their respective admittance or impedance the counter E. M. F.'s of the motor, or E. M. F.'s induced by the quadrature component of main flux. It would extend the paper too far, however, and thus must be postponed for a later occasion, and only some general conclusions drawn.

While any desired torque can be produced by the use of resistance and inductance and mutual induction as starting devices, the torque is necessarily far below that which can be produced in a polyphase motor with the same expenditure of volt-amperes or of watts, that is the apparent torque efficiency and the torque efficiency are lower. A much better starting torque efficiency, and apparent torque efficiency, under circumstances almost as good or better as in a polyphase motor, can be produced by the use of capacity. Capacity, however, is generally only suitable for a sine wave of E. M. F. and most generators do not give a sine wave, and in general the use of a wave differing from sine shape is preferable for other reasons, while for the motors proper, the wave shape is immaterial. Furthermore, looking over the curves of starting torque and apparent torque efficiency given in paragraph 2, the general feature is noticeable that capacity gives very high values for a very limited range only, but low values outside thereof. Thus, when securing high starting torque by means of capacity, with the change of admittance during acceleration, the conditions become unfavorable much faster than by the use of resistance, inductance and mutual induction. Hence, while good starting torque can be produced by capacity, in general this torque is not maintained during acceleration up to the speed where the main torque of the motor is sufficient for further acceleration, and thus such a motor will start, but not run up to speed.

A. PHASE SPLITTING DEVICES.

In these the starting torque depends upon the relative proportion of the internal or motor admittance and the external admittance of the starting device, and is thus essentially affected by the change of admittance during acceleration in a motor with short-circuited low resistance secondary.

Thus, for instance, in Fig. 12, in a motor with impedance $Z = r - jx = 1 - 3j$ of each of the two primary coils at standstill, and inductive reactance $-ja$ in circuit of one of them, the apparent torque efficiency is very low and fairly constant, about 10 per cent. of that of a polyphase motor, for a wide range of reactance. During acceleration r increases, x decreases and the relative apparent torque efficiency approaches that of the motor $Z = 3 - 1j$, that is increases considerably. If, however, a great starting torque was produced by capacity as shown on the left side of Fig. 12, the relative apparent torque efficiency decreases during acceleration by passing from curve $Z = 1 - 3j$ towards curve $Z = 3 - 1j$.

The right hand side of Fig. 12 represents also the effect of resistance as a starting device, but with the two curves exchanged, the higher one representing $Z = 1 - 3j$, the lower one $Z = 3 - 1j$. Thus by using resistance a in one of the motor circuits, a good starting torque, of nearly 50 per cent. of that of the polyphase motor of same volt-ampere input, is produced in a motor with low resistance secondary, but during acceleration it falls off due to the increase of power factor of the motor impedance, and the motor, while starting under good torque, will probably not be able to run up to speed, even under fairly light load.

Still more instructive is Fig. 13, two reactances, of which at least one is a capacity reactance.

As long as one of the reactances $-jb$ is inductive, the two curves; $Z = 1 - 3j$ representing a motor with low resistance armature, and $Z = 3 - 1j$ representing a motor with high resistance armature, and thus approximately the conditions of a motor with low resistance armature at speed, give fairly the same results, using, however, two capacity reactances, an enormous apparent torque efficiency can be produced in starting, more than three times that of the polyphase motor, for $b = -2$. But with increasing power factor of impedance, that is during acceleration, this torque decreases to zero and then reverses, and $Z = 3 - 1j$ gives—61% of the polyphase apparent torque efficiency. Thus with this device, a low resistance motor will start with very powerful torque, but with increasing speed the torque produced by the starting device falls to zero and then reverses, and if the main torque of the motor is not very large at fairly low speeds, the motor will not run up to speed even at light load. Hence this device of two capacities in the two motor circuits is unsuitable for low resistance motors, although it gives a very powerful starting torque.

B. INDUCTIVE DEVICES.

The inductive devices depend still more than the phase splitting devices upon the power factor of the motor admittance. As seen in paragraph 2, even the direction of the torque given by the starting device depends upon the power factor of the motor impedance.

For instance, the shading coil or the accelerating coil acts as retarding coil if its power factor is higher than a certain value depending upon that of the motor, etc., and as accelerating coil if its power factor is lower than this value. Hence with a very low reactance shading coil and a high reactance motor secondary, a fairly good torque is secured in starting, but this torque rapidly disappears and then reverses during acceleration, and this device can thus be used only with motors giving a main torque curve, however, requires fairly high armature resistance and thus gives low torque for the starting device. Hence, the shading coil is suitable only for very small motors starting under light load. The accelerating coil requires a high resistance secondary and when used with a motor with variable armature resistance, the motor can be made to start in one direction with the resistance in, but in the opposite direction by cutting out the resistance. In the latter case the motor obviously does not run up to speed, due to the reversal of the torque, except if after starting, the accelerating coil is cut out and the resistance cut in again. Torque curves of such a starting device will be shown in the following:

The monocyclic starting device, especially with resistance inductance, is scarcely at all affected by a change of the power factor of the admittance, and is improved by the decrease of admittance during acceleration, since a decrease of the motor admittance is equivalent to an increase of the admittance A, that is an increase of the teaser E. M. F. Thus it is the most satisfactory starting device, and is more fully discussed in the following.

2nd.—Effect of the counter E. M. F. of the motor upon the starting device and inversely.

In the phase splitting device, where a definite phase displacement is produced in circuits of different impedances, the induction of the counter E. M. F. in these circuits necessarily throws these circuits more or less out of phase. The same applies to external inductive devices.

Where several circuits are in multiple between the same primary mains, but displaced in position on the motor primary, the counter E. M. F's induced by the main flux of the motor in these circuits are displaced in phase from each other, and thus form more or less a short circuit, through the parallel coils, and thereby produce a current which reduces the counter E. M. F., and thus the main torque of the motor.

Still more is this the case with the internal inductive devices. The shading coil as well as the accelerating coil form a dead short circuit for the component of main flux in their direction, and thus practically annihilate this flux by the demagnetizing effect of the induced current. The result is a great decrease or even reversal of torque, and a falling off of output. For instance, in a single phase motor giving a maximum torque at 96 per cent. of synchronism of 217 lbs. at 1 ft. radius, with 93 amperes input at 220 volts, the maximum torque is reduced to 132 lbs. at 89 per cent. of synchronism, while the current is increased to 320 amperes, that is, the apparent torque efficiency has fallen off to 17.7 per cent. of its previous value, due to the short circuit caused by the inductive starting device of the accelerating coil. A number of torque curves of a motor with accelerating coil are shown in Fig 39 with different values of resistance in the secondary. This motor is the 1-8-30-900-110 of which the three-phase curves are shown in Fig. 1 and 2 of my previous paper on the polyphase induction motor, the single-phase curves in Fig. 9 and 10 and the curves with monocyclic starting device in Fig. 42 of this paper. The motor has a three-phase winding, of which one coil is excited as primary coil, one short-circuited and one open, thus the accelerating soil is displaced 60° from the main coil.

As seen, with short-circuited secondary, the starting torque is negative, 4 pounds and remains so up to a speed where the main torque of the motor overpowers the reverse torque of the starting device, or the latter disappears, due to the increase of the power factor of the motor, at 30 per cent. of synchronism. With medium resistance in the secondary the torque is 24 lbs. in starting, increases due to the increase of power factor of the motor as discussed before, reaches a maximum of 40 lbs., but then decreases again and reverses at 80 per cent. of synchronism, due to the short circuit. It becomes — 49 lbs. at synchronism. With high resistance in the secondary, the torque is a maximum of 14 lbs. at 1 ft. radius in starting, and then decreases due to the short-circuit, becomes zero at 48 per cent. of synchronism, and gives at synchronism —61 lbs. reverse torque.

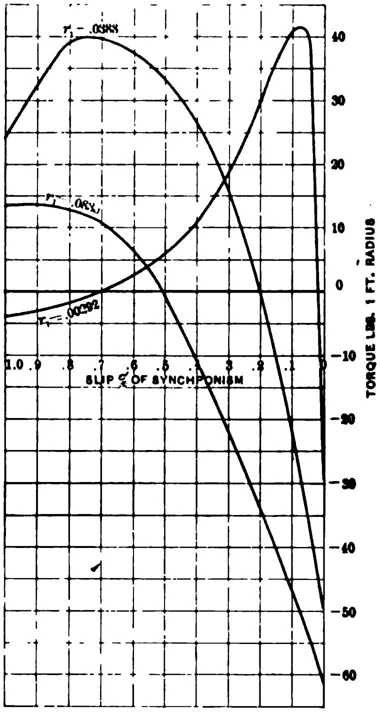

FIG. 39.
1.8 80-900-110. Single-Phase Motor.
Speed Curves with Inductive
Starting Device.
One Circuit Excited. One Circuit Short
Circuited. One Circuit Open.

These curves show best the interaction of the three effects; the main torque of the motor, zero at standstill and increasing with speed, the torque of the starting device, increasing in positive, or decreasing in negative direction, due to the change of power factor of the motor admittance, and the retarding effect of the short-circuit of main flux by the accelerating coil. The current in either of the curves is very large, thus the apparent torque efficiency low.

With the monocyclic starting device the effect of the counter E. M. F. is to raise the altitude of the monocyclic or teaser triangle, and thereby to increase the torque, up to the speed where the counter E. M. F. equals the altitude of the teaser triangle at open circuit. At this speed the teaser current becomes zero, (or very small since some current flows due to the difference of phase between teaser and counter E. M. F.), and the torque equals the main torque of the motor, that is the starting device has become ineffective. Beyond this the counter E. M. F. is higher than the impressed E. M. F. and current returns over the teaser, with the effect of reducing the torque of the motor by a partial short-circuit. With a motor of a three-phase winding with

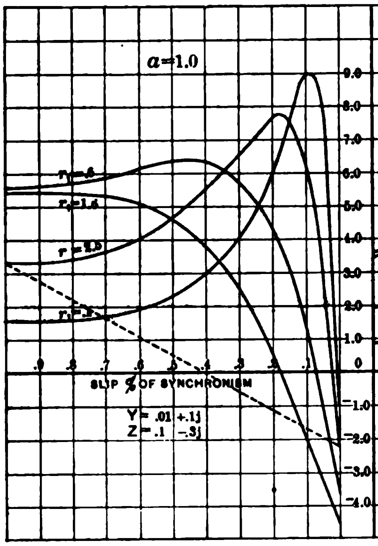

FIG. 40.

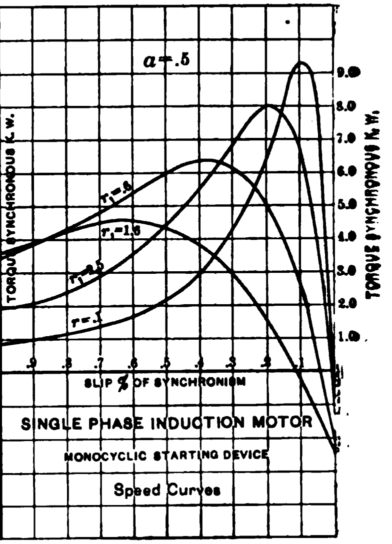

FIG. 41.

two terminals connected to the single phase mains of E. M. F. e and the third terminal to the teaser or intermediary connection of a resistance inductance monocyclic starting device, the maximum counter E. M. F. of the motor in the teaser circuit, neglecting internal drop, is $\frac{1}{2}\sqrt{3}\,e$ or $.867\,e$. The maximum teaser voltage (at open circuit) is $e / 2$, thus at $\frac{.5}{.867} = 58\%$ of synchronism the teaser current should cease and the monocyclic starting device become inactive and should be cut out. In reality, due to the drop of voltage in the motor, the point where the starting device becomes inactive lies at higher speed, from 60 to 65 per cent. of synchronism.

Assuming approximately the auxiliary torque of the monocyclic starting device as proportional to the difference between teaser E. M. F. and counter E. M. F. of the motor, the resultant torque is the sum of the auxiliary torque of the starting device and the main torque of the motor.

In Fig. 40 and 41 are plotted the curves of Fig. 40, 41, resultant torque of the single-phase motor in Fig. 6, 7, 8, with the resistance-inductance starting device in Fig. 31 of paragraph 2, for the secondary resistances $r_1 = .1$, or open circuit, $r_1 = .25$, $r_1 = .6$ and $r_1 = 1.6$ ohms per circuit, and for $a = 1.0$ and $a = .5$. The starting torque is taken from Fig. 31 in paragraph 2. It decreases with increasing speed in a straight line, becomes zero at 60 per cent. of synchronism, and negative beyond this, as shown in dotted line for $r_1 = .25$, $a = 1.0$ in Fig. 40. This torque added to the main torque in Fig. 6, Section 1, gives the torque curves of Fig. 40 and 41. As seen, these torque curves have very much the same shape as those of a polyphase motor, and change in the same manner with the change of secondary resistance, but do not become zero at synchronism, but at a definite speed below synchronism. The range of the curve near synchronism is of less interest, since the starting device is expected to be cut out of circuit between half-speed and two-third speed. It is of interest to compare these speed curves of the single-phase induction motor with monocyclic starting device in Figs. 40 and 41 with the speed curve of the same motor as polyphase motor in Fig. 10 and 11 of my previous paper, and as single-phase motor in Fig. 6, 7, 8, paragraph 1. As seen, with increasing a, the curves gradually change from those of the single-phase motor to those of the polyphase motor.

In Fig. 42 are shown the speed torque curves of a Fig. 42 induction motor with monocyclic starting device as found by test, for three values of secondary resistance; short-circuit, medium and high resistance, together with the curves of the teaser current I_0 and the average of the two main currents $\frac{I_1^1 + I_2^1}{2}$, for high resistance in the secondary. As seen, the teaser current I decreases proportional to the speed, reaches a minimum at 65 per cent. of synchronism, and then increases again as return current, up to synchronism, exactly as to be expected theoretically.

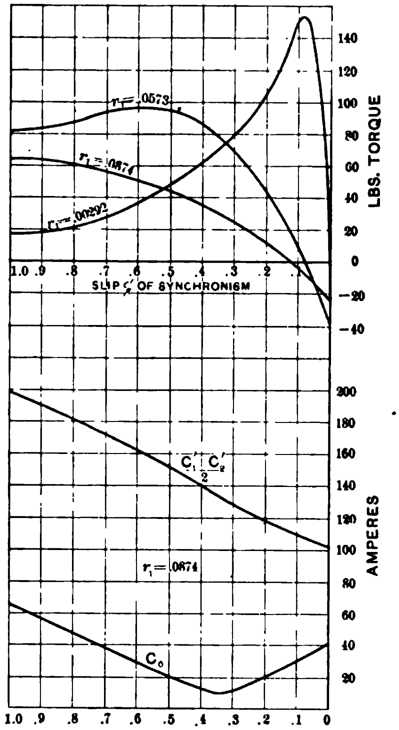

FIG. 42.
1.8-30-900-110. Speed Curves with Monocyclic Starting Device.
Resistance — Inductance
$Y_1 = 2\ 13.$ $Y_2 = .085 + 2.12 j.$

Of the same motor the single-phase speed curves as shown in Figs. 9 and 10, Section 1, and the three-phase speed curves in Figs. 1 and 2 of my previous paper. All these three sets of curves are taken at the same impressed voltage and frequency and are thus directly comparable. These tests, however, were made some years ago and thus the motor no longer represents the present state of the art.

Herefrom it appears, that of all single-phase induction motor starting devices the monocyclic device most nearly reproduces in starting and accelerating, the conditions of the polyphase motor.

DISCUSSION.

THE PRESIDENT:—This paper of Mr. Steinmetz is another valuable contribution to our TRANSACTIONS, of which he has already given us several, and as he himself said, it is a continuation of previous work. The single-phase induction motor is rather a new device. It resembles somewhat the synchronous motor in being incapable of starting itself, and has small torque at speeds below synchronism. This limitation is brought out by the fact that Mr. Steinmetz devotes more than three-fourths of his paper to the starting devices and the effect that they have upon the action of the motor.

The paper is open for discussion. Will Dr. Kennelly favor us with a few remarks on the paper?

DR. A. E. KENNELLY:—The paper before us is certainly an abstruse one from the point of view of electric motors, because we generally suppose that an electric motor is a very simple piece of apparatus. But I think if we eliminate that major portion of the paper which is devoted to starting; the remainder devoted to the normal action of the motor, resolves itself into one of comparative simplicity. As the President has remarked, the single-phase induction motor is a sort of intermediary device between the multiphase induction motor, with which we have some familiarity, and the synchronous single-phase machine. The single-phase machine must be brought up to speed in order to start, and must run strictly in synchronism or it will stop. The multiphase induction motor will not only start with a full load torque, but even with a torque considerably in excess of full load, and it will not run at exact synchronism. The intermediary device of the single-phase induction motor is one which will not start itself like its friend the single-phase synchronous motor, but is more easily started from rest, and when once started will run nearly in synchronism—more nearly in synchronism than the multiphase induction motor; but if pulled out of that synchronism by an overload, it has a greater tendency to stop than the multiphase induction motor. I think that the relation between the two machines is perhaps more readily comprehended by the mental device of assuming a double rotation of the field than in any other way. Perhaps I may make that clearer by a diagram on the blackboard. If we consider the multiphase induction motor, we can assume that the field travels around at a perfectly definite rate, say right handedly In the case of a single-phase induction motor, we can imagine that the alternating field consists of a double rotation so that the full field divides itself into two halves, one half going around right handedly and the other half going around left handedly, and each of these is a simple rotating field. Either of these components might be considered as a simple multiphase component in the absence of the other. You must have both components when you employ the single-phase current. The armature does not know which component to follow at starting, and you must determine which component it shall follow by giving it the initial impulse. Once it has been brought up nearly into synchronism with either component, it will follow that component as though the other did not exist, but when following the right hand component say at nearly synchronous speed, the left hand component will be rotating relatively to the armature at twice that speed. Therefore, if you superpose upon the ordinary multiphase induction motor a component of magnetic field revolving relatively to the armature, at double the speed, in the opposite direction, I think the results are those that are deduced by Mr. Steinmetz in his paper. The importance of course of supplying the necessary starting power to the motor renders it necessary to use these various devices which are described in the long appendix of the paper. These become of great importance in view of the small torque which the machine normally possesses at starting.

Mr. Steinmetz:—I held the same opinion some time ago, but in attempting to get results agreeing with experience from this theory of two magnetic fields of half intensity revolving in opposite directions, I have found that the theory does not represent the facts, and had to be given up, for several reasons.

1st—At standstill the magnetic field of the single-phase induction motor is undoubtedly alternating, and can be resolved into two equal and oppositely revolving fields. At speed however, and especially at synchronism, one component has disappeared altogether and the other component is of full intensity, that is the field is a uniformly revolving field as shown by the fact that in a turn at right angles to the primary coil the same E. M. F. is induced, as in a turn parallel to the primary coil, but the E. M. F. is displaced in phase by 90°.

2nd—The current consumed by the single-phase induction motor when running light, contradicts the theory of the two oppositely revolving fields of half intensity. According to this theory the current running light should be equal to the sum of the exciting current of a polyphase motor of half impressed E. M. F. plus the current taken by a polyphase motor of half impressed E. M. F. when driven backward at full speed. This latter current, however, is frequently many times larger than the current actually observed in a single-phase induction motor at synchronism.

3rd—The torque curve of the polyphase induction motor with low resistance secondary is as shown in *t* in Fig. 1. The torque

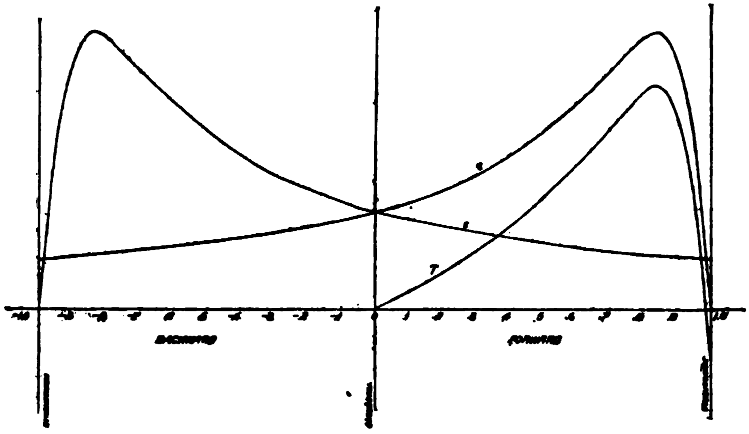

Fig. 1

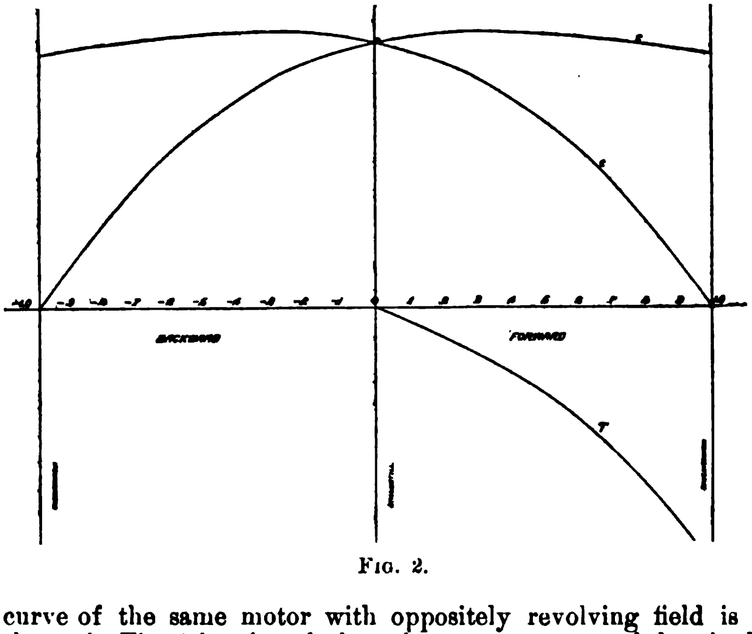

Fig. 2.

curve of the same motor with oppositely revolving field is as shown in Fig. 1 by t^1, and thus the torque curve of the single-phase induction motor should be the difference between *t* and t^1, or *T* in Fig. 1. It is in reality only approximately of similar shape, in a motor with low resistance armature, but it entirely disagrees in a motor with high resistance armature. With very high resistance in the armature or secondary, the torque curve of the polyphase motor is as shown by t in Fig. 2, with the maximum beyond standstill. The same motor with oppositely revolving field gives a torque curve t^1, and a single-phase motor should thus have as torque curve the difference $T = t - t^1$ as shown in Fig. 2, that is, should have negative torque over almost the entire range. This does not agree with experience, since we know that no matter how high the secondary resistance of the motor is, the torque still remains positive.

For these reasons, the theory of two equal and oppositely revolving fields must be given up, although it is still occasionally used in publications.

DR. KENNELLY:—The explanation which Mr. Steinmetz has given as to the discrepancy between the facts based upon the double revolving theory, and the facts based upon a simple calculation of what takes place without referring to that theory, do not however include the consequences of the magnetizing influence of the currents in the revolving armature. In other words, he admits that when the armature is at rest, or when the machine is not in operation, as it were, the double revolving theory undoubtedly applies. Now, when you start the armature in operation you superpose upon that double revolution, which he admits is there, the effect of the currents in that revolving member and those effects, when superposed upon both halves and upon both members of the revolving field, will, I believe, come to the same thing as the effects which he traces out directly in his paper. Of course we cannot neglect the effects of the currents in the revolving member upon both components, but if we take them into consideration, I think the results are the same as when the matter is treated in the able manner Mr. Steinmetz has treated it in his paper. It seems to me that the double revolving theory can be made to give the same results and is a simpler way of looking at the matter in theory, a simpler way of regarding the matter. For example, all the main results mentioned by Mr. Steinmetz in his paper follow directly from the consequences of a double revolving field; namely, the power of the motor being so much reduced because the two components are divided, the relatively feeble torque of the motor, the double frequency component of current—all these three things are consistent with the double rotation theory, and while it is true as pointed out by Mr. Steinmetz that the double rotation theory simply considered is not apparently in accordance with that fact, still I take the position that if allowances are made for the effect of the revolving armature, if the armature reaction be taken into account, so to speak; that the double field theory can be made to agree with the facts.

The vector method is the only one up to the present date, that can simply and directly deal with ordinary current phenomena. Any one who will compare a single expression of alternating current motor phenomena as developed by the formula of vectors and developed by any other formula, will be struck by the vast contrast presented by the two--one, simple, direct, compact; the other complex, vague and enormously extended.

Mr. Steinmetz:—I agree with Dr. Kennelly that by amending the theory to magneto-motive forces instead of magnetic fluxes, and taking in view the effect of induced currents, the theory of two opposite and equal rotations can be made to better agree with experience.

It would read then, that the primary induced circuit of the single-phase induction motor can be resolved into two equal and oppositely rotating M. M. F.'s, and the secondary circuit produces a M. M. F. proportional to the speed and additive to the one, subtractive to the other component of impressed M. M. F., thus annihilating the latter and doubling the former at synchronism.

Prof. W. S. Franklin:—I am much pleased with the paper which I have heard discussed and partly read this evening, and I feel very thankful to Mr. Steinmetz for what he has given us. I wish to express my belief with Dr. Kennelly that the theory of the induction motor might easily be developed from the double rotation field theory. In regard to the vector method for studying alternating currents, a method which from the narrow point of view of a teacher I have always thought of as a graphical method, I may say that I have had considerable experience with it and I have always been skeptical of Mr. Steinmetz's method until I came to look over his book and some of his recent papers and I must say, that I am entirely converted to the author's point of view. I think the graphical method is inadequate except for the use we teachers make of it. I don't know whether Dr. Kennelly means Mr. Steinmetz's method when he speaks of the vector method, or whether he means simply the graphical method.

Dr. Kennelly:--I mean Mr. Steinmetz's method, which is a vector method and a most applicable one.

Prof. Franklin:—I thought perhaps that Dr. Kennelly might include both the graphical and the symbolic method in the vector method and I don't know but it is quite proper to do so.

Mr. Steinmetz:—I want to draw attention to the investigation on page 80. If you will look at the diagram you will see there are nine different currents and still more E. M. F.'s. Now I defy anyone to get results by any other method of investigation in such a complex system without neglecting hysteresis and neglecting exciting current and neglecting self-induction and some other things, and ultimately getting results which are entirely worthless. I may add that the method used here is used successfully to predetermine the starting torque of induction motors and agrees with experience.

MR. TOWNSEND WOLCOTT:—If anybody will start with differential equations, even in the simplest case of alternating currents, he will find that he gets into deep water very quick. The only objection raised to this method is that it assumes sinusoidal variation. Now Mr. Steinmetz and others who have tried it in practice, say that the practical results justify the use of the method. Of course it is not theoretically correct, but if you get practical results from it, it is like a great many other things, justified in the application. Even in designing an ordinary continuous current dynamo you make assumptions about the flux in the field magnet which are not true, but at the same time you get practical results which are near enough true for all practical purposes. The true distribution of magnetic flux in the field magnet of an ordinary dynamo is unknown; that is, the analytical difficulties are so great that you cannot express it in a manner which is theoretically correct, but you can get at it near enough for practice with simple arithmetic. And it is just so with this method of Mr. Steinmetz. It is practically correct, whatever theoretical objection there may be to taking sine waves to represent a wave of any form.

PROF. FRANKLIN:—Mr. Wolcott has mentioned a thing which has often been in mind in contrasting the graphical method, or in its algebraic form, Mr. Steinmetz's method, with the analytical method or the use of differential equations in the study of the alternating current. We find that the method of differential equations is the one that does not assume a sinusoidal current, but, if you consider the matter, having a given saw-tooth form of E. M. F. your saw-tooth problem reduces itself to a series of sinusoidal problems. Now the problem to solve for the first member in that series is repeated for the second member and so on, and the problem which is based on any one of the harmonics of the alternating E. M. F. is precisely the problem which Mr. Steinmetz handles in his symbolic method, and which is handled by the ordinary method of graphical vectors, and we lose sight of the fact I think that the vector method is by using a series of diagrams applicable to any sort of a curve.

MR. WOLCOTT:—In Mr. Steinmetz's method, we assume the equivalent sine wave, which procedure has been objected to by some electricians, especially in England. The justification of it is in the practice as I understand it. There may be mathematical objections to doing it in this case, but we also do it elsewhere. For instance when we introduce 2 π into the expression for impedance we have already assumed the sinusoidal wave. That is if it happens to be some other shape, we assume an equivalent wave of simple sinusoidal form, instead of working out a whole series of terms, although it may not be correct from an analytical point of view.

DR. KENNELLY:—I hope to see the vector method used practically by engineers because of its simplicity, directness and usefulness. I think it is a great mistake to suppose that the vector geometrical method is limited to the conception and hypothesis of sinusoidal waves of electro-motive force, magnetism or current. When you go into an electric light station and see an alternating current dynamo that is producing a thousand volts by the voltmeter, and is producing say 30 amperes by the ammeter and 25 kilowatts by the wattmeter, you may form two suppositions; one is that you have an unknown, peculiar complex type of wave, and analyze it all out by supposing that you have a certain sine fundamental wave, and then the harmonics, and go through the various orders; or you can assume, which is equally nearly correct for all practical purposes, that the machine produces a sinusoidal E. M. F., a pure sine wave of a thousand volts, and that the load is such as to produce a lag of the current represented by the power factor determined from the wattmeter. The wattmeter shows that there is a power factor in the whole load of so much, and that will represent to a sinusoidal electromotive force a certain combination of inductance and resistance. It is, strictly speaking, a false hypothesis, but it meets all the purposes of the case. The vector method may be considered to assume that you can treat the E. M. F. as a simple alternating sinusoidal electromotive force. By that means you eliminate all the complication incident to Fourier's method and you arrive at results which are practical and useful at once.

MR. STEINMETZ:—I fully agree that it is a matter of definition whether it is permissible to use equivalent sine waves or not. No matter what the shape of the wave is, we can always resolve it into a series of sine waves of different frequencies, and the theory of the equivalent sine wave merely means that the total energy is included in the fundamental wave, and thereby all the higher harmonics made wattless waves. In consequence thereof in dealing with the fundamental wave only, as equivalent sine wave, we find results which check with experience, since this wave includes, and takes account of the total effect.

There are, however, undoubtedly cases where the theory of the equivalent sine wave cannot be used, as for instance in the case of the alternating arc, in which we have distortion between current and E. M. F. without phase displacement, and thus get a power factor without an angle of lag, or when attempting to calculate the angle of lag its sign becomes ambiguous.

Regarding, however, the use of Fourier's theorem or the use of equivalent sine waves, I have never seen any publication where real alternator waves, that is waves as given by machines in commercial operation, have been used, and the calculation carried out by the infinite series of Fourier and any results derived, so that it appears to me merely an academic discussion whether it is permissible to use equivalent sine waves or not, since you cannot use the complete series of Fourier anyway.

Prof. Franklin:—If I may be permitted to make one more remark I wish to make clear what I said a moment ago, and that is that the vector method, including Mr. Steinmetz's method, is precisely the analytical method. It is the solution corresponding to the fundamental harmonic. You could get another corresponding to the second harmonic, etc. Indeed Mr. Steinmetz might write a Fourier series of papers, one for the first harmonic, one for the second and so on *ad infinitum* upon each subject which he brings before the Institute. I wish particularly to make the point that the analytical method with its Fourier's series is precisely the same thing as the vector method including Mr. Steinmetz's method, except that the latter as ordinarily carried out is not complete. Further, in regard to the conception of the equivalent wave. The use of this conception arises from the practical necessity of our being satisfied in our calculations with the results of one solution instead of a Fourier's series of solutions; and while in some respects the actual fundamental harmonic of the given E. M. F. or current may represent the actual state of affairs more closely than any other sinusoidal E. M. F. or currents, in other respects we know it does not, and we are justified in basing our single solution upon a sinusoidal E. M. F. or current which represents the state of affairs most closely in respect of those things which are of importance in the result.

Mr. Elias E. Ries:—It seems to me that we have had a great deal of mathematics and quite a little theory here this evening and so far as it goes it has been very interesting. I note from Mr. Steinmetz's paper, however, that the single-phase induction motor requires, in order to make it practical, a self-starting device or rather a separate starting device, and he goes into considerable detail as to various methods that might be used. Now, it is a well known fact that the single-phase synchronous motor, which is one of the first of the successful alternating current motors of which we have any record, is deemed objectionable from a practical point of view, mainly because of the necessity of employing some means of starting it. I should like to inquire, since I do not see in the paper any reference made as to the particular type of motor, if an actual motor was used in making these tests, and I should like to ask what the practical results were that Mr. Steinmetz obtained in making these tests and whether or not he has come to the conclusion that the single-phase induction motor, as a practical and available machine, is in advance of the single-phase synchronous motor. Of course we understand that the induction motor possesses the advantage in most cases of dispensing with the commutator and other complicated mechanical devices, but as a practical machine, taking everything into consideration, has he found and is he in a position to state to the members of the Institute as a result of his experiments that this single-phase induction motor, as compared with the polyphase induction motor, is in a position where it can be applied to practical, every-day use. I think the INSTITUTE would be interested in hearing something on that side of the question.

MR. STEINMETZ:—I may state that the single-phase induction motor is a standard article of manufacture and has been built and sold in sizes up to 100 H. P.

On high frequency circuits these motors are used only in sizes up to 15 H. P., not because large sizes cannot be built, but due to the nature of most high frequency circuits, in which parallel operation is not practiced, and usually a number of small generators are employed and circuits of limited capacity which do not permit the massing of larger loads as do large single-phase induction motors.

Low frequency single phase motors are used to a limited extent only, since most low frequency circuits or more modern installations employ either a polyphase system or a monocyclic system, and in either case the self-starting polyphase motor can be used.

The essential difference between the single-phase induction motor and the single-phase synchronous motor is that the single-phase synchronous motor has to be brought up to complete synchronism and is thrown out of step, that is comes to a standstill if the frequency changes suddenly. Thus it cannot be used satisfactorily in these high frequency stations in which the alternators are not operated in parallel but with the changes of load the circuits are switched over from one machine to another machine, that is in most high frequency stations. In such stations, with increase of load on one generator, circuits operated by this generator are thrown over to another generator, which being lightly loaded, usually runs at a higher speed, that is higher frequency, and in consequence thereof all the synchronous motors operated on such a circuit are thrown out of step, which obviously is very objectionable, and the main objection against introduction of the single-phase synchronous motor. The single-phase induction motor, however, in such a case will keep running, since it does not depend upon exact synchronism but operates at a speed somewhat below synchronism.

MR. RIES:—What I had in view in putting the question was an application for the single-phase motor which has not yet reached a practical stage to any extent. I had in mind the employment of single-phase motors for electric railway work, long distance transmission and so on, in which alternating currents are used, with special reference to a system of secondary distribution employing a single supply and return conductor such as now used in direct current railways, and it was in that connection that I wanted a little further information from Mr. Steinmetz as to what particular stage the single-phase induction motor has reached as compared with the well known synchronous form. For stationary motors, where there is no particular difficulty in running a third wire, a two-phase or three-phase system of power distribution may have some advantages, at least under existing conditions. In the case of locomotors, however, the use of three separate conductors and sets of collecting devices for maintaining contact with them is productive of mechanical complications which may as well be avoided and which can best be overcome by the adoption of an efficient single-phase transmission system.

MR. STEINMETZ:—I do not see what I can say regarding that inquiry. As far as I know, no single-phase synchronous motor has ever been tried on a railway car, and no single-phase induction motor either as far as I know, and since it is much easier to use a direct current motor, and wherever the distance is great to transmit the power over a three-phase transmission line by rotary converters, there has thus far been very little call for alternating railway motors, and the only promising field which I could see for them would be very heavy railway work or very high speed roads, that is 100 miles or more per hour, and other kinds of special work in which a polyphase induction motor, or perhaps even a single-phase induction motor may perhaps be satisfactorily employed.

[Adjourned.]

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

New York, March 23d, 1898.

The 123d meeting of the INSTITUTE was held this date at 12 West 31st Street, and was called to order by President Crocker at 8:20 P. M.

THE PRESIDENT:—The Secretary has a few announcements to make before taking up the business of the evening.

THE SECRETARY:—At the meeting of the Council held this afternoon the following associate members were elected:

Name.	Address.	Endorsed by
Davis, Albert G.	Acting Manager, Patent Dep't, General Electric Co., Schenectady, N. Y.	Chas. P. Steinmetz. Ernest Berg. Eskil Berg.
Gallatin, Albert R.	Student at Columbia University, residence 58 W. 55th St., New York City.	F. B. Crocker. W. H. Freedman. W. H. Ripley.
Gaytes, Herbert	Electrical Engineer, Realty Syndicate Railways, Piedmont Power House, Oakland, Cal.	W. M. Stine. B. J. Arnold S. A. Rhodes.
Griffin, Russell Agnew,	Purchasing Agent, American Telephone & Telegraph Co., 15 Dey Street, New York City.	F. A. Pickernell. S. D. Field. R. W. Pope.
Lee, Francis Valentine T.	Engineer, (Pacific Coast Dept.) Stanley Electric M'f'g Co., 300 California St., San Francisco, Cal.	F. A. C. Perrine. C. L. Cory. F. P. Medina
Loewenthal, Max	Associate Editor, *The Electrical Engineer*; residence, 831 Park Ave., New York City.	F. B. Crocker. T. C. Martin. Max Osterberg.
Pope, Henry W.	Special Agent, American Telephone & Telegraph Co., residence, 200 W. 83d Street, New York City.	S. D. Field. R. W. Pope. T. D. Lockwood.
Reichmann, Fritz	Instructor of Physics, The University of Texas; 309 E. 11th St., Austin, Tex.	A. L. McRae. H. H. Humphrey. Brown Ayres.
Theberath, Theodore E.	Pacific Coast Engineer, Stanley Electric M'f'g Co., 300 California St., San Francisco, Cal.	F. A. C. Perrine. Geo P. Low. F. P. Medina.

FLIESS, ROBERT ANTON,	Student of Electrical Engineering, Columbia University; residence, 201 W. 55th St., New York City.	F. B. Crocker. G. F. Sever. W. H. Freedman.

Total 10.

In accordance with the wishes of the meeting which was held at New York and Chicago to discuss the question of standardizing generators, motors and transformers, the Council this afternoon appointed the following committee of seven to consider the question and report to the Council:

FRANCIS B. CROCKER,
CARY T. HUTCHINSON,
ARTHUR E. KENNELLY,
J. W. LIEB, JR.,
C. P. STEINMETZ,
L. B. STILLWELL,
ELIHU THOMSON.

At the same meeting, in accordance with the Constitution, the Council selected the following nominees for the coming election from the nominations sent in by the membership:

For President:
ARTHUR E. KENNELLY.

For Vice-Presidents:
ROBERT B. OWENS,
WILLIAM STANLEY,
CARY T. HUTCHINSON

For Managers:
HERBERT LLOYD,
SAMUEL SHELDON,
GEORGE F. SEVER,
CHARLES P. STEINMETZ.

For Secretary:
RALPH W. POPE.

For Treasurer:
GEORGE A. HAMILTON.

The nominations sent in very clearly expressed the desire of the membership that the present incumbent should serve for another term as President, but Dr. Crocker positively declined, on account of his probable absence during the next year, beginning in the fall. He expects to go abroad and he wished to cut loose from all duties, of which the presidency was one. The paper this evening was to have been read by the author, but I received from him this morning a letter explaining his unavoidable absence.

THE PRESIDENT:—It is quite unfortunate that Prof. Fessenden cannot be here to present his paper, as it is an interesting subject. The paper was printed in advance and has been accessible to some of the members. But as most of the members ahve not had an opportunity to read it and as the author is not here to give us an abstract, it would be well to have the paper read and Mr. Ryan has kindly offered to do this.

A paper presented at the 123rd Meeting of the American Institute of Electrical Engineers. New York, March 23rd, 1898, President Crocker in the Chair.

INSULATION AND CONDUCTION.

BY REGINALD A. FESSENDEN.

A thing insulates because it is possessed of two distinct properties, first, the ability to stand the mechanical and electrical stresses due to the voltages used; and, secondly, because it is such a poor conductor that but a negligible small current can flow through it and leak away. In other words, it will neither allow the current to break through it, nor to steal through it. The first property is called by Maxwell the "dielectric strength" of the insulator, the other property is called the ohmic resistance. The two together form its insulating power.

In the two great branches of electrical work, the requirements for an insulator are widely different. For apparatus used for the transmission of intelligence as a rule low voltages are used, and so dielectric strength is of relatively small importance, but the currents used are small, the circuits long, and material of high ohmic resistance is needed. For apparatus designed for the generation and transmission of electric energy, on the other hand, where the voltages are high and the currents large, dielectric strength is the main thing desired and the leakage of a small amount of current is not objectionable. Consequently the two branches of the profession have come to use the word "insulation" in quite different senses, the former and older as meaning something having high ohmic resistance, and the latter branch using it with reference chiefly to material having great dielectric strength.

Confusion sometimes occurs through this double meaning, and the writer himself has been taken to task by a European engineer for stating that pure water was approximately as good an nsulator as rubber, the critic having reference, as was apparent, to its ohmic resistance, whilst the original note was principally concerned with its dielectric strength. It is therefore considered best to define the sense in which the word is used, in spite of the fact that attention has previously been called to the distinction to be made between these two properties; notably and very lucidly by Mr. Steinmeitz in this INSTITUTE's proceedings, vol. ix., p. 815.

Before entering upon the discussion of the various purposes for which insulation is used and of the substances best suited to each case it may be as well to give a brief account of the manner in which the current passes through materials.

1. *By actual convection.*—That is by particles of the insulator, or of foreign substances, taking a charge from one electrode and moving with it to the other terminal under the influence of the voltage. This action is similar to that of the moving pith ball between the two knobs of a Holtz machine.

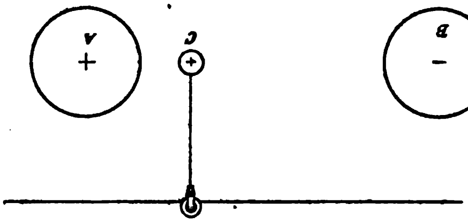

FIG. 1.

The ball C having touched A and got a + charge, is repelled and moves over to B, where it gives up its charge, takes up a — charge and moves back to A.

This phenomenon is not known to take place in solids, but it is quite marked in gases, vapors and fluids.

Until recently it was a question of no practical importance in electrical engineering, but with the high voltages now in use or contemplated it may give serious trouble, and apparatus must be designed to check this form of leakage. It was not so long ago that Ferranti's 10,000 volts was looked upon as monstrous, but some experiments of the large companies, of which I have been informed, seem to show that 100,000 volts may be quite practicable, even in quite unfavorable climates. With overhead wire the leakage will merely mean a loss of energy, and the use of porcelain for all insulation, as any oxidizible material (used for instance to protect the primaries of transformers), would be speedily destroyed by the ozone. Where, however, oil is used in the transformers, the leakage may cause quite serious trouble, owing to the large surfaces and their proximity. In addition, as Prof. Elihu Thomson pointed out some years ago, with high potentials, impurities in the oil are apt to group themselves along the lines of highest slope of potential like the iron filings around a magnet, and if, as is generally the case, the impurities have a higher specific inductive capacity than the oil such a group is thus apt to form a bridge between two points of great difference in potential hence causing an arc. In those convection currents it is not, I believe, the very small particles which cause the trouble, because small bodies, when charged from a comparatively large and smooth one are not repelled but attracted; consequently a small grain of dust after touching a highly charged flat conductor would remain close to it if there were no negatively charged particles near it to drag it away or no currents in the oil to wash it off.

The relation between the size of the particle, the voltage and the radius of the charged conductor when the particle after touching the conductor is neither attracted nor repelled can be obtained by the method of images, but the formula so derived is rather long and complicated and I have not had time to work out the numerical results.

It is evident, however, from it, that for a convective current to take place the radius of the particles carrying the discharge must be a quite appreciable fraction of the radius of the charged conductor. Consequently this form of leakage is due to the motion of a portion of the oil as a whole and not of its individual particles, and if we can break up mechanically these currents we can to a great extent stop the leakage from this cause. This may be done in three ways:—

1. By using oil of great viscosity, in which case, however, we lose the chief advantage of oil insulation, *i.e.*, its ability to reinsulate quickly after a discharge.

2. By putting pure dry cellulose in some form or other between the charged surfaces loosely, so that the oil can filter through it easily and any air escape readily, but sufficiently close to prevent any rapid flow. Pure cellulose has the great advantage that when well boiled in the oil it has approximately the same specific conductive capacity as the oil. No varnish or shellac should be used in the oil for reasons given later.

3. By dissolving a solid, non-disassociating substance in the oil in such excess that it crystallizes out at ordinary temperatures and forms with the oil a soft gelatinous mass, not fluid, but yet capable of allowing the oil to ooze through its substance. This has many of the disadvantages of 1, but it has one advantage, in that the substance chosen may be one, like paraffin, having a large specific heat of liquefaction, and consequently an overload will not raise the temperature of the oil above a fixed point till the paraffin is all melted.

The effect of points in promoting convective discharges in air is well known. It is usually attributed to the great surface density of electricity which a point must take in order to make the potential all over the conductor the same, and hence, since the repulsive force varies as the square of its surface density, it is evident that there will be a great tendency for discharge from a point from this cause. But there is another and very important one, *i.e.*, the fact that, as mentioned above, a particle cannot take a charge and move away unless its radius is larger than a certain fraction of the radius of the curvature of the conductor at the point where it touches the latter; consequently when the charged surface is a plane only large aggregations of atoms can move away; these move slowly and carry small charges in proportion to their mass. But at points where the radius of curvature is very small, small particles can move away with great rapidity and with relatively large charges. Rounding off or flattening the charged surfaces thus acts in a double way, by reducing the surface density and by preventing all but large sized particles moving away.

2. *Conduction in Solids.*—It is not absolutely certain that all conduction is not by convection, but the terms are here used with their usual signification. In solids we do not know as yet exactly how the discharge is handed on, but I have noted a very remarkable fact, which is quite significant and suggestive, *i.e.*, that the conductivities of metals are proportional to the quantity

$\sqrt{\frac{\text{elasticity}}{\text{density}}} \div$ valency. The following table shows this.

This fact was discovered by the writer in 1892,[1] as the result of several years tedious work in collecting physical data and combining them into formulæ to see if any law could be found.

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[1] *Science*, July 22, 1892.

TABLE OF CALCULATED AND OBSERVED RESISTIVITIES.

METAL.	ATOM. VOL.	ATOM. WT.	VALENCY.	R. CALC.	R. OBSERVED.
Silver	10.2	108.	1	100	100
Copper	7.1	63.3	2	126	106
Gold	10.2	197.	1	135	137
Aluminium	10.5	27.	3	152	159
Magnesium	14.	24.4	4	220	275
Zinc	9.4	65.5	4	300	352
Cadmium	13.	112.2	4	456	450
Tin	16.2	118.	8	1030	878
Thallium	17.3	204.	6	1060	1190
Lead	18.2	207.	8	1470	1305
Iron	7.2	56.	8	480	646
Beryllium	2.	9.	4 or 8	50 or 100	....

Out of the hundreds of combinations tried, this and another one (really the same ultimately, but expressed in terms of other properties), were the only ones which seemed hopeful. It was stated in the article referred to, that this formula could not be quite correct. This was for the following reason: Silver, gold and aluminium should, as will be seen from the formula given below, have resistances proportional to the square roots of their densities multiplied by their valencies, *i.e.*, in the ratio of

$$\sqrt{10.6} \ : \ \sqrt{19.26} \ : \ \sqrt{2.65} \times 3$$

i. e.,

$$100 \ : \ 136 \ : \ 150.$$

Now at this time the best determinations of the resistance of aluminium with which I was acquainted gave it as 193 to silver 100. With such a wide discrepancy therefore between calculation and observation, *i.e.*, 193 instead of 150, it did not seem probable that the high observed value could be modified by subsequent determinations so as to agree with the calculated one. It was, therefore, with considerable pleasure that I saw the recent determination of Messrs. Richards and Thomson (published last year in the *Journal of the Franklin Institute*). Their results for aluminium, 99.66 pure, were:

Aluminium : Silver : : 163 : 100,

and they expressed the opinion that the value for pure aluminium, when hard-drawn, would be 66 per cent. of the conductivity of copper. This result is so close to the calculated result given in the paper referred to, *i.e.*,

$$17 : 27 = 100 : 159,$$

though such a high conductivity for aluminium was considered beyond the bounds of probability at that time, that I feel justified in considering that the formula given may be found fairly accurate when more exact determinations shall have been made.

This formula throws a certain light on the nature of conductivity in solids, and why some solids are insulators. For the formula $\sqrt{\frac{\text{elasticity}}{\text{density}}}$ is the same as that for the velocity of sound in a body. Now, in the convective discharge, the electricity was handed on with the same velocity as that with which the particles moved. In fluids, as we shall see, the electricity is handed on with the velocity with which the ions move. In both cases the electricity travels along on the particles of matter.

The idea that electrical flow in solid conductors might also be a simple handing on from one atom to another suggested itself nearly a decade ago to Professor Lodge. That brilliant and careful reasoner and experimenter, who has cleared up so many patches of scientific jungle, gives a very clear description of the manner in which this would happen if such were the case. I cannot do better than quote him, as it will show how well this idea agrees with all the facts then known, but one.

> "But if we are not satisfied with this vague analogy, and wish to penetrate into the ultimate nature of heat and the mode in which it can be generated, then we can return to the consideration of a multitude of oscillating and colliding particles, moving with a certain average energy which determines what we call the temperature of the body. If now one or more of these bodies receives a knock, the energy of the blow is speedily shared among all the others, and they all begin to move rather more energetically than before: the body which the assemblage of particles constitutes is said to have "risen in temperature." This illustrates the production of heat by a blow or other mechanical means. But now, instead of *striking* one of the balls give it an electric charge; or, better still, put within its reach a constant reservoir of electricity from which it can receive a charge every time it strikes it, and at the same time put within the reach of some other of the assemblage of particles another reservoir of infinite capacity which shall be able to drain away all the elec-

tricity it may receive. In practice there is no need of infinite reservoirs: all that is wanted is to connect two finite reservoirs, or "electrodes," as one might now call them, with some constant means of propelling electricity from one to the other, *i.e.* with the poles of a voltaic battery or a Holtz machine.

What will be the result of thus passing a series of electric charges through the assemblage of particles? Plainly the act of receiving a charge and passing it on will tend to increase the original motion of each particle; it will tend to raise the temperature of the body. In this way, therefore, it is possible to picture the mode in which an electric current generates heat. But although this process may be used as a possible analogy, it cannot be a true and complete statement of what occurs; for it is essentially the mode of propagation of *sound*. Sound travels at a definite and known velocity, being a mechanical disturbance handed on from particle to particle in the manner described. But heat, being some mode of motion, must also be handed on after some analogous fashion, so that when heat is supplied to one point of a mass it spreads or diffuses through it. It is difficult to suppose the conduction of heat to be other than the handing on of molecular quiverings from one to another; and yet it takes place according to laws altogether different from those of the propagation of the gross disturbance called sound. The exact mode of conduction of heat is unknown, but, whatever it s, it can hardly be doubted that the conduction of electricity through metals is not very unlike it, for the two processes are the same laws of propagation: they are both of the nature of a diffusion, they both obey Ohm's law, and a metal which conducts heat well, conducts electricity well also."

I have said, "with all the facts then known but one." This because, as mentioned in the abstract given above, there seemed to be no good evidence for the view that there was any connection between the conduction of sound and of electricity. The reason for this lay in the fact that very few determinations had been made of the velocity of sound in the pure metals, though a considerable number had been made on alloys and commercial materials.[1]

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[1] I am here moved to again call attention to the fact that an immense amount of physical experimental work is misdirected. It is no doubt quite gratifying to ascertain, after several years laborious work, that a particular piece of brass or steel of not very definitely known composition and in a quite indefinite physical state has a temperature coefficient of expansion expressed by five significant figures, but such information must be considered as pieces of philosophic virtú-intrinsically worthless, but possibly possessing a value by reason of their uniqueness and associations. I have pointed out elsewhere (*Jour. Frank. Inst.*) that at the present time, in spite of the fact that much has been done, notably by

Consequently no general law could be discovered, though it cannot be doubted but that had the formula for the relation between Young's modulus and atomic volume discovered by the writer[1] been known at that time, this evidence of a still more intimate connection between sound, heat and electricity would have been discovered by Dr. Lodge.

The formula referred to is:

$$\text{Young's Modulus} = \frac{78 \times 10^{12}}{(\text{atom. vol.})^2}.$$

Hence it is possible to predetermine the velocity of sound in wires by the formula:

$$\text{Velocity in cms. per sec.} = \frac{883 \times 10^4}{\text{atom. vol.} \times \sqrt{\text{density}}},$$

and the electric resistivity is given roughly by:

$$\text{Resistivity} = 45 \times 10^{-9} \times \text{atom. vol.} \times \sqrt{\text{density}} \times \text{valency}.$$

This formula possesses a general interest, inasmuch as it would seem that while the strain in the dielectric is propagated with the velocity of light, *i. e.* $\sqrt{k\mu}$, the actual electricity in the wire is handed on with the velocity of sound, and is proportional to $\sqrt{\frac{k}{\mu}}$. The significance of this will be treated of elsewhere.

Suppose a wheel, with elastic spokes and a heavy rim bound outside with a band of horsehair, the horsehair rubbing against a series of violin strings mounted parallel to the axis of the wheel, as shown in Fig. 2. Suppose each violin string has mounted upon it a small metallic bead charged with electricity, so that when the strings vibrate the beads can touch. Then on grasping the wheel at B, after a time depending upon the elasticity and mass of the *wheel*, a spark will be seen at A, but the actual velocity with which the electricity moves round the circuit of violin strings will depend upon the elasticity and mass of the *strings*. In passing, we may note several things:

Matthiessen, Roberts-Austen and others, we have not at present any data in regard to 90 per cent. of the more important properties of the simpler metals used in the arts. The importance of having a standard state for solids; of a central bureau to furnish pure materials in a standard physical state to experimenters, and the exclusive use of such materials by experimenters, cannot be overestimated.

[1] *Elec. World*, Aug. 22, 1891; *Science*, July 22, 1892.

1st. That for this analogy to hold at all, the atoms must be charged even in a conductor not carrying current; which is significant when taken in connection with the fact pointed out by the writer in the papers above referred to, that if we calculate the tensile strength, rigidity and Young's modulus on the assumption that these effects are due to charges on the atoms, we get results agreeing very closely with experiment.

2nd. That in a circuit having many atoms in the cross section the energy could be handed on without actual contact by electrodynamic processes.

3d. That if one part of the circuit were composed of violin strings tuned to a different note-period from the other we would get effects similar to those of thermo-electricity.[1]

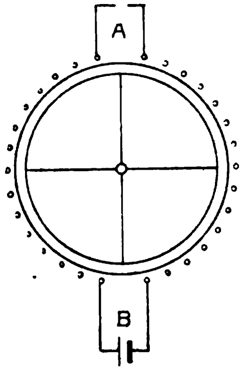

FIG. 2.

4th. That the reversal of the point of greatest drop of potential in a circuit of air and carbon from the + to the — electrode as the pressure is reduced may be due to the fact that, as shown by the beautiful experiments of J. J. Thomson, the molecular conductivity of air at low pressures is extremely high, the electrode heated thus depending upon whether the solid conducts better than the gas, or vice versa.

5th. That this same formula would also be applicable to a diffusion phenomenon, and indeed the presence of valency in the formula makes it exactly analogous to that for the diffusion of heat. Moreover, Roberts-Austen, in a series of striking experi-

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[1] Compare the analogous problem of two portions of gas of different densities in a closed ring tube, and junctions heated. Neuman, Jahrberichte f. Chem., 1874, p. 15.

ments, has shown that diffusion can take place in solids at ordinary temperatures. If a current be however a diffusion, it may be shown that for fairly large current densities the atoms must move several cms. per second and we might therefore expect interpenetration when brass and zinc terminals are joined. But this does not occur to any considerable extent. We may also take it as an electrolytic diffusion, as is suggested by J. J. Thomson in his "Dynamics Applied to Physics and Chemistry," but in this case, even assuming the theory suggested by him to account for some atoms preferring a plus to a negative charge, I find it difficult to imagine the manner in which the atoms could be charged and discharged at the surface of the conductor. It is to be noted that in gases the phenomenon of diffusion, sound velocity and heat conductivity are all linked together.

It will be noticed that in the table given, while the metals follow each other in the order they should from calculation, yet the agreement is in some cases not so close as in others. This may arise from several causes:—1. The conductivities of but few of the metals are accurately known. 2. The elasticities of but few of the metals are accurately known, and the formula given for the Young's modulus only roughly takes temperature into account. 3. The temperature coefficients of the metals are not the same. For instance, that for copper is over .4 : .415, having been obtained by Swan and Rhodin, and .404 by Kennelly and the writer, whilst silver is only .38, and gold .36. Consequently the ratio will vary with the temperature, and at higher temperatures the ratio, resistivity of copper : resistivity of silver will be less. This, it is interesting to note, holds true for the velocity of sound, for from Wertheim's results we have, velocity of sound in silver : velocity in copper = 1.35 at 20° C., and only 1.19 at 200° C., and hence, just as in the case of electrical conductivity, the sound conductivity of copper diminishes at a faster rate than that of silver.

The magnetic metals, as iron and platinum, are very difficult to obtain pure. Their true resistance is therefore at present doubtful.

What has been mentioned thus far concerning the resistance of solids has had no immediate bearing on the subject of insulation. It was necessary, however, in order to introduce the following considerations.

In the formulæ, the valency was introduced. This term has no definite meaning, as the valency varies with the compound. Consider the writer's chart of the elements, (Fig. 3), a modification of those of Meyer, Newlands and others. On one side are seen the metals of the arts. Above them in vertical rows are marked the figures 1, 2, 3, 4, etc. These figures indicate the number of chemical linkages which as a general rule the elements under the figures tend to take up. But there is no very definite rule. Among the univalent metals some unite with bivalent atoms, as does copper, and in general all that can be said is, that a certain valency holds generally and not in general. Consequently when we find that by taking a group of metals having very closely the same values of Young's modulus, as for instance, gold, silver and aluminium, their conductivities are, within the limits of errors of observation, proportional to the velocity of sound ÷ valency; and that in any of the group of metals having

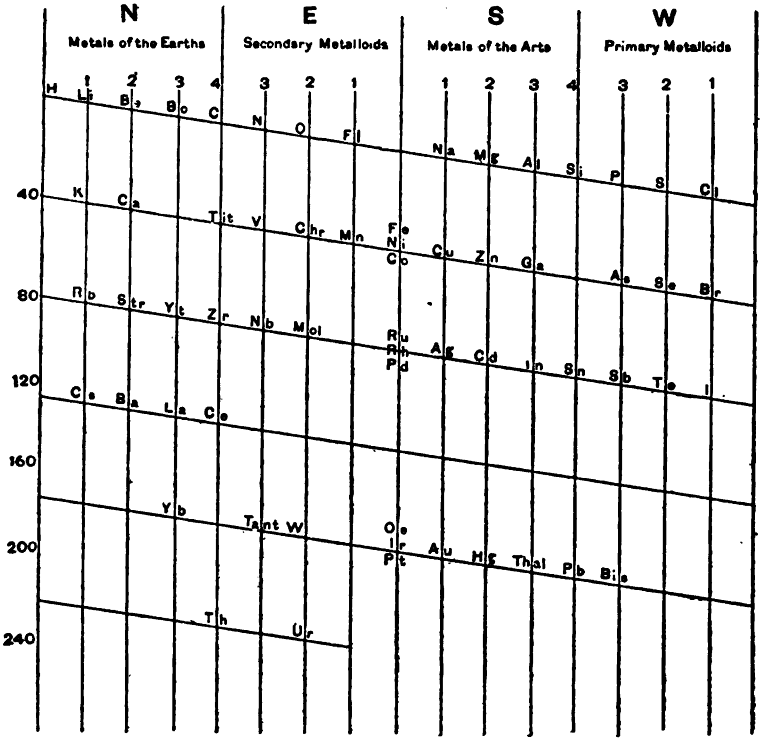

FIG. 3.

the same valency the conductivity is directly proportional to the velocity of sound, within experimental errors, we are to a certain extent justified in making a choice of valencies when this is needed. Fortunately, however, this only occurs in two cases: 1st, we must suppose copper to have twice the valency of silver, which we might, *a priori*, have granted, for though they are in the same group yet copper has markedly through all its salts, twice the valency that silver has. 2nd, that thallium has twice the valency of aluminium, a supposition which has no other justification than the fact that since the formula holds in other cases where the valency are known we have a certain right to use the formula to find the valency.

Now it is well known, especially from facts in organic chemistry, that similar atoms or molecules can combine together to form what are called polymerized substances. For instance three molecules of $C_2 H_2$ acetylene can form one molecule of benzol, $C_6 H_6$. In general we find that these polymerized compounds are more crystalline and have higher melting points than the original substance. Also we note that the number of atoms in such a polymer is generally a multiple of the valency of the atom. Carbon, for instance, seems to prefer to go in groups of four.

Considering now the table of elements, we see that as we pass along from row to row, and as the valency increases, the substances get more crystalline and in many ways evince a linking together.

1st. As mentioned, they are crystalline.

2nd. Their specific heats get abnormally low, this indicating that they are polymerized, or plexed.

3d. They are capable of existing in allotropic forms.

4th. Their vapor densities show that several atoms are jointed together into one molecule, and hence they are almost certainly polymerized as solids since the general tendency of heat is to disassociate. Consequently there is some evidence for the theory that metalloids differ only from metals in that they have a greater tendency to polymerize from their higher valencies, which are probably in some way dependent upon the shapes of the atoms, and are so more crystalline, etc. We might therefore look for some evidence of polymerization among the metals. This is readily found, as before from the variation of the specific heat from its theoretical value. If this linkage were but loose, it is evident that it might affect the specific heat but little, and yet have a marked effect on other phenomena. For instance, we might suppose that it would affect long sound waves less than short ones.[1]

We might therefore consider that when the period of a sound wave coincides with that of the molecules, it is a heat wave, and that heat is transmitted with the velocity of short sound waves, but with a large logarithmic decrement. If this be proven by experiment we would have this relation; *The electric conductivities are in the same ratio as the velocities of very short sound waves*, being thus analogous to Maxwell's law for the velocity of light in insulators, in that the velocity varies with the periodicity.

We have seen above that the electric resistivity varies directly as the valency. Also it has been indicated that there is some evidence to show that the polymerization or plex varies as the valency. Therefore we are led to assume that increase of resistance accompanies polymerization or the linking together of the atoms into groups. We see that this might hinder the transmission in various ways since the groups would not vibrate so quickly as the single atoms and there would be fewer of them per unit cross-section. Anything, therefore, which tends to give molecular complexity, tends to give high resistance; hence we see why alloys are generally higher in resistance than the average of their components.

The resistance increases with density and molecular complexity and inversely with the elasticity. Consequently whether a resistance increases or decreases with temperature will depend upon whether the molecular union is weakened at a less or greater rate than the elasticity falls off.

In getting a concept of this we may consider a conductor as analogous to a government department, the different atoms or officials being bound together into groups by valency bonds, the analogue to which is evidently "red tape." The rate at which a given impulse is handed on will evidently depend inversely upon the amount of red tape and the density, or stupidity, of the individual official. The two causes are often confused.

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[1] The writer ventures to suggest that the velocity of very short waves of sound in copper may be found somewhat less than half of that given now for audible tones, while that of lead may be reduced to but one-eighth of its value as given at present.

We must therefore, for solid insulation, get substances which are strongly linked together, of great density, and of small modulus of elasticity. The first is the property which varies most, since density and elasticity vary between comparatively narrow limits.

3. *Conductivity in fluids.*—The nature of the manner in which electricity is conducted in electrolytes has been very thoroughly worked out by Clausius, Arrhenius, Hittorff, Kohlrausch, Nernst, Ostwald and others, and the work of these physicists has led to the linking together of results in a way which is simply marvelous. As the results can be obtained from works on physical chemistry, a very brief resumé is given.

The atoms of a solid are held together by the force of cohesion and driven apart by the hitting of the atoms on each other, due to the fact that they are in vibration, possessing kinetic energy proportional to the temperature. The molecule may also be pulled apart by the cohesive attractions of its atoms for other atoms. Whether a substance is a solid or a gas depends upon whether the fraction:

$$\frac{\text{Cohesive force of atoms for one another} + \text{external force}}{\text{Kinetic repulsion} + \text{cohesive attraction for other atoms}}$$

is greater or less than unity. We can thus turn a substance into a gas in two ways, *i. e.* by increasing the kinetic energy of the atom by heating it, or by bringing it in contact with other atoms, when, if the sum of the terms in the denominator is greater than the numerator, it will dissolve.

We have to distinguish two kinds of linkages in solids, the cohesive force of the atoms for one another in uniting to form a molecule, and the attraction of the molecules for each other. The former generally is stronger than the latter; consequently we may have a substance which on being put into contact with a solvent will have its molecules pulled apart from one another but not its atoms. In the presence of another solvent however, the second term may be sufficiently great to pull apart not only the molecules but also the atoms of the molecules. The substance is then said to be not only dissolved but disassociated. But dissolved substances give an osmotic suction per sq. cm. which is equal numerically to the kinetic pressure which the substance would have if it were turned into a gas at the same temperature and volume as the solution. A number of proofs of more or less validity have been given for this, but it seems to the writer to follow at once from the obvious fact that if we take a solid and heat it and dissolve it, the kinetic repulsion must always equal the cohesive attraction plus the vapor pressure when equilibrium is reached.

This phenomenon of osmosis has been generally treated of as due to pressure and the dissolved substance to exercise a pressure equal to that which it would have if turned into a gas at the same temperature and volume. The writer (in the *Elec. Review*, London, Nov. 27, 1891) pointed out, as above, that the results were better explained by supposing that the solvent took up the cohesion of the solute, and that this got rid of the great difficulty of the disassociation theory, *i.e.*, that solution was generally accompanied by heating. Recently this theory has been put forward by other well-known physicists. Prof. Poynting (*Phil. Mag.*, Oct., 1896) has treated the subject mathematically, and whilst the mathematical reasoning cannot be considered conclusive, as Prof. Poynting himself states, yet, as he puts it, it shows "that it is not necessary to ascribe osmotic pressure to disassociation, but rather to association, or some kind of combination of salt and solvent." I have ventured therefore, in view of this fact, to do what I would not have done otherwise, *i. e.* to substitute my own conception of a suction for that of a pressure, otherwise making no change.

In this way by measuring the osmotic suction we can tell whether a salt is disassociated or not; and it is found that only those salts which are disassociated can conduct electricity. The molecules split up generally into two parts, one charged with positive, the other with negative electricity. These charged parts or ions when placed in an electro-static field, move with a velocity proportional to the slope of potential and to the specific ability of each ion to move among the crowd of molecules of the solvent. Consequently the faster an ion can get along through the crowd of other molecules, *i. e.* the faster it can diffuse, the faster will the electricity be carried, and the greater the amount carried per second for a given slope of potential; also the greater the quantity of electricity carried per ion the greater the current. The total quantity carried will be the sum of that carried by each ion, so that by adding the velocities of the ions we get the total velocity with which the electricity is moving.

The conductivity of a solution is thus dependent upon the following:

1. How powerful the attraction of the molecules of the solvent is for the ions of the solute, for on this depends how much of the solute is disassociated, *i. e.*, how many ions are set free to carry the current.

2. How fast the ions move.

3. What the valency of the ions is.

In designing insulations, the first is the important point. For from it we see that two good insulators mixed do not necessarily make a good insulator. A solid may dissolve in one substance and be an insulator in solution, but in another solvent may conduct quite well.

This is what makes the chief difference between fluid insulators, for practically all the fluids which are not simple elements, like mercury, have very high ohmic resistance, and all have practically about the same dielectric strength. The ohmic resistance of pure water is, according to Kohlrausch and Heydweiller, about one meghom per cubic centimetre, consequently on account of its non-inflammability and great specific heat, its great heat of vaporization and low boiling point, it would be a very valuable insulator for some types of apparatus were it not for the fact that it dissolves almost everything in slight proportions and splits them up into ions. Varnished paper will dissolve in some high resistance oils, forming a conducting solution.

C. *Conductivity in Gases.*—There is much evidence to show that conduction in gases is electrolytic, more especially J. J. Thomson's beautiful work on this subject. Also the fact that in air or CO_2 carbon is deposited on the negative pole, sometimes to the thickness of more than an inch in enclosed arc lamps, according to Marks, while in hydrogen or hydro-carbons in many instances the carbon is deposited on the positive carbon, would seem to favor this view. Also in its favor is Prof. Elihu Thomson's observation of the formation of copper "trees" in incandescent lamps with coppered filament joints. Against this is Schuster's observation that the metallic lines in the spectrum have a fairly high velocity, and also the general appearances of the arc, which looks as if something were going in one direction down its centre and something else back on the outside. Also there is one other phenomenon which looks as if it were convective. This is the fact that if we take a solid carbon and bring it nearer to a similar carbon while the current is passing, the resistance first decreases and then increases. This was I believe first pointed out by Mrs. Ayrton in her admirable paper on the subject. The reason of it has not I believe been given; it seems to be due to a necessity for circulation in the arc. If we have two carbons as in Fig. 4, at 1, the centre part of the current seems to flow all right, but the part B cannot flow unless the + carbon is very hot, and this is only cured by either increasing the current so as to heat the whole carbon up or by reducing the cross-section, as at 2 in Fig. 4. Whether a carbon is cored or not has nothing to do with this increase of resistance on the distance being shortened, as all that coring does is to diminish the cross-section of the carbon, and I have repeatedly found by actual test that the difficulty is entirely obviated by using carbons of × or — cross-section, provided the greatest thickness at any point of the cross-section is less than that of the cored. The phenomenon is evidently analogous to the jumping back of the discharge in a Geissler tube when the electrodes are brought too close together. The theory of this was given by J. J. Thomson, and it was by applying this that I got over the difficulty with the carbons. A true arc can be run from a much lower voltage in open air than is generally supposed when the section of the carbon at any point is not more than $\frac{1}{10}$ cm. thick. On the whole, the evidence seems to be in favor of the belief that both convective and electrolytic discharges take place in air. The whole subject is very fully treated in J. J. Thomson's "Recent Researches in Electricity and Magnetism." There can be, in my opinion, very little doubt but that when a true electrolytic discharge takes place, as it does in a hot flame, the conductivity is proportional to the velocity of sound in the gas, though so far I am not aware that any experiments have been made on the subject. It is possible that in certain cases the elasticity itself may be a function of the slope in the electrostatic field. As the vacuum increases up to a certain point, the dielectric strength decreases, and this point depends somewhat on the electrodes and

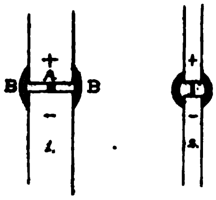

Fig. 4.

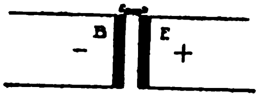

Fig. 5.

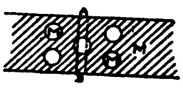

Fig. 6.

voltages, and has led to the amusing result, that on the average every two years the discovery is announced that a vacuum is a good conductor. Above this, the discharge appears to get more and more convective, and a fact may be stated which I have not seen mentioned, *i. e.*, that the largest quantity of X-rays is not got from a tube unless the path of the positive particles back to the cathode is blocked up as much as possible. An experimental tube made by Mr. Meadowcroft for the writer last spring, in which there is a small tube running from the back of the anode to the back of the cathode which can be blocked up by tilting it, shows this very nicely.

As regards the electrolytic discharge, this can only take place when the gas is disassociated by heat or by a strong slope of potential. To the convective discharge the same remarks apply as to the convective discharge in gases. At ordinary pressures the only gases which allow a discharge to pass easily are helium, argon and possibly that unknown gas whose spectrum we see in the light of the Aurora Borealis. Helium, as shown by Ramsey, behaves at ordinary pressure much as air at low pressure, and a spark will jump through it for about thirty times the distance it will through air at the same pressure, when the pressure of both approximates that of the atmosphere.

Having got rid of the theory which was necessary in order to give opportunity to condense later, and which has led me to wonder if it were ever possible to find the pleasing mean between the conciseness of the Carpenter and the discursiveness of the Walrus, we shall take up the practical part of the subject.

HIGH RESISTANCE INSULATION.

In laboratory apparatus in many cases, for instance with electrometers and resistance boxes, we need as high ohmic resistance as it is possible to get. Here however we are met by the fact that the two substances most commonly used, *i. e.* hard rubber and glass, are among the poorest insulators known for this class of work.

Rubber is very objectionable from the fact that whilst it presents a nice bright appearance when new, it contains sulphur and is very easily oxidized, especially when exposed to light. A film of sulphuric acid is thus formed on the surface, and if the tongue be applied to a piece of rubber which has been in use for some time the taste of the acid is very strong. I have seen the top of a Wheatstone bridge, supposed to be capable of measuring accurately to one part in 5000, in which the total length exposed to leakage, divided by the average distance between which leakage could take place and the average voltage was only .008, with the top so acid that the tongue could hardly be allowed to touch it.

As a rule it is very hard to remedy this; rubbing the surface does no good as the acid extends in to some distance. Rubbing with cigar ashes is advocated by some, but I should fancy it would be almost impossible to remove the last traces of alkali. The method used by the writer is to steep the rubber in warm 10 per cent. caustic soda, then in warm distilled water, frequently renewed, then drying in the dark quickly and rubbing with pure paraffin, treated as described under paraffin, then polished while warm. This does good for a time, until the paraffin takes up dust.

For rods, a good way is to treat as above and coat half an inch thick with paraffin; then run over the rod with a wooden die and cut a thread in the paraffin. Run over the thread about once a month, and good results will be obtained.

With bridges, however, it is impossible to remove the top, and the only thing which can be done is to keep them covered up from light.

Rubber has also one other disadvantage, in that it does not show dirt, and where rubber comes in contact with copper it is apt to rot.

Glass is very bad because the alkali in it has a great affinity for moisture. The alkali is slightly soluble, and hence it is the custom with analytical chemists to boil all beakers used in exact work for several days before using, so as to get the soluble alkali and silica out of them. When possible this should be done with the glass of electrical apparatus. Another very serious trouble is that the angle of contact between water and glass is zero, so that when a drop of water is placed in the middle of a pane of clean glass it immediately spreads all over it in a thin film. This method is used by chemists to determine when a glass is clean. Nothing much can be done with glass but to keep it dry. Sulphuric acid is generally used, but it sometimes, if allowed to get dust in it, gives off vapors which condense on the sides of the apparatus. This, however, does not often happen.

Evidently we need some substance of high ohmic resistance and one which water will not wet. Boys, who has earned the thanks of electricians for his happy discovery of an almost perfectly elastic fibre, has given us also, as he himself has pointed out, such an insulator in quartz. Dip a thread of glass in water and lay it between the knob of a charged electrometer and the ground, and the leaves close almost at once, the whole fibre being covered with a film of water. Treat a quartz fibre similarly and the water slides off it, or remains in alternate big and little drops, each separate from its fellow, and the insulator is apparently as good as the air itself.

Quartz should therefore be used as much as possible in electrical instrument work. It can be melted in a powerful gas flame furnace and though it can never be melted down free from small bubbles, these make no difference except in appearance. It is however, possible to obtain glass which contains no alkali, and resembles quartz in that it is not wet by water. Such a substance is Faraday's borate of lead glass, as he himself points out. This is however too brittle for most work, but by an admixture with silica a glass could no doubt be made which would be perfectly satisfactory. If some glass manufacturers would take up this question and furnish us such a material for electrical instruments, the greater part of the present annoyance met with in making delicate experiments would vanish. It would not leak, would show dirt, could be readily cleaned, and would be free from one of the great disadvantages of rubber, *i. e.* a large coefficient of expansion, which is always making trouble by bending terminals of resistance coils, thus changing their value and sometimes opening the circuit.

It is also probable that a fine grade of porcelain would be a great benefit to the electrical profession, if coated with a good non-alkaline glaze.

For insulating the coils of resistances it is doubtful if we have any good solid material. For paraffin cannot be used, as its expansion and contraction are so great that large pressures are put upon the wire and the resultant strains change the resistance. It might be easy enough to prevent the strain on the first solidification in a way similar to that devised by Rowland for cementing flat mirrors without buckling them, *i.e.*, by mixing a little glycerine with the beeswax; the glycerine not dissolving in the beeswax makes it act like a viscous fluid, *i. e.*, deform under the action of infinitesimal forces in time. The glycerine however finally works its way out like zinc in a resistance alloy, (as first pointed out by Mr. Weston), and if a similar method were used with the coils, it would still be subjected to strains on change of temperature. Another objection which has been made in England is that paraffin absorbs moisture. It is possible that this is due to the dissimilar methods of producing American and English paraffin as I have never had to complain of this, except of course when cold paraffin was placed in saturated moist air. The insulation resistance of paraffin seems however to be markedly increased by the treatment mentioned below. The great objection to paraffin is its tendency to collect dust. Shellac has been recommended, and since the coils are in the dark the material will oxidize but slowly, and if care be taken to use pure alcohol for a solvent, and not denaturized spirit, (which sometimes contains conducting impurities) has a very high resistance when dry. Some forms of Japan lac seem to remain flexible permanently, as for instance the sample *a* (composition unknown) which is ten years old.

Oil is sometimes used for resistance coils, and this is without doubt the best method, since the great point in the use of resistance coils is to know their temperature. The writer's experience with manganin and constantin as practical laboratory standards has been unfortunate and he has hence decided to use only standards of pure lead run into glass tubes and kept in water. The reason is that, other things being equal, the most sensitive Wheatstone bridge is that which takes the greatest current without appreciable heating, and in the ordinary form of resistance coil a very small current will heat the interior up to such a temperature as to alter the value. Moreover, if the coil is of a material not affected by such changes of temperature, it (with our present alloys) will have a larger temperature coefficient, and as the temperature of the interior of the coil is not known this introduces another uncertainty. With the oil mounting, however, this is all done away with, and pure oil has a very high resistance for low voltages.

For condensers and induction coils it is not only necessary to have materials of great ohmic resistance and of great dielectric strength, they must also be perfectly pure and free from admixture. For the first two properties there is nothing so good as paraffin, when properly used, all compositions such as beeswax, (cerotic acid), etc., being quite inferior in both respects. Paraffin, and what is practically the same thing, pure ozokerite, will stand, according to the tests of Mr. Chesney, which I had the pleasure of witnessing, at the rate of 500,000 volts per inch. This I have confirmed up to 60,000 volts, alternating. Most substances, such for instance as glass, are at once cut out from consideration from the fact that they have too much electrical absorption, and heat when subjected to a fluctuating voltage.

We must have an electrically homogeneous dielectric, *i. e.* one of the same specific inductive capacity all through. This is for two reasons. First, because, if we have a dielectric A between two charged conductors, the introduction of a dielectric of greater specific inductive capacity, even if of infinite dielectric strength and ohmic resistance, will cause A to break down. To take a numerical case,—suppose we have two plates, 1 cm. apart, and attached to the terminals of a 10,000 volt A. C. dynamo. (Fig. 5.) Suppose the dielectric, air, to support 50 per cent. more than this pressure. Introduce two plates of glass of $K = 8$, each $\frac{1}{4}$ cm. in thickness. Since the voltage divides itself up inversely to the capacitance, we will now have 8,889 volts between C and D. This being at a rate of 17,778 volts per cm. and as it only supports 15,000, we will get a spark between C and D at every reversal of the voltage, which will quickly heat the glass and make it conduct. The full potential of 10,000 will then be between C and D, and a regular arc will form. Thus we see that the introduction of a good insulator will, in all cases where an intermittent or alternating voltage is used, have the paradoxical effect of weakening the insulation, unless the whole space is filled up with the material. This weakening is not generally apparent at once, as the spark takes some time to eat its way back, and this explains why many induction coils only last for a few years of operation.

Another cause is that treated of by Poisson, Clausius and Maxwell.[1] This is, that layers of dielectrics of different capacities and resistances show electrial absorption, and this theory has been proven experimentally by Muraoka, who showed that by taking two fluids, neither of which showed absorption, a layer of one on top of the other did do so. Maxwell treated the general case. It has, however, been treated in a more specialized way by A. Hess in *La Lumiere Electrique*, Nov. 26, 1892. In this paper are brought out the following points:—

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[1] "Elec. and Mag.," vol. 1, chapter x.

1. A dielectric, as in Fig. 6, containing conducting particles of water, for instance, may be considered as an arrangement of condensers and resistances in series and shunt with each other. Two cases, shown in Figs. 7 and 8, are worked out, and Fig. 9 gives the curve of charge in the cases of Fig. 7; E is the voltage on the condenser part, and E′ that on the condenser and resistance.

2. A condenser can show large residual charge, though its true ohmic resistance is infinite.

3. With dielectrics showing absorption, there will be found some discharge time at which the amount of discharge will be constant at all temperatures.

4. Why in some tests insulation seems to be lower with higher voltages.

5. Why the presence of conducting particles increases apparent capacity.

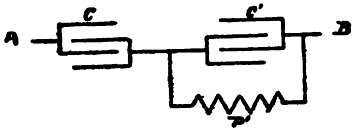

FIG. 7.

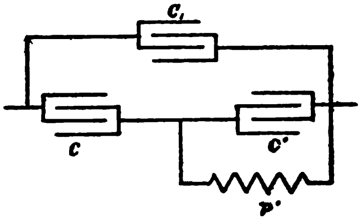

FIG. 8.

6. That to get true ohmic resistance of most dielectrics, voltage must be kept on for a long time, even for days.

7. Why Siemens' method of taking the rate of loss of charge by electrometer does not give correct results.

8. That specific inductive capacity of such dielectrics can only be determined by rapidly alternating currents. This possibly explains an effect noticed by the writer many years ago, *i. e.* that an A. C. static wattmeter immersed in water did not give anything like the torque it should have if the true value of K for water were 80.

9. The importance of getting out the last traces of water in gutta-percha and paper when used for cables.

As mentioned, this author considered a simple case of Maxwell's general theory and proved the above results by making actual measurements on condensers and resistances connected up so as to correspond to a simple case of a dielectric of high resistance with conducting particles in it. This paper should be read by all electricians, especially those concerned with cable work. I would like to speak of this subject more in detail, but for lack of time will only add that most of the conclusions in that paper have been confirmed by me, and that some which had been arrived at independently were seen to be in perfect agreement.

It is this absorption and the consequent losses which make glass useless as an insulator against high A. C. voltages. In some experiments made by Messrs. Stanley and Chesney which were shown me, the glass plates of the condenser when on an A. C. voltage, (though thick enough to have stood ten times the D. C. voltage) after a few moments got hot, sparks could be seen passing inside the glass, and the plates finally broke down. Glass is not homogeneous, as it is made up of a number of substances, some much better conductors than others, and of different capacities and all stirred together but not dissolved. This is shown by the

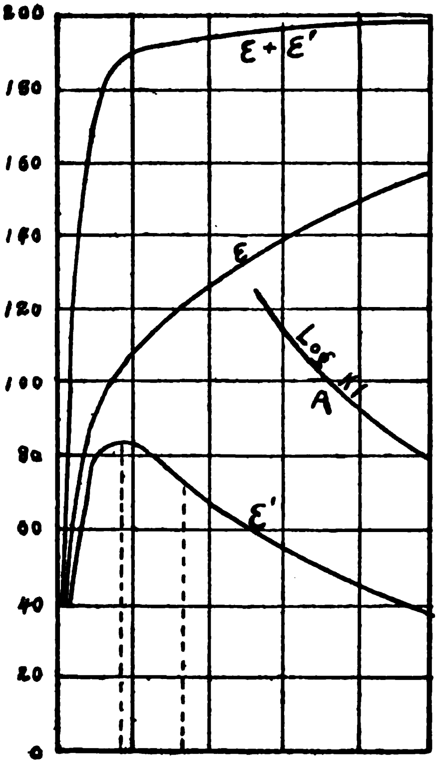

Fig. 9.

care which has to be used in getting glass homogeneous enough for optical purposes, if even having, as has been told me by Mr. Brashear, to be kept perfectly horizontal when annealing, as the heavier parts tend so much to sink down to the bottom, even when the glass is only plastic, that the only way to do is to keep the levels of different density parallel to the surface of the disk so that their effect on the light will be as equal as possible for all rays. Otherwise one side of the lens would be of heavy glass and the other light, while at present it is so arranged that one face is dense and the other light. Mica is much less objectionable, especially if its cracks are filled up and it is well dried. Paraffin when properly treated makes very good condensers. The old method of piling together pieces of paraffin paper and tin foil and then pressing them, left much air and moisture inside. This produced large electrical absorption and gave large capacity. Messrs. Hutin and La Blanche were the first to discover that good condensers could be made by heating such condensers till the moisture and air were expelled. Their results[1] showed that the specific inductive capacity of this more homogeneous dielectric could be reduced from 8 to 2.5. I have myself found it come down as low as 2. They then found that the same results could be obtained by heating the paper before making up the condenser. Since then, this method of forming condensers by heating them to expel moisture, air and acid has been used quite generally, with some modifications and improvements resulting in a shortening of the process.

It may be said as a general rule that the capacity of all substances showing absorption may be reduced by this treatment, if the heating be kept up long enough. A great many oils, for instance, are given high capacities, but I have found that in many cases this can be greatly reduced by this method, and that the slight remaining excess of κ over that called for by Maxwell's theory can be almost entirely removed by removing the free fatty acids, mucins, etc. Oils tested by me were olive, castor, linseed and cottonseed. All these have very high insulation resistance and low specific capacity when so treated and purified but they soon lose this again when exposed to air. It is evident, therefore, that the anomalous results obtained by Hopkinson and others

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[1] *La Lumière Elec;* July 25, 1891.

were due, in some cases at least, to impure material, and such results must be considered as forming a strong proof of the correctness of Maxwell's theory.[1]

But when the substances are not themselves solid, but viscous, they must have a mechanical backing. For this pure cellulose is generally used. Pure cellulose contains some loosely combined moisture. Consequently it can exist in two states. Dried below 100° C. it decreases its specific inductive capacity very much, and has very high resistance and is flexible. Kept above 100° C. for any length of time it loses some of its combined water, has a much higher ohmic resistance and its specific inductive capacity sinks to 1.9 or 2. It however becomes very brittle, and even though the temperature be only a few degrees above 100 C. it finally cannot be bent without breaking.[2] (This brittleness must be carefully distinguished from the so-called rottenness which cotton fabrics get when dipped in linseed oil and dried. The fact that cotton tears easily in such a condition is due to the same cause as makes a wire mosquito netting tear when painted, *i. e.* the fibres are stuck fast by the varnish and cannot help one another. This can be proven by removing the dried oil when the fibre will be found to have nearly its original strength.) In this condition it is best suited for making condensers. The paraffin itself is greatly improved, as was pointed out by Hutin and Lablanc, by heating to about 140 C. Three hours heating I have found satisfactory. The dried paper, immediately on removal from the oven, is plunged into the hot paraffin, so as to protect it from absorbing moisture. The condenser is then made up and boiled for several hours, so as to remove the air. This boiling method was described in a recent patent as a novelty, but it was used by Mr. Chesney at Pittsfield in 1891.

A condenser so made, if perfectly pure cellulose is used (perfectly pure paper is used in practice), and with pure paraffin, will stand 250 volts per thousandth of an inch when the dielectric is

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[1] A rule connecting this effect with the sign of the Kerr's electrostatic optical effect has been given by the writer.—*Elec. World*, Jan. 2, 1897.

[2] It is for this reason that electric apparatus should never run above 212° F. As engine rooms sometimes reach 130° F., this means a limit of 82° F. or 45° C. above the air. But when this is taken with thermometer, the rise indicated by the thermometer should be much less. With the introduction of high speed rotary engines we may expect to see much higher field strengths, hotter armatures and different insulation, say armatures with copper bars enamelled in the iron sheets.

less than .01 inch, and at a higher rate for greater thicknesses, when the effect of small defects in one sheet of paper is not so serious.

Practically the same remarks apply to the making of induction coils. Here, however, we meet with the great difficulty that the paraffin in cooling is sure to shrink, and will leave hollows inside. The way to get over this is to construct the coil so that when cooling the shrinkage will take place outside, just as if one were making a casting of some metal having great contraction. The coefficient of adhesion also should be less between the walls of the mould and paraffin, than between the wire and paraffin; also the outside should never be let harden first, as then, of course, a hollow space is left inside. Another precaution is to expel all gases by heating the paraffin for some time above the temperature at which the coils are to be boiled. The coils should be boiled above 100° C. for some hours to drive off the loosely combined water. This destroys the mechanical strength of the cellulose, but as the whole coil forms a solid mass this is of no great consequence.

Silk should never be used where high insulation is required, as pure cellulose dry and boiled in paraffin is so much superior to it that there is no comparison. With pure cellulose, coils with only 1700 feet of wire per inch of spark stand perfectly, *i. e.* the spark may be five times longer than the coil, In ordinary use, coils having a spark length 3½ times that of the coil have been run for long periods with no break-downs.

As regards oil insulation for ordinary induction coils, the writer has not had sufficient practical experience. I believe, however, that very good results are obtained. With regard to the Thomson high-frequency coil,[1] there is no question of the efficacy of oil there, especially with regard to ease of repair. As is well known, however, the oil and coil should always be heated above 110° C. for some time if the best results are to be obtained. A very curious increase of insulating power for high frequencies in oil has been noted by Elihu Thomson, who has suggested that it might be due to inertia of the molecules of oil. To test this, one of the writer's students, Mr. Bennet, constructed a two-phase high-frequency electrostatic field. Though insulators placed in this rotated even when placed within a $\frac{1}{16}$ inch glass flask, the

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[1] Popularly known as the Tesla coil, on account of his having brought it into prominence through his use of it in his lectures; though it was invented and first described by Elihu Thomson.

effect was found to be due to air currents, and when these were eliminated no movement wàs obtained, so that the cause of this effect is still unknown, and it is doubtful if true dielectric hysteresis has ever been observed.[1]

So far as Mr. Chattock's experiments and the experience of the writer go, there is not a great deal of difference between the dielectric strength of different substances. It is probably related to the tensile strength. As mentioned previously, the writer[2] pointed out that there was strong evidence to show that the tensile strength of a substance was due to the mutual attraction of charges on the atoms and that the observed values agreed well with the calculated and followed the same law. Some time later Chattock[3] in a very interesting and able paper showed that, as the results of his experiments, the dielectric broke down when the slope of potential was great enough to pull apart atoms having charges of the same dimensions as the ionic charges. This was shown for gases, fluids and solids, and forms a very interesting—and, I believe, independent—corroboration of the writer's electrostatic theory of cohesion. Consequently, the nearer the atoms are together and the greater their rigidity, the greater also their dielectric strength.

Chattock's experiments give for solids and fluids—

SUBSTANCE	VOLTS PER CM. FOR BREAKING DOWN.
Glass	919.000
Water	1.050.000
Oil	980.000

which agrees well with the theory.

From the above it will be seen that if the materials are pure, and ohmic resistance is of not much importance, a compound having its molecules held together tightly will have a good dielectric strength for D. C. voltages.

This paper is already so long that I cannot touch in detail on the question of cables. There are also other papers in existence written by men better equipped for the task. I had intended saying something about what Siemens has called the "absurd

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[1] Righi some time ago published a paper in which he claimed to have observed dielectric hysteresis, and gave a law for its amount. Since Mr. Bennet made his experiments, however, Righi has retracted his statements, having found the effect due to other causes.

[2] *Elec. World*, Aug. 8 and 22, 1891.

[3] *Phil. Mag.*, Dec., 1892.

craze for high insulation resistance," but the fact is now generally recognized, except by inexperienced engineers, that the best cables are those of medium ohmic resistance. I will only mention two methods which have occurred to me as feasible for certain purposes. One is based on the fact that the dielectric strength of air, as shown by the experiments of J. J. Thomson and Peace increases very rapidly with the pressure at 90 lbs. per sq. inch being equal to that of a good quality of rubber. A similar plan, though not requiring any very large pressure, is due to Mr. Westinghouse, who thought of employing it four or five years ago in Philadelphia. The second occurred to the writer on reading Elihu Thomson's article on the use of liquid air as an insulator. It is this: Since ice at only 12 below freezing has a specific resistance of over 1000 meghoms, *i. e.* as good as some brands of insulation, why not make the conductors hollow, lay them in a trench filled with water, pass cold brine through the pipes, use the brine for cooling houses, making ice etc., and let the frozen water act as the insulator. A rough calculation shows that this is commercially feasible, even neglecting all sources of profit from the furnishing of the brine, (*i. e.* if it were used only for cooling the pipes.) After making all allowance for friction of fluid, cost of power, etc., the balance comes at the right end, if the line is always fully loaded.

The question is sometimes raised, whether we can ever hope to have a non-inflammable substance which shall be elastic like india rubber. The probable cause of the elasticity of rubber is known, [1] and it would seem as if there was no reason why such a substance should not be prepared. All we have to do is to coagulate one substance in the midst of another. In fact we have at present in tetrametaphosphate of sodium such a substance, elastic as rubber, transparent and tough, and when pure a good insulator. It would be an admirable material if it were not for the fact that the elasticity is due to water, and when this dries out it becomes brittle.

As regards an organic artificial rubber, I have very little doubt but that it will be made as soon as it is understood by chemists that its properties are due to structural and not chemical causes.

Armature windings.—The present methods of using mica leave little to be desired. The writer might mention, however, one novel method he used in a case where very heavy currents

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[1] Molecular Physics, Franklin Inst., Sept. 18, 1896.

were to be carried. Asbestos and silicate of soda, as is well known, form a good coating. which is however, poor mechanically. The armature bars were wrapped with asbestos string and then coated with the silicate. This made when dry an extremely firm covering which could only be removed with a hammer. Though at first a bank of 100 lamps could be lit up through the insulation, after a little running it dried out to quite a high figure and the machine did good service, at one time running several hours as I am informed on good authority, under such an overload that the carbon brushes were red hot.

In cases where cloth is to be treated we have a very different question. There are two ways of using cloth, 1st, as a backing merely, by coating it on the surface with some substance which is supported by it, as plaster on lathing. Many substances work well in this situation but the fact that little tubes of cellulose are very apt to stick up through the coating, as was pointed out to me by Mr. F. R. Upton many years ago, and that if moisture gets in at the edge it spreads all over, renders it not the best kind of insulation. Rubber is sometimes applied in this way to cotton tape, but though of very high resistance and insulation at first it rapidly deteriorates. In general it should be said, that where a permanent result is desired rubber should never be used unless kept in the dark and out of contact with air. If these precautions be neglected the life is very short. The other method is to saturate the whole cloth with some substance which will penetrate every crevice, but when this impregnating substance has solidified it must continue to fill these crevices and capillary tubes. For this reason no substance which is dissolved in anything else can be used. If for instance we try a varnish dissolved in alcohol, it will be found that the strength of the solution in the capillary tubes is much smaller than outside, for the same reason that sea water filtered through sand becomes fresh.[1] Consequently on drying these capillary spaces are not filled up and let water in. Therefore unless we adopt the first method and plaster the insulator on thickly and deep enough so that it does not matter whether the support insulates or not, we must use melted solids or drying oils. Unfortunately but few solids which melt are *elastic*, since this elasticity is obtained by a structure which is destroyed by melting, and those solids which melt into thin liquids and remain *flexible* when solid do not preserve this property ex-

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[1] J. J. Thomson, "App. on Dyn. to Phys. and Chem.," p. 190.

cept within narrow limits of temperature, as can be easily tested by holding under a cold water tap and striking the specimen sharply. Soft paraffin can be used in some cases if the cellulose be well dried and thoroughly saturated. The asphalts cannot as a rule be used, as they never get sufficiently fluid on melting. There is, however, one notable exception: uintaite or, as it is commercially called, gilsonite. This substance I found many years ago had the peculiar property that, when melted, like paraffin or oil, it would pass into the pores of cellulose or cloth. Having a very high melting point, nearly 300° if I remember, and mixing perfectly with paraffin in all proportions, it gives mixtures which are admirably adapted for induction coil work as these compounds can be made to have high melting points and to penetrate a coil thoroughly. I also some years later, in 1891, used this material in combination with linseed oil for transformers, the process at first proposed being boiling in vacuum, but it was found that even without this saturation was complete. I understand that this method is still used, though modified in form, by the company for which I first devised it. Of the drying oils, with the exception of some foreign oils as Chinese wood oil, and an African oil whose name I cannot recollect or ascertain, linseed and the drying nut oils are the best. Linseed oil has the remarkable property of expanding on drying. This enables it to fill up all pores. Its durability is evinced by the good condition of old oil paintings. The varnishes crack and go, but the oil remains. Its insulation is not injured up to very high temperatures at which shellac, rubber, etc., would be worthless. This material was used a great deal by the Edison company in its early days, but it often broke down. The trouble was traced to the lead drier, and after many experiments Mr. Marshall who had charge of this work finally settled upon the use of pure raw oil. This gave excellent results and was long used but took some time to dry, and the writer finally, after many tests found that borate of manganese drier got rid of the trouble, while as is well known, it gives a very quick drying varnish. This was used by the United States company in Newark on their machines, with the result that in 1890 after use for a year, the foreman reported only two armatures so treated as returned for repair, (they were injured by lightning) and no fields. This material was also used by the Stanley company for transformers. Another advantage of this borated oil is that it always retains a slight stickiness, and so gives a good joint when wrapping around wires, etc. Many substances so used are not sticky and let moisture in through the joints. Where a smooth surface is required, it is readily obtained by dusting on a little talc, a method first suggested, I believe, by Mr. Edison. It can also be given a coat of Japan on the outside. Varnish gums should never be used with linseed oil, as they are brittle, and the dried oil is only just flexible enough. Consequently when the oil has dried the resultant varnish is always very brittle. A temporary elasticity is given at first by the fact that when the solvent has dried off the oil is still fluid and undried, and as the varnish gum keeps the air from getting at it rapidly, it sometimes remains flexible for a year. Such mixtures also crack when cold.

Sample *c* is a specimen of borated oil saturated cloth, which is now between eight and nine years old. It will be noted that it is still fresh and flexible, and a recent dielectric strength test showed up very high, 15,000 volts if I recollect. The pure raw oil is boiled at about 200° with ½ per cent. of borate of manganese for several hours till it begins to be thick.

Non-inflammmable materials can be made, as I have pointed out elsewhere, by taking out the hydrogen atoms of hydrocarbons and substituting chlorine. Even paraffin can be thus treated if kept warm, and first turns to a fluid and then to a solid. At one time it seemed as if this process might be valuable, but the use of enclosed conduits has done away with the greatest source of danger from fire.

I will conclude by describing a couple of devices which I have found useful in preventing insulation from being spoiled. Soldering acid, as commonly used, is a solution of chloride of zinc. If this falls on cellulose it turns it to a paste. It never evaporates and always takes up moisture from the air, and will gradually eat its way through quite a thickness of insulation. Whether it is acid or neutral makes no difference so far as its action on the insulation is concerned, though the neutral solution does not corrode the wire. Rosin has the disadvantage that it is not a fluid and is clumsy to handle. I have found that by shaking up powdered rosin in very strong ammonia, an ammonia soap is produced which works well in most cases. The ammonia dissolves the copper oxide and evaporates afterwards, leaving the powdered rosin, which is an insulator.

Apparatus can be protected from overheating by putting in the apparatus a small glass tube filled with carnauba wax. This melts near the danger point, but remains quite hard up till then, so that by imbedding a spring and contact in the wax, when the apparatus gets too warm the wax gives, and the spring expanding causes a short circuit which blows the fuse.

The largeness of the subject must be my excuse for the fragmentary nature of this paper. After I had begun it, I found I had made a mistake; what I should have undertaken was to write a book. I trust, however, that some of the points I have developed may prove of interest.

DISCUSSION.

THE PRESIDENT:—I can only repeat what I said before, that it is most unfortunate that the author was unable to be present. It strikes me that there is no very direct connection between the first part of the paper, which is theoretical, and the last part which is extremely practical. I fail to see anything but a connection in name between the two. But there are a number of very significant points in the theoretical portion and a number of practical ideas in the second part, based on considerable experience. The first part seems to be somewhat empirical, a sort of a groping, as it were, for some formula which would give an indication of the conductivity of substances. But that is always the way that science progresses, by laying down somewhat empirical laws which are afterward more clearly understood and appreciated. There certainly are a number of important physical facts that are almost within sight and many of them would appear to be more or less touched by these formulæ.

I believe Prof. Franklin had read this paper and considered it before the meeting. I will call upon him to discuss it.

PROF. W. S. FRANKLIN:—I would say, Mr. President, that my estimate is very much as you have expressed yourself in regard to the relation between the first and second parts of this paper. I am very much impressed with the desire of Professor Fessenden to arrive at some theory which will enable him to classify and systematize our knowledge of the phenomena of conduction and so on, and a great deal of the matter in the first part of the paper is entirely new to me. There is one thing, however, which I would like to say in connection with the molecular theory in its application to physics. You will notice that the first part of the paper is based wholly upon the molecular theory, and what I wish to say is this, that the most active part of physics at the present time, namely physical chemistry, has practically discarded the molecular theory altogether. You never hear a physical chemist talking about molecules unless he is finding fault with somebody else who has been talking about them. The only things that physical chemists tolerate in the fundamentals of the subject are those which can be either felt or seen or taken hold of or measured, and I have at times thought that this tendency will gain the upper hand, and that we will in time drop the molecular theory entirely. I think it would be a very good thing if it could be dropped. Notwithstanding that fact, it seems to me that the author has shown some very remarkable relations between the mechanical properties of substances and their electrical properties by the help of the molecular theory.

In connection with the matter which is discussed in the opening paragraph, namely the two distinct properties of an insulator, there is one quite striking illustration of that which perhaps may be of interest.

Electrical insulation, or the prevention of electrical motion, is analogous to the mechanical operation of fixing bodies by ropes and beams to prevent their motion; and, considering the materials which are used as insulators, it is very much as if we had only molasses or pitch to make our ropes and beams of. If we had only pitch to make ropes of, there would be two very distinct items of strength. If you wished to subject a pitch rope to a given stress you would need to consider: First, at what rate the rope would lengthen. This rate of lengthening multiplied by the stretching force would give the rate at which energy would be continuously dissipated in the stretched rope.

Second, whether the given stress would be sufficient to snap the rope in two.

We have thus a complete mechanical analogy of the two items of strength of insulators. In one case the insulator gives way continuously under the electrical stress and in the other case it breaks to pieces.

There is one other point in this first part, which, as it occurs to me, might well be mentioned, and that is the relation between the conduction of sound or the transmission of sound in substances and that of electricity. Of course when I first read the paper, it struck me that the two things were so entirely different that you could not conceive of any relation between them at all. Sound has a definite velocity, while we all know that electricity has no definite velocity through a substance. But that really is not an essential difficulty when you think about it, for this following reason:

In the first place the transmission of sound through a substance is essentially identical to the action which we call stationary waves, so that the conception of velocity of transmission is not inseparably connected with the mechanical movements which we call sound. In the second place the enormous rapidity with which an electric current spreads along a wire is known to depend upon wave motion (ether waves) in the medium surrounding the wire, while the movements at a point in a wire which constitute the conduction of the current at that point may be sluggish movements of the small parts of the wire itself of a character similar to the motion which constitutes stationary sound waves.

I am not able to say much concerning the practical part of this paper except that I have been very much interested in it, and that it seems to me to show that the author has had a great deal of actual experience in the matter of the properties of insulators. I may say however that I have had considerable experience in the making of galvanometer coils using paraffin, and boiling in vacuum, and this method seems to get rid of moisture so much better than any method that I have ever tried that I am surprised to find that Professor Fessenden has tried the method and discarded it. It may of course be unnecessarily complicated for many purposes, but it seems to me that it would be the very best method for treating induction coils and transformers.

THE PRESIDENT:—Is there any further discussion on this subject?

PROF. FRANKLIN:—It seems to me that there are two extremely valuable suggestions that Professor Fessenden makes in this paper, one is in regard to the possible discovery of a kind of glass which would be free from the insulation defects of ordinary glass, and the other is in regard to the great importance of in some way managing it so that a man who wishes to make a test and is willing to put a great deal of time in making an accurate test can get pure material to work on. I suppose every one here has had difficulty in that respect. I myself have put in simply an enormous amount of time in testing, for example, the magnetic properties of iron, and of course as you all know it is almost impossible to know what kind of iron it is you are buying. You get a sample of wire and the man you buy it from does not know anything about it, and the man he buys it from perhaps does not know anything about it, and if you could possibly trace it back through two or three steps you might come to the manufacturer who could perhaps tell you a little about it but will not take the trouble, as a rule. But the getting of pure materials for the tests which are being carried out in great numbers all over the country seems to me to be a thing which is of extreme importance and Professor Fessenden's remark ought to be taken note of and acted upon in some way or other. It seems strange that we should annul the value of work which is costing the country literally thousands of dollars per day, by neglecting this fundamental matter which would cost almost nothing at all!

DR. PUPIN:—Mr. President, although rather late, I think that a few words should be added to this voluminous paper. I think that the first part, as you yourself have observed, has hardly any connection with the second part. It is unnecessary as far as the appreciation of the second part is concerned. It reminds me very much of the proceedings of a certain number of ladies forming a literary club One of the members is appointed to deliver a lecture on something which is as a rule very advanced indeed, and usually very obscure and very uninteresting. But fortunately it is always relieved by a nice supper afterward, and the hostess ordinarily does not neglect the quality of the supper, because without the supper the lecture would not draw. So scientific writers who have something very important to communicate, something really very interesting and enjoyable, will sometimes preface that by something that is not very interesting or enjoyable.

There is no doubt that many among us have thought a great deal about the purely theoretical side of conduction. There is nothing perhaps in the whole range of the science of electricity which is so little understood as the conduction of current What is the process that is called the conduction of the electrical current? Who has any definite idea about it? I do not think that Maxwell has ever expressed a definite opinion on the subject at all. In fact, the theory of the mechanism of conduction has never been attempted until within the last few years, and then it was attempted in consequence of the marked advances which have been made in physical chemistry. There is no doubt that the conductivity of a salt solution is very intimately connected with its degree of dissociation, so that if you know the osmotic pressure or the vapor tension depression of a salt solution you can by indirect method calculate its conductivity, starting, of course, from the hypothesis that the conductivity is due to the dissociated molecules. Then a great deal has been done on the conduction of current through rarefied gases by the beautiful experiments of Prof. J. J. Thomson in which he showed that a vacuum tube will act as a screen for electric waves, etc. Now in all these cases we cannot help being led to the conclusion that the mechanism of electrical current consists in the carrying of electrical charges, by the dissociated ions of the gas in one case, and of the salt in the solution in the other case. Whether we have a right to infer from this particular class of conduction that in the case of metallic conductors the conduction takes place by a sort of dissociation or not, remains to be seen. I certainly think that we have no right so far as experimental data at present are concerned. A generalization of the kind was suggested by Prof. J. J. Thomson in his book on "Recent Researches in Electricity and Magnetism." Now whether the electrical mechanism of conduction be a sort of electrolytic convection or not I do not really see how the coarse mechanical properties of a substance, like elasticity and density, can have any direct connection with electrical conduction. To be sure these empirical formulæ which Prof Fessenden has given are very suggestive. But I do not think we ought to take them *au serieux* They are simply interesting empirical formulæ and not anything else, and I do not think Prof Fessenden intends that they shall be taken in any other way than simply as suggestive formulæ. They serve to assist our memory in remembering the electrical properties—the electrical and physical constants of materials.

I cannot say that the author has always been entirely correct in his statements of the opinions and theories of former physicists It is too late now to go into a close discussion of this matter. But one statement seems to me to be very much out of the way, and that is the statement on page 131 where he says: "The electric conductivities are in the same ratio as the "velocities of very short sound waves, being thus analogous to "Maxwell's law for the velocity of light in insulators, in that "the velocity varies with the periodicity." *In that the velocity varies with the periodicity*—now, as far as I remember, Maxwell has never given that law, and in fact Maxwell's theory is incomplete in this very point, in that it gives the same velocity for all periodicities. It is only due to recent advances in the theory of electricity that the dispersion of light has been explained on the basis of Maxwell's theory. Dispersion of light is possible only if different periodicities travel with different velocities. So that I do not see where Prof. Fessenden has found that in Maxwell's theory. That seems to me to be an entirely erroneous statement.

I think the practical part of the paper is most excellent. It shows that the author has had a very large experience in the handling of various materials, of conductors and non-conductors, and although I think that to most of the electrical engineers who have had considerable experience in research work, all these statements will not be new, still I think it is very useful to have all these experimental data classified and recorded as something to which we can refer. I think, therefore. that it is a very good thing to have in the TRANSACTIONS a few pages like these where valuable suggestions concerning the properties of materials are recorded in a systematic way. For that part of the paper most of us, I think, feel as I do, that we ought to be very grateful to Prof. Fessenden.

[Adjourned.]

[COMMUNICATED AFTER ADJOURNMENT BY REGINALD A. FESSENDEN.]

I regret that an important business meeting rendered it impossible for me to personally present this paper before the INSTITUTE, but I take the opportunity to touch on some of the remarks made during the discussion.

First, with respect to the connection between the different parts of the paper, I would say that this is much more close than appears to have been appreciated; in fact, it is almost too obvious to require mentioning that a knowledge of the theory of insulation requires a knowledge of the theory of conduction. Insulation is one of the most important points in electrical design, but I have no hesitation in saying that there are not more than one or two companies in the United States whose insulations are worth more than so much bare cotton cloth after two years' service. By this I mean that if a piece of apparatus be taken after one or two years' use and put in a box, and the bottom of the box flooded with water, the insulation resistance of the apparatus will begin to go down and in a short time it will fail to pass a voltage test, thus showing that the insulation is no insulation at all, properly speaking, but merely a mechanical means for keeping the wires apart and insulating only just as much as a piece of cotton tape would. To take one example, I had recently sent me by a large manufacturer of street railway motors a piece of insulating material for which he claimed very considerable virtues; which had been the best insulation he had used so far and which he had only abandoned on account of its very high price. On my testing a sample taken from a motor about a year old I found that it had been originally a very good quality of canvas, covered, above all things in the world, with rubber. Of course, the rubber had totally gone to pieces and was in the form of a black non-cohesive powder. Its insulating properties proved so poor that on placing a drop of water on one side of it, in 30 seconds it came through on the other side.

The trouble is that the insulating department of a company is generally put in charge of some young man of very little practical experience. He is generally a good and able man, makes a lot of experiments which have been made over and over again by others, but not published; thinks he has found some good things, and after a year or so, when he begins to see how the machines brought in for repair look and is really beginning to learn something, is promoted to a better position, and the next man goes through the same thing. To again take an example, one of the most common things for the beginner to do is to make up a gum varnish as an insulator. I know personally at least ten cases of this. Now, old hands know that a gum varnish is no good, that it cracks within a year, that it splits in cold weather, that it never makes a good joint when used on paper or cloth, and that its only virtue is that it looks pretty for a time. Yet I suppose that there are at the present time at least a dozen companies using varnishes for insulation, at from $1.50 to $4.00 per gallon, when pure borated oil, superior in every respect, can be got for about 30 cents per gallon.

Now all those details would make a long paper, too long to read at such a meeting as that of the INSTITUTE, and I have therefore merely indicated a general theory of the subject with a few illustrations.

I thoroughly appreciate the kind remarks of Professors Franklin and Pupin. I however disagree with them entirely on certain points. First, with respect to Professor Franklin's remark about molecules. I have myself some knowledge of chemistry, and was for some years head chemist of Mr. Edison's laboratory. I have also made a specialty for some ten years of physical chemistry, and I have no hesitation in saying that the foundation of almost all good work in chemical physics must be the behavior of the molecule. It is true that there has been a good deal of manipulation of energy equations lately by the chemists, and I will not deny that some good work has been done in this line, but it must not be forgotten that this is only one small branch of physical chemistry, and that the results so obtained can generally be obtained by much simpler methods. I think Professor Franklin will appreciate this if I ask him to predetermine the density of, say, cæsium chloride; to predetermine the tensile strength of magnesium; to predetermine the angles of a crystal whose chemical composition is known, without resorting to other analogous salts; to determine a law for the compression of gases which shall have but one arbitrary constant and shall yet express with more exactness than Van der Waal's equation the pressure volume curves for *all* gases, or to give a strict and satisfying mathematical proof that Dulong and Petit's law is a true physical law and not a coincidence. I think that it will be admitted that this cannot be done without resource to molecular theories, but all the above have been done by the writer, and all published except the last. Many beautiful instances are given by Professor Roberts-Austen in his papers, for instance the predetermination of the tensile strength of alloys. I venture to express the opinion that the recent work of Larmor on combinations of vortex rings, together with the newly discovered fact that the unequal shifting of the lines in Zeeman's effect must depend upon the valency of the atom; that the valencies of an atom must be separate and distinct things, as distinct from each other as two interlaced rings; that each valency must give rise to a distinct set of lines, shifting differently to the lines due to another valency, the shifting being given by a simple expression, will give fresh impetus to work in this direction. There is reason to believe that this year will ever be memorable as the date on which we first began to obtain definite information in regard to the structure of the atom.

It is not true that atoms cannot be measured. They have not been measured very accurately at present, but any chemist who should determine the latent heat of vaporization and the surface tension of mercury would be able to determine from them the size of the atoms, and hence that of the molecules, with a degree of precision approaching that of many atomic weights.

I am very much pleased with Professor Franklin's mechanical analogy. It brings out things in a very pretty way. With regard to the question of boiling in vacuo, I would say that Professor Franklin is perfectly right in saying that it is better than in air, but my experience has been that if the boiling is done as I have described, the difference is very slight. I do not know the reason of this; possibly it is that when the cellulose begins to decompose, it drives out the rest of the air, and when the paraffin cools, the hydrocarbon vapors are absorbed by the paraffin. I have never made any experiments to test this theory, however.

With reference to Prof. Pupin's remarks, I hope he will pardon me if I say that he would never have made the statement that the rate of flow of a current "could not have anything to do with such coarse mechanical properties of matter as elasticity and density," if he were not deeply versed in the writings of the modern mathematical physicists who have treated of electrical problems. I will add, if he were not *too* deeply versed. I have a complaint to make against these gentlemen: they cannot be got to realize that there is a difference between a force and a flux, between H and B for instance. In a paper in the very last *Philosophical Magazine* for example, the formula for the Zeeman effect is given wrongly, H being written throughout for B. As a consequence of this neglect of μ, they out-Maxwell Maxwell, and any one reading their papers would get the impression that, as one of them has actually put it, the only function of a wire was to dissipate energy.

This is going too far. It is entirely false. The dissipation of energy is merely an incident and has nothing to do with the function of a wire, which is to carry what we call the quantity of electricity. Take for instance a copper wire at absolute zero. It then dissipates no energy, but does any one suppose that we could then remove the wire and still have a current? Not unless the ether at absolute zero were a conductor, which is negatived by the fact that the sun's light traverses space, which it could not do if the ether in space were not a perfect insulator. A sensational idea, even in science, is hard to kill, no matter how false; as witness, the often repeated statement that light is due to charges oscillating on the atoms, as in small condensers, though this statement has been refuted time and again, and by the very man who first made it. And so we must be prepared for some years to hear that the ether is the all important thing, whereas, as a matter of fact, it is merely the thing which pushes along the thing which we call the current.

Now we know three ways of producing a current. Convection, electrolytic conduction and metallic conduction. We *know* that in convection the current does not travel with the velocity of light, but that, by putting charged balls in the insulated buckets of a coal conveyor, we may have any current we please, and the electricity traveling as fast or as slow as we please. In electrolytic conduction we have very good reason to believe that the electricity travels on the atoms, and at a speed of only a few centimetres per second. Having thus one instance in which the current is *known* not to travel with the speed of light, and one in which it is almost certainly known not to do so, does not the burden of proof that the current in a wire does not flow also at some slower rate fall upon these "all ether" physicists?

Now, as to the actual relation given by me, the facts are these: Dr. Lodge, as I have pointed out, many years ago showed that it would be a natural thing if the current flowed at the velocity of sound, but, having no data for the velocity of sound in wires, or rather, incomplete data, stated that there did not seem to be any relation. I, working in an empirical manner, found a formula showing a relation between the velocity for sound and the conductivity. This I published years ago, and gave in it the conductivity of aluminium as 66 per cent. that of copper, the best determination at that time being that it was only 50 per cent.; but as I had forgotten about Lodge's work, I did not refer to it. *Now* the latest determinations of the conductivity of aluminium give it as I had predicted it.

In spite of this, Professor Pupin says that he "does not think that we ought to consider these formulæ *au serieux*." To which I can only say that I conceive Professor Pupin to be possessed of a very happy disposition. To speak seriously, no real advance of importance can be made until we give up this idea of attributing everything to the ether and come back to face the facts. Permeability and specific inductive capacity are real things, even their general forms are known, and we can prove from Faraday's law of electrolysis[1] that at least one of them must be a complex quantity. A great deal of harm has been done by this neglect of the functions of matter, and many students have had their ideas confused by it. Too much has been laid to the ether.

With regard to Professor Pupin's remarks on Maxwell's law, they are perfectly correct, but I never wrote the sentence as he quotes it. The compositor has seen fit to introduce a colon before the word "these" which should not belong there, and as originally written, the nominative of the verb "being" was the word "relation." The sentence thus means that Maxwell's law, $k^{\frac{1}{2}}\ \mu^{\frac{1}{2}}$ is proportional to the slowness of light, and my rule, that $\mu^{\frac{1}{2}}/k^{\frac{1}{2}}$ is proportional to the slowness of sound, have this in common, that the function of k and μ varies with the

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[1] This was indicated, of course, long ago by some of the optical theories, but it has been shown by Rayleigh and others that this does not give satisfactory results in all cases. The proof depending upon Faraday's law is however unexceptional, though at first sight there would seem to be no immediate connection.

periodicity of the motion. Maxwell, of course, in his law never made any statement that k or μ varied with the periodicity, though he shows that k does in other portions of his work. I would thank Professor Pupin for calling my attention to this slip.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

New York, April 27th, 1898.

The 124th meeting of the American Institute of Electrical Engineers was held this date, at 12 West 31st Street, and was called to order at 8:30 P. M. by the Secretary.

The Secretary:—The Vice-Presidents and Managers who are on the standardizing committee are engaged in quite an important session, and they will be in attendance later. Meanwhile we will proceed with the business of the evening, and if some gentleman would be kind enough to nominate a Chairman to act until the President arrives, I will entertain the motion.

Mr. Joseph Wetzler:—I move that Mr. Leonard occupy the Chair temporarily in the absence of the President.

The motion was carried, and Mr. H. Ward Leonard took the Chair.

The Secretary:—At the meeting of the Executive Committee this afternoon the following associate members were elected:

Name.	Address.	Endorsed by
Allen, Wyatt H.	Care H. F. Allen, 202 California St., San Francisco, Cal.	Louis Duncan. H S. Hering. Alex. Stratton.
Fitzhugh, Wm. H.	Supt. Bay City Electric Plant, Bay City, Mich.	F. B. Rae. F. S. Hunting. Thomas Duncan.
Fleming, John Breckenridge,	Mill Superintendent and Cons Engineer, Austin Mining Co., Austin, Nev.	R. W. Pope. Edw. Caldwell. W. F. C. Hasson.
Henry, Geo. J. Jr.,	Engineer for N. Y. Branch, The Pelton Water Wheel Co., 143 Liberty St., N. Y. City.	W. W. Blunt. P. N. Nunn. J. N. LeConte
Hopkins, N. S.	Ass't Engineer, General Electric Co. Box 825, Schenectady, N. Y.	H. G. Reist. A. L. Rohrer. C. P. Steinmetz.

Lindsay, Robert	General Supt. The Cleveland Elec. Ill. Co., 717 Cuyahoga Building, Cleveland, Ohio.	M. C. Canfield W. S. Barstow. J. W. Lieb, Jr.
Muschenheim, Fred'k A.	Electrical Engineer, Western Electric Co., 57 Bethune St., residence, 41 W. 81st St., N. Y. City.	H. F. Albright. E. S. Keefer. Geo. A. Hamilton.
Schloss, Newton L.	Consulting Engineer, 39 Cortlandt St., residence, Stuart House, N. Y. City.	Jos. Wetzler. T. C. Martin. R. W. Pope.
Tolman, Clarence M.	Electrical Engineer, with Edw. G. Stoiber, Silverton, Colo.	C. E. Doolittle. E. Friedlaender. H. G. Reist.
Vinten, Ernest Stiles	Draughtsman, Walker Co., New Haven, Conn.; residence, 89 Pearl St., New Haven, Conn.	Chas. N. Black. H. McL. Harding. F. G. Daniell.

Total, 10.

The following paper on "An Economy Test of a Central Station" was presented by the Secretary in the absence of the author:

A Paper presented at the 124th Meeting of the American Institute of Electrical Engineers, New York, April 27th, 1898, Mr. H. Ward Leonard in the Chair.

AN ECONOMY TEST OF A CENTRAL STATION.

BY W. E. GOLDSBOROUGH.

INTRODUCTION.

During the summer of 1895, I made a study of one of the large electric lighting stations of Baltimore city, from an economic stand-point. A series of somewhat general observations, led, finally, to a decision to subject the plant to a number of rigid economy tests, to determine along what lines, if any, the method of operating the station could be modified to improve its efficiency. The tests were initiated largely as a matter of engineering interest; for the station, even at that time, was adjudged efficient. Arrangements for these tests were perfected about the end of the summer, and in the following pages is given an account of the more interesting matters that came to my notice during their progress.

Since 1895, the station has been so extensively improved, both as the result of these investigations and the natural growth of business, that the paper can hardly be said to be a record of the economic performance of any at present existing plant. New boilers have been added, as well as new engines. With but one or two exceptions the old engines have been refitted with new cylinders and valves, and the electrical units, dating as far back as the tests, have been so thoroughly renovated as to be practically new.

The station is to-day, without doubt, more efficient than in 1895, and the improvement is in a great measure due to the removal of the defects to which your attention will be called. Tests of the character of those discussed have an undoubted value, and there is many another plant to be studied and regulated in virtually the same manner before it attains the maximum efficiency. A combination of boilers, engines and generators, however efficient they may be severally, do not necessarily produce an efficient station. Each station must be regarded as a special problem by the engineer, and must be studied as such.

The interest taken in investigations of this character by Mr. James Frank Morrison, general manager of the company controlling the station, made the tests possible, and it is through his kindness in consenting to the partial publication of the results obtained, that I am privileged to read before the INSTITUTE this abstract of my report. If the facts do not appear in some cases to bear out the conclusions, it must be remembered that it has been possible for me to embody in this paper only a small part of the original data.

Purdue University, La Fayette, Ind.,
March 1898.

THE STATION.

The West Pratt Street Station of the Edison Electric Illuminating Company of Baltimore city is situated on the north-west corner of Pratt and Penn streets, Baltimore, Maryland.

The station occupies a substantial one-story brick building that fronts on Pratt street and extends back 178 feet to King street. The general character of the building is very well illustrated in the ground plan and elevation of it that is contained in this paper. The Pratt street end contains the boiler plant; this room is 60 feet long and 67 feet wide. North of the boiler room is the engine room; it is 118 feet long and 60 feet wide.

From Pratt street the station presents a pleasing appearance. Its front is rectangular, 35 feet high and broken by large double doors and windows.

The Boiler Room.—The boiler room contains nine water-tube boilers of the type manufactured by the Campbell and Zell Company which are arranged in four batteries of two each, with one large boiler in the south-west corner by itself.

The boilers have a total rated capacity of 1,750 horse-power.

As shown by the ground plan of the station above referred to, the boiler plant is equipped with three large iron stacks. One of these receives the products of combustion from the furnace of boiler No. 1. Another is in the northwest corner of the boiler room and forms the continuation of the flues of boilers Nos. 2,

3, 4 and 5. The third is in the northeast corner of the boiler room and is built to accommodate the large boilers, Nos. 6, 7, 8 and 9, on the east side of the station.

The location of the steam mains is not shown in the station drawing. A single 10-inch main extends along the west side of the boiler room over boilers Nos. 1, 2, 3, 4 and 5. It is carried through the north wall and terminates in a "straight line" centrifugal separator placed just inside the engine room. On the east side of the station a similar line of 16-inch pipe extends over and collects the steam from boilers Nos. 6, 7, 8 and 9. It is extended on into the engine room. The east and west steam mains are connected by a 10-inch pipe which runs parallel to the dividing wall just inside the boiler room. The cross main is equipped with a large stop valve and an equalizer connection.

The equipment of the boiler room also includes one 500 H. P. "national" feed water heater, one 500 H. P. "excelsior" heater and purifier and one 1500 H. P. double open and closed feed water heater made at the Bass Foundry and Machine Works.

There are three duplex pumps at the north end of the boiler room, where the heaters are also placed. The steam cylinders of these pumps are 12″ x 12″ and the water cylinders 7″ x 12″

As a rule it is found that one pump is sufficient to supply the boilers, and during the tests made upon the station, only one pump was used. The feed water flows from the city mains directly to the heaters in which it is heated by the exhaust steam from the engines. It is drawn from the heaters and forced into the boilers by the pumps. During the tests the heaters were found to be very effective. They do not apparently increase the back pressure in the exhaust mains and yet save over 11 per cent. of the fuel.

The Engine Room.—The newer part of the station building north of the boiler room contains the engines and the electrical machinery. The floor of this room is about level with the ground. The foundations of the engines all extend above the floor and there are no wheel pits, etc. in the station. The aggregate rating of the engines is 2065 H. P.

The piping between the engines and boilers is ample in its dimensions. Engines Nos. 1, 2, 3, 5 and 8 are on the east side main. This main is constructed of 16-inch pipe up to the point where the supply pipe of No. 1 engine is connected.

Beyond this point it is reduced to 10-inch pipe and is carried over to the west side of the station; it is then extended north over engines Nos. 5 and 8. Where the east main crosses the middle of the station a "straight line" centrifugal separator has been inserted. This is the only separator on this line of pipe.

The pipe connections between engines Nos. 1, 2, 5 and 8, and the east main are quite direct and short; the connection to No. 3 is however, necessarily long; it extends entirely across the station.

Engines Nos. 4, 6 and 7 are connected to the west side steam main. This main extends almost due north from the boiler room and is composed of 10-inch pipe throughout its entire length.

The exhaust mains extend north and south underneath the floor. They connect directly with the heaters, and all waste steam not condensed by the feed water is discharged through exhaust heads into the air. All of the engines exhaust into these mains except engine No. 1, which exhausts directly into the atmosphere through an exhaust head.

The normal steam pressure at which the engines are operated is 130 pounds by gauge. The entire plant is non-condensing.

The station is equipped with electrical machinery designed to supply 13,000 16 C. P. incandescent lamps and 1,420 2,000 C. P. arc lamps. The arrangement of the units is shown on the ground plan of the station. They are all belted to the engines.

The dynamo leads are carried to the switchboard, which is raised nine feet above the floor of the station, through subways underneath the floor. From the switchboard the leads are carried out of the station on suitable racks through the skylight that covers the greater portion of the roof of the engine room.

A very good idea of the appearance of the station and the general arrangement and setting of the machinery can be obtained from the cut of the engine room. The cut brings out the arrangement of the steam piping and wiring very clearly.

The Arc Lighting Plant.—In the arc lighting plant, the usual American practice of transmitting power to numerous dynamos from one engine by means of shafting and belting is followed. The entire equipment is divided into three sets.

Engine No. 1, which is a 600 H. P. horizontal cross-compound high-speed Ball and Wood engine, is directly connected to a line shaft that extends along the east side of the station, and to which twelve 80-light Wood 2,000 C. P. arc light machines are belted. Each of these dynamos will safely develop 38.4 K. W. or 51.47 H. P., making a possible total load of 618 H. P. for the engine, over and above the friction load due to the line shafting.

Engine No. 2 is also directly connected to a line shaft extending along the eastern wall of the station. The engine is a simple four valve horizontal high-speed Russell engine of 170 H. P. and drives a 10 K. W. 500-volt Wenstrom generator and three 80-light Wood 2,000 C. P. arc light dynamos, which are all belted to its line shaft. The total maximum rated electrical output of this equipment is 168 H. P.

Engine No. 3 is a 125 H. P. simple single valve, high-speed horizontal Russell engine. It drives two 80-light and one 60-light Wood 2,000 C. P. arc light dynamos that are belted to pulleys on a short extension of the engine shaft. The total normal rated output of this equipment is 141.5 E. H. P.

The normal current output of the arc machinery is 9.6 amperes. The practice at the station, however, is to regulate the machines at about 9.5 amperes, and this current value was used during the tests, except in the case of machines Nos. 4 and 6, which supply the arc motor circuits and are operated above their normal capacity at 10 amperes.

The Incandescent Plant.—The single-phase alternating current system is exclusively employed for the distribution of power to the incandescent lighting circuits. A uniform pressure of 1000 volts is supplied to the distributing mains, and this is reduced by means of transformers to 50 volts at points where it is supplied to consumers.

To meet the increasing demands upon the station and to admit of the most economical adjustment of the load under existing conditions the incandescent plant has been enlarged from time to time until at present it comprises five distinct equipments each operated by a separate engine. The arrangement of this machinery is very well exhibited in the cut of the ground plan and side elevation of the station contained in this paper. Referring to it:

Alternator A, is a 150 K. W. Wood machine compounded for 1000 volts. It is operated by a 300 H. P. tandem compound "ideal" engine.

Alternator B, is a 100 K. W. compound Slattery machine.

Alternator C, a 50 K. W. Thomson-Houston machine, both of which are operated by a 300 H. P. cross-compound Ball and Wood engine.

Alternator D, is a 100 K. W. Slattery machine, driven by a 145 H. P. Buckeye engine.

Alternator E, is also a 100 K. W. Slattery machine and is driven by a 145 H. P. Buckeye engine.

Alternator F, is a 150 K .W. compound Wood machine and is driven by a 300 H. P. Ide engine.

As the diagram indicates, all of the alternators are belted, solid leather belts being used. Their exciters are supported on separate bases, and are belted to pulleys placed on the collector ends of the shafts of the alternators.

THE TESTS.

The tests that were made upon the station took place during the last week in August, and the first week in September, 1895.

In planning for the tests *no effort was made to improve the condition of the plant in any respect.* The engines and other machines were operated just as they had been running during the months previous, and absolutely no modifications were made in the methods of adjusting the load to the various units, in the way in which the boiler plant was handled, or in the usual control of the water and coal supply; except on Sept. 1st and 2nd as explained later. The station employees were in no wise instructed to modify their habitual practice, and they were at all times left perfectly free to perform their accustomed duties.

In carrying out the details of the tests, in the construction of additional apparatus, the calibration of instruments and the fitting and adjustment of the same, in fact, for the perfection of all the varied requirements of so large an undertaking, competent extra help was employed.

Every effort was made to have each detail of the general plan accurately outlined, worked up and perfected. For the measurement of the water supply a large weir was built on the northeast corner of the boiler room roof almost directly over the 1500 H. P. feed water heater. Measurements were taken of the water level in the weir at 5 minute intervals throughout the entire period of the tests with a Boyden hook gauge, and a continuous record was also obtained with a very sensitively adjusted chronograph. As a check upon these readings, the water-meter, through which all the water passed that entered the station, was read at 15-minute intervals. Furthermore every water connection, through which leakage could possibly occur, was tested, and made water tight if found imperfect.

In figuring up the amount of water that was supplied to the boilers, the levels shown by the hook gauge and the chronograph records were checked against one another, and the chronograph records were all integrated with an Amsler planimeter. The results that were obtained in this way were then compared graphically with the water meter readings. The weir and water meter curves follow one another quite closely, and show that up to the rate of flow of 2200 pounds of water per hour the water meter registers *less* than the true amount of water, but that over that rate it measures *more* than the true amount of water.

The scales used in measuring the coal were made by Fairbanks, and their accuracy was assured by testing them with a block of iron, the weight of which had previously been ascertained on the standard scales at the United States Sub-treasury.

Each barrow of coal was passed over the scales and balanced accurately for 400 pounds of coal before being carried into the station.

All the steam gauges used in connection with the tests, were standardized by comparing them with a *new* Thomson and Robertson gauge testing set. The thermometers used in making calorimetric tests of the quality of the steam had been calibrated previous to the tests and were calibrated again immediately after the tests. These calibrations were found to correspond. The calorimeters used were three carefully constructed throttling calorimeters and one Carpenter separating calorimeter. The pyrometer used in measuring the temperature of the flue gases was calibrated by inserting it into a steam pipe and comparing its readings with determinations made of the temperature of the steam from the readings of two calibrated gauges connected to the same steam pipe. During the tests, each steam cylinder of the engines and the pump was equipped with a steam indicator, and proper indicator riggings were fitted up to ensure the accuracy of the cards taken. Engines Nos. 1, 5, 7 and 8 were equipped with two-way cocks in connection with the indicator fittings, but on the other engines, valves placed on either side of the indicator had to be relied upon when taking cards from the opposite ends of the cylinders.

The speed of each of the engines was taken every 15 minutes with the usual form of Starrett hand speed indicator. The speed of engine No. 1 was always taken at the time the indicator cards were made, and the speeds of the other engines immediately thereafter. This method is not so exact as that of using tachometers or constant speed counters, but owing to the fact that there were no *sudden* changes in the load on any of the engines, the plan adopted was considered sufficiently accurate.

Testing Instruments.—For taking the record of the output of the arc dynamos quite an amount of special wiring was necessary. Three standard high range Weston voltmeters were available for determining voltage readings. Three tables were therefore constructed with a double row of mercury contacts arranged along one side of the top. The tables were nailed to the floor and connections made between the terminals of each of the arc machines and a pair of the mercury contacts. One of the standard voltmeters was placed on each table, and was used to take the voltage readings of the machines connected to that table by successively inserting a flexible insulated connector into the mercury contacts.

As it was impossible to provide ammeters for all the arc circuits, one standard Weston direct current ammeter was used for testing all of them. A test was made of all the circuits every 15 minutes during the five minutes immediately preceding the time for taking the general station readings. It was found that the currents remained practically constant as the loads were subject to only slight variations.

The voltmeters and alternating current indicators employed on the alternator circuits are of the older types supplied by the makers of the machinery, but the ammeters on the distributing mains are of the most improved Wood pattern. Wirt lightning arresters are used on all the distributing circuits.

The arrangement of the switchboard connections is such that it is possible to connect any one alternator to only about half of the distributing circuits at any one time. The changing of a circuit from one alternator to another is effected by the manipulation of a series of double-throw switches, which when placed in a certain order to bring a proper load on one alternator, may prevent the completion of the combination of connections that would be most advantageous in loading some other machine. The restrictions imposed by the switchboard have the effect at times of causing the operation of a dynamo which could be dispensed with were a thoroughly flexible system of switchboard connections provided. The remodelling of the board would in fact greatly facilitate the economical operation of this portion of the station, and would result in a considerable saving in the operating expenses. This point is well brought out in the tests made upon the plant.

In this station each alternator is operated entirely independent of any other, *i. e.*, parallel working of the machines is not attempted.

Calibration of Instruments.—To ensure the thorough reliability of the readings of the electrical switchboard instruments they were all carefully calibrated by comparing them with standard Weston instruments obtained especially for this purpose direct from the Weston Electrical Instrument Company.

The calibration of the switchboard voltmeters was effected by connecting a standard 110-volt Weston alternating and direct current voltmeter, and a multiplying coil that multiplied its readings by 10, directly across the 1,000-volt mains and comparing its readings with the readings of the switchboard instrument undergoing calibration. The switchboard instruments were not removed from their normal positions or their connections disturbed in the least, the variations in the voltage between the leads to which the instruments were attached being produced by changing the field excitation of the respective dynamos to which they were connected.

The calibrations of the switchboard ammeters were effected by employing an indirect, though perfectly successful, method. A large non-inductive resistance was constructed by stretching a quantity of No. 17 B. & S. gauge german silver wire on a number of 12-foot boards by passing it around porcelain insulators screwed to the boards. These resistances were then connected to an old arc light switchboard so that any number of them could be connected either in series or in parallel as the case might require. A switch was fixed so that the arc switchboard with the resistances could be short-circuited when not in use. The lead that connected the ammeter to be tested with its dynamo was disconnected and led to one side of the arc switchboard just described. After being made to pass through the non-inductive resistance of the board, the circuit was then connected to the current terminals of a standard Weston wattmeter. From the other current terminal of the wattmeter the circuit was connected to the ammeter to be tested. The ammeter was in this way placed in series with the non-inductive resistance and the current coil of the wattmeter. The voltage terminals of the wattmeter were connected as a shunt around the non-inductive resistance, and a standard Weston voltmeter was arranged to measure the fall of potential through the non-inductive resistance, *i. e.*, it was also shunted around the resistance. In this way means were provided for measuring the power absorbed in the resistance by the wattmeter, and by dividing the wattmeter reading by the reading of the standard voltmeter the current flowing through the resistance and therefore through the switchboard ammeter tested, could be determined. By varying the load on the alternators the current readings of the ammeters were varied over the working range of the respective machines, and the readings of the ammeters were then compared with the determinations of the true values of the currents made as described above.

The calibration tests indicated that the instruments were not very far out, and but a slight correction in the results recorded during the tests was necessary. The necessary correction was made in every case.

Determination of Power Factors.—On transformer circuits the power factor is not a constant, as the inductance of the line varies with the number of incandescent lamps that are turned on. Under ordinary circumstances, however, the power factor for any given circuit will be very nearly a constant for any given load on the circuit, whatever be the distribution of the load between the several secondary circuits supplied; it is therefore possible to plot a curve showing the relation of the apparent power to the real power for all loads for any given circuit, and having once obtained this curve the real power can always be obtained from the apparent power by reference to it.

As the standard Weston wattmeter already referred to was obtained on the 4th of September, and all tests had to be completed before the 8th of September, it was impossible to determine the power factors for each of the circuits. It was possible however, to make these determinations collectively for the several circuits supplied by "A" and "F" alternators during their all-day runs on September 6th and 7th respectively, and from the results so obtained a very fair estimate of the power factors that should be used for the tests has been arrived at.

The power factor varies between 88.2 and 99.6 per cent., with the majority of the points falling at about 91 per cent.

These results are for the *day load.* After carefully reviewing the results of both of the tests of the incandescent plant, and making numerous comparisons, it was decided to use the power curve for all determinations of the *real power* developed by the several alternators, between 7 A. M. and 6 P. M., and 12 P. M., and 7 A. M., on each day on which tests were made, but between 6 P. M. and 12 P. M. a factor of *100 per cent.* was used for all circuits. This course was followed, since between 6 P. M. and 12 P. M., the load on the station is very heavy and therefore all the factors very high.

Any error that may be introduced by this procedure is slight at most, as the uniformity of the efficiencies obtained during the day and night runs plainly indicates.

DURATION OF TESTS.

The first test began at 7 A. M. on August 31st and continued until 7 A. M. on September 1st. During this time measurements were taken, as already described, on all the machinery and boilers operated in the station. During the hours of the heavy load, between 6 P. M. and midnight, 41 men were employed in taking readings.

The second test began at 5:45 P. M. on September 1st, and continued till 5 A. M. on September 2nd. This test was made to determine the efficiency of engine No. 1 and boilers Nos. 6, 7 and 8. It was made on Sunday night, because, owing to the arrangement of the steam piping and the large load on the station at other times during the week, the necessary adjustment of the boiler plant could only be effected at this time. For this test 24 men were employed.

The third test began at 7 A. M. on September 7th and ended at 7 A. M. on September 8th. It was carried out in all respects like the first test. The maximum number of men engaged in taking readings at any one time on this day was 42.

Each of the tests was thoroughly successful, and although a very severe storm raged during the afternoon of August 31st, the test made on that day was not seriously interfered with. On the contrary, the men showed remarkable coolness in carrying on their work quietly and in an orderly manner in the face of considerable danger.

The plan adopted for recording the results was to take simultaneous readings every 15 minutes from all the instruments, etc., at a signal given by blowing a steam whistle in the engine room.

THE BOILER TESTS.

The Boilers :—The boiler plant of the station is composed of four batteries of two boilers each, and one odd boiler. They are all of the water tube type and of the same general design, as they were built by the same company, but on account of having been placed in the station at different times, they differ somewhat from one another in the minor details of their construction.

The data on the dimensions and capacity of the boilers that are given in table 1 were obtained from the representatives of the Campbell and Zell Company, the makers of the boilers, and they have been checked up with the drawings from which the boilers were made and by measurements taken in the boiler room.

Boiler No. 1 was the first to be placed in the station; it is a double boiler and is rated by the builders, as a 250 H. P. boiler. The present practice of the builders, as stated on page 59 of their catalogue, is to rate their boilers on the basis of "11½ square feet of heating surface in the water tubes alone," per horse power. If this method of determining the capacity of boiler No. 1 is followed, its rated capacity figures out to be 186.5 horse power. (See item 34, table 1.)

Boilers Nos. 2, 3, 4 and 5 occupy space on the west side of the boiler room and form batteries 2 and 3. They were placed in position some time after boiler No. 1, and are of a more recent design. Their capacity by the original builders rating is 125 H. P. per boiler, and on the basis of "11.5 square feet of heating surface in the tubes alone," it is 61.2 H. P. per boiler.

Boilers Nos. 6, 7, 8 and 9 are of quite recent design. The builders rate them at 250 H. P. each, but their capacity figured on the 11.5 square feet of heating surface basis is 242.6 H. P. per boiler.

Summing up we find that the total rated capacity of the boiler plant is 1750 H. P., or 1401.7 H. P. when figured on the basis of 11.5 square feet of heating surface per horse power, *in the tubes alone.*

On the mornings of each of the days on which the tests were made, the fires under boilers 6, 7, 8 and 9 were burning bright, were clean and all the ashes had been removed from the ash pits.

The ashes that accumulated during the 24 hours' run were carefully weighed before being wet, and the fires burning at the end of the tests were left as nearly as possible in the same condition as were those which were burning when the tests began. In determining the moisture in the coal, samples were selected from the coal yard and dried.

In determining the moisture in the coal used Aug. 31st, account had to be taken of the fact that there was a heavy rain fall in the afternoon. In view of the fact however, that another determination was made of the moisture in the coal on the next day, it was possible to approximate the true percentage of moisture for the whole test with a considerable degree of accuracy.

TABLE I.

	Boiler. No. 1.	Batteries. No. 1 and No. 2.		Batteries. No. 3 and No. 4.	
Designation of the Boilers by the Edison Elec. Illuminating Co. ...	No. 1.	Boilers 2, 3, 4 and 5.		Boilers 6, 7, 8 and 9.	
1. Length of tubes..............	16'	14'	14'	18'	18'
2. Tubes per section...........	4	2	2	4	4
3. No. of sections	32	24	24	37	37
4. Total No. of tubes, per boiler..	128	48	48	148	148
5. Diameter of tubes.........	4"	4"	4"	4"	4"
6. Length of water drums......	18'	16'	16'	20'	20'
7. No. " "	4	1	1	2	2
8. Diameter of water drums ..	18"	18"	18"	30"	30"
9. Sq. ft. heating surface per tube.	16.752	14.658	14.658	18.846	18.846
10. " " " " " sect	67.008	29.316	29.316	73.384	73.384
11. Total sq. ft. heating surface in tubes	2144.3	703.58	703.58	2789.2	2789.2
12. Sq. ft. heating surface per drum	75.74	67.34	67.34	139.72	139.72
13. Total sq. ft heating surface in drums.....	302.96	67.34	67.34	279.44	279.44
14. Total sq. ft. heating surface...	2447.3	770.92	770.92	3068.6	3068.6
15. Width of grate surface in ins..	120	47	47	90	90
16. Length of grate surface in ins.	78	72	72	84	84
17. Area of grate surface in sq. ft..	65	23.52	23.52	52.5	52.5
18. Ratio heating to grate surface.	37.65	32.77	32.77	58.43	58.43
19. Ratio heating to super-heating surface					
20. Super-heating surface . .					
21. Length of tubes, inches	156	138*	138*	177.5	177.5
22. No. of tubes	16	6*	6*	12	12
23. Diameter of tubes.....	4"	4*	4*	4"	4"
24. Sq. ft. heating surface per tube.	11.52	12.03*	12.03*	15.479	15.479
25. Total heating surface sq. ft. ..	184.32	72.18*	72.18*	185.75	185.75
26. Area cyl. one water drum sq. ft.	84.18	75.36	75.36	157.08	157.08
27. Super-heating area one water drum sq. ft.	9.04	8.02	8.02	17.36	17.36
28. Total for water drums sq. ft...	36.16	8.02	8.02	34.72	34.72
29. Length of steam drum, inches.	120	47	47	90	90
30. Diam. of steam drum, inches..	42				
31. Area of cylinder of steam drum sq. ft.............	109.96	42* 43.1	42* 43.1	42 82.47	42 82.47
32. Total super-heating surface....	330.44	123.3	123.3	302.94	302.94
33. Horse-power allowing 11.5 sq. ft. of heating surface per H. P. in tubes alone....	186.5	61.2	61.2	242.6	242.6
34. Horse-power allowing 11.5 sq. ft. of heating surface per H. P. in tubes and drums	212.8	67.02	67.02	267.	267.
35. Rated horse-power of boilers..	250.	125.	125.	250.	250.

*No positive data—approximated. Data is given per boiler.

The engineer's and the assistant engineer's reports show that the same firemen were on duty during the same hours on Aug. 31 and on Sept. 7. So that the results of the two day's tests are as thoroughly comparable from this stand-point as from any other.

The Boiler Test of August 31st:—This test began at 7 o'clock on the morning of August 31st and ended just 24 hours later. During this time the station was operated according to the usual daily schedule and no attempt was made to modify or better the usual conditions in any way.

The log of the boiler test is exhibited graphically in Fig. 1. Table 2 contains the data and calculated results upon which the report of the boiler test given in table 4, column 1, is largely based, and it explains the method used for determining the true average grate surface, heating surface and horse power rating of the boilers. Such a process had to be resorted to in view of the fact that all of the boilers were not in service all of the time.

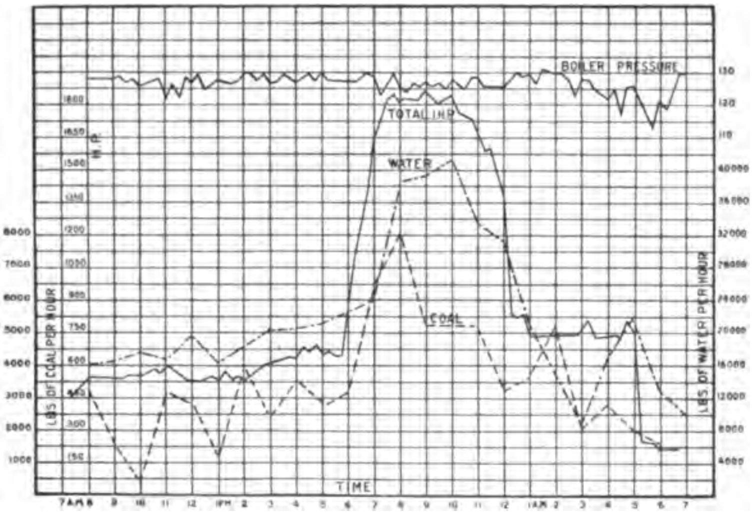

Fig. 1.—Pratt Street Station, Graphical Record, Aug. 31, Sept. 1, 1895.

All of them were in service some of the time, and some of them were in service all of the time.

In view of the fact that great care was taken during the trial to have the coal and water supplied to the boilers in just the proportions that were necessary to meet the demands made upon the boilers by the engines, it has been thought advisable to work up the data of the boiler trial over the portions of time during which certain of the boilers were in continuous service, in order that an estimate might be gained of the relative evaporative efficiency of the different batteries.

In column 3 of table 4 are presented the results of the boiler trial between 7 A. M. and 1 P. M. on Aug. 31. During this time boilers 6, 7, 8 and 9 were continuously in service and operated alone.

In column 5 of table 4 are presented the results of the boiler trial between 3 P. M. of August 31st and 1 A. M. of September 1st. During this time the entire boiler plant was in continuous service.

In column 7 of table 4 the results of the boiler trial during the hours of the heavy load, between 7 P. M. and midnight of Aug. 31 are given.

These results, when studied in connection with those of the trial of Sept. 7, reveal much valuable information regarding the efficiency of the boilers as well as the most economical methods to be employed in operating the boiler plant.

The Boiler Test of Sept. 7th.:—The boiler test of Sept. 7th was similar in all its details to the tests made on Aug. 31.

The records of the test are contained in tables 3 and 4. By comparing the data in tables 2 and 3 it will be found that the boilers were cut in and out on Sept. 7, at almost the same hours as the same boilers were cut in and out on Aug. 31. For example the trials were commenced on both days with boilers 6, 7, 8 and 9 in service; at about 2:20 P. M., boilers 1, 2, 3, 4 and 5 were cut in and from that time on till 1:45 A. M. of the second day of each test, none of the boilers were cut out. This fact has made it possible to report the trials in precisely the same manner. The general report for the entire 24 hours is given in table 4, column 2. The results here recorded are based upon boiler log and the average square feet of grate surface, water heating surface and horse power rating that are given in table 3. The "average rated horse power" is based upon the basis of the builders horse power rating, and the "average real horse power" is determined upon the basis of 11.5 square feet of heating surface in the boiler tubes being the equivalent of one horse power. This explanation also applies to items 44—44.5—45 and 45.5 of the boiler reports.

A report on the trial of boilers, 6, 7, 8 and 9 between the hours of 7 A. M. and 1 P. M. of Sept. 7 is set forth in column 4 of table 4. During this time the boilers mentioned were the only ones in service.

TABLE 2.

Record of Test of Station. August 31 and September 1, 1895.

Table showing the number of hours during which the respective boilers were in service.

No. of Boilers.	Hour started. Aug. 31.	Hour stopped. Sept. 1.	No. of hours in service. Hrs.	Min.	Sq. ft. grate surface.	Sq. ft. grate surface hours.	Sq. ft. water heating surface.	Sq. ft. water heating surface hours.	Rated Horse-power.	Rated Horse-power hours.	Real Horse-power.	Real Horse-power hours.
1	2:15 p. m.	3:25 a. m.	13	10	65.	855.40	2447.3	32206.46	250	3290.00	186.5	2454.34
2	" "	2:50 "	12	35	23.52	295.88	770.92	9698 17	125	1572.50	61.2	769.896
3	" "	2:50 "	12	35	23.52	295.88	770.92	9698.17	125	1572.50	61.2	769.896
4	" "	1:45 "	11	30	23.52	270.38	770.92	8865.58	125	1437.50	61.2	703.80
5	" "	1:45 "	11	30	23.52	270.38	770.92	8865.58	125	1437.50	61.2	703.80
6	7:00 a. m.		24		52.5	1260.00	3068.6	73646.40	250	6000.00	242.6	5822.40
7	" "		24		52.5	1260.00	3068.6	73646.40	250	6000.00	242.6	5822.40
8	" "	5:45 "	22	45	52 5	1194.37	3068.6	69810.65	250	5687.50	242.6	5519.15
9	" "	5:30 "	22	30	52.5	1181.25	3068.6	69043.50	250	5625.00	242.6	5458.50
Totals						6883.54		355480.98		32621.50		28024.182

Average square feet grate surface $\frac{6883.545}{24} = 286.73$

Average square feet water heating surface $\frac{355480.98}{24} = 14811.7$

Average rated horse-power $\frac{32621.50}{24} = 1359.2$

Average real horse-power $\frac{28024.182}{24} = 1167.66$

TABLE 3.

Record of Test of Station. September 7–8, 1895.

Table showing the number of hours during which the respective boilers were in service.

No. of Boilers.	Hour started Sept. 7.	Hour stopped Sept. 8.	No. of hours in service. Hrs.	Min.	Sq ft. grate surface.	Sq. ft. grate surface hours.	Sq. ft. water heating surface.	Sq. ft. water heating surface hours.	Rated Horse-power.	Rated Horse-power hours.	Real Horse-power.	Real Horse-power hours.
1	2:25 p. m.	6:00 a. m.	15	35	65.	1012.895	2447.3	38128.93	250	3895.75	186.5	2996.229
2	" "	3:15 "	12	50	23.52	301.76	770.92	9890.90	125	1603.75	61.2	785.196
3	" "	" "	12	50	23.52	301.76	770.92	9890.90	125	1603.75	61.2	785.196
4	" "	3:20 "	12	55	23.52	303.64	770.92	9962.57	125	1613.75	61.2	794.892
5	" "	" "	12	55	23.52	303.64	770.92	9962.57	125	1613.75	61.2	794.892
6	7:00 a. m.		24		52.5	1260.00	3068.6	73646.40	250	6000.00	242.6	5822.4
7	" "		24		52.5	1260.00	3068.6	73646.40	250	6000.00	242.6	5822.4
8	" "	12:45 "	17	45	52.5	931.87	3068.6	54787.15	250	4437.50	242.6	4306.150
9	" "	5:50 "	22	50	52.5	1198.57	3068.6	70467.07	250	5625.00	242.6	5538.558
Totals.....						6874.135		350382.89		32393.25		27555.913

Average square feet grate surface $\frac{6874.135}{24} = 286.45$

Average square feet water heating surface $\frac{350882.89}{24} = 14599.7$

Average rated horse-power $\frac{32393.25}{24} = 1845.71$

Average real horse-power $\frac{27555.913}{24} = 1147.32$

In column 6 of table 4 the results contained in the boiler log between the hours of 3 P. M. Sept. 7, and 1 A. M, Sept. 8, are given in the form of a report on a test of all the boilers in the station operating at one time, and in column 8 a similar record is reported of the economy of the plant when working under the heavy load that comes on the station between 7 P. M. and midnight.

The graphical records of this boiler trial are presented in Fig. 2 and for the value of the comparison the total indicated horse power curve is plotted, in connection with the curves that pertain purely to the boiler tests.

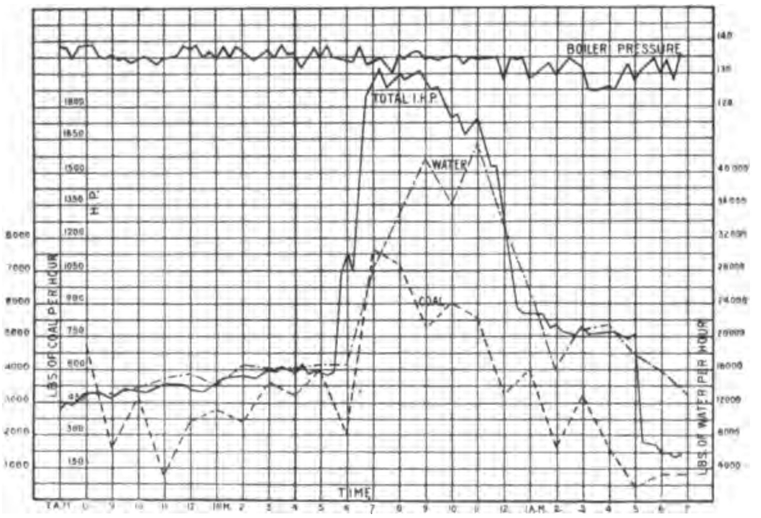

FIG 2.—Pratt Street Station, Graphical Record, Sept. 7, 1895.

REVIEW OF THE BOILER TESTS.

As the tests and portions of tests that have been reported amount to nine in all, and require a table containing ten columns, it is necessary to refer to the tabulated quantities by numbers.

The signification of the numbers is as follows:

1. Number of boilers in service.
2. Duration of trial.
3. Boiler pressure by gauge.
13. Temperature of steam.
15. Temperature of feedwater leaving heater.
15.5 Temperature of feedwater entering heater.

17. Per cent. of moisture in coal.
19. Per cent. of refuse in coal.
24. Per cent. of moisture in steam.
31. Water actually evaporated per pound of dry coal, from actual temperature and pressure.
32. Equivalent water evaporated per pound of dry coal, from and at 212 degrees Fah.
33. Equivalent water evaporated per pound of combustible from and at 212 degrees Fah.
35. Dry coal actually burned per sq. ft. of grate surface per hour.
39. Water evaporated from and at 212 degrees Fah. per sq. ft. of heating surface per hour.
43. Commercial horse power.
44. Horse power by builder's rating.
44.5 Horse power on a basis of 11.5 sq. ft. of heating surface in the tubes per horse power.
45. Per cent. of item 43 below item 44.
45.5 Per cent. of item 43 below item 44.5.

TABLE 4.

BOILER TEST DATA.

0	1	2	3	4	5	6	7	8	9
Number	7 A. M. Aug. 31, to 7 A. M. Sept. 1.	7 A. M. Sept. 7, to 7 A. M. Sept. 8.	7 A. M. Aug. 31, to 1 P. M. Aug. 31.	7 A. M. Sept. 7, to 1 P. M. Sept. 7.	3 P. M. Aug. 31, to 1 A. M. Sept. 1.	3 P. M. Sept. 7, to 1 A. M. Sept. 8.	7 P. M. Aug. 31, to 12 M.M.	7 P. M. Sept, 7, to 12 M.M.	6 P. M. Sept. 1, to 5 A. M. Sept. 2.
1	All at Times.		6, 7, 8, and 9.		1, 2, 3, 4, 5, 6, 7, 8, 9.		1, 2, 3, 4, 5, 6, 7, 8, 9.		6, 7, and 8.
2	24	24	6	6	10	10	5	5	11
7	126	134	127	136	127	135	126	135	126
13	353	357	352	357	354	357	353	358	353
15	200	200	207	200	205	200	206	200	191
15.5	71.3	70.5	71.4	70.8	71.3	70.5	71.3	70.0	71.4
17	13.8	6.26	3.1	6.26	13.8	6.26	13.8	6.26	3.1
19	10.4	10.	10.4	10.	10.4	10.	10.4	10.	10.5
24	.81	.97	.70	.83	.90	1.04	.95	.91	.87
31	7.18	7.04	8.33	5.80	7.23	6.48	7.88	7.40	10.1
32	7.59	7.46	8.87	6.15	7.77	6.86	8.34	7.84	10.7
33	8.32	8.29	9.90	6.83	8.77	7.62	9.31	8.71	12.0
35	10.4	10.6	9.53	11.6	10.8	12.2	12.5	13.8	11.4
39	1.53	1.54	1.46	1.22	1.79	1.73	2.11	2.24	2.09
43	655	654	515	430	900	895	1116	1158	557
44	1359	1359	1000	1000	1750	17.50	1750	1750	750
44.5	1168	1147	970	970	1402	14.02	1402	1402	728
45	51.7	51.8	48.5	56.6	48.5	49.0	36.2	33.8	25.7
45 5	43.8	43.9	46.9	55.2	35.7	36.1	20.5	17.5	25.4

The quality of the coal fired to the boilers during the tests was only fair, and as shown in item 19, contained quite an amount of ash and other refuse. The coal was soft and a great deal of it very fine, and it crumbled to pieces under very slight pressure. Altogether I should say that its quality was considerably below the average of the coal that is mined at George's Creek, western Maryland, the point from which the coal in question was obtained.

Nevertheless the evaporative efficiency of the plant is very fair. Item 31 shows that the evaporation per pound of coal varied from 7.04 to 10.1 pounds of water under actual conditions, and the equivalent evaporation from and at 212° F. varied from 8.29 to 12 pounds of water per pound of combustible as stated in item 33. The fluctuation in these values is due partly to the fact that some of the boilers are more efficient than others, but the most potent factor in the reduction of the economy is the inefficient loading of the plant.

During the greater portion of the time the boilers were not developing 60 per cent. of their capacity based upon 11.5 square feet of heating surface in the tubes per horse-power, and at other times they were not developing half of their capacity. This statement is equivalent to saying that during a considerable portion of the test a good share of the heat of the furnaces was used up in heating the iron frame work and the walls, instead of being utilized in evaporating water into steam.

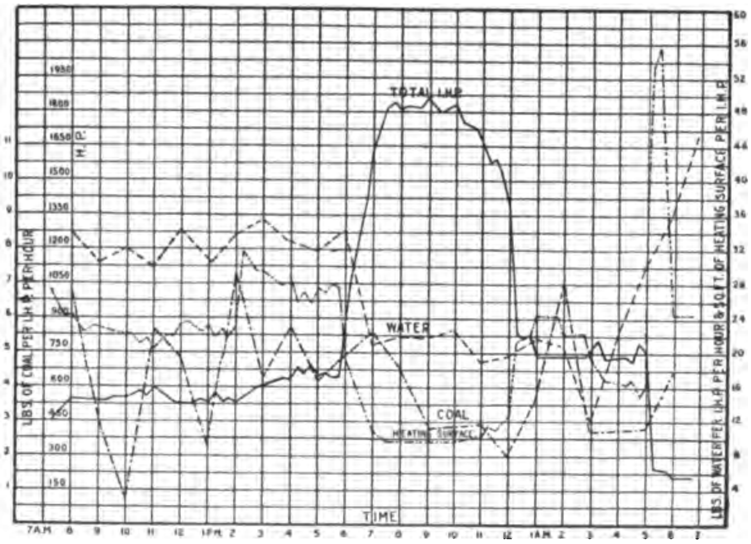

FIG. 3.—Pratt Street Station, Economy Record, Ang. 31, Sept. 1, 1895.

To illustrate this condition of affairs more clearly, an economy record has been plotted in Figs 3 and 4. These plates show the relative amount of coal, water and square feet of heating surface in the boilers per indicated horse-power. The "heating surface" curves are the ones to which I would call your attention at present. It will be noticed that up to 2 o'clock in the afternoon of each day there was an average of over 22 square feet of heating surface in the part of boiler plant in active operation to each indicated horse-power developed by the engines. Between two o'clock and six o'clock, the ratio of heating surface to horse-power is increased to 29, and it is not until 7 P. M. that the ratio falls within the limits of economic operation. Between 7 P. M. and midnight on August 31, the boiler plant developed within 20 per cent. of its true horse-power and as a result the economic evaporation went up to a very good value—9.3 pounds of water per pound of combustible. The same result was apparent during the same period on the night of September 7, and although the evaporative efficiency is not apparently as high, it is well above the average evaporative efficiency of the plant for the whole 24 hours. In considering the results of the partial tests it must be borne in mind that they are not absolute. They are based on the assumption that the water and coal were supplied to the boilers in just the proportion necessary to meet the requirements of the load, but of course it was not possible to do this with absolute accuracy. For instance, the curves in Figs. 1 and 2 show that proportionally more coal and less water were supplied to the boilers on August 31 between midnight and 7 A. M., than during

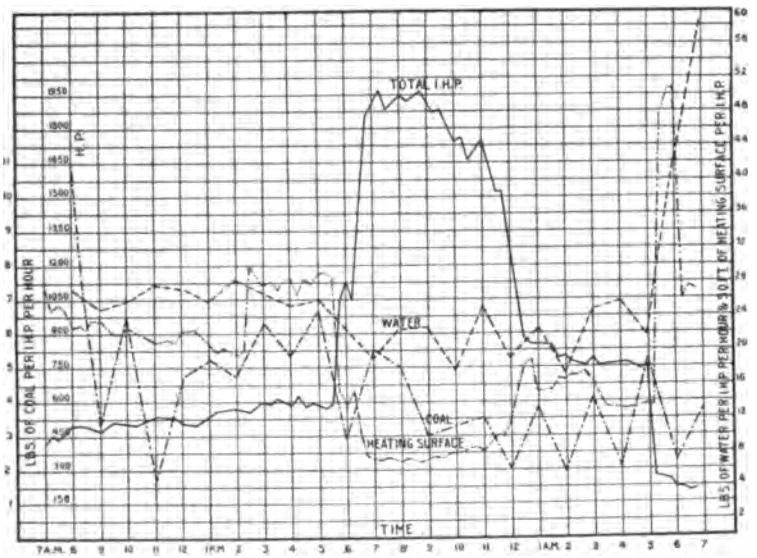

FIG. 4.—Pratt Street Station, Economy Record, Sept. 7 and 8, 1895.

the same hours on September 7, and the effect of this is to reduce the apparent evaporative efficiency of the boilers on September 7, during the periods covered by the partial reports. None of the partial reports take in the early morning hours.

It is noticeable, however, that the efficiency of the boilers is relatively lower during the periods when the average heating surface per I. H. P. is high than at other times. Between 3 P. M. and 1 A. M., for instance, when there is an average of about 16 square feet of heating surface per I. H. P., the boilers only develop 64 per cent. of their capacity and only evaporate an average of 8.19 pounds of water per pound of combustible (see item 33).

Some of the boilers seem from the results to be less efficient than others. In bringing out this point let us compare the evaporative efficiency of the "new" boilers on the east side of the station with that of the "old" boilers on the west side of the station. On September 7, between 7 A. M. and 1 P. M., the "new" boilers were the only ones in service. By item 45.5 they were developing only 44.8 per cent. of their capacity, but their evaporative efficiency per pound of combustible averaged 6.8 pounds of water.

On the morning of August 31, the same boilers evaporated 9.9 pounds of water per pound of coal when loaded to only 53 per cent. of their capacity, and on the night of the special test (see column 9, table 4) they evaporated an average of 12 pounds of water per pound of combustible when working under a load of less than 75 per cent. of their capacity. These figures are all excellent when the conditions are taken into consideration and indicate that the "new" boilers are highly efficient.

Now, although the old boilers were never operated alone, and we have no records showing their absolute evaporative efficiency we can nevertheless judge of their economy very accurately by noting the effect they have upon the evaporative efficiency of the plant when they are operated in connection with the "new" boilers. For instance, between 3 P. M. and 1 A. M. of each of the 24-hour tests the whole plant was loaded to 64 per cent. of its capacity and it evaporated an average of only 8.2 pounds of water per pound of coal. This figure does not begin to equal the evaporation of the "new" boilers when operated alone, at a less percentage of their capacity. Again the whole plant even when operated at an average of 81 per cent. of its capacity between 7 P. M. and midnight did not reach the evaporative efficiency that the "new" boilers developed on the morning of Aug. 31, and did not come within 17 per cent. of the evaporative efficiency of the "new" boilers during the special test, although they were more efficiently loaded.

It seems that sufficient evidence has been produced to establish the assertions that the evaporative efficiency of the "new" boilers is good, and that the evaporative efficiency of the whole plant is only fair. This means that there is a disturbing element present somewhere and the general indications are that the defect lies in the old boilers. It would not be surprising to find that the "old" boilers will not evaporate over 6.5 or 7 pounds of water per pound of coal even under the most favorable conditions of loading and when fired with the best quality of coal. During my stay at the plant, I several times had my attention called to the fact that great difficulty was often experienced in keeping up the steam pressure in the "old" boilers, and this was expressly noticeable whenever the "new" boilers were cut out for any reason and the "old" had to be depended upon to furnish the steam supply.

The quality of the steam evaporated by the boilers remained fairly constant. At no time during any of the tests however was the slightest trace of superheating discernible. The smallest percentage of moisture recorded is that at 2 P. M. on Sept. 7, when only .3 of one per cent. of moisture was apparent. The greatest percentage of moisture was recorded at 6 A. M. on Sept. 7, when there was 1.24 per cent. of moisture in the steam. On the whole however, the percentage of moisture is low and it is also very uniform for all loads. It may be well to note that the pipe condensation, as determined by collecting and weighing all the drainage water from the separators and steam traps, proved to be .505 of one per cent. of the total water actually evaporated on Aug. 31; .31 of one per cent. of the water actually evaporated on Sept. 7; and nearly .5 of one per cent. of the water actually evaporated during the special test. These figures represent to a large extent the proportion of the entrained water and water of condensation that was extracted from the steam by the separators, as most of the drainage water was taken from them, and it is safe to say that the separators extract fully 70 per cent. of the moisture contained in the steam, from the steam. This leaves the steam practically dry when it passes the separators. The average of about 2 per cent. of moisture that the steam in the steam pipe of engine No. 1, was found to contain on the night of the special test, was largely due to there being no separator between the engine and the boilers.

The greatest amount of coal is fired to the boilers on both days between 7 and 8 o'clock in the evening when the fires are being built up for the heavy night load. At this time the coal is supplied at the rate of 7500 pounds per hour. On this account exception may be taken to the evaporative efficiencies determined for the boilers between 7 P. M. and midnight on the score that the proportion of the coal fired within this time is in excess of the normal requirements of the boilers. In answer to this I will call attention to the fact that the fires were about burnt out at midnight, as the coal curves of Fig. 1 and 2 both show that the rate of firing had to be increased immediately after midnight.

The rate of combustion per square foot of grate surface conforms to the practice common with boilers of this class. The maximum rate maintained was 13.8 pounds on September 7, during the heavy night run, and the lowest appears to have been on the morning of August 31, when it amounted to 9.5 pounds. The maximum efficiency of the boilers will probably be attained when the combustion averages between 12 and 13 pounds of coal per square foot of grate surface per hour. The rate of combustion per square foot of heating surface is also rather low and plainly indicates that even during the heaviest loads the limit of economy in this respect was not reached by 20 or 25 per cent.

Finally, the results of the tests demonstrate the fact that the daily economy of the station would be greatly improved if greater care were exercised in the adjustment of the capacity of the boilers in service to the load. Boilers Nos. 6, 7, 8 and 9 will easily and economically generate an actual indicated horse-power for every eight square feet of their heating surface. This will make the capacity of each boiler, relatively to the demands of the engines, equal to 350 H. P., and will represent a total capacity equivalent to 1,400 I. H. P. If the requirements of the load had been economically met, only boilers 6 and 7 would have been operated between 7 A. M. and 6 P. M. on the days of the tests; between 6 and 7, boilers Nos. 3, 4, 5, 8 and 9 would have been cut in; between 11:30 P. M. and 12:30 A. M., boilers 3, 4 and

5 would have been cut out, and between 12:30 A. M. and 1 A. M. boilers 6 and 7 would have been cut out. This would have left boilers 8 and 9 in service to carry the load until 5 A. M. when one of them could have been cut out and the other left to carry the Sunday load, which is always light. Such a boiler schedule would have entirely eliminated the necessity of operating the entire plant and would have resulted in an average economic evaporation of between 11 and 12 pounds of water per pound of coal.

This would mean a saving of between 25 and 31 per cent. of the coal fired into the boilers. These figures are based on the assumption that boilers 1, 2, 3, 4 and 5 will evaporate the water for one indicated horse-power per hour from each 11.5 square feet of their heating surface, and that boilers 6, 7, 8 and 9 will evaporate the water for an indicated horse-power per hour from each eight square feet of its heating surface. Under these conditions the boilers would be economically loaded and capable of developing their best economy in consequence.

If we compare the actual economy of the station boiler plant with the results that have recently been published by the *National Electric Light Association*, we find that the actual evaporation per pound of coal is above the average, that the actual evaporation per pound of combustible is about equal to the average, and that the evaporation from and at 212 degrees, per pound of combustible, is a little below the average of the figures published for these quantities.

This simply means that there is room for improvement, although it must be admitted that the coal used in the stations exceeding the economy of the Pratt Street Station seems to be of better quality.

During the heavy loads the economy of the boiler plant was above the average of tests reported, and during the " special " test it exceeded everything reported by the *National Electric Light Association.*

NOTES ON THE ARC LIGHTING MACHINERY.

The special test of Engine No. 1 and Dynamos No. 7 to No. 18 :—Three tests were made upon engine No. 1 and the arc light machinery driven by it. Two of these, the first and the last, were made in connection with the general station tests of Aug. 31st and Sept. 2nd, but the second was for the special purpose of determining the evaporative efficiency of the newer part of the boiler plant; namely, boilers Nos. 6, 7, 8, and 9, and the steam consumption per indicated horse power per hour of the engine in question.

For the special test it was decided to use boilers, Nos. 6, 7, and 8, thus providing a total boiler capacity of 750 H. P. to meet the requirements of the load on the engine, which frequently amounted to over 700 H. P.

The stop valves leading to engines Nos. 2, 3, 5, and 8 were securely closed. Suitable small tanks were provided to receive the water that acccumulated in the separator in the centre of the station and to catch the condensed steam, when it was removed from the various points at which it collected. The total amount of pipe condensation for the eleven hours' run was 1168.9 pounds or 0.5 of one per cent. of all the water evaporated in the boilers.

The report of the trial of the boilers is given in table 4, column 9. The performance of the boilers was very creditable. The evaporation of 12 pounds of water per pound of combustible from and at 212° Fah. is far above the average evaporation obtained in the central stations throughout the country and will compare favorably with the best tests yet reported upon water tube boilers. The average horse-power developed by the boilers during the test was 25.75 per cent. below the rating of the boilers, allowing 11.5 sq. ft. of heating surface in the tubes per horse-power. The evaporation of 12 pounds of water would therefore probably have been exceeded had the load upon the boilers been heavier, as they are designed to admit of a considerable overload.

The quality of the steam evaporated was determined by a throttling calorimeter placed in the side of the east main between boilers No. 7 and No. 9. The results showed that at no time was there more than 1.07 per cent. of moisture in the steam and that at times this figure was reduced to 0.7 of one per cent.

The pyrometer test of the flue gases showed that their temperature at the base of the stack, where the pyrometer was placed, was about the same as the temperature of the steam generated in the boilers. This indicates that little of the furnace heat is wasted, and speaks well for the design of the boiler.

The load on the engine was practically constant at 700 H. P. during the earlier part of the evening, and was reduced to a value of about 480 H. P. during the latter part.

The average I. H. P. for the whole test is 553.82 H. P. and the average E. H. P. is 382.6 H. P. The ratio of these would give an apparent efficiency of conversion of 69.04 per cent. This is the usual method of determining such efficiencies and it gives a very gratifying result, when we compare it with similar results of tests on lighting plants of this type that have been published. The real average efficiency, however, is the average of the ordinates of the efficiency curve which is 66.7 per cent. This is the lowest value obtained on either of the three tests made upon this engine, a fact that is probably due to the load having been somewhat lighter than during the other tests.

One object of this test, however, was to determine the actual water consumption of the engine. The values were obtained by dividing the pounds of water delivered to the boilers during each hour by the average I. H. P. for the corresponding hour. The amount varies from 26.9 to 38.3 pounds, the average being 32.96 pounds of water per I. H. P. per hour. This value is extremely high for an engine of this type. The theoretical value computed from the indicator cards gives an average of about 18 pounds of water per I. H. P. as the water consumption. If we add to this the percentage for internal condensation that practical experience has shown is necessary, we find that the engine ought not to require over 23 pounds of water per I. H. P. and everything above this value is in excess of the limit of even fair economy. This excessive water rate is partly due to the low ratio of expansion employed, but chiefly to leakage of steam past the pistons of the engine.

An examination was made of the cylinders, and the valves and pistons were tested for leakage. The inside of the high pressure cylinder was found to be quite a good deal cut all round, especially on the left side parallel to the axis of the cylinder. When steam was turned on it blew past the piston uniformly all round, except in one place on the right side where the leakage was somewhat greater. The steam chest cover was removed and the valve examined. The design of the valve is such that it delivers steam from both sides. It seemed to be tight on its seats but the steam leaked through a joint in its center into the receiver.

The steam chest cover and the high pressure cylinder cover were replaced and the low pressure cylinder head removed. The bottom and the sides of the low pressure cylinder half way up, showed a good deal of wear, the surface of the cylinder being quite rough. With the crank of the high pressure piston on a dead center, steam was turned on. It leaked into the receiver, and the pressure in the receiver rose to 15 pounds gauge pressure in one minute, although steam was blowing past the low pressure piston freely all the time.

Fifteen pounds pressure in the low pressure cylinder should have been sufficient to blow the piston rings out to the sides of the cylinder and stop the leakage past the piston had the piston, its fittings and the sides of the cylinder been in good condition. There can be no reasonable doubt but that there was leakage of steam past the pistons of this engine during its operation. This fact can also be detected from the indicator cards. The results of the calorimeter tests that were made of the quality of the steam in the steam pipe and the receiver during the run of Sept. 1st and 2d, show that at 10 P. M. the steam entering the high pressure cylinder contained 1.86 per cent. of moisture, but that when it was discharged into the receiver it *contained only* 0.79 *per cent. of moisture.* About this same quality was determined for the steam in the receiver during the entire time of the heavy load, but whenever the load became lighter (500 H. P. or less), so that the steam expanded to about twice its initial volume in the high pressure cylinder, between 7 and 13 per cent. of moisture became apparent in the steam in the receiver. In other words the steam was wet when discharged from the high pressure cylinder. These results were obtained with a throttling calorimeter on the steam pipe, and a throttling and a separating calorimeter on the receiver, and have an important bearing upon the water consumption of the engine.

So far nothing has been said regarding the mechanical efficiency of engine No. 1.

The engine is directly connected to a very large line of shafting extending along the east side of the station a distance of 70 feet. This line shaft is supported on eight evenly spaced pedestal bearings, and is equipped with 12 friction clutch pulleys to which the dynamos are belted.

The average indicated friction horse power of the engine amounted to 54.31 H. P. with the clutches thrown on, and to practically the same (54.1 H. P.) with the clutches thrown off. These are the lowest values of the friction load recorded, and it is a noticeable fact that the friction of the clutch pulleys is about the same as the friction of the armatures and belts of the dynamos. It would therefore seem that although the use of friction clutches reduces the wear on the dynamos when they are out of service, they do not reduce the friction load.

The friction cards taken on Aug. 31st indicated that the power absorbed in the friction of this shafting is often in excess of the figures just noted. In fact, the results of the tests made on Sept. 1st and 7th show a difference of over 225 H. P. at times between the indicated horse power of the engine and the total electrical horse-power developed. If we allow 40 H. P. of this amount for

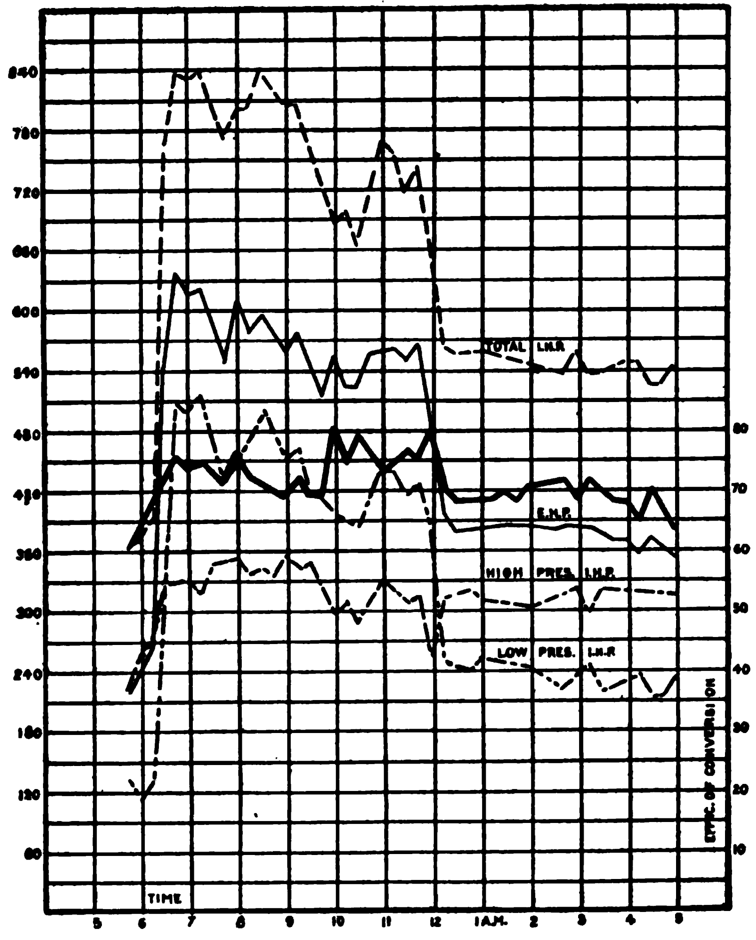

FIG. 5 —Engine No. 1. Dynamos Nos. 7 to 18, Sept. 7 and 8, 1895.

the friction of the engine alone, and the same amount for the friction of all the loaded dynamos, 145 H. P. or 18 per cent. of the power developed by the engine still remains unaccounted for, and since an ample allowance has been made for the engine and dynamos, it may be attributed to the friction of the shafting. This excessive friction only occurs during the heavy loads of 700 I. H. P. or over. On the night of August 31st the friction horse-power during the heavy load averages somewhat less than 225 H. P.; only about 150 H. P. in fact. During the lighter loads of 500 H. P. or less, the three tests show a very uniform friction loss of about 145 I. H. P. If we assume therefore that this engine is operated for 11 hours a day during 313 days in the year (which is practically the case) then there is an average total friction loss of 175 H. P., during that time, of which 100 H. P. is due to the friction of the line shaft alone.

TABLE 5.

DATA FROM TESTS OF ARC MACHINES.

No. of arc dynamo.	Resistance.		Average Voltage Developed.			Average electrical efficiency. per cent.
	Armature.	Regulator and series field.	Aug. 31.	Sept. 1.	Sept. 7.	
7	13.63	30.81	3773	3728	3819	90.22
8	13.2	32.42			4097	90.44
9	13.05	31.96	2957	3110	3368	88.01
10	13.47	30.5	2545	3387	3330	88.04
11		30.1	2810	3801	3784	
12	12.43	29.7	3849	2970	3867	89.89
13	13.1	30.55	3606	3667	3896	89.72
14	13.2	30.59	3344	3706	3142	88.80
15	13.05	30.8	3622	3631	3858	89.85
16	13.11	31.09	3450	3320	3690	89.22
17	12.5	29.01	3240	3440	3799	89.83
18	12.51	30.4	3452	3505	3644	89.62

Economy of the Arc Machines.—The average commercial efficiencies of the dynamos for the three tests recorded show that an average greater than 76 per cent. was maintained each day. These percentage ratios were obtained by dividing the total E. H. P. by the D. H. P. of the engine and are therefore decreased by the friction losses of the line-shaft and of the dynamo belts. The true efficiencies of the dynamos are therefore higher than these figures would indicate, and although it was impossible to make any exact determination, the following condensations lead us to a very close approximation. In table 5 will be found a statement of the average electrical efficiencies of the dynamos. These are determined from the measurements that were made of the resistances of the armature and field windings of the machines and the average electrical horse-power developed by each machine during the three tests. The average of these efficiencies is 89.4 per cent., and if 5 per cent. is allowed for the remaining losses, we get 84 91 per cent. as the average commercial efficiency of the dynamos.

If we assume that the average yearly load upon the engine is 606 H. P., 68 per cent. of it is delivered as electrical energy for distribution, about six per cent. is absorbed in overcoming the friction of the engine, 10 per cent. is dissipated as heat due to the electrical and mechanical losses of the dynamos and 16 per cent. is absorbed in running the line-shaft.

Engine No. 2, Arc Machines Nos. 4, 5 *and* 6, *and the Wenstrom Dynamo.*—The engine is of the Russell four valve type, and as originally designed was regulated by an automatic fly-wheel governor. As, however, the fly-wheel governor did not work satisfactorily under 125 pounds boiler pressure, it was removed and the engine equipped with a throttling governor after the valve gear had been somewhat modified.

Previous to the tests the engine was thoroughly examined. The cylinder was in good condition. It was found, while measuring the clearance of the cylinder heads, that the piston and valves leaked water, but on the other hand they proved to be tight to steam when it was turned on to its full force.

During the tests a steam gauge was placed on the steam chest and a throttling calorimeter connected near it. These were the only special arrangements made.

The distribution of the power developed by the engine, between the ends of its cylinder was very nearly equal. There seemed however, to be a tendency to over-balance on the head end. But the most striking feature in connection with this engine is the action of the throttling governor. The initial steam pressure shown by the cards and the boiler pressure are graphically exhibited in Fig. 6. It is noticeable that although the boiler pressure is practically constant at something over 125 pounds gauge pressure, the steam chest pressure remains at about 35 pounds all during the day and falls as low as 20 pounds whenever the I. H. P. of the engine falls below 50 H. P. Even when the engine is developing 160 I. H. P. the steam chest pressure does not average above 50 pounds by gauge. This excessive throttling of the steam to from .4 to .16 of its initial pressure is very wasteful of the heat energy contained in the steam and results in a high water consumption per I. H. P. per hour.

The calorimeter tests made upon the quality of the steam in

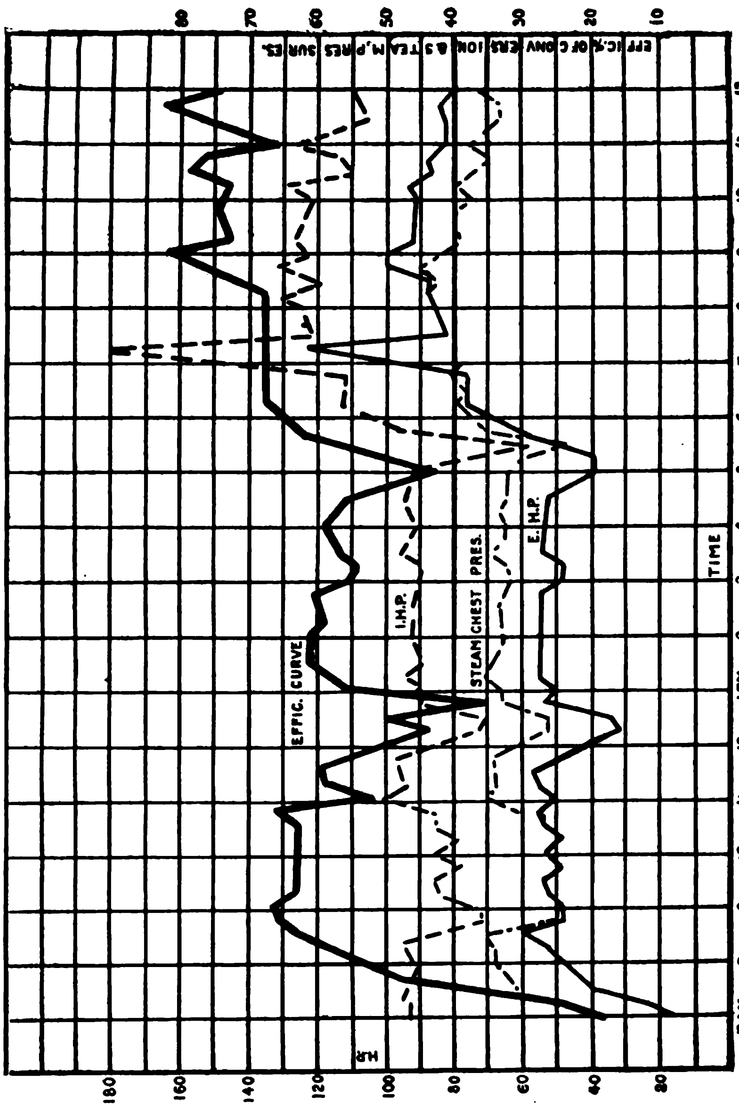

Fig. 6.—Engine No. 2. Dynamos 4, 5, 6 and W. Sept. 7 and 8, 1895.

the steam pipe, and in the steam chest, showed that as high as 24.4 degrees superheat is developed in steam initially containing 1.27 per cent. of entrained water.

In the calculations that have been made of the actual water consumption of the engine per indicated horse-power per hour, the theoretical results have been assumed to be correct, owing to the superheated condition of the steam entering the cylinder, and no allowance is made for cylinder condensation. Even under these conditions, the water consumption is high; during the light loads of about 50 H. P. it amounts to 49 pounds of water and during the heavy loads of 158 H. P. it runs as high as 30 pounds of water. Had the same correction for condensation been made here as in the case of the other simple engines the above figures would have been 64 and 35 pounds of water respectively.

The difference between the I. H. P. and the E. H. P. during the two days tests seem to average about 35 H. P. *for all loads* above 80 I. H. P. of the engine. This shows at once the advantage to be gained by keeping the engine well loaded.

To secure high efficiency it is by all means necessary to operate arc dynamos as near full load as possible, their efficiency at half load being little better than 70 per cent. and at one quarter load only about 50 per cent. The bearing of this fact upon the case in hand becomes evident when it is known that during the day all the dynamos operated by this engine are loaded to less than one-half their normal capacity.

Engine No. 3 *and Arc Dynamos Nos.* 1, 2 *and* 3:—Upon examination, the equipment was found to be in good order. The engine proved to be sound in every particular.

In view of the fact that this engine, one of the oldest in the station, is in such good condition, and that it is operated under low pressure superheated steam, the temperature of which is almost as high as the temperature of the high pressure steam in the steam pipe, it does not seem probable that the excessive cutting in the cylinders of some of the engines can be due either to grit brought over in the steam from the boilers, or to the temperature of the steam interfering in the least with the cylinder lubrication. It would appear rather to be due to the fact that the engines referred to have not been properly designed for use with such high pressure steam, and that in consequence the piston rings bear upon the cylinders with such force that trouble ensues. Frequently the piston rings break, and then the weak spots in a cylinder suffer severely.

Like engine No. 2, the engine under discussion is regulated by means of a throttling governor, and all of the peculiarities that were found to be characteristic of engine No. 2 are present in engine No. 3, only in an intensified degree. See Fig. 7.

During the light loads of 40 I. H. P. the water consumption accounted for by the cards averages about 55 pounds. For the heavier loads requiring 125 I. H. P. or over, the water consumption by card falls off to 30 pounds. At these loads however it is

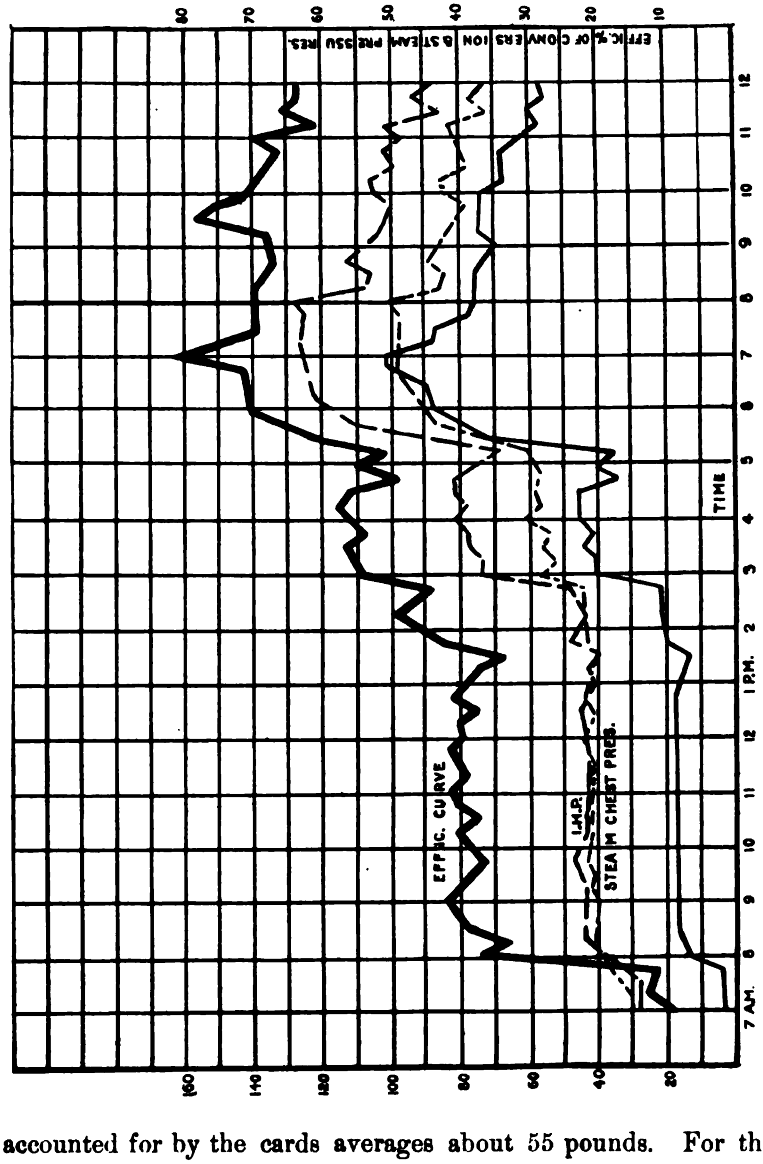

FIG 7.—Engine No. 3. Dynamos Nos. 1, 2 and 3. Sept. 7 and 8, 1895.

doubtful if the superheating is as effective in reducing cylinder condensation as at the lighter loads, both because the ratio of expansion by pressures is increased, and because the throttling of the steam during the heavier loads is very much less. Probably for these loads 25 per cent. should be added to the theoretical value for condensation.

The value of 42.59 pounds of water corresponds to the theoretical value obtained from cards showing about 70 I. H. P.; and, as during these loads the stem is throttled from 130 pounds to 25 pounds by gauge, the theoretical value is assumed to be equal to the real value.

The tests of the Arc Lighting Plant:—Being familiar with the general results of the tests made upon the arc lighting equipments considered independently of one another, it remains to give an account of the economic working of this machinery when considered in the light of a single plant. To this end the results of tests of the three separate equipments have been summed up.

On Aug. 31st the I. H. P. developed by the engines did not amount to over 150 H. P. up to six o'clock in the evening, it then rose to about 975 H. P. as the night load of commercial arc lamps and street lights came on. The total arc load remained about constant until twelve o'clock at night, when engines 1 and 2 were shut down and the commercial circuits opened. After this time the load was carried by No. 1 engine, and it remained about constant at 475 H. P. until the early morning. The efficiency of conversion averages about 61 per cent. between 7 A. M. and 6 P. M. and 12 P. M. and 5 A. M., but between 7 and 11:30 P. M. it averages not far from 77 per cent.

	Aug. 31.	Sept. 7.
The maximum I. H. P. recorded is..................	999	1146
The maximum E. H. P. recorded is..................	760	847
The average I. H. P. recorded is..................	404.8	434.8
The average E. H. P. recorded is	284.2	296.7
The average efficiency of conversion is	66.2%	61.9%

The arc lighting plant record for Sept. 7 and 8, is graphically represented in Fig. 13. The load on Sept. 7, did not average as high during the day as it did during the first test, but at night it made up for it very handsomely. The load increased on engines 2 and 3 about 5:30 P. M. and when engine No. 1 was started at six o'clock it immediately rose to a high value.

Eleven hundred and forty-six H. P. is just 250 H. P. in excess of the rated capacity of the engines, and if it had been evenly distributed would have amounted to an overload of 27 per cent. The maximum electrical load was 7.6 per cent. below the rated capacity of the electrical machinery. On account of the load being light during the day, the average efficiency up to six o'clock .P M. is but little better than 51 per cent. and even during the heavy load between 6:30 P. M. and midnight the efficiency averages 4 per cent. lower than it did on the night of Aug. 31. During the morning run, however, when No. 1 engine was operated alone under an average load about 100 H. P. heavier than the load was during the morning of Sept. 1 the efficiency improved upon the first test about six per cent.

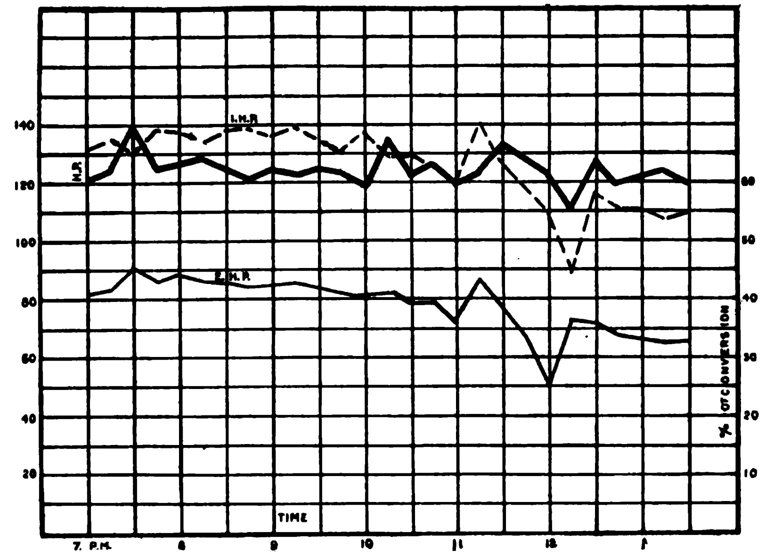

FIG. 8.—Engine No. 4, Dynamo E. Sept. 7 and 8, 1895.

Now the variations in the total efficiency of the arc plant on the two days are simply due to the fact that engines No. 2 and No. 3 were not loaded as heavily on Sept. 7 as they were on Aug. 31, and consequently although the load on the entire plant was heavier on the second day, the inefficient operation of a part of the plant entirely counteracted the good effect that usually comes with good loads.

If we calculate the apparent efficiency and take the ratio of the average I. H. P's. to the average E. H. P's. we obtain a very gratifying but a very deceptive result.

The apparent efficiency for the run of Aug. 31 is 70 per cent., and the apparent efficiency for the run of Sept. 7 is 68 per cent. A glance at the efficiency curve on Fig. 13 will immediately show that these results are of little value as an aid to gauging the *average hourly efficiency* of the plant. The "apparent efficiency" is however, of great value in determining the daily commercial economy of the machinery, since it equals the ratio of the average hourly product of the indicated horse power and the efficiency of conversion, to the average indicated horse power.

Had the entire day load been carried by engine No. 2, and had engine No. 3 not have been put in service until six o'clock (on either day,) No. 3 would have been just nicely loaded, and would have developed an efficiency of 75 per cent. or over. This would have had the result of making the all day efficiency of the plant about 73 per cent. on Aug. 31st and about 74 per cent. on Sept. 7th, instead of 66 per cent. and 61 per cent. respectively. When we remember that the steam economy of the plant during the day run would have been increased in even a greater proportion, the real increase in economy to be gained by such an arrangement becomes apparent.

NOTES ON THE INCANDESCENT LIGHTING MACHINERY.

Engine No. 4 and Alternator E.—This set consists of a simple horizontal high-speed Buckeye engine that is belted to a 16-pole Slattery alternator.

A very important point brought out by the tests on engine No. 4, is the necessity of having the valve of an engine properly adjusted. Without exception the cards from this engine showed that the admission of steam into the cylinder was far from free.

Between admission and cut-off the steam pressure was reduced about 40 per cent., whereas the corresponding decrease in engine No. 6 was practically negligible. As the steam pipe connections to these engines are of the same dimensions, with the advantage on the part of engine No. 4 of being nearer the boilers on the same steam main, the throttling of the steam must occur in the valve of engine No. 4. The effect of this throttling is to increase the apparent water consumption of engine No. 4, as shown by the cards, 14.7 per cent. above that shown by the cards of engine No. 6.

Engine No. 5 and Alternator F.—The engine runs very smoothly and regulates well, and the dynamo is so well designed and compounded that it needs practically no attention.

The only thing to mar the perfect adjustment of the engine was the fact that the ratios of expansion and the I. H P. developed during the test were not equalized between the cylinders. The ratio of expansion in the high pressure cylinder was about twice as great as the ratio in the low pressure cylinder. The power indicated in the high pressure cylinder was also much greater than in the low pressure cylinder.

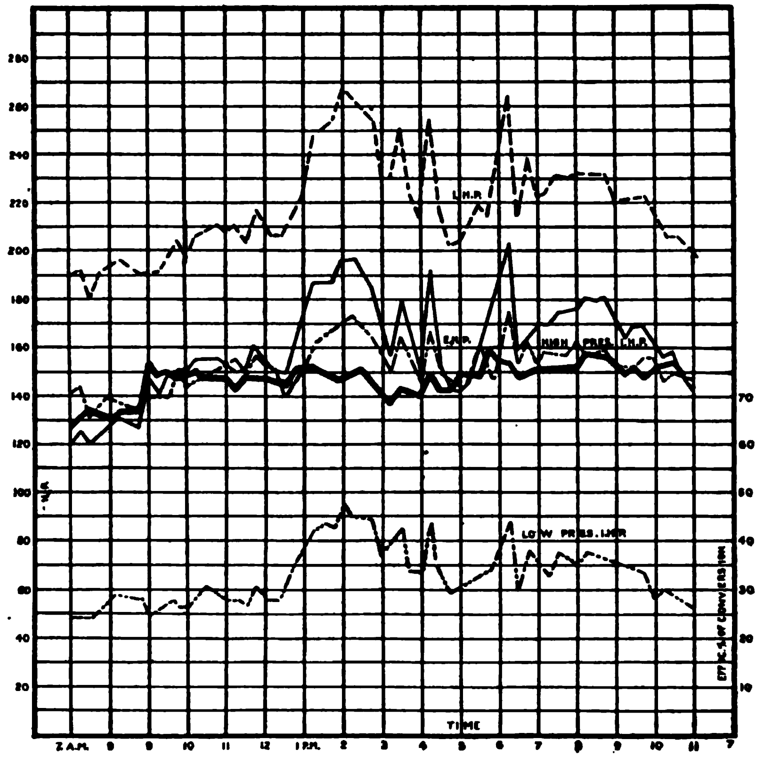

FIG. 9.—Engine No. 5. Dynomo F. Sept. 7 and 8, 1895.

During the tests, the load on the equipment required an average of 216 I. H. P. and there were no fluctuations of long duration on either side of this mean value of over 12 per cent. (see Fig. 9). If, therefore, the valves had been properly set for 216 I. H. P., there would have been a gain of several per cent. in the water consumption economy of the engine.

On the whole the performance of the engine was very creditable. It did not require much over 22 pounds of steam per I. H. P. per hour and the steam was expanded over nine times before being exhausted.

From the measurements that were made of the resistances of the various windings it would appear that the full load electrical efficiency of this dynamo is about 95.5 per cent., including the exciter and the exciter circuit. At full load the alternator develops 201 E. H. P.

The efficiency of the equipment on the basis of a full load of 200 E. H. P. on the dynamo, is 86.5 per cent. for the engine efficiency, 89.5 per cent. for the dynamo efficiency, and 77.3 as the efficiency of conversion.

Engine No. 6 and Alternator D.—The engine and dynamo that form this equipment are counterparts of engine No. 4 and dynamo E.

The dynamo was in good mechanical running order and developed no weak points during the tests.

The determinations that were made of the "actual" water consumption of the engine from representative indicator cards, ranged between 21.39 and 26.21 pounds of initially dry and saturated steam per indicated horse-power per hour, and after a careful review of the results and the conditions governing the test, it has been thought safe to assume that the engine did not consume on an average more than 22.6 pounds of steam per indicated horse-power per hour. The steam was expanded over 4.5 times, both by pressures and volumes.

The commercial efficiency of this set seems to be better than that of engine No. 4 and dynamo "E." In fact there is a difference of about four per cent. for all loads.

The efficiency of the engine is about 84 per cent. when the dynamo is fully loaded, and the efficiency of the dynamo is 88.2. These deductions are based upon the assumption that the full load efficiency of conversion of the equipment under the conditions of a constant load would be 73 per cent.

Engine No. 7 and Alternators B and C.—The engine is of the high speed cross-compound type manufactured by the Ball & Wood Company. Upon examination it proved to be in very good condition.

The records of the power developed in the cylinders indicate that the division of the work between the ends of either of the cylinders considered by itself was very nearly equal, but that the division of the work between the two cylinders was very unequal. During light loads of 150 I. H. P., 73 per cent. of the power of the engine was developed in the high pressure cylinder, and during the heavy loads of about 240 I. H. P. 60 per cent. of the total power was developed in the high pressure cylinder. Following this same proportion it appears that the power developed in the cylinders would be equal when the engine is indicating 310 H. P.

With the engine loaded to 310 H. P. it is probable that the water consumption shown by the cards and the ratios of expansion of the steam in the two cylinders would be more nearly equal, since in this event the receiver pressure would increase and compression in the high pressure cylinder decrease.

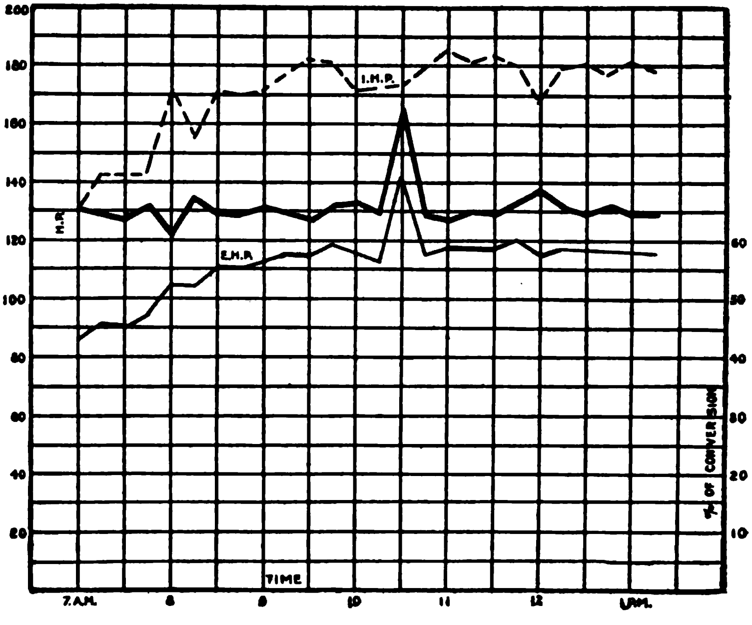

Fig. 10.—Engine No. 6. Dynamo D. Sept. 7 and 8, 1895.

At the time of making the tests, however, the valve setting was not at all adapted to the load. Cut-off in the low pressure cylinder and compression in the high pressure cylinder occurred much too late, and in consequence the receiver pressure is low, and the low pressure piston compresses the steam to a pressure between 10 and 15 pounds higher than the receiver pressure.

These things cause the water consumption shown by the cards to be greater in the low than in the high pressure cylinder. As, however, by far the *greater portion of the work* performed by the engine is done in the *high pressure cylinder*, and as the ratio of expansion in this cylinder is much higher and, therefore, the cylinder condensation proportionally greater than in the low pressure cylinder, the "actual" water consumption determined from the high pressure cylinder cards is considered to be a fairly accurate determination of the real water consumption per I. H. P. per hour of the engine.

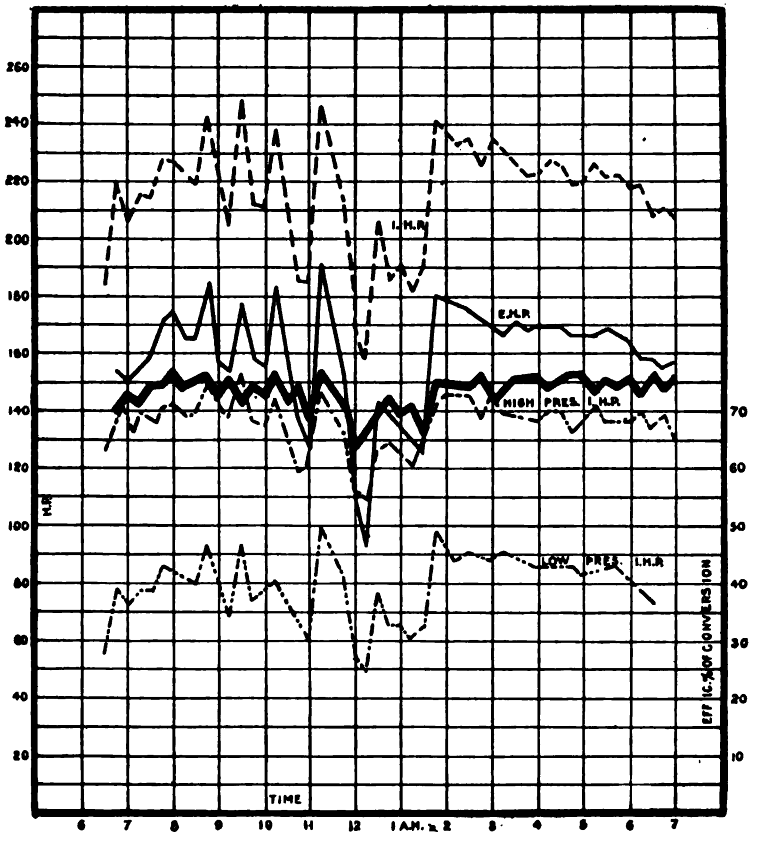

FIG. 11.—Engine No. 7. Dynamos B and C. Sept. 7 and 8, 1895.

Based upon these assumptions, the engine showed an economy of 21.5 pounds of water per I. H. P. per hour during the tests.

The final results of the tests (see Fig. 11.) show that the efficiency of this equipment, in spite of the fact that it contains *two* belted units, is very good. During the run of Aug. 31, the average efficiency of conversion was only 63 per cent. but this was because the load on the engine was very light during a considerable portion of the time, so that between 4 P. M. and 7 P. M. the efficiency of conversion averaged but little over 55 per cent. Later in the night when the load rose to 240 H. P. the efficiency also improved and averaged above 70 per cent. The importance of keeping units well loaded cannot be too strongly emphasized.

Engine No. 8 and Alternator A.—Alternator A is of the same size and type as Alternator F. The engine is very similar in its general appearance to engine No. 5, and was manufactured by the same company.

Upon examination the engine cylinders were found to be very badly cut. The high pressure cylinder was scarred around the lower half in the middle, the scars beginning and ending about three inches from the cylinder heads. The top of the cylinder was smooth as it was not subjected to the same wear as the lower surface.

The low pressure cylinder piston fitted quite loosely also. The cylinder was badly cut on the right side below the horizontal diameter and extending past the bottom line two or three inches.

When the crank was placed on its dead centers and steam turned on, it leaked past the high pressure piston a little, but *past the piston valve into the receiver to quite an extent.* During the tests it was found that this leakage was sufficient to modify the cards to a marked degree.

The greater proportion of the power was developed in the head ends of the cylinders (see Fig. 12). In fact 63 per cent. of all the work done in the high pressure cylinder was performed in the head end of that cylinder, and 56 per cent. of the work done in the low pressure cylinder was performed in its head end. But the greatest discrepancy was that due to the unbalanced distribution of the load between the cylinders. When the engine was working under light loads of 160 I. H. P. I found that 62 per cent. of the load was carried by the low pressure cylinder. As a rule, it will be remembered, the high pressure cylinder carries the greater portion of the load during the light loads on an engine, and one would naturally expect the same thing to occur in the present case. As the load increases the condition of things is improved very little, and when the engine is indicating between 260 and 300 H. P., between 60 and 65 per cent. of the power is still developed in the *low pressure cylinder.* This is of course wrong, and it occurs largely on *account of the leakage* of the steam past the high pressure piston valve into the receiver.

Under these conditions it is not surprising that the calculations for the water consumption of the engine should result in high values being obtained from the low pressure cards. Under the circumstances the value of 29 pounds of water per indicated horse-power per hour, recorded as the average performance of the engine during the tests, should be regarded as a conservative estimate, and it is fortunate if the engine did not make a greater demand upon the boilers than these figures indicate.

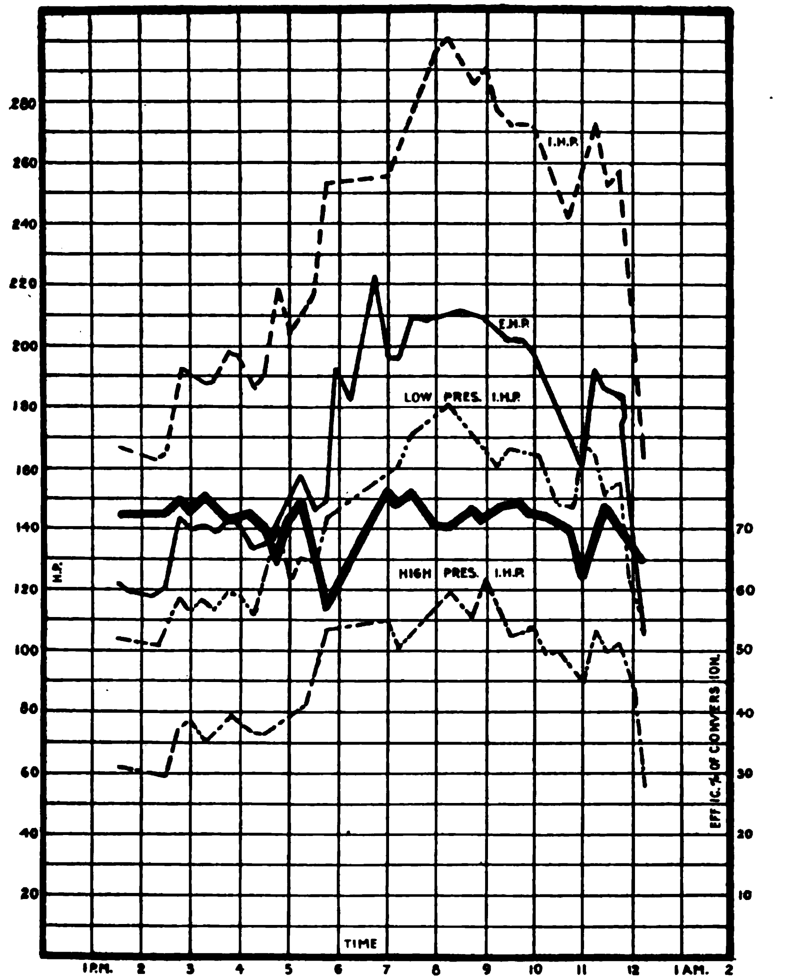

Fig. 12.—Engine No. 8. Dynamo A. Sept. 7 and 8, 1895.

The Tests of the Incandescent Lighting Plant.—We now come to a point where it will be interesting to discuss the tests that were made upon the incandescent lighting equipments collectively. It has been shown that it is possible under favorable conditions to operate these equipments at an average efficiency of conversion of 75 per cent., and it is of importance to know just what proportion of this figure was attained. If we take the average of the daily efficiencies actually attained by the several equipments, we obtain 66.48 per cent. from the figures for Aug. 31, and 69.30 per cent. from those for September 7. These results are hardly accurate, however, as they neglect the fact that all of the engines were not operated for the same length of time, and that the parts of the load they severally carried varied in amount quite as much as did the lengths of the runs.

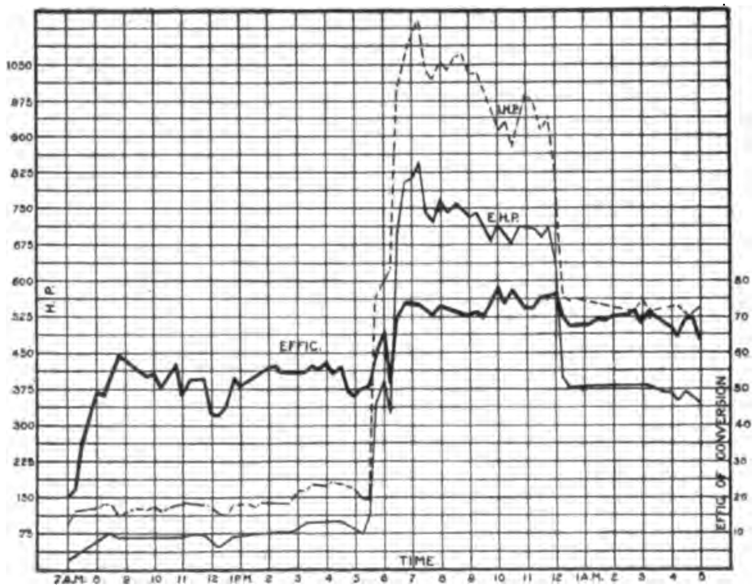

FIG. 13.—Arc Lighting Plant, Load Curves. Sept. 7 and 8, 1895.

The correct method to be followed is to sum up the indicated and the electrical powers developed for the machines for each set of readings, and from these results calculate the hourly efficiency of the incandescent plant. The average of the hourly efficiencies determined in this way will be the real average daily efficiency of conversion of the plant.

This method has been followed in making the determinations of economy that are set forth in Fig. 14.

The load diagrams show that the incandescent load of the station varied about the same on both days, both as regards the time of the variations and their amount. It starts at 7 A. M., at 350 H. P. and rises gradually to 500 H. P. which it reaches about 6 P. M.; between 6 and 8 P. M. it rises rapidly, the crest of the curve being reached about 8:15 P. M.

During the time of the maximum load about 850 I. H. P and 625 E. H. P. are developed, but this only lasts about an hour and a half, after which it rounds off gradually and finally drops to 250 H. P. about one o'clock in the morning. From this time on it remains practically constant till the end of the tests.

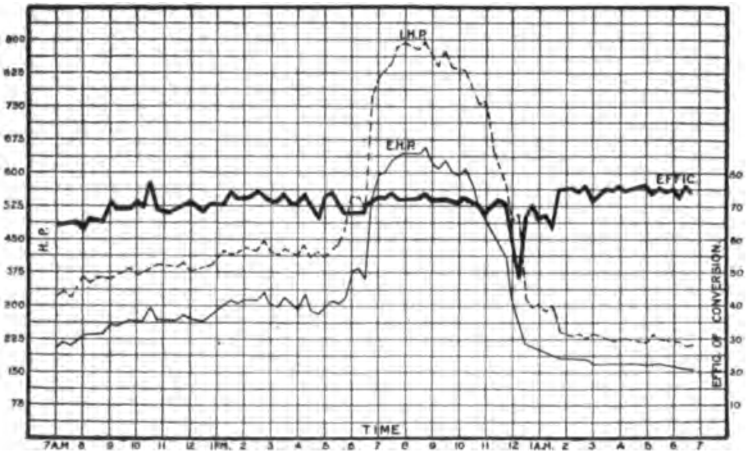

FIG. 14.—Load Curve for Incandescent Machines. Sept. 7 and 8, 1895.

On account of the greater portion of the load having been carried by the most efficient of the equipments, and the fact that all of the equipments were fairly well loaded, the efficiency of the plant remains very nearly constant during the 24 hours, and the average efficiencies are higher than the figures mentioned earlier in the discussion.

	Aug. 31.	Sept. 7.
The maximum I. H. P. recorded is	876	900
The maximum E. H. P. recorded is	598	661
The average I. H. P. recorded is	458.0	451.0
The average E. H. P recorded is	317.0	332.8
The average efficiency of conversion is	69.0	71.0

The average efficiency maintained on September 7 of 71 per cent. is very creditable when it is remembered that at times the load was divided between four belted equipments. It would seem, however, that even this result could be improved upon if it were possible to distribute the load to the best advantage between the electrical units.

In table 6 is given in tabulated form the results of a careful comparison of the actual electrical load upon the incandescent plant with the actual *rated* capacity of the electrical apparatus supplying the power, and an additional statement is given of the nearest approximation that could be made to the actual load *without going above the rated capacity of any of the electrical units.* The comparisons are expressed in terms of the per cent. that the rated power is above the power actually developed.

TABLE 6.

Time.	Per cent. of the rated capacity of dynamos running above the load.		Per cent. of the rated capacity of the best arrangement of dynamos above the load.	
	August 31.	September 7.	August 31.	September 7.
8:30 A. M.	33	42	7	19
12:30 P. M.	45	10	21	10
4:30 P. M.	60	40	7	12
8:30 P. M.	23	13	5	13
12:30 A. M	25	60	25	30
4:30 A. M	33	22	33	22

In some cases the rated capacity of the machines is 60 per cent. higher than the load, *i. e.*, the rated capacity was over twice as great as the load; and it never approaches it nearer than 25 per cent. on August 31, and 10 per cent. on September 7. The table shows, however, that in almost every case the conditions could have been greatly improved without overloading any of the machines, and if an allowable percentage of overloading were indulged in, a very much greater improvement could be made.

If the above suggestions were carried out in practice, there would not be the least element of danger introduced on account of running the machines near the limit of their rated capacity, as the overloading that every good machine can stand will amply provide for unusually rapid changes in the load.

The load diagram for every day in the week should be constructed and studied by the switchboard attendant, and he should also be informed regarding the load curves of each of the feeders leaving the station, in order that he may be able to make the best possible distribution of the load at all times. This end can, however, only be accomplished by having a very flexible arrangement of the switchboard connections and having the lighting circuits planned out and wired so as to come within the limit of the capacity of the various units.

There are some twelve incandescent circuits leaving the station, and it would appear that a more economical adjustment of the load could be made were sufficient switchboard appliances provided. In spite of the fact that the load on the plant *never* reached the capacity of the machines in operation, some of the units were nevertheless overloaded at times, and in one instance alternator A was overloaded over 30 per cent. for quite a while.

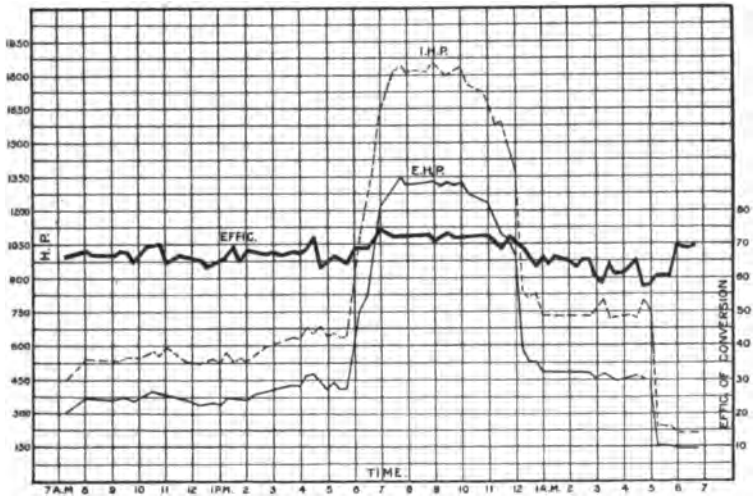

Fig. 15.—Pratt Street Station, Load Curves. Aug. 31, and Sept. 1. 1895.

It would appear from glancing over the records that engine No. 4 was needlessly operated for about four hours on August 31, and that engine No. 6 was run for even a longer period on September 7 without apparent cause.

These are the things that reduce the efficiency of a plant. They not only increase the losses between the boilers and the engines but also the losses between the engines and the switchboard.

STATION ECONOMY.

The Tests of the Station Lighting Plant.—As the heading implies, the matter that follows deals with the economy attained by the various equipments in the engine room, taken collectively, or as if they had formed but one unit. A log of the hours of starting up and stopping the engines on the two days, upon which tests of the plant were made, is given below in table 7. The data in the table only refer to the runs that were made by the engines for the purpose of developing electricity for the lighting circuits; it does not include the "friction runs." It will be noticed that the schedules upon which the engines were operated were very much the same on both days. The only differences of any importance were caused by interchanging the hours of operating engines Nos. 7 and 8.

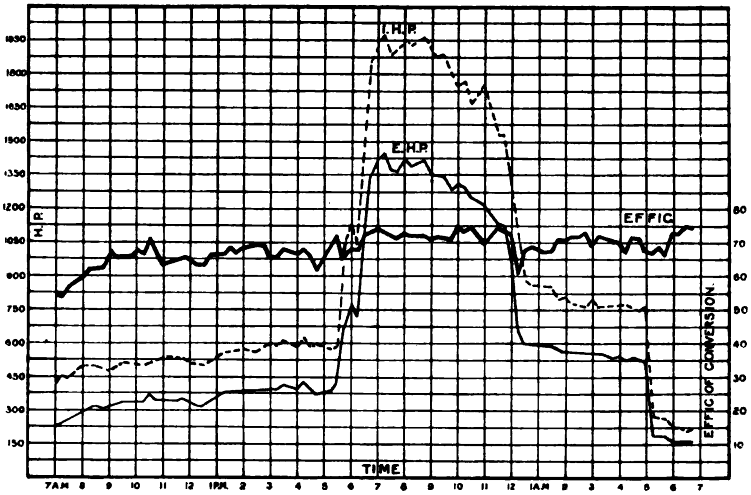

FIG. 16.—Pratt Street Station, Load Curves. Sept. 7 and 8, 1895.

The hourly records of the total indicated and electrical power developed by the station machinery are given in the graphical records constructed on Figs. 15 and 16. It is noticeable that the station load diagrams bear a strong resemblance to the load diagrams of the arc lighting plant for corresponding days, and this is especially true of the load curve for the test of September 7. This is due to the fact that the differences between the day and night loads of the incandescent plant are not so marked as are those of the arc plant. The station load diagrams for the two days are also very much like one another, and except for the peaks on the curves of Sept. 7 and 8, that occur between 7 and 8 o'clock in the evening, the curves would practically coincide if plotted on the same chart. There is also a marked similarity in the efficiency curves between the hours of 9 A. M. and 12 P. M. The low point at which the efficiency curve of Fig. 16 begins is due to the light load on the arc machinery at that time. The curve in Fig. 15 would have had the same appearance, probably, if the electrical readings from the arc machines No. 1, 2 and 3 had been obtained during the first hour of the run of Aug. 31.

TABLE 7.

HOURS OF STARTING AND STOPPING ENGINES.

No. of Engine.	August 31.			September 7.		
	Time of Starting.	Time of stopping.	Duration in hours.	Time of Starting.	Time of stopping.	Duration in hours.
1	5:50 P. M.	5:00 A. M.	11 16	5:30 P. M.	5:10 A. M.	11.67
2	7:00 A. M.	12:05 "	17.08	7:00 A. M.	12:05 "	17.08
3	7:00 "	12:05 "	17.08	7:00 "	12:05 "	17.08
3	5:00 "	6:00 "	1.00	5:10 "	5:45 "	.58
4	7:00 "	7:20 "	.33	6:45 P. M.	1:32 "	6.78
4	6:50 P. M.	10:45 P. M.	3.92			
5	7:00 A. M.	12:55 A. M.	18.92	7:00 A. M.	11:03 P. M.	16.05
6	7:20 "	10:55 "	3.58	7:00 "	1:20 "	6.33
7	2:00 P. M.	11:45 P. M.	9.75	6:30 P. M.	7:00 A. M.	12.50
8	10:45 A. M.	2:00 "	3.25	1:20 "	12:20 "	11.00
8	4:25 P. M.	6:55 A. M.	14.50			

Between 9 A. M. and 5:45 P. M. the I. H. P. curve rises gradually from 475 to 610 H. P. There is a noticeable drop in both the load and efficiency curves at noon when the arc motors are shut down, since the efficiency of the arc plant is lowered and the effect is necessarily transmitted to and made apparent in the station curves. During the day the efficiency averages about 67 per cent.

The heavy load comes on the station between 6:30 and 7 P. M. The load curves are rising very rapidly at this time, and the jump from 600 to 1800 H. P. takes place within an hour. As is to be expected, the efficiency of the station increases as the load comes on. Between 7 o'clock and midnight on Aug. 31, the load on the engines averages over 1700 H. P. and the efficiency of conversion fully 73 per cent. The efficiency attained on Sept. 7, during this period of the test averages about the same, although it is to be noticed that during the very height of the load, when the I. H. P. averages 1900 H. P. the efficiency is only about 71.5 per cent.

The lowering of the efficiency during the very heaviest load is rather peculiar. If we trace it back, we find that it comes from the load curves of the arc lighting plant and it can finally be traced to engine No. 1. At this time it will be remembered engine No. 1 indicated over 800 H. P., but an examination of the records shows that the equipment operated by this engine reaches its maximum efficiency when the engine indicates about 700 H. P. and that for loads above this value the efficiency falls off.

The greatest difference, however, between the efficiency curves of the two station tests occur during the early morning. Between 1 A. M. and 6 A. M. on Sept. 1, the load was carried by engines Nos. 8 and 1. Between 1 A. M. and 5 A. M. on Sept. 8, the load was carried by engines Nos. 7 and 1; and the variation in the efficiency is largely due to the better economy attained by the equipment driven by engine No. 7 relatively to that of the equipment driven by engine No. 8. The variation in the efficiency of engine No. 1, on the two mornings is also marked, and No. 8 is really only about half responsible for the drop in the curve.

Summing up the results, it appears that:—

	Aug. 31.	Sept. 7.
The maximum I. H. P. developed is................	1863	1975
The maximum E. H. P. developed is..	1347	1421
The average I. H. P. developed is..................	863	885
The average E. H. P. developed is....	601	629
The average efficiency of conversion is............	68.10	68.50

The average efficiency attained is excellent, and shows that the station is operated far more efficiently than is to be expected when the numerous drawbacks that have to be contended with are remembered. A high *average* efficiency means much more than a high "apparent" or, more properly perhaps, a high "commercial" efficiency. *A high average efficiency* means that the plant is working economically *all the time*, for a low efficiency of conversion maintained for a very few hours will play havoc with the average efficiency for the day.

As an example of this it is worth while to recall the average efficiency of 73 per cent. maintained by engine No. 5 for a period of 16 hours on Sept. 7. The apparent or commercial efficiency of this equipment was also 73 per cent. *A low average efficiency* means that the plant is working uneconomically all the time or very uneconomically part of the time. As an example of this, it is only necessary to turn to the test of the arc lighting plant for Sept. 7. The commercial efficiency developed by this plant was 68.31 per cent. and the average efficiency of the plant was 62 per cent.

The commercial efficiency of the station on Aug. 31, was 70 per cent. and the commercial efficiency on Sept 7, was 71 per cent. These figures speak for themselves, and are values not often attained with the prevailing central station methods.

As regards the distribution of the load on the station throughout the entire 24 hours it is interesting to note that 42 per cent. of the total watt-hour output of the station is developed during the five hours preceding midnight. The remaining 57 per cent. is distributed fairly evenly over the rest of the day. During the heavy load 8.6 per cent. of the total daily output of the station is developed per hour, while during the other portions of the day only about 3 per cent. per hour is developed.

The Engines and Dynamos:—A review of the results obtained during the tests of the machinery in the engine room will necessarily involve numerous comparisons.

In table 9 a complete summary is given of the economic performance of all the equipments and of the station.

These results have been collected from the data given in the reports on the several equipments, and the quantities tabulated are primarily based upon measurements taken from the indicator cards.

In the case of engine No. 1, however, the water consumption is based upon the results of the special test made upon it on Sept. 1, and the values given for the water economy of the station are deducted from the general results of the tests as follows:

TABLE 8.

STATION ECONOMY.

Items.	Aug. 31.	Sept. 7.
1. Pounds of water actually evaporated corrected for moisture	513304	511992
2. Pounds water actually evaporated per hour corrected for moisture	21390	21330
3. Pounds of dry coal actually fired to the boilers	71506	72667
4. Pounds of dry coal actually fired to the boilers per hour	2980	2985
5. Average I. H. P. developed by engines	862.8	885.3
6. Average E. H. P. developed by dynamos		
7. Commercial efficiency	69.68	71.11
8. Average pounds water per I. H. P. per hour	24.79	24.90
9. Average pounds coal per I. H. P. per hour	3.454	3.372
10. Watt-hour output per lb. of coal	150.5	157.3

Referring to table 8, items 1 and 3 were taken from the boiler reports, and items 5 and 6 are the averages of the total horse-power records. The commercial efficiency is the ratio of the average E. H. P. to the average I. H. P. and it is made use of in deriving item 10 from item 9. In table 9 the "pounds of coal per I. H. P. per hour" are obtained by dividing the "pounds of water per I. H. P. per hour" by the economic evaparation of the boilers. The watt-hour output is obtained from the "coal per I. H. P." as stated above.

Table 9 also contains the average results of the horse-power records, the average efficiencies of conversion, the commercial efficiencies of all the equipments of the arc and incandescent lighting plants and of the station. It is an interesting fact that a comparison of the "average" and "commercial" efficiencies shows in every case whether or not there is a great variation in the hourly efficiency of conversion of an equipment.

Table 9 also contains a comparison of the actual average water consumption per I. H. P. per hour, with the average water consumption of the engines per I. H. P. per hour calculated upon the basis of the water consumption of the engines determined from the indicator cards, and the per cent. of the total output of the station developed by the corresponding equipments.

The calculated average water consumption per I. H. P. per hour for August 31 is 31.18 pounds of water which is 20.60 per cent. greater than the actual average water consumption. The calculated result for September 7 is 28.66 pounds of water per I. H. P. per hour, which is 16 per cent. higher than the actual water consumption.

The differences between the actual and calculated values are partly due to the fact that the water consumption of the engines was not constant for all loads as it is assumed to be, since the water consumptions were figured from cards that showed an indicated power equal to the average indicated power of the engines. It must also be remembered that the amounts of the leakage that was present in the cylinders and valves of engines No. 1 and No. 8, are quantities that undoubtedly varied at times. The comparison is valuable since it shows that the water consumption credited to the engines is at least *not too low*.

The general summary contained in the table just described shows that the greater part of the output of the incandescent plant was carried by its most efficient units, engines 5 and 7, and that consequently the average commercial efficiency and water economy of the incandescent plant are higher than the corresponding results for the arc plant. Although the incandescent plant developed 52.7 per cent. of the total output of the plant, it required only about 42 per cent. of the total amounts of water and coal that were used on August 31. On September 7, owing to the fact that engine No. 8 was not operated for so long a time and engine No. 7 substituted for it, the economy of the plant is even better and apparently it consumed only 40 per cent. of the coal and water, while at the same time it developed a commercial efficiency of 73.8 per cent.

The arc lighting plant necessarily, in view of what has just been said, suffers by comparison with the incandescent lighting plant. The great difference in the economy is due to the fact that the arc lighting equipment is working at a disadvantage from every point of view. Not only is the electrical efficiency of arc lighting dynamos lower than that of incandescent machines, but the additional shafting and belting necessary for their operation introduces still other disturbing elements. When to these things is added the fact that the engines themselves are relatively less efficient than the engines driving the incandescent machinery, it is not surprising that they do not make a better showing. The mere fact that engine No. 1, which operates an equipment developing 36 per cent. of the total output, requires over 30 pounds of water per I. H. P. per hour, is sufficient to explain any difference in economy.

TABLE. 9.

ECONOMY RECORD.

No of Engine.	Pounds water per I. H. P. per hour.		Pounds coal per I. H. P. per hour.		Watt-hour output per lb. of coal.		Dynamo driven by engine No.	Total watt-hour output.		Output in per cent. of station watt-hour putput.	
	Aug. 31.	Sept. 7.	Aug. 31.	Sept. 7.	Aug. 31.	Sept. 7.		Aug. 31.	Sept. 7.	Ang. 31.	Sept. 7.
1	32.96	32.96	4.584	4.682	114.30	114.8	1	3509000	3946000	37.75	35.02
2	32.81	34.52	4.571	4.904	116.70	96.80	2	1014000	819000	9.42	7.27
3	42.59	42.59	5.922	6.049	80.08	72.30	3	564600	546600	6.07	4.85
4	25.87	25.52	3.604	3.625	128.31	127.79	4	140350	541300	1.30	4.80
5	22.42	22.42	3.118	3.185	171.98	171.29	5	2122900	1942200	19.73	17.23
6	22.55	22.55	3.136	3.203	156.71	152.80	6	349650	542900	3.25	4.82
7	21.49	21.49	2.988	3.053	162.60	179.60	7	949100	1542300	8.82	13.68
8	29.03	29.03	4.037	4.124	127.30	131.00	8	2110000	1389400	19.61	12.33
Station.	24.79	24.09	3.454	3.372	150.5	157.3	Arc.	5087800	5311600	47.28	47.14
....	Sept. 1.	....	Sept. 1.	....	Sept. 1.	....	Incan	5674000	5958100	52.72	52.86
1	32.96	....	3.18	....	158.5	....	Station.	10761800	11270700	100.00	100.00

No. of Engine.	Pounds water per I. H. P. per hour.		Proportional part of water used by engine.		Average indicated horse-power.		Average electrical horse-power.		Average efficiency of conversion.		Commercial efficiency.	Commercial efficiency.
	Aug. 31.	Sept. 7.	Aug. 31.	Sept. 7.	Ang. 31.	Sept. 7.	Aug. 31.	Sept. 7.	Aug. 31.	Sept. 7.	Aug. 31.	Sept. 7.
1	32.96	32.96	12.44	11.54	588.00	644.15	413.09	460.05	68.8	71.03	70.22	71.41
2	32.81	34.52	3.09	2.51	110.19	100.71	78.80	63.65	69.6	64.3	71.51	63.21
3	42.59	42.59	2.58	2.06	71.94	72.53	45.75	42.47	55.2	51.3	63.60	58.55
4	25.87	25.52	.34	1.22	115.08	126.17	70.4	78.4	61.9	62.1	61.97	62.14
5	22.42	22.42	4.42	3.86	214.70	218.95	154.70	160.20	71.9	75.1	72.03	73.16
6	22.55	22.55	.73	1.08	179.43	170.51	117.21	111.95	65.90	65.6	65.32	65.66
7	21.49	21.49	1.89	2.94	203.12	217.62	132.54	159.30	63.80	73.5	65.23	73.20
8	29.03	29.03	5.69	3.45	226.79	232.12	157.3	169.3	68.90	72.4	69.33	72.92
Arc.	....	....	....	....	404.8	434.3	284.2	296.7	66.23	61.90	70.21	68.31
Incan.	....	....	....	....	458.0	451.0	317.0	332.8	69.00	71.00	69.20	73.80
	Real											
Station.	24.79	24.09	....		862.8	885.30	601.2	629.5	68.10	68.50	69.68	71.11
	Calculated		Special test of engine		Sept. 1.	....	Sept. 1.	....	Sept. 1.	....	Sept. 1.	....
Data.	31.1	28.66	No. 1............		553.82	....	382.6	....	66.7	....	69.08	....

Per cent. excess of the calculated water consumption of the station above the actual water consumption, Aug. 31, 20.60, Sept. 7, 16.00.

The effect that the engines have upon the average water consumption of the station is very well illustrated in Figs. 3 and 4.

In the mornings when engines 2, 3, 6 and 5 are in operation, the water rate averages 32 pounds of water per I. H. P. per hour on August 31, and 28 pounds per I. H. P. per hour on September 7. The difference is due to the fact that the morning load was lighter on September 7 than on August 31, and consequently the engines, especially engines 2 and 3, were relatively less efficient.

During the latter part of the test of August 31, the water rate falls to about 21.5 pounds per I. H. P. per hour, which is a remarkably good showing and indicates that some of the engines, probably Nos. 5 and 7, were operating very efficiently. At the same time on September 7 the water rate is somewhat higher. It averages fully 22.5 pounds of water to the horse-power, and the difference is probably due to the fact that engine No. 1 required more water proportionally on the latter night owing to its heavier load.

The coal economy can hardly be approximated from the curves owing to the fact that they are so very irregular. If it were possible to have the firing done constantly and regularly it might then be possible to obtain more uniform results for plotting purposes, but where it is only done at intervals, "when the fires seem to need more coal," very regular results cannot be obtained.

It may be interesting, in connection with this review, to estimate what maximum economy could be secured under the most favorable conditions which it is probable could be obtained at the station.

If we assume that the boilers in service are kept loaded to their full capacity, they will probably develop an economic evaporation of 10 pounds of water per pound of coal. This figure is slightly less than the actual evaporation per pound of coal developed by boilers 6, 7 and 8 on the night of September 7. Furthermore, if the engines and dynamos are kept up to the point of their maximum efficiency; if there are no leaks in the valves or past the pistons of the engines, if the governors and valves are properly adjusted to give the most economical distribution of the steam between the cylinders of the engines, if the dynamos are kept in good order, with well balanced armatures, low resistance contacts and sparkless commutation, and if good lubrication is maintained and all line shafts and bearings are kept properly lined up, then an economy such as is outlined in table 10 may possibly be secured. This table represents the high-water mark of economy of the station. It may be thought that the values given are rather extreme, and that the percentage increase represents an impossible gain in economy, and yet it can be demonstrated that there are power plants of similar and even smaller capacity that are giving better results than these figures indicate. The plants referred to are not, however, electric lighting plants. It must furthermore be remembered that a very large proportion of this increase, in fact 40 odd per cent. of it would be due to the increased economic evaporation of the boilers, and it cannot for a moment be questioned but that the station economy has been greatly improved in this direction.

TABLE 10.

MAXIMUM ECONOMY.

No of Engine.	Average I. H. P.	Average E. H. P.	Average efficiency of conversion.	Lbs. water per I. H. P. per hour.	Pounds coal per I. H. P. per hour.	Watt-hour output per lb. of coal.	Per cent. increase in output.
1	600	420	74.0	18	1.8	307	167
2	170	131	77.0	28	2.8	205	75.
3	135	103	76.0	30	3.0	189	51.
4	145	106	73.0	21	2.1	259	100.
5	260	201	77.3	19	1.9	303	76.
6	145	106	73.0	21	2.1	259	66.
7	270	201	75.0	19	1.9	294	63.
8	260	201	77.3	19	1.9	303	132.

In the report presented to the *National Electric Light Association* on May 7, 1896, by its committee on data, attention is called to the fact that in a recent statement of the economy of the Chestnut Hill Pumping Station, at Boston, it was found that in actual water lifted, a horse-power was produced by the consumption of 1.34 pounds of coal. Assuming that the efficiency of pumps compares favorably with the efficiency of generators, and making no allowance for variation in load, one pound of anthracite coal used with the same economy in electrical work should produce 557 watt-hours. Although it is not to be forgotten that the economy reported for the pumping station was obtained under most favorable conditions, with dry high pressure steam and multiple cylinder engines, and although the relative conditions under which it and the present tests were made are not at all comparable, the fact still remains that the report represents an economy of 400 watt-hours per pound of coal over and above the economy of the Pratt Street Station, or in other words it represents an increased economy of 255 per cent.

Now under the conditions outlined in table 10 the station would develop an economy of about 300 watt-hours per pound of coal. This would be an increase of 91 per cent. over its present economy and certainly represents a result worth striving for.

Now that we have discussed what the station could do under favorable conditions, let us see what it does do under actual conditions in comparison with other central stations of the country. This side of the situation is certainly as interesting as the other, since it brings us into immediate touch with the commercial competitors with whom the station has to contend.

For this purpose we cannot do better than turn again to the report of 1896 of the committee of the *National Electric Light Association*. The information published is certainly not below the economy of the stations represented, as contributors would tend to over-rate rather than under-rate their equipments in gauging their output; and again, we have the statement of the committee to the effect that although it realizes "that in the case of alternating currents the product of the amperes times the volts may not give the absolute watts, this method has been considered sufficiently accurate for this work." Of course "this method" increases the figure for the watt-hour output above its true value.

It is also certain that the statements contained in the report have been obtained from thoroughly representative plants, as their watt-hour per day output is too large for them to be otherwise.

Referring to the data contained in the report we find that the Pratt Street Station stands 15th in the order of the merit of producing the greatest watt-hour output per pound of coal; 15th in a list of 82 stations represented. Of the 14 stations that give a better record of economy only 3 have a greater watt-hour output per day. Of all the plants represented 7 have greater watt-hour outputs per day. "The average efficiency of the 81 reports using coal as fuel is 108 watts-hours per pound of coal," and the Pratt Street Station shows an economy of 45 per cent. in excess of this figure. One station, that has a watt hour per day output of 3207392 watt-hours, reports an economy of 237 watt-hours per pound of coal. The Pratt Street Station develops 65 per cent. of this economy.

The average watt-hour output of all the 14 plants that show a greater economy than the Pratt Street Station is 175 watt-hours per pound of coal, and the Pratt Street Station develops 90 per cent. of this economy.

All the plants that make a better showing than the subject of this paper seem to be better equipped from an economic standpoint.

Of the fourteen, three are equipped with triple expansion condensing engines; six are equipped with compound Corliss condensing engines; one is equipped with simple condensing Corliss, and high speed compound condensing engines belted direct to dynamos: three are equipped with high speed compound condensing engines belted direct to dynamos; and one with simple high speed condensing engines, belted direct to the dynamos. As regards their electrical machinery, two are equipped with direct connected multipolar dynamos; three are equipped with alternating current dynamos; one is equipped with bi-polar dynamos belted from jack shaft; and in the copy of the report that I have the others are not designated. In five of these plants water tube boilers are used alone; in two of them water tube and horizontal tubular boilers are used; and in the others horizontal tubular boilers are used alone.

It will be noted that the engines of the above mentioned plants are condensing, and it will be interesting now to review the non-condensing plants.

Of the 82 plants reported upon, 44 of them are operated with non-condensing engines. Of these, a number seem to be very well equipped. For instance, two are reported having compound Corliss and high speed compound engines, water tube boilers and alternating current dynamos. Six others are reported as having high speed compound engines, with various types of dynamos and boilers, and in only one of them do the dynamos seem to be belted from jack-shafts.

In speaking of the plants that are running with non-condensing engines, the committee makes the following comparison:

"In engine efficiency, eight stations report the water consumption per I. H. P. The triple expansions lead in economy, report 80 showing a consumption of 15.5 pounds, and report 3 showing 18 pounds of water per I. H. P.; these comparing reasonably with report 29, where an I. H. P. is produced by non-condensing engines with 26 pounds of water."

In the Pratt Street Station an indicated horse power is developed with 24 *pounds of water.*

The committee further says:

"Attention is called to the reports from plants running with non-condensing engines, in which report 26 is able to show 129 watt-hours per pound of coal; report 32, 113 watt-hours; report 33, 109 watt-hours; report 37, 100 watt-hours; and report 38, 95 watt-hours."

The Pratt Street Station shows an economy of 157 *watt-hours per pound of coal, and develops an economy* 22 *per cent. in excess of the best showing made by the* 44 *plants running with non-condensing engines.*

A Paper presented at the 124th Meeting of the American Institute of Electrical Engineers, New York, April 27th, 1898, Mr. H. Ward Leonard in the Chair.

A NOVEL FORM OF THERMO-ELECTRIC BATTERY.

BY C. J. REED.

If further proof were needed of the very high thermo-electric power of metals in contacts with electrolytes, a very striking and conclusive proof may be found in the following experiments.

The apparatus consists of a fused mass of caustic potash or soda maintained at a temperature of 500° to 800° C. into which two conducting rods are inserted, both of the same metal and as nearly alike as possible in every respect except form. One of the rods, marked B in Figs. 1 and 2, is of cylindrical form. The other, marked A, is in the form of a cylinder having a deep recess cut or turned out near one end, leaving at the end a short cylindrical head attached to the rod by a very narrow stem.

In order to obtain two pieces of metal having, as nearly as possible, the same molecular structure and chemical composition, a uniform rod of Bessemer steel $\frac{5}{16}$ inch in diameter and two feet long, was cut in two equal parts. The severed ends which were originally together at the middle of the rod are turned smooth and flat to form the lower or contact ends of the rods, A and B, shown in Figs. 1 and 2. The head formed on the end of A is $\frac{1}{4}$ inch long and the stem by which it is attached is half an inch long and $\frac{1}{20}$ inch in diameter. The two rods thus prepared are held parallel to each other and about $\frac{1}{4}$ inch apart in a wooden clamp with their ends in the same plane at right angles to their axes.

The rods are now inserted in a vertical position to a depth of $\frac{1}{2}$ inch into the fused caustic alkali. The surface of the fused alkali should come above the head of the rod, A, but not above the stem, as shown in Fig. 2. The cup used in this experiment to hold the molten alkali is of sheet steel about two inches in diameter and three inches deep. The rods are inserted in the center of the cup, in order that the temperature and chemical composition of the mass of alkali immediately surrounding the rods, as well as the temperature of the air surrounding them may be as nearly homogeneous as possible. By these precautions all effects of every nature are eliminated, except such as may be due to the difference in temperature between the submerged ends of the two rods caused by their difference in form, which enables the rod, B, to get rid of its communicated heat by conduction more rapidly than the rod, A. The temperature of the alkali is maintained at about 700° C. After the rods have remained in the melted alkali a few minutes and the room has been darkened, they are quickly withdrawn for inspection. The cylindrical head on the rod, A, is seen to be at a uniform bright red heat, while the rod, B, is only perceptibly dull red at the extreme end. The difference in temperature between the cylindrical head of A and the hottest part of B is probably not less than 100° C. The reason for this difference in temperature is apparent. The narrow stem of A conducts heat away very slowly, while the rod, B, of uniform diameter conducts away its heat with a rapidity many times greater. Assuming that both rods receive heat from the surrounding liquid initially at the same rate per unit of surface, the head of rod, A, must become much hotter than any part of B, since it has a relatively larger surface of contact with the communicating liquid and loses its heat by conduction much more slowly.

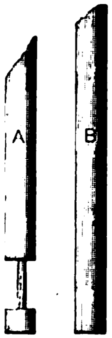

FIG. 1.

FIG. 2.

In this arrangement we have two pieces of metal as nearly alike as possible in chemical composition and molecular structure, subjected to the same conditions in all respects, except that the temperature of one at its junction with the electrolyte is higher than the temperature of the other at its junction with the electrolyte. In other words, the electrolyte has one hot and one cold junction with pieces of the same metal inserted in it to the same depth and subjected as far as known to no other disturbing influences.

This arrangement gives an electromotive force, varying with the temperature and constitution of the electrolyte between — 0.2 volt and + 1 volt. The difference in temperature between the two junctions evidently increases with the temperature of the fused alkali, being zero when the temperature of the communicating liquid is the same as that of the surrounding air. The difference in temperature between the junctions increases rapidly for a certain period from the beginning of the experiment, while the rod, B, is comparatively cold and capable of dissipating heat rapidly and while the temperature of A is rapidly rising. Following this will be a period, during which the difference in temperature between the junctions will diminish until both rods attain throughout their entire lengths the maximum temperatures they are capable of attaining under the conditions.

I have previously shown [1] some of the peculiar variations of electromotive force under changes of temperature and alterations in the constitution of the electrolyte, which are exhibited in a cell consisting of an iron cup containing fused alkali as one electrode and an iron or other conducting rod inserted in the alkali as the other electrode. In that apparatus the iron cup imparted heat to the alkali and the alkali imparted heat to the rod. From this circumstance it follows that the junction of the electrolyte with the iron cup is necessarily hotter than the junction of the electrolyte with the rod. The cup, being the hotter of the two pieces of iron in that experiment, should act in the same qualitative manner as the rod, A, in the experiment illustrated in Fig. 2 above, A being the hotter of the two rods. But the difference in temperature between the two rods, A and B, can never be as great as the difference between that of the heated cup and that of the rod, B. These conclusions are entirely con-

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[1] See *Electrical World*, July 25, 1896.

firmed by the experiment, the rod, A, acting in the same manner as the cup, with the exception that the electromotive force obtained from it is not so great.

In attempting to explain the electromotive force developed between the heated cup and the inserted rod as a result of chemical action, some have resorted to the argument that the upper layers of the liquid may have an affinity for iron different from that of the lower layers, assuming that oxidation of iron in the upper layers causes reduction of iron in the lower layers and at the same time evolves electrical energy. The experiment with the two rods inserted to equal depths evidently leaves no room for such an argument, aside from its inherent absurdity. As a matter of fact there is no evidence of the existence of any such layers of varying chemical composition, the entire mass being continually stirred up by rapid convection currents like boiling water. The same results are obtained even when the rods extend to within a millimeter of the bottom of the cup. I have also obtained an electromotive force of nearly one volt between the cup and an inserted iron rod when the rod actually rested on the bottom of the cup, metallic contact being prevented only by a thin film of oxide or of the electrolyte.

Admitting that the chemical affinity between hot iron and the electrolyte is undoubtedly different from that between cold iron and the electrolyte, no energy could be evolved in any form due to this differential affinity, except energy derived from the heat of the furnace, since the existence of this differential affinity depends only upon the difference in temperature. To suppose that the electrical energy of this cell is derived from chemical action, involves the assumption that iron has a greater affinity than *iron* for oxygen, or that oxygen will select and combine with one of two similar pieces of iron while it dissociates from the other, and the further assumption that such a process will evolve energy. If this is possible, it can be possible only because of the difference in temperature, which in turn can be maintained only by a constant expenditure of heat from the furnace. Otherwise we should have an inexhaustible source of energy. If oxygen can evolve energy by leaving one piece of iron and combining with another, it may, with equal reason, leave the second and re-combine with the first, evolving an equal amount of energy, and there would be no limit to the number of such reversals, all evolving energy.

The experiment shows that the rods, A and B, evolve electrical energy and exhibit a high electromotive force under circumstances that are identical in all respects except temperature, and that the action is, therefore, thermo-electric.

The experiment may be varied by using two rods in the form of B. In this experiment there is no evidence of electromotive force when the rods are in a vertical position, so that both are equally heated by the electrolyte, as shown in Fig. 3. Upon inclining the rods so that one barely makes contact with the electrolyte, while the other extends about a quarter of an inch below the surface, as shown in Fig. 4, the rods acquire a considerable difference in temperature, which is clearly indicated to the eye, one being distinctly red and the other black. At the same time an electromotive force is developed, which in some experiments has reached as high as 0.6 volt. Upon reversing the position of the rods, so that the hot one becomes cold and the cold one hot, the direction of the electromotive force slowly reverses. This reversal I have found may be repeated indefinitely, provided the other conditions of the experiment are maintained.

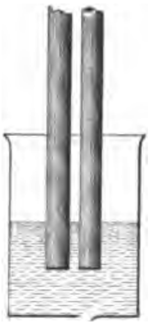

FIG. 3.

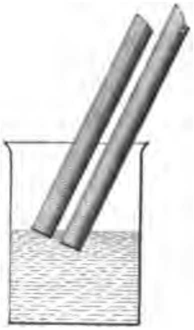

FIG. 4.

Rods of carbon, copper and various other metals may be substituted for the iron rods, and other electrolytes substituted for the caustic alkali. In all cases similar results, differing only in degree, are obtained. Many of these results are highly interesting and will be described later in detail.

The changes in the constitution of the alkali hydrate, which take place during its gradual dehydration have not yet been definitely determined. It is quite certain that these changes have a marked effect on the thermo-electric power of the cell.

If any current be allowed to flow, the electrolytic action of the current immediately causes the formation of oxide of iron at one electrode and the reduction of previously existing oxide of iron at the other electrode. This necessarily produces a change of chemical composition in the electrolyte adjacent to the electrodes or on the surface of the electrodes themselves.

As long as oxide of iron remains dissolved in the electrolyte and in contact with the electrodes in sufficient quantity to transmit the current, the electrolytic action will neither absorb nor evolve energy, since the amount of iron oxidized at one electrode will be equal to the amount reduced at the other. The resistance of the electrolyte as a conductor only will cause a fall of the potential difference on closed circuit. If no oxide of iron is present in a dissolved condition in the electrolyte and if there is none on the surface of the hydrogen electrode available for reduction, the current can no longer flow without reducing some other constituent of the electrolyte, such as sodium or hydrogen. In other words, a counter-electromotive force or "polarization" ensues.

It was found by Deville[1] that sodium hydrate does not decompose at any temperature into water and sodium oxide, but at about 1100° C. it decomposes into sodium, hydrogen and oxygen. If, therefore, a condition should ensue, in which no oxide of iron is available for reduction while the current continues to flow and ferric oxide continues to form at the oxygen electrode, the electro-chemical reaction would be

$$3\,NaOH + 2\,Fe = Fe_2O_3 + 3\,Na + 3\,H.$$

This reaction could take place electrolytically at ordinary temperatures by the absorption of 115,000 calories, corresponding to a counter-electromotive force of $\frac{115,000}{6 \times 23,240} = 0.82$ volt. At the temperature of 500° C., at which the thermo-electromotive force of the cell is about 1 volt, the reaction would absorb approximately 72,000 calories, corresponding to a counter-electromotive force of $\frac{72,000}{6 \times 23,240} = 0.52$ volt.

There is reason to believe that this condition of the electrolyte does actually ensue at a certain stage of the experiment when the circuit is closed, and under certain conditions metallic sodium may be evolved in considerable quantities at the inner surface of

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[1] *Comptes Rendus*, xlv. 859.

the cup. The maximum quantity of iron that can be dissolved in the fused caustic alkali is very small, and this appears to be held in solution only while there is present more water than corresponds to the formula for the alkali hydrate. This excess of water is driven off very slowly, the last trace leaving only at a temperature above 500° C.

Liebenow and Strasser [1] found that when the alkali, fused in an iron cup, reaches a temperature of about 550° C. after prolonged heating, it undergoes a radical change in properties, changing color from green to dark brown and simultaneously absorbing heat and causing its own temperature to be temporarily reduced. With this change in the electrolyte the electromotive force undergoes a sudden change of about one volt.

The absorption of heat and consequent reduction of temperature can be accounted for only by a chemical change in the electrolyte which causes the heat to become latent. Such a reaction may be explained on the supposition that the electrolyte changes at this temperature from an aqueous solution to a dehydrated fused electrolyte. While water is present, the iron probably remains in solution as ferric acid (the highest known oxide of iron) in combination with the alkali as potassium or sodium ferrate, which in the highly concentrated solution has a green color if any sulphur is present. When the water which holds this salt in solution is finally driven out, the ferric acid, being insoluble in the dehydrated alkali hydrate, is decomposed into ferric oxide, potassic oxide and oxygen, the reaction being

$$2\,K_2FeO_4 = 2\,K_2O + Fe_2O_3 + 3\,O.$$

The insoluble ferric oxide precipitated in the solid state by this reaction gives the dark brown color to the mass, which was observed by Liebenow and Strasser. This precipitate is found disseminated through the solidified hydrate on cooling. The dissociation of the ferric acid should be accompanied by the absorption of considerable heat—probably at that temperature about 150,000 calories. This would be sufficient to account for the remarkable fall of temperature, observed by Liebenow and Strasser to accompany the change of color from green to brown. A further examination of the results obtained by these investigators reveals the fact that this fall of temperature occurred only in those experiments in which either iron or nickel was present in the electrolyte.

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[1] *Zeitschrift fur Elektrochemie*, Feb. 20, 1897.

The experiments referred to of Liebenow and Strasser are a series of elaborate investigations on a number of alkaline thermo-electric cells, the results of which are entirely in accord with the explanation given above, and form the basis on which that explanation is chiefly founded. I am unable to agree with those investigators, as before stated, in some of their conclusions; as, for instance, the conclusion that electrical energy or any other form of energy can be evolved from the "passivity" of a metal or from any other property of matter, and I believe the experiments they have described do more towards disproving their own preconceived theory than any experimental work that has been done relating to this subject.

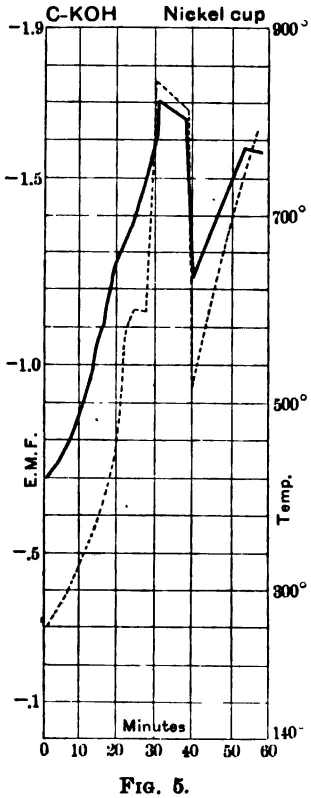


FIG. 5.

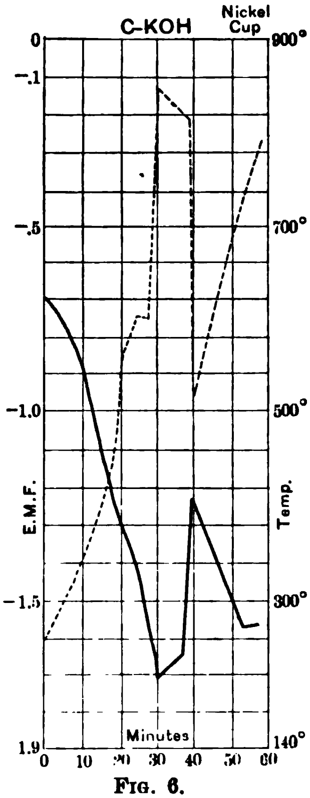


FIG. 6.

In those experiments the effects produced by various alterations of the electrolyte on the potential difference between various electrodes and an arbitrary "normal electrode" were determined. Simultaneous measurements of electromotive force and temperature were made which throw much light upon the nature of these cells. Unfortunately no measurements were made to determine at the same time the difference of temperature between the various electrodes.

The relation between the temperature of the electrolyte and the electromotive force of the carbon-caustic-potash cell, as indicated by the results of Liebenow and Strasser, is well illustrated in the curves shown in Fig. 5. In this diagram the abscissa represents the time measured from the beginning of the experiment, and the corresponding ordinate of the dotted line represents the temperature, while the ordinate of the full line represents the simultaneous difference of potential between the carbon rod and the "normal electrode." Liebenow and Strasser apparently failed to see the relation between the curves of temperature and electromotive force, simply because the direction of this electromotive force happened to be opposite to that which they had been arbitrarily measuring as increasing towards the top of the diagram. They, therefore, measured electromotive force downwards and the corresponding temperatures upwards and obtained the diagram shown in Fig. 6, which is not quite so easily interpreted. They apparently failed to get any meaning from it, merely remarking that it did not agree with the formula they had empirically deduced.

When the intensity of the electromotive force is compared directly with the temperature, instead of inversely, the relation becomes apparent, as shown in Fig 5. In this particular case the diagram shows decidedly that the electromotive force increases and decreases with the temperature of the electrolyte. From the nature and arrangement of the apparatus we know that the difference of temperature between the electrolyte and the rod will also increase and decrease with the temperature of the electrolyte. This dependence of electromotive force upon difference of temperature is shown in nearly all the diagrams of Liebenow and Strasser, when the electromotive force, whether positive or negative, is measured in the same direction as the temperature. And it must be so measured in order to make a direct comparison. The polarity or direction of the electromotive force has no particular bearing on the relation between its intensity and variations in temperature, but is dependent merely on the accidental position of the neutral point on the thermo-electric diagram.

When any thermo-electric couple is heated up from a very low to a very high temperature without any great change in the difference of temperature between the hot and cold junctions, the electromotive force will diminish with increase of temperature until the neutral point is reached, where it will become zero and change sign. From that point it will increase with the temperature if the difference in temperature between the junctions does not diminish.

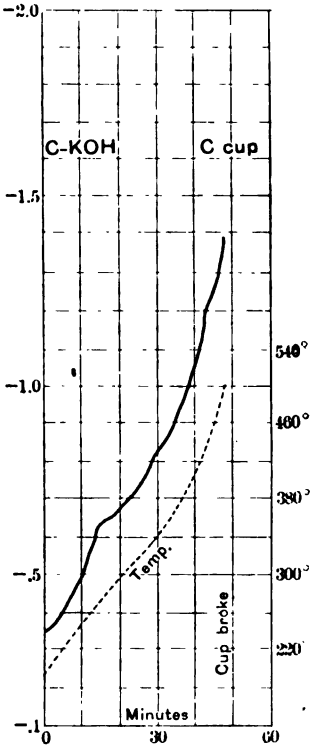


Fig. 7.

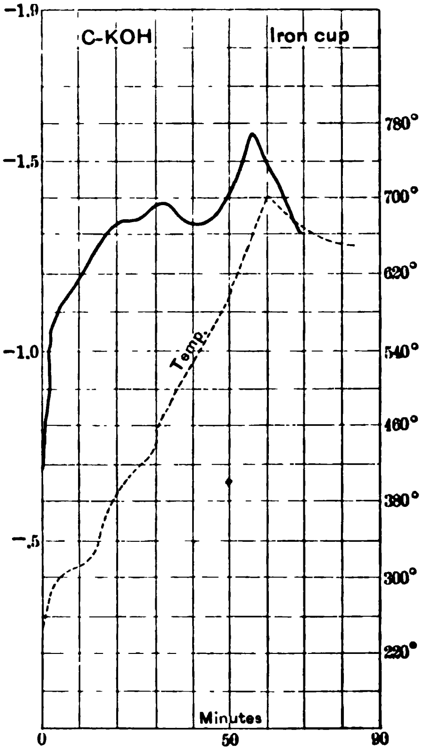


Fig. 8.

In the case shown in Fig. 5 it is evident that the electromotive force does not change sign. This means only that in this particular case (carbon-caustic-potash junction) the neutral point, if there be any, lies outside of the range of temperatures employed in this experiment, that is, the neutral point does not lie between 260° and 850° C.

When these facts are all taken into account the results obtained by Liebenow and Strasser, as far as they go, show that the electromotive force was produced by and depended upon the difference of temperature between the rod and the electrolyte, except in those cases where they purposely introduced disturbing elements. In such cases they do not describe the details of their apparatus and *modus operandi* sufficiently to enable us to judge what effect upon the temperature of various parts of the apparatus may have been produced by the various gases they introduced in some of their experiments and by closing the crucible with a cover, which would naturally tend to keep the temperature of the rod and that of the electrolyte more nearly alike at the point of contact.

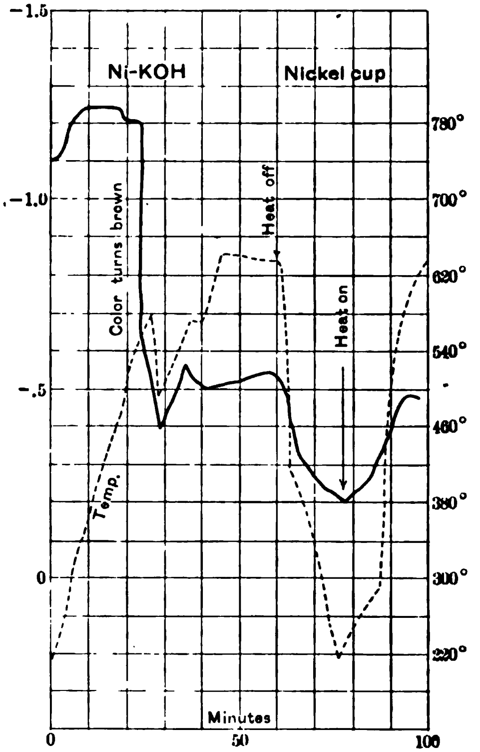


FIG. 9.

The experiment with the carbon rod and caustic potash was varied by Liebenow and Strasser by substituting for the nickel cup used in Fig. 5, in one case a carbon and in another case an iron cup. The results are exhibited (by inverting the curves of Liebenow and Strasser) in Figs. 7 and 8 respectively, which agree with Fig. 5 in showing that the curve of electromotive force in the carbon-caustic-potash couple follows in general the curve of temperature, and that the neutral point of this couple does not lie between 200° and 700° C.

A second group of most instructive experiments with metal rods substituted for the carbon rod (the results of which are exhibited in Figs. 9, 10, 11 and 12) demonstrate in an equally convincing manner that a change in the temperature of the electrolyte produces a corresponding change in the electromotive force. These curves were also inverted on the temperature curves in the diagrams of Liebenow and Strasser. In Fig. 9, showing the result when a nickel rod and cup are used, there are no less than eight well marked points of flexure in the temperature curve, each corresponding to a similar point in the curve of electromotive force. Fig. 11 differs from Fig. 10 only in the substitution of caustic soda for caustic potash.

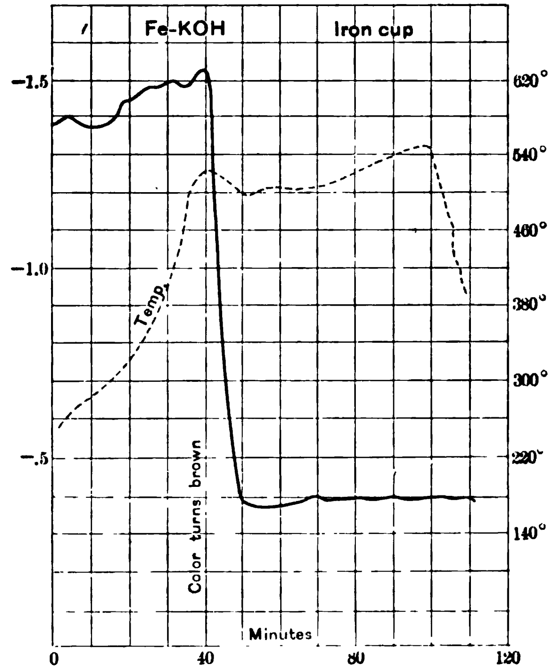


FIG. 10.

An examination of these four curves shows some very instructive coincidences, among which are the following:

1. The electromotive force increases with increasing temperature from the beginning of the experiment up to the moment the brown color of the electrolyte appears, indicating a chemical change and probably a condition of dehydration. This change was not marked in Fig. 11 by Liebenow and Strasser, but the curves of electromotive force and temperature both show that it must have occurred at the end of 26 minutes.

2. When this point is reached there is a sudden and very great change in electromotive force.

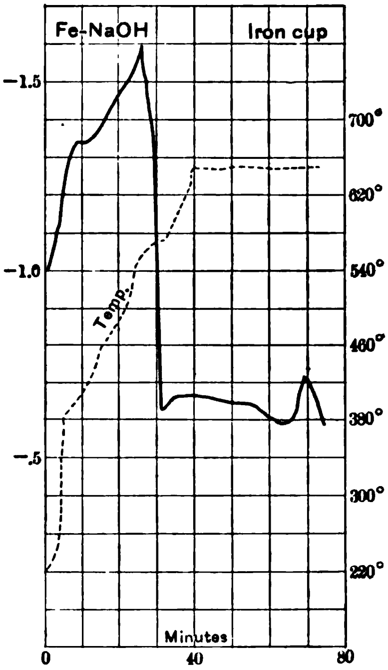


FIG. 11.

3. Simultaneous with this change of electromotive force and change of color, an absorption of heat occurs in the electrolyte, which causes a sudden reduction of its temperature. In Fig. 11 this reduction of temperature is indicated only by a flattened portion of the temperature curve. This reduction in the temperature of the electrolyte would necessarily greatly reduce the difference between its temperature and that of the metallic rod to which it communicates heat. It is conceivable that in some cases, where the absorption is very marked and sudden, heat

may actually flow back from the rod to the electrolyte. This sudden reduction in the temperature of the electrolyte accounts satisfactorily for the change of electromotive force accompanying it.

4. From this point to the end of the experiment the curve of electromotive force follows in general the temperature curve.

In all cases except that of silver, Fig. 12, the temperature at which the sudden change occurs, lies between 524° and 580° C. The more rapidly the heat is applied, the higher is the temperature at which this change occurs and the more nearly vertical is the curve of electromotive force at that point. In Fig. 9 the dehydration point was reached in about 23 minutes and the temperature attained before the change was 580°. In Fig. 11 the time was about 26 minutes and the temperature attained 570°. In Fig. 10 the time was 40 minutes and the temperature 524.°

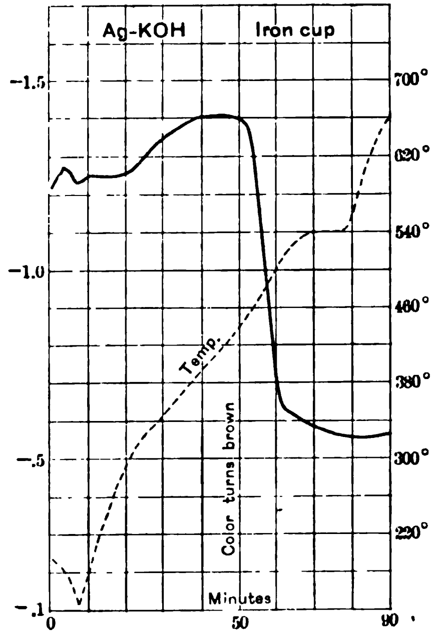


FIG. 12.

In Fig. 12 the time was 50 minutes, the temperature 460°, and no reduction of temperature was observed to accompany the change of color. This may be accounted for on the supposition that, owing to the slowness of the reaction in this case the continuous application of external heat was sufficient to prevent an actual fall of temperature.

In Fig. 13 the conditions were the same as those of Fig. 12, excepting that a silver cup was substituted for the iron cup and, consequently, there was no iron present in the electrolyte. The marked irregularities in the curve of electromotive force shown in Fig. 13 are to be expected from the high thermal conductivity of the silver cup and rod, which makes the apparatus very sensitive to fluctuations in the source of heat. The absence of any indication of chemical change or change of color in the electrolyte or of any corresponding absorption of heat or change of electromotive force is accounted for by the fact that there is no iron or nickel in the solution and that the dehydration is accomplished without any chemical change due to the presence of impurities.

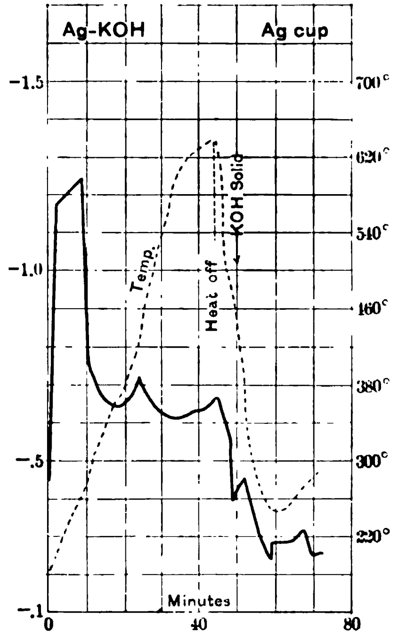


FIG. 13.

Figs. 14 and 15 show the result of substituting for the normal electrode in Figs. 8 and 6 respectively, rods of iron and nickel. The effect of this change was to remove the arbitrary zero of potential established by the introduction of the normal electrode and to transfer the neutral point, at which the electromotive force changes sign, to a position within the diagram. The neutral point on these diagrams corresponds to the temperature of 555° ± 5°, coinciding with the temperature at which the chemical change and the absorption of heat occur. These curves are not inverted, but are copied without change from the curves given by Liebenow and Strasser.

In Figs. 16 and 17 the results are further complicated by the use of various disturbing influences. The most important change introduced in these experiments was to close the cup with a practically air-tight cover, through which a carbon and an iron rod were inserted. This entirely prevented the circulation of air over the surface of the electrolyte and around the lower ends of the rods. The temperature of such a closed chamber above the electrolyte would be only slightly less than that of the electrolyte itself after the apparatus had become thoroughly

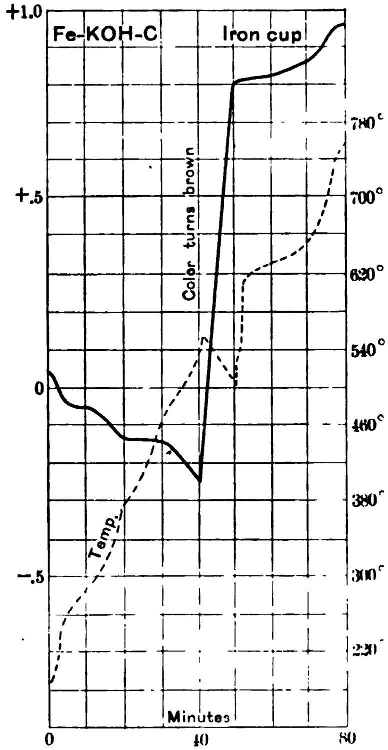


Fig. 14.

heated. The lower ends of the carbon and iron rods, being surrounded by an atmosphere nearly as hot as the electrolyte, would have little difference in temperature at their surfaces of contact with the electrolyte, nothwithstanding their great difference in conductivity. Such an arrangement would result in a very much lower electromotive force. Liebenow and Strasser reported no experiments under exactly these conditions, but gave in Figs. 16 and 17 the results obtained by various modifications of these conditions, viz., by passing through the closed chamber various gases.

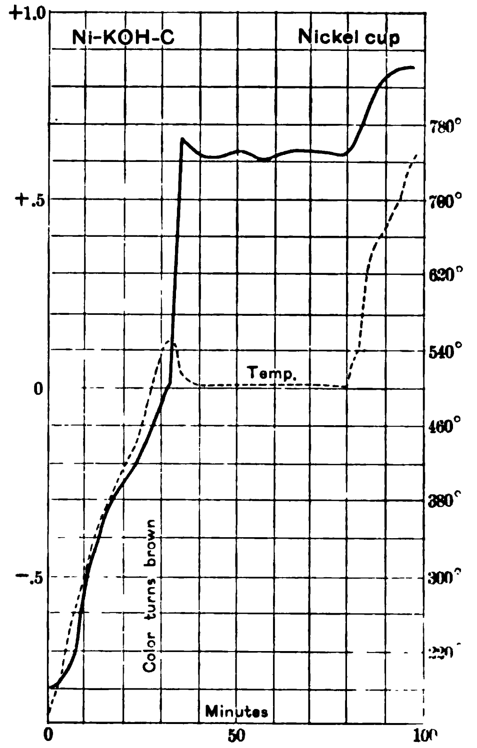


Fig. 15.

Unfortunately sufficient attention was not given to the details of these experiments to enable us to decide to what extent, if any, the results were due to the chemical action of the gases introduced, and to what extent they were due to their cooling effect. If the air and all the various gases were passed through the closed chamber at the same temperature and all with the

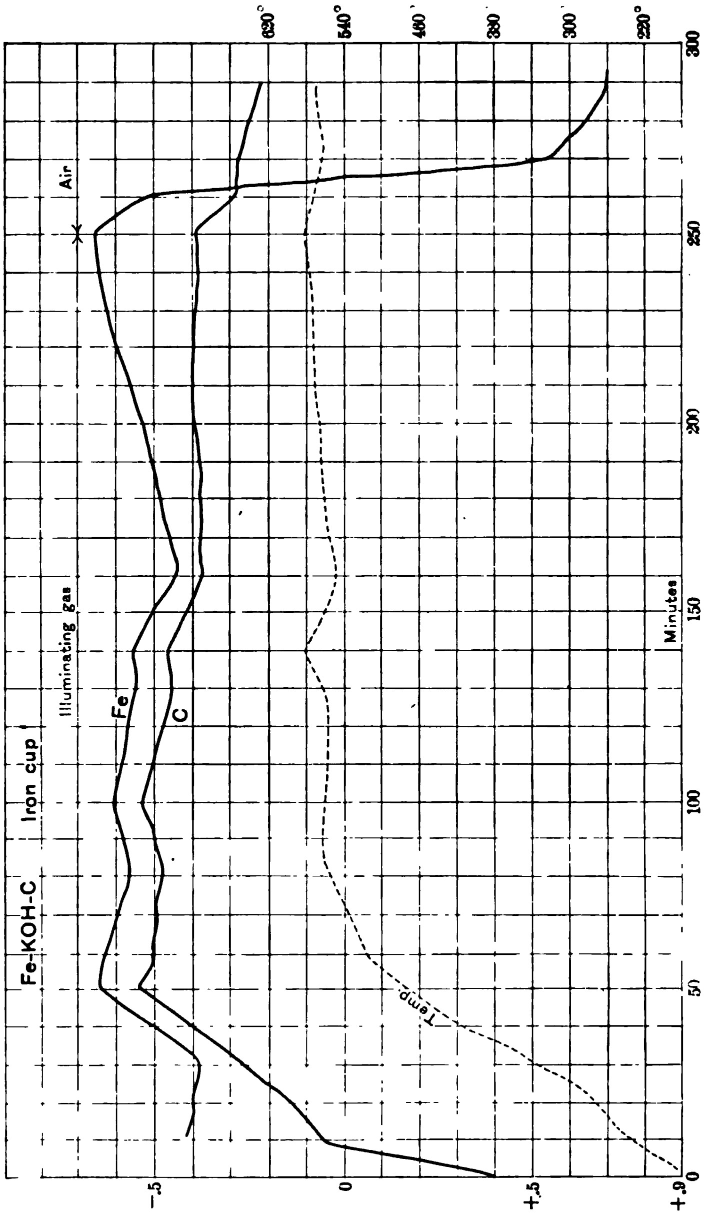


FIG. 16.

same velocity, the only difference in their cooling effects would be that due to the differences in their specific heats. These could not be very great and would probably be negligible. If, on the other hand, the gases were passed through the cell with greatly varying velocities, their cooling effects, particularly on the iron rod, would be very different.

Fig. 16 shows the result obtained by passing illuminating gas through the cell for four hours and ten minutes, then replacing it by air. At the end of the first hour the temperature and the electromotive force became practically constant and remained so until the change was made from illuminating gas to air. When this change was made there was a noticeable, though not great fall in the temperature of the electrolyte, a corresponding change in the electromotive force of both the carbon and the iron as compared with the normal electrode, the change in the iron being very great. These curves, which are also the inverted curves of Liebenow and Strasser, are seen to follow the temperature curve in exactly the same manner as the curves of carbon and iron shown in Figs. 5 to 12.

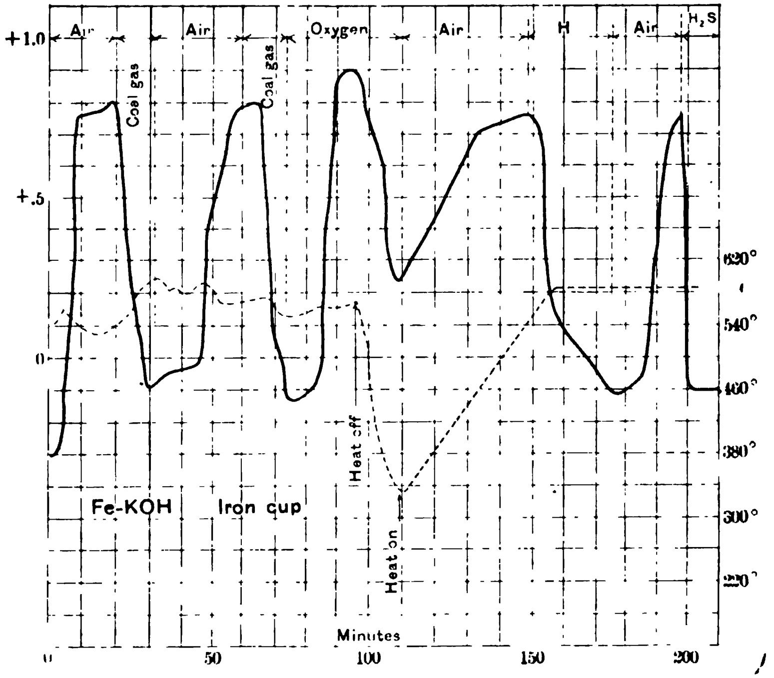


FIG. 17.

In the absence of any statement to the contrary by Liebenow and Strasser the inference is reasonable that the air forced through the cell was in a large or unlimited quantity, while the flow of the combustible gases was adjusted to make the issuing jet burn with as small a flame as possible. If such were the case, the cooling effect of the air on the rods could not fail to produce the result shown in Fig. 16. The same explanation applies with equal force to the results shown in Fig. 17, in which various gases were successively passed through the cell. There is no doubt that the results are also complicated by various chemical changes resulting from the gases introduced. The introduction of pure oxygen, for example, in contact with the red-hot carbon would certainly result in a vigorous combustion of the carbon, which would tend to increase its temperature even above that of the electrolyte and augment the effect shown in Fig. 17. But the lack of more detailed information concerning these experiments makes it useless to speculate further.

DISCUSSION.

MR. EDWARD P. THOMPSON :—I have been considering whether the proposition Mr. Reed has put before us has been strengthened by him by a variety of experiments. As I understand from his remarks, the electromotive force is due to the difference of temperature between the two electrodes. I was thinking that if that is what he considers it to be due to, it ought to be proved not merely by one experiment, but by several,—that is, several kinds of experiments. He arranges two electrodes so that one becomes hotter than the other by the heated electrolyte, and of course, in that case, there is not such a very great difference of temperature. I should think that he might obtain a great difference by some outside means. For example, suppose he should heat the electrode A by an outside furnace, so as to get it to a great deal higher temperature, and then insert it, and see whether the electromotive force has increased; or reverse the experiment by heating the electrode B, so that it is about as hot as electrode A, and see whether the electromotive force is zero. I am inclined to agree with Mr. Reed's presentation, but at the same time more than one kind of experiment should be in evidence.

It might be argued, although not on very solid grounds, that the reason why there is an electromotive force, is because there is less surface on one electrode than there is on the other. Now in Fig. 3, the two surfaces are equal, and there is no electromotive force. In Fig. 4 again the two surfaces are unequal and there is an electromotive force; so that a person, merely as a matter of argument, could say that the relative amounts of surface of the two electrodes might have something to do with the production of current, although I do not think that he could uphold his argument.

Referring again to my first point, I would like to ask the author whether he has caused one of the electrodes like that in Fig. 3 to be heated to a great deal higher temperature by some *outside* source, for instance, by putting it into a furnace and then dipping it into the electrolyte; or it could be heated while it is in there by some convenient arrangement. It seems to me that the matter ought to be proved more conclusively by a variety of experiments.

Mr. Reed:—Those experiments have been tried, and I was going to try this evening the experiment of reversing the electrodes to show that the electromotive force is brought to zero and reversed. Then in regard to the surfaces, in Fig. 3 the surfaces of contact are equal. If we incline the rods in the position of Fig. 4 both rods will still be wet with the electrolyte as before. The same amount of surface would still be in contact with the electrolyte in both cases, although part of it may be in a thin layer on one electrode. However, it seems to me that if we are to argue that the electromotive force can be caused by exposing two similar electrodes to contact of a single electrolyte, if we can suppose that the electromotive force is caused by merely a difference in the surfaces in contact with the electrolyte, then we could get an electromotive force by using any electrolyte, inserting two pieces of iron of different sizes, or two pieces of zinc. It seems to me we could try innumerable experiments of that kind, and I guess they have been tried to the satisfaction of every one who has tried to get energy in that way. We certainly could not get electrical energy by inserting two pieces of zinc or anything else into an electrolyte, simply by inserting one to a greater depth or giving it a greater contact of surface. If we could, that would be a cheap way of getting energy. I do not know whether that answers the question.

Mr. Thompson:—That was merely a superficial argument. I did not believe in it at all myself; only I said it was an argument a person could present. But the principal one, is whether you have heated one electrode from an outside source to a great deal higher temperature than that of the other and whether you obtained better results.

Mr. Reed:—Yes; I have tried a great many experiments of that kind which were entirely satisfactory. I did not think it was worth while to take the time of the Institute to enumerate them all in this paper, and I tried a great many different electrolytes and other substances besides iron. I will say that this question of the thermo-electromotive force of a metal in contact with an electrolyte has been investigated by quite a number of observers. Nearly twenty years ago Bouty made some experiments to determine the electromotive force of contact between electrodes and electrolytes (see Fig. 18). Bouty took two test tubes filled with an electrolyte; sulphate of zinc was one electrolyte on which he experimented; then connected them with a small tube filled with the same solution, inserted a thermometer into each and also a piece of amalgamated zinc. Then he surrounded one of the tubes with water, maintained at zero or some fixed temperature, and the other with water which he kept at a different temperature. In that way he determined the electromotive force between the two pieces of zinc inserted in the zinc sulphate. one piece being at a different temperature from the other. He determined this electromotive force with reference to a number of electrolytes. The same thing was done later by Chroustchoff and Sitnikoff and also by Carhart. They all found that the results agreed with the formula for the relation between the electromotive force and the chemical energy of the reaction between the electrolyte and the electrode, plus or minus the thermo-electromotive force of the circuit which Helmholtz showed to be equal $t \frac{dE'}{dt}$; that is, the absolute temperature into the first differential coefficient of the thermo-electromotive force with respect to the temperature. The results all agree in showing this formula to be correct: but they all claim that this thermo-electromotive force was due entirely to the Peltier effect; that is; due to the electromotive force of contact between the electrode and the electrolyte, and I think none of their experiments proved that. Their experiments merely showed the thermo-electromotive force. They did not show that it was due to the Peltier effect alone. In reality you will see that what they determined was the thermo-electromotive force of the entire circuit composed of two conductors. one being the electrolyte, and the other being a

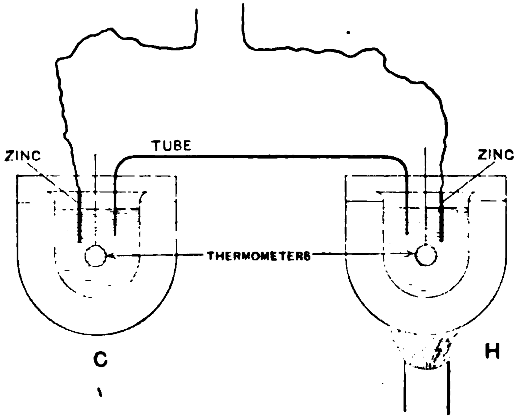


FIG. 18.

metal interrupted at one point, one point, H, of the circuit being heated and one point, C, being cold. There is nothing in their experiments to show that that electromotive force was due to the Peltier effect alone. If we simply take the figures they give and that arrangement it would indicate rather that it was due to the sum of the Thomson and Peltier effects. They made no measurements to determine the difference of temperature between the electrode and electrolyte. It is evident that the electrodes would have nearly the same temperature as the electrolyte in each case.

Mr. C. O. Mailloux:—I am interested to know if among the electrolytes Mr. Reed has used he has tried any of the metals melting at a low temperature, such as fusible alloys, and even lead which could be retained fluid at the temperatures at which he has been working. If the function of the fluid is merely that of disseminating heat, it is improper to term it and treat it as an electrolyte; it is more a menstrum for the conveyance of heat. In that case, by the use of a metal instead of a liquid, he would avoid the phenomenon of polarization, because the only effect which could take place at the points of contact by the passage of current would be the Peltier phenomenon, which, while it would introduce an electromotive force, would be of opposite polarity at the two electrodes, and therefore would have no effect upon the resultant electromotive force.

Mr. Reed:—The question which has been in dispute, and which I attempted to determine by these experiments, was the fact that there is a high electromotive force, or thermo-electric power, I should say, between the fused electrolytes and solid conductors in contact with them. I did not know that there was any question about there being a thermo-electromotive force between metals in contact.

Mr. Mailloux:—Perhaps I did not make myself sufficiently clear. I meant to say that if we were to substitute for the fluid, lead in a molten state at a temperature from 300 to 350° C, or at some temperature which is just below its evaporation or volatilization point (the melting point of lead being about 330° C.) and if at that temperature, under those conditions, we obtained practically the same electromotive force for the same difference of temperature between the electrodes,—that, it seems to me, would show conclusively, that the phenomenon was due entirely to difference of temperature, and that the term electrolyte was not applicable, and that the liquid was merely a convenient substance for disseminating or conveying heat. It seems to me that an experiment of that character would strengthen the position taken by Mr. Reed, if the results thereof showed that the electromotive force obtained was still a function of the difference of temperatures, the liquid substance merely serving as a means for the conveyance of heat and at the same time as a conductor.

Mr. Reed:—I do not think there is any question about there being thermo-electromotive force in circuits composed wholly of metals. I consider that that question has been settled by the work of Kelvin, Tate and others a good many years ago.

MR. MAILLOUX:—Would the electromotive force be the same?

MR. REED:—No, very different. That is just the point which I originally noticed and which seemed to me a curious phenomenon and which induced me to investigate this subject further. I noticed that the electromotive force between the electrolyte and metals in contact was very much higher, in most cases hundreds of times as high as what we could obtain from a thermo-electric battery or junction consisting of metals. For instance, the thermo-electric power of any two metals is only a few millionths of a volt per degree centigrade; whereas with the electrolytes it is all the way from ten to a hundred times, or three or four hundred times as much. One of the first experiments which I observed in that connection was with two pieces of copper containing a thin film of copper oxide between them. They were placed in contact (two pieces of copper wire, for example), one of them may be heated only say one hundred degrees hotter than the other to get an electromotive force on nearly half a volt, as long as there is copper oxide between them. But as soon as the copper oxide is reduced by the passage of the current, or in any other way, and metallic contact occurs, the electromotive force drops so that you could not measure it with a voltmeter of this kind. In other words, if we take two pieces of metal in actual contact and heat one of them hotter than the other and get as great a difference in temperature as possible, we get a result which is not anything like what we get in the case of an electrolyte. I do not know whether that answers your question or not.

MR. MAILLOUX:—It answers it partly. The principal object of my question was to know whether if you were to substitute lead for the caustic potash there, the electromotive force would be approximately the same or not.

MR. REED:—Nothing like it. We have two pieces of iron here, and merely maintaining those two pieces of iron at slightly different temperatures and having them connected by melted lead would give us only a very small electromotive force; it would be the thermo-electromotive force of iron against lead.

MR. MAILLOUX:—What I mean is to repeat the experiment as shown in your Figure 2, using lead instead of caustic soda.

MR. REED:—You would not get any electromotive force to speak of.

MR. MAILLOUX:—You still get the same difference of temperature between two rods, owing to the difference at which the heat would be disseminated. One would be imbedded. You would have exactly the same condition as far as heat distribution is concerned.

MR. REED:—But you would not get the same electromotive force.

Mr. Mailloux:—Then it is not altogether the difference of temperature that produces the electromotive force. That is the point on which I wished more light.

Mr. Reed:—It is a different kind of junction. The thermo-electric power of a couple consisting of an electrolyte and a metallic conductor is very different from the thermo-electric power of a junction consisting of two metals.

Now I will ask Mr. Mailloux if he will be kind enough to come and read the voltmeter, which is the only instrument I have here convenient, to take these measurements. The liquid is now approaching redness.

The Chairman:—I should like to ask Mr. Reed what variations he found with different electrolytes. Is the difference very pronounced?

Mr. Reed:—Very pronounced. In electrolytes which consist of aqueous solutions, such as those experimented upon by the investigators I have already mentioned, the thermo-electric power seems to be very small. In the fused electrolytes, which seem to have the very high thermo-electromotive force, it may be due to the fact that they are capable of being maintained at very much higher temperatures.

I am afraid this heat will not be enough to dehydrate the liquid. I cannot get it hot enough to show in this light any difference of temperature between the two rods as indicated by their appearance. In fact I have not got it hot enough yet to actually fuse the electrolyte around those rods.

The Chairman:—What voltage did that show?

Mr. Mailloux:—Two one-hundredths.

The Chairman:—What voltage did you expect, Mr. Reed, if you got the full heat?

Mr. Reed:—If you get the full heat and get it rapidly you get about nine-tenths of a volt.

Mr. Mailloux:—It jumps to about two-tenths. [Position of rods now reversed.] It reverses now to about four one-hundredths.

The Chairman:—Those rods are similar, are they, Mr. Reed?

Mr. Reed:—Yes, sir. We now reverse them again.

Mr. Mailloux:—It comes back to zero. Now it is at zero, passes zero. It is now about .04, .06, .1, about .2, .18—back to zero.

Mr. Reed:—I think that is as much as we can get with this source of heat. In order to show this successfully the source of heat must be such as we can control to get any temperature needed. In making experiments, with the voltmeter in circuit, of course we have a battery on closed circuit. While there would only be one or two milliamperes flowing through this instrument, we must remember that the battery has a very small surface, and considering the surface it is a large current. In similar experiments after leaving the voltmeter switch closed some time the solid cylindrical rod appeared after washing, to be of a dark blue color, due to the presence of reduced iron, while the head of the other rod is covered with spots of a bright red color, evidently ferric oxide. That result, of course, would be due to the passage of the current which would oxidize this electrode, and reduce iron upon the other. In order to get satisfactory results, we must have heat enough so that the electrolyte will act to a considerable extent upon the iron cup and dissolve a sufficient amount of iron in the solution to allow the current to pass without polarization with this instrument. I am sorry to say that I am not able to get heat enough. The pressure of the gas here is much less than where I have been experimenting. I will try this once more. [Changing position of lamp]. It may be a little hotter.

Mr. Mailloux:—It is .04—about .06.

Mr. Geo. F. Atwood:—I would like to ask Mr. Reed if the electrolyte undergoes any change with the continuous discharge of current.

Mr. Reed:—Certainly. The slightest current must produce a chemical change

Mr. Atwood:—I meant to ask if the electrolyte loses power and becomes weakened and has to be replenished.

Mr. Reed:—Yes. As soon as the iron or other impurities capable of undergoing oxidation and reduction are entirely gone from the electrolyte, then no further current can pass without the reduction of some other constituent of the electrolyte, such as sodium or hydrogen. They would be the only two present capable of reduction, and that reduction requires the absorption of considerable energy. In other words, it would act as a counter-electromotive force or polarization. Does that not answer the question?

Mr. Atwood:—Yes sir; that is the point.

Mr. Reed:—We are not able here to get heat enough to bring the electrolyte up to the proper condition. If you will turn in the paper to Figs. 10 and 11 you will see that the change in electromotive force is only a few hundredths of a volt until the temperature reaches in the neighborhood of 550°, and we have not got anywhere near that temperature here. At that temperature there was a sudden change, the direction of the current reversed; that was at the end of forty minutes in that experiment. (Fig. 10). You will see the line where it says "color turns brown." The temperature there is nearly 540°, and at that point this change takes place in the electrolyte, and the electromotive force then reverses and goes up very rapidly. In our experiment here we did not not get to the temperature at which the electromotive force reverses. The same thing is shown in Figs. 11 and 12.

Mr. J. P. Wintringham:—The remarkable thing about these diagrams seems to me to be the very large change of electromotive force for small changes of temperature. But of course it is the difference of temperature of the two rods which is the governing factor and not the absolute temperature of the mass.

In the first two diagrams, 5 and 6, the electromotive forces follow the temperature very closely, and then in the others and in the following diagrams they vary widely from it.

I suppose that is due to the change of the electrolyte with the brown color, and that the thermo-electric force due to the electrolyte previously and after that is very different. I was wondering if one electrode was introduced first and allowed to heat and then the other was introduced, if that would show very much electromotive force or whether it would require warming a little before the current could pass at all?

Mr. Reed:—A cold electrode suddenly inserted, chills the electrolyte around it and forms a non-conducting shell.

Mr. Wintringham:—Then there is a question if the absorption of heat might not be due to something else besides a chemical change. In heating or cooling metals, certain changes take place abruptly in the line on a diagram showing the gain or loss of temperature against time as an ordinate.

I believe the word recalescence is associated with some such change in iron—possibly a change of molecular structure or specific heat.

Mr. Reed:—This is a liquid. You must bear in mind that this electrolyte is a liquid all the time.

Mr. Wintringham:—I understand that, but still the great absorption of heat is not only at the melting point and at evaporation, but at other points there may be considerable absorption of heat without a corresponding rise of temperature.

Mr. Reed:—Then while it remains liquid, after it reaches a certain temperature, it suddenly absorbs heat without changing to the solid state.

Mr. Wintringham:—I know. But there are much changes in the heating of single metals alone. If you have a rod of iron red hot, white hot, and allow it to cool, it cools off slowly to a certain temperature and then becomes hotter again, brighter, and then goes on cooling.

And then on page 229 the formula shows free oxygen. Does the chemical boil? Is there evidence of free oxygen being given off?

Mr. Reed:—Well, you could hardly call it boiling in the sense that water boils. There are minute bubbles of gas or steam coming off from the time the experiment begins until the end.

Mr. C. P. Steinmetz:—Reading Mr. Reed's very interesting paper, I am not satisfied that the effect described therein is really a thermo-electric effect and not electro-chemical or galvanic The abrupt change of the E. M. F. at the temperature at which chemical dissociation is shown to occur by the change of color, rather points to electro-chemical action. The magnitude of E. M. F. points the same way.

If two electrodes of different chemical affinity are inserted into an electrolyte, chemical combination takes place at the one, dissociation at the other electrode. The energy produced by chemical combination at the one electrode is greater than the energy consumed by dissociation at the other electrode, and the difference of energy appears as electric energy. As well known, chemical affinity is a function of temperature, increasing in general with increase of temperature up to a maximum and then decreasing again and reaching zero at the dissociation temperature of the compound. Thus, if two electrodes of the same material, but at different temperatures, are inserted in an electrolyte their chemical affinities are different and they thus act like two different materials, that is, form a galvanic couple and chemical combination takes place at the electrode of a temperature giving a higher chemical affinity, and an equal amount of chemical dissociation at the electrode whose temperature gives a lower chemical affinity. This seems to me the effect observed by Mr. Reed. It is thus not thermo-electric, but electro-chemical, or the same as, for instance, in a zinc copper cell, the only difference being that the chemical energy which produces the electric energy is ultimately derived from heat energy.

The cycle of matter is thus: Iron and oxygen combine at one temperature, the compound is brought to another temperature, there dissociated into iron and oxygen, and the iron and oxygen brought back to the first temperature, where they combine again. The corresponding cycle of energy is: Energy is consumed at the one temperature by dissociation, transferred by the specific heat while bringing the iron and oxygen from the one to the other temperature, energy produced by chemical combination at the second temperature and energy transferred by the specific heat of the oxide of iron when being brought back to the first temperature. Thus the difference of specific heat of the oxide of iron from the specific heat of iron and oxygen equals the difference of chemical affinities and is thus the source of energy which produces the E. M. F. The phenomenon is analogous, to a certain extent, to the pyro-electric machine, in which iron is withdrawn from a magnetic field at a temperature beyond the critical temperature, that is while unmagnetic, then cooled below the critical temperature and attracted by the magnetic field again while magnetic. Here the source of energy is the difference of specific heat of the iron in the magnetic and in the unmagnetic state.

MR. REED:—Do I understand that you admit the source of the energy is heat?

MR. STEINMETZ:—Yes, sir, the ultimate source of energy is heat.

MR. REED:—That is all I have attempted to show. Although we got only small amounts we have got some electrical energy here. I do not think there is any known process by which heat can be converted directly into electrical energy, except by thermo-electric conversion. I think, if you look into the question carefully, that you will see that the energies exactly balance each other, which you speak of as resulting in an evolution of energy by the differences of specific heats. I admit that there are differences in specific heats. I admit that it is possible that there are differences of affinity. There is undoubtedly a difference between the affinity of oxygen for iron at high temperatures and at low temperatures. But can that difference of affinity, under these conditions, evolve energy, when we must produce the same amount of oxide of iron which we reduce. In other words, keep in mind that the amount of iron oxide reduced at one electrode is equal to the amount produced at the other, can we evolve any energy by that process?

MR. STEINMETZ:—It is this very point which I intend to explain that by combining iron and oxygen to oxide of iron at one temperature and dissociating the same amount of oxide of iron at a different temperature, more energy must be transformed in one case than in the other, due to the difference of chemical affinity, and thus an E. M. F. produced which is galvanic or electro-chemical but not thermo-electric, although ultimately due to the difference of specific heat of the compound and its constituents.

We have a double transformation: of heat into chemical energy and of chemical energy into electric energy, but no direct conversion of heat into electric energy, that is no thermo-electric effect. The process is essentially the same as for instance in the zinc copper cell where the affinity of the zinc is ultimately produced by heat also, only more efficiently by a separate process, the electro-metallurgical reduction of zinc from its ores.

MR. REED:—Assume we have an isolated system like that—suppose we take away the flame for a few moments, we have got a certain chemical condition and a certain amount of heat not uniformly distributed. Can we then by an internal process convert part of that heat into chemical energy so that in the end the chemical energy and conditions shall remain the same, and at the same time evolve electrical energy without a thermo-electric conversion when the only tendency towards any change is that of uniform distribution by conduction?

MR. STEINMETZ:—Yes, by a transfer of heat from higher to lower temperature. By changing the temperature of a compound and oppositely changing the temperature of its constituents we get less heat energy back than put in, and the difference is transformed into chemical affinity, which again is transformed into electric energy if the electric circuit is closed.

MR. REED:—In other words, it is equivalent to the theory that instead of this being a thermo-electric process it is a thermo-chemical transformation of heat into chemical energy.

MR. STEINMETZ:—Yes sir,

Mr. Reed:—And the chemical energy so produced evolves electrical energy, the initial and final chemical conditions being identical?

Mr. Steinmetz:—Yes sir.

Mr. Reed:—And that the oxidation of the iron evolves more energy than the reduction of an equal amount of iron which goes on simultaneously with it?

Mr. Steinmetz:—At the different temperatures, yes.

Mr. Reed:—At the different temperatures. Well, of course there is nothing in these experiments to prove that that is not true; but if we assume that, then we might apply that same reasoning to almost any chemical action. We might say a chemical action could take place in one part of an electrolyte and reverse in another part and evolve electrical energy.

Mr. Steinmetz:—It seems to me to be impossible otherwise. Since the chemical affinity is different at different temperatures, if in the same electrolyte oxidation and reduction of equal amounts of materials take place simultaneously but at different temperatures, more energy must be produced by the one than consumed by the other, and thus a difference left which is a function of the difference of temperature of oxidation and reduction.

Mr. Reed:—I do not see that there is anything in these experiments to disprove your theory, but I do not see anything in these experiments or in similar ones to prove it. I admit there is nothing to actually disprove that that is the process by which the heat of the flame may be converted into electrical energy. My object was, as already stated, to show that the source of this electrical energy was the heat. Now as to the processes through which the energy might pass before it becomes electrical energy, of course, it is easy to assume that it may pass through a thermo-chemical process such as you have mentioned. I do not see how we could prove that that was not so. These experiments certainly do not prove that.

Mr. Steinmetz:—The ultimate source of energy is undoubtedly heat, but the electric energy is not produced by heat, but by chemical action of matter just as in any galvanic couple.

Mr. Reed:—I think there is one evidence against that theory. It is that chemical affinities do not act in that way. Chemical affinities do not depend on differences of temperature. Under a given pressure a chemical reaction takes place at a given temperature and continues as long as the products of the reaction do not interfere. The energy evolved by a chemical reaction does not increase with the temperature at which it takes place But the experiments of Bouty, Chroustchoff, Sitnikoff and Carhart all show that the electromotive force increases with the absolute temperature according to the formula for thermo-electromotive force determined by Kelvin and Tait for metallic conductors. If chemical affinity causes this evolution of electrical energy and absorption of heat, we should, after reaching a certain temperature, be able to convert any quantity of heat into electrical energy.

Mr. Mailloux:—I think that we are mostly wrangling about definitions in this matter. Our knowledge of chemistry has been progressing somewhat as a consequence of the work done by such men as Berthelot, Julius Thomson, and others, who have done so much in the field of thermo-chemistry. To-day there are chemists who tell us that oxidation and all cognate chemical phenomena are nothing more than thermo-dynamical phenomena; that the reactions which take place therein are functions of change of volume and of internal stress; that, in a word, we are dealing with a problem of thermo-dynamics pure and simple, in nearly all if not in all chemical reactions. When we heat a substance it changes in size, in physical condition and in temperature. A part of the heat which it absorbs goes to dilate the body, and becomes latent. It does physical work against some resistance, probably purely mechanical, inside the molecule. It is the intrinsic energy absorbed by the body itself in overcoming atmospheric pressure or its own molecular elasticity, or in causing changes of internal stress. A portion of the heat energy remains available and ready to do work. It may be provisionally locked up and may play a part in certain internal phenomena in the molecular structure just referred to, but upon proper conditions being established that energy is immediately restored and can do work outside of the molecule from which it has been released. Many chemists believe to-day that we shall soon have to treat chemical reactions as problems in physics. Even the word molecule is looked upon with suspicion. We are coming soon to a state when the advance in the science of thermodynamics will give us all the information that is necessary to explain chemical phenomena. Some ten years ago, in a lecture before the Franklin Institute, I called attention to this fact, and I ventured to express the belief that the changes in volume of the chemical substances in the electrolytes and in the plates in the storage battery are a criterion of the electrical phenomena involved and probably will be made a measure of it; and that, in general, the amount of energy necessary to change the volume of a chemical substance can be measured by the change in volume and internal stress. It seems to me that in this instance we are dealing with a case where we put energy at the heat end, some of which is necessarily absorbed and stored in dilating the substance, or in other internal physical changes or reactions (so to speak, for want of a better term), while a portion of it is available for other purposes. At the time that we unlock this combination of heat with a body (which chemists call an oxide or any other compound—it is merely a substance which has undergone change of volume by reason of energy which has been put into it), that is to say, when we make the transfer of energy, and bring back the substance to its original volume and to its original state, if we do it at a lower temperature, it is evident that the mere change of temperature makes a difference in the intrinsic energy of the body; just as much as there is a difference in the heat energy necessary to dilate a pound of water at 100 degrees and at zero degrees centigrade. So it seems to me that in this instance we have a great deal of energy which is not at all chemical. It is merely physical energy involved in the change of the molecular volume of the substance. Faraday's law tells us that the amount of electric current due to the transformation of iron into oxide and of oxide into iron again must be the same, yet it is done under different conditions of electrical pressure, if that pressure be due to molecular changes, whether it be due to the heat itself, or whether it be due to any other physical condition produced by the heat, there must necessarily be a change of energy, a difference in energy. I believe that the phenomenon is merely one in which we have changed the volume or the internal stress by changing the temperature, and that that energy is the very one that enters into play and is rendered available as electrical energy. I do not think that my explanation is as clear as it might be, because this is a problem on which most of us are still largely in the dark. I have tried simply to convey the idea, that in chemistry we are dealing largely with thermodynamic phenomena, and that in this case we are probably dealing with a thermodynamic phenomenon in wich a transfer of energy takes place from the hot to the cold body, or vice versa, according to the case, merely by virtue of the change of volume, or of internal stress caused by the heat.

SECRETARY POPE:—It is getting late, but I am sure we would all be glad to hear a word from our distinguished foreign member, Mr. W. M. Mordey, who is with us this evening. I believe he has a point which he wishes to clear up, and at the same time he might perhaps elucidate some of the points that have been raised in this discussion.

THE CHAIRMAN:—We should be very much pleased to hear from Mr. Mordey.

MR. MORDEY;—As I came in late I did not have the advantage of hearing the paper read. There is one question I wish to ask, but before doing so I will say, as this is the first occasion I have had the honor of being at one of your meetings, although I have been a member a few years, how very glad I am to be a guest at this meeting and how much I feel the advantage of being a member of this INSTITUTE. I have looked to this INSTITUTE to keep me acquainted with progress on this side and I have admired the energy and ability with which the proceedings of the INSTITUTE have been conducted. By the papers you have read here and the discussions, and the way in which they are presented in the Journal, I think you have set an example to our older institution on the other side which we might very well follow. In fact, I have often thought that you show the evidence of youth and virility on this side in your electrical institution as you do in other ways. Before asking the question, if the author would permit a moment, I would like to take the opportunity of saying how much I appreciate the great kindness that I have received, the hospitality and attention I have received from my fellow electrical engineers in all parts of the country during the visit of some five or six weeks I have been making here—a most instructive visit to me—and I have been very glad to renew my acquaintance with a good many members and to make the acquaintance of others.

The only question I wished to ask here was as to whether the arrangement of Figure 1 was not merely an arrangement for getting a difference of temperature between the two rods and whether any other arrangement by which he obtained the same difference of temperature would not have the same effect; whether, for instance, if he had two rods, as shown in Figure 3, and he surrounded one of them by a cooling jacket of some sort, or had, we will say, a couple of small holes drilled down, and circulated water through the rod, whether he would not in that way, by getting a difference of temperature, have got another result in Figure 3, as he obtained in Figure 1 and Figure 2.

I think so far as I have been able to follow the paper by glancing through it after the reading of it was finished, and the discussions, that I would complain that the author has not given us the right title, but I think Mr. Steinmetz has indicated the explanation of his experiments; I think in using the term thermo-electric, he made perhaps a wrong use of the word that we are familiar with in another sense. In a thermo-electric battery we are accustomed to look for chemical action. I think the whole of the author's experiments are to be explained on the supposition that he has by difference of temperature, chemical actions set up—the difference of temperature in one to be more susceptible to chemical action than the othor. The paper is thoughtfully written, and I have no doubt that the author has made a great many experiments that are not detailed here, and possibly he has made an experiment such as I suggest in the cooling by artificial external means of the two electrodes. I would ask; if he has done so, whether he has not found the difference of potential that he got in the arrangement shown in Figure 2.

Mr. Reed:—I would reply that I have made those experiments and found in all cases that any means by which we can maintain a difference of temperature between the two electrodes will give the result. Liebenow and Strasser, in their paper previously referred to,, repeated an experiment which I tried a year or so before, and described in another place, of using two iron tubes bent—U tubes which were dipped into the electrolyte, one being kept cold and the other hot by a stream of air or a liquid, and they reported that a difference of E. M. F. of about one volt was obtained in that way. The only object of presenting this in this form was, as I thought, to get an arrangement in which there could be no doubt whatever that the E. M. F. was due solely to a difference in temperature between the two electrodes. In other words, that it could not be maintained that in these experiments it was due to the fact that one electrode was near the surface of the electrolyte and the other deeper down, as was claimed by Liebenow and Strasser. That was their explanation. As a matter of fact, as stated in the paper, an electromotive force of about a volt can be obtained between the iron cup and the iron rod inserted when the rod actually rests on the bottom, metallic contact being prevented by a thin film of oxide or of the electrolyte. The object of this arrangement was merely for that purpose.

MR. STEINMETZ:—I do not agree with the last objection of Mr. Reed to my explanation, that the process would be continuous and contradict the law of conservation of energy. Since the difference of electric potential is due to difference of chemical affinity caused by difference of temperature, it ceases as soon as the temperature has become uniform, that is, heat has ceased to flow from higher to lower temperature.

THE SECRETARY:—Before we adjourn, I would like to move a vote of thanks to the author of the paper for the trouble he has taken in showing these experiments, and to express our regrets that the quality of our gas is not equal to the municipal gas they formerly had in Philadelphia.

[The motion was seconded by Mr. Steinmetz and carried and the meeting adjourned.]

[COMMUNICATIONS RECEIVED SINCE ADJOURNMENT.]

MR. J. P. WINTRINGHAM:—The writer of this paper seems to be unusually well informed and to have given a good deal of thought to the subject. I suppose he had only one object in view, to establish the seat or origin of the electromotive force. This, he argues, is due to a thermo-electric effect between iron and an electrolyte, melted caustic potash. Incidentally he claims that melted potash must conduct electrolytically. Yet many insulators allow a current to flow when highly heated and generally their resistance decreases with a rise in temperature. His argument is that heat of combination of the iron is always a constant quantity and the electromotive force cannot be due to the chemical affinity which is measured by the heat of combination, for an absorption of energy would take place at one pole equal to that given off at the other, so no electromotive force can be attributed to that source.

I think it must be admitted that chemical affinity does vary with the temperature. What seems still to be wanted is a crucial experiment that will show what the source of the electromotive force is. I can only suggest that the differences of the temperature of the rods should be measured, and plotted against the voltage measured by an electrometer so as not to allow of any flow of current. If such a curve approached a straight line or was free from abrupt changes it might be judged that the voltage was caused by a thermo effect and not by chemical affinity.

MR. C. J. REED:—In view of the foregoing discussion and the consensus of opinion that the energy of this cell is derived entirely from the external heat, and in view of the suggestion by Mr. Morday that I have merely made a mistake in the title of the paper in calling the cell thermo-electric, I believe it might have been conducive to a clearer understanding of what this apparatus was intended to exhibit, if, instead of a thermo-electric battery, I called it "*a novel form of galvanic battery, in which the only source of electrical energy is external heat absorbed by the circuit while it is in action.*" The importance of distinguishing between a galvanic battery of this character and a thermo-electric battery did not occur to me until after reflecting on the arguments presented at the meeting. My reason for calling the action of such a cell thermo-electric was that it has heretofore always been recognized as such, and because no process, except thermo-electric inversion, has yet been defined, by which external heat is absorbed directly into an electric circuit and simultaneously evolved as electrical energy. What name shall we give to the new process?

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

New York, May 17th, 1898.

The annual business meeting of the Institute was held this date, and was called to order by President Crocker at 8:35 P. M.

The following associate members were elected at the meeting of the Executive Committee in the afternoon:

Name.	Address.	Endorsed by
Cadou, Felix Louis.	Superintendent and Electrician, Washington Street Railway Co., Washington, Ind.	F. S. Hunting. A. A Serva. W. J. Hammer.
Dempster, Thomas.	Electrical Engineer, General Electric Co., Schenectady, N. Y.	Chas. P. Steinmetz. Eskil Berg. James Lyman.
Letheule, Paul	Electrical Engineer, Commissioned by French Government, 24 Front St., Schenectady, N. Y.	Chas. P. Steinmetz. Ernest Berg. James Lyman,
Johnston, Livingston, Jr.	Islip, N. Y.	W. H. Ripley. F. B. Crocker. W. H. Freedman.
Joslyn, Howard	Assistant Engineer, Snoqualmie Falls Power Co., Seattle, Wash.	D. C. Jackson. B J. Arnold. R. W. Pope.
Mahoney, James J.	Engineering Assistant to Manager Railway Dep't. General Electric Co., 115 W. 47th St., New York City.	W. B. Potter. W. J. Clark. G. F. Sever.
Taylor, Irving A.	Motor Inspector, Edison Electric Illuminating Co., 360 Pearl St, Brooklyn, N. Y,	Jos. Wetzler. W. D. Weaver. C. J. Field.
Turnbull, Wallace Rupert.	Foreman of Experimental Room. General Electric Lamp Works; residence, 29 S. Arlington Ave., East Orange, N. J.	Jno W. Howell. J. T. Marshall. W. S. Howell.
Winfield, James H.	Sup't. Eastern Division, Nova Scotia Telephone, Ltd., New Glasgow, N. S.	Norman Ross. F. A. Bowman. A. R. Cogswell.
Wood, Fred. W.	General Manager, Los Angeles Railway Co., 1722 S. Flower St., Los Angeles, Cal.	Frank Van Vleck. W. F. C. Hasson. Harrison C. Wybro.

Total 10.

TRANSFERRED FROM ASSOCIATE TO FULL MEMBERSHIP.

Approved by Board of Examiners, April 2nd, 1898.

Burch, Edward P.	Electrical Engineer, Twin City Rapid Transit Co., Minneapolis, Minn.
Redman, G. A.	Gen'l Sup't. Electrical Dep't Brush Electric Light Co., and Rochester Gas and Electric Co., Rochester, N.Y.
Boggs, L. S.	Pioneer Electric Co., Ogden, Utah.
Fischer, Gustave J.	Engineer for Tramway Construction, Public Works, Dept., Sydney, N. S. W.
Scott, James B.	Electrician and Mechanical Engineer, 227 East German St., Baltimore, Md.

Total 5.

The President appointed Townsend Wolcott and J. P. Wintringham as tellers, and Prof. W. A. Anthony, C. S. Bradley and Charles Blizard as a Proxy Committee.

The following reports of the Council and of the Treasurer were read and accepted:

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

Report of Council for the Year Ending April 30th, 1898.

New York, May 17, 1898.

As required by the Constitution, the Council presents for the information of the Institute at large, a report of its work and the financial standing of the organization at the close of the year.

Three meetings of the Council, and eight meetings of the Executive Committee have been held during the year.

Badges of the new design referred to in the last report of Council, have since been manufactured for sale, and 150 have been sold to the membership. The different styles are kept in stock so that there has been no delay in furnishing them. They are numbered consecutively as purchased and usually forwarded the day following the receipt of order About 232 of the previous design are still outstanding, 32 having been returned for exchange.

The monthly meetings during the past season have been held on the fourth instead of the third Wednesday of each month This change was made in order to avoid conflicting dates with the meetings of the American Society of Civil Engineers, as many of our members belong also to that society.

A change has been made in the application blanks used by candidates for membership, separate forms now being used for associate members and for subsequent application for transfer. The old form used for both purposes gave rise to some confusion which is now avoided.

The National Electrical Code, which was formulated by the National Conference on Standard Electrical Rules, was submitted to the Institute for approval accompanied by a report by Dr. Francis B. Crocker, who was the official delegate representing the Institute in the conference. The Code was submitted for discussion by the members at meetings held in New York and Chicago, September 29th, 1897. The Code was approved, and by recommendation of the meeting, a committee was subsequently appointed by Council to report to the INSTITUTE any revisions which in its judgment are advisable. Certain recommendations have already been made by this committee which is composed of the following members:

CARY. T. HUTCHINSON, Chairman.
A. E. KENNELLY, S. DANA GREENE.

By direction of the Executive Committee, the Committee on Papers and Meetings was authorized to arrange for a meeting to discuss the question of the Standardization of Dynamos, Motors and Transformers. This meeting was held at New York and Chicago, January 26th, 1898. After a thorough discussion the whole matter was referred to Council, which at its meeting March 23d, appointed the following committee to consider and report upon the subject:

FRANCIS B. CROCKER, Chairman.

CARY T. HUTCHINSON,	C. P. STEINMETZ,
A. E. KENNELLY,	L. B. STILLWELL,
J. W. LIEB, Jr.,	ELIHU THOMSON.

This committee has already held two meetings, but on account of the nature of its work, no final result has yet been reached, although very satisfactory progress has been made.

In accordance with instructions given by Council last year an account has been opened with the State Trust Company, in which the amount of $600 has been deposited which will be known and reported hereafter as the Compounded Membership Fund, drawing interest at 2 per cent.

In renewing the lease of the INSTITUTE's headquarters in the Havemeyer Building, a slight change has been made in the arrangement, by which a separate and more commodious office has been secured at the same rental for the use of the Secretary and for committee meetings.

At the meeting of Council January 26th, it was voted that the next General Meeting of the INSTITUTE be held at Omaha, Neb., and the date of its opening was subsequently fixed for June 27th.

The total membership at the close of last year's report was 1,073, classified as follows:

Honorary Members	2
Members	350
Associate Members	721
Total	1,073
Restored to Membership	2
Associate Members elected May 1st, 1897, to April 30th, 1898	89
" " " previous year and since qualified	8
Total	1,172

Resignations have been received during the year and accepted from the following members in good standing:

CHARLES L. EIDLITZ,	JAMES W. CROSBY,
STANLEY G. FLAGG, Jr.,	CHARLES D. SHAIN,
EDWIN H. HALL,	J. P. B. FISKE,
FRANCIS R. HART,	G. P. WARDELL,
E. M. IZARD,	C. H. SHARP,
LAWRENCE A. McCARTHY,	A. G. WEBSTER,
F. J. A. McKITTRICK,	P. R. MIDDLEMISS,
W. G. M. THOMPSON,	LOUIS S. WRIGHT,
LEONARD C. WASON,	WM. HOCHHAUSEN,
FRANK P. MILLS.	GEO. W. TUTTLE,

Total resignations 20

There have been the following deaths during the year:

JAMES E. GRIST,
ARTHUR DE LA M. LOZIER,
NORMAN R. WEAVER,
WM. W. GRISCOM,
NELSON W. PERRY.
GUSTAV A. LIEBIG, Jr.,
HORACE S. L. VERLEY,
WM. H. COTHREN,
O. B. SHALLENBERGER,

Total deaths	9	
Dropped as delinquent	28	
Elections cancelled	1	
Elected but not yet qualified	16	74
		1,098

Leaving a total membership of 1,098 on April 30th, (a net gain of 25), classified as follows:

Honorary Members	2
Members	352
Associate Members	744
	1,098

A list of the members elected during the year accompanies this report. The names have already appeared in the TRANSACTIONS.

The reports of the Secretary and of the Treasurer show in detail the financial standing of the INSTITUTE at the close of the fiscal year, together with an itemized statement of receipts and disbursements during the entire year:

SECRETARY'S BALANCE SHEET.

FOR THE FISCAL YEAR ENDING APRIL 30, 1898.

Dr.		*Cr.*	
Receipts for the year	$10,027 01	By cash to Treasurer	$9,805 61
		Cash on hand	221 40
	$10,027 01		$10,027 01

ITEMIZED STATEMENT OF RECEIPTS AND DISBURSEMENTS OF THE INSTITUTE.

FOR FISCAL YEAR ENDING APRIL 30, 1898.

GENERAL ACCOUNT.

Receipts.		*Disbursements.*	
Treasurer's balance from previous year	$1,284 06	Chicago Meetings	$37 00
Entrance Fees	425 00	Library	4 50
Life Membership (C. T. Hutchinson).	100 00	Ice	26 60
Past Dues	655 64	Laundry	9 75
Current Dues	7,879 79	Office Expenses	26 69
Advance Dues	80 00	" Fixtures	18 55
Electrotypes Sold	8 36	Express	117 36
Transactions Sold	445 71	Telegrams	4 99
Transactions Subscriptions	211 50	Stenography and Typewriting	845 83
Advertising	149 92	Stationery and Miscellaneous Printing	369 06
Received for Binding	33 50	Postage	425 97
" " Certificates	2 00	Messenger Service.	3 95
" " Congress Book	19 79	Salary Account	2,500 00
" " Reprints Vol. 4	15 80	Meeting Expenses	198 09
		Rent Office and Auditorium	1,095 00
		Copyright	5 00
		Engraving and Electrotyping	489 78
		Binding	193 22
		Publishing Transactions	2,627 99
		Design for Badge	26 00
		Engrossing	11 25
		Compounded Membership Fund	600 00
		Secretary's Balance to next year	221 40
		Treasurer's Balance to next year	1,453.09
	$11,311 07		Total, $11,311 07

COMMERCIAL DEPARTMENT.

Dr.		*Cr.*	
Cash from previous year	$162 07	Badges, etc., bought	$497 28
Sales to May 1st	555 75	Engraving Names	35 04
		Badges on hand	137 00
		Bills Receivable	25 00
		Cash on Hand	23 50
	$717.82		$717 82

All outstanding bills against the INSTITUTE, were paid in full April 27th....
There is due the INSTITUTE and probably collectible $760 00

Property on hand according to inventory May 1, 1898.

Office furniture and fittings	$209 79
Catalogue Type, Cases, etc	233 78
Transactions on hand	3,107 79
Congress Books	764 71
Library	204 50
	$4,520 57

TOTAL NET ASSETS.

Building Fund	$973 48
Treasurer's Balance Mercantile Bank	1,453 09
Secretary's Balance, Cash on Hand	221 40
Secretary's Commercial Fund	185 50
Compounded Membership Fund in State Trust Co	600 00
Property as per Inventory	4,520 57
	$7,954 04

Respectfully submitted for the Council,

RALPH W. POPE,
Secretary.

New York, May 17, 1898.

TREASURER'S REPORT.

FROM APRIL 30, 1897 TO MAY 1, 1898.

GEORGE A. HAMILTON, TREASURER, in account with

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

Dr.

Balance from May, 1897	$1,284 06	
Received from Secretary, April 30, 1897 to May 1, 1898	9,805 61	$11,089 67

Cr.

Payments from May 1, 1897, on warrants from Secretary, Nos. 879 to 996 inclusive	$9,636 58	
Balance to new account	1,453 09	$11,089 67

BUILDING FUND.

(Mercantile Trust Co.)

Balance as per last report	$850 00	
Interest accrued to May 1, 1898	123 48	$973 48

COMPOUNDED MEMBERSHIP FUND.

(State Trust Co.)

Cash from General Fund, Oct. 1, 1897	$500 00
Life Membership, C. T. Hutchinson	100 00
	$600 00

Cash book and warrants herewith for audit. Vouchers are in the hands of the Secretary, to whom they are returned for filing after payment.

GEORGE A. HAMILTON,
Treasurer.

New York, May 17, 1898,

The Tellers subsequently submitted the following report:

FOR PRESIDENT.

Total Number of Votes Cast........341

Arthur E. Kennelly	293	Thomas A. Edison	2
Francis B. Crocker	24	Edward L Nichols	1
Thomas D. Lockwood	10	Lewis B. Stillwell	1
Charles P. Steinmetz	5	Joseph Wetzler	1
Harris J. Ryan	3	Alexander Jay Wurts	1

Total.... 341

FOR VICE-PRESIDENTS.

Total Number of Votes Cast.... ...1018

William Stanley	321	Stephen D. Field	2
Robert B. Owens	306	William D. Weaver	2
Cary T. Hutchinson	260	J. J. Carty	1
Carl Hering	35	Gano S. Dunn	1
Charles F. Scott	34	S. Dana Greene	1
C. O. Mailloux	8	Elisha Gray	1
M. I. Pupin	6	James Hamblet	1
William A. Anthony	5	Angus S. Hibbard	1
Bion J. Arnold	4	Charles R. Huntley	1
Louis Bell	3	Dugald C. Jackson	1
Charles E. Emery	3	Thomas D. Lockwood	1
Francis W. Jones	3	Edward L. Nichols	1
F. A. Pickernell	3	F. A. C. Perrine	1
Lewis B. Stillwell	3	Frank J. Sprague	1
Frederick Bedell	2	Nikola Tesla	1
Charles R. Cross	2	Herbert Laws Webb	1
Charles Cuttriss	2	Joseph Wetzler	1

Total.... 1019

FOR MANAGERS.

Total Number of Votes Cast...... .1357

Charles P. Steinmetz	324	Samuel Insull	3
Samuel Sheldon	318	William Maver, Jr.	3
Herbert Lloyd	316	M. I. Pupin	3
George F. Sever	311	Joseph Wetzler	3
William J. Hammer	7	Elmer G. Willyoung	3
C. O. Mailloux	4	Louis B. Marks	3
Harris J. Ryan	4	Ralph D. Mershon	2
William D. Weaver	4	Max Osterberg	2

Robert B. Owens	2
Wm. Lispenard Robb	2
E. P. Roberts	2
Albert L. Rohrer	2
Nikola Tesla	2
F. N. Waterman	2
Norman W. Storer	2
Frederick Bedell	2
Henry S Carhart	2
Arthur V. Abbott	1
William S. Barstow	1
Edward D. Brown	1
J. Stanford Brown	1
G. Herbert Condict	1
Francis B. Crocker	1
Charles Cuttriss	1
Wm. C. L. Eglin	1
Louis W. Emerick	1
Charles E. Emery	1
Reginald A. Fessenden	1
William H. Freedman	1
Caryl D. Haskins	1
Edward E. Higgins	1
Dugald C. Jackson	1
A. A. Knudson	1
Philip A. Lange	1
Thomas D. Lockwood	1
T. Commerford Martin	1
Richard H. Pierce	1
E Wilbur Rice, Jr	1
Howard S. Rodgers	1
Frank Stuart Smith	1
Frank J. Sprague	1
Lewis B. Stillwell	1
Wilbur M. Stine	1
Charles F. Uebelacker	1
H. Fleetwood Albright	1
Alexander J. Wurts	1
Total	1357

FOR SECRETARY.

Total Number of Votes Cast........339

Ralph W. Pope	338
James Hamblet	1
Total	339

FOR TREASURER.

Total Number of Votes Cast 338

George A. Hamilton	338
Total	338

The total number of voting envelopes handed to the tellers by the Secretary, was 370. Of these there were 20 which did not bear the address of the sender, and were therefore rejected without opening, according to the established rule. There were furthermore four members who had duplicated their votes, and the tellers in each case rejected without opening, the envelope bearing the earlier date, in accordance with a ruling of the President. This left 346 envelopes to be opened.

Among the contained ballots were two endorsed with the sender's name, which were forthwith rejected in accordance with a ruling of the President. The remaining 344 ballots were counted with the foregoing result.

Respectfully submitted.

TOWNSEND WOLCOTT,
J. P. WINTRINGHAM.
Tellers.

The Proxy Committee reported that 151 proxies had been presented in the names of the following members :

R. W. Pope	122
C. T. Hutchinson	20
C. P. Steinmetz	5
Gano S. Dunn	1
James Hamblet	1
Samuel Sheldon	1
C. P. Steinmetz	1
Total	151

At 10:35 P. M. the meeting adjourned.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

FIFTEENTH GENERAL MEETING.

OMAHA, NEBRASKA,
June 27, 28, 29 and 30, 1898.

The meeting was called to order by President A. E. Kennelly on Monday, June 27th, at 9:45 A. M.

THE PRESIDENT:—Before we open our regular proceedings, I have the pleasure of introducing to this INSTITUTE Acting Mayor Bingham, of this city. He informs me that Mayor Moores is unable to be with us, and in his place Mr. Bingham will be so kind as to say a few words to us.

MR. BINGHAM:—Mr. President and Gentlemen:—Our city charter provides that during the absence of the Mayor from the city, the President of the City Council shall perform the functions of the Mayor's office. Mayor Moores was obliged to leave the city on Saturday, and it is therefore my privilege and duty as Acting Mayor to extend to the members of your distinguished body a cordial welcome to the city of Omaha. The people of the west, like those of the south, have a reputation for hospitality, and I assure you that the brand dispensed in Omaha is the best in the market, and that the supply is unlimited.

We welcome you to the State of Nebraska—a wonderful State. Could you traverse our rich prairies and see our happy people, with their luxuriant crops and sleek herds and attractive homes, you would be amazed if you have hitherto had the impression that Nebraska is a State where drouth, hot winds, cyclones and blizzards, regularly follow each other with the changing seasons. Last year Nebraska acknowledged no State her superior for fertility and productiveness of soil, and many of you would be astonished to see the multitude of corn cribs and wheat granaries which line the railroad tracks throughout the state filled, even at this season of the year.

We welcome you also to our city. We are proud of its industrial and commercial supremacy in this central trans-Mississippi region. We are proud of our city because of the character of her citizens, to whose liberality, skill, push and energy the great Trans-Mississippi and International Exposition bears tribute. We are proud of our schools, proud of our public buildings. We are proud to welcome you, gentlemen, because you represent the progressive spirit of our times. This has been called the "Age of Electricity;" and certainly no other description could better characterize the progress of the last half century, so much of it due to the changes wrought by the use of electricity. Gentlemen, as we think of the wonders you have wrought in the past, we have come to expect great things from you, and we are prepared to accept, with scarcely a look of surprise, the great discoveries in the field of electricity which we know you will bring to us in the next decade. And now, gentlemen, in order to more effectively convince you of the welcome which Omaha and her citizens extend to you, I present you with these keys of the city, and express the hope that your visit in Omaha may be a pleasant one.

THE PRESIDENT:—I think our INSTITUTE may be proud of these insignia presented to us by his honor, the Mayor. We can heartily assure him of our intention to thoroughly enjoy the many advantages and pleasures which have so kindly been extended to us.

We intend to see and thoroughly enjoy the Trans-Mississippi Exposition at Omaha, and we have the honor of the presence of Mr. Wattles, who is President of that institution, and if he will favor us with a few remarks, we will be obliged to him.

MR. WATTLES:—Mr. President, I have been in the management of the Trans-Mississippi and International Exposition, and as such manager I take pleasure in extending to you a most hearty welcome to this city at this particular time. As you know, we have one of the largest expositions that has ever been held in the world, in progress here within the limits of the city of Omaha at this time. We have an electrical display on these grounds which I think you will admit stands perhaps as the master-piece of electric lighting effects of any that has ever been produced. I extend to you a hearty and cordial invitation to visit the grounds frequently and observe what has been wrought out there as the result of skill and genius in the great field of electricity during the past few years.

THE PRESIDENT:—Not only have we received the keys to the city from Mr. Bingham, but we have received the keys to the Exposition from Mr. Wattles. I am sure we shall all appreciate these kindnesses most heartily.

We have with us a gentleman who has been largely identified with the electrical matters, as well as with other matters in Omaha, and who is an electrician of long standing. I allude to Mr. E. Rosewater. We shall be very pleased to hear from him.

MR. ROSEWATER:—Mr. President, forty years ago this year I entered upon my apprenticeship in the electrical science, if such it might be called. During something like thirteen years I don't remember of having lost more than five or six days in the labor connected with telegraphy. I remember that while stationed in northern Alabama in the year '59 I was so anxious to perfect myself in the art of telegraphy or whatever there was in electrical science that I wrote a letter to Professor Morse asking him for advice, and I received an autograph letter of something like four pages, which I regret very much was lost in the war while in the neighborhood of Manassas during the year 1862, while I was campaigning with Hooker. Prof. Morse wrote me there were no books and nothing in the way of printed literature that would be available to instruct me, or to suggest even what studies I might enter upon in order to perfect myself in the electrical science, but he advised me to observe the phenomena that occurred on the wires, and by observing it get that information that was in the reach of operators. In those days we could not "climb the ladder of office," but we had to climb telegraph poles very nearly every other day, because in that country the operator had as a part of his duties the business of keeping the line in repair, and very often he had that work to do in a temperature of 120 in the sun or 105 or 106 in the shade, and he had to carry his climbers and insulators on his back and walk ten or fifteen miles and climb ten or twelve poles, and making observations in those days and under those conditions was not always as agreeable as it might have been. I remember once in middle Tennessee I was ordered to repair a line that had been broken. In those days the wires were so arranged that they would slip through the insulators, and spring away from the pole two or three hundred yards or half a mile because they were not fastened, and I had to hire a man to assist me. Although the sky was clear we were both knocked down by a terrific discharge of electricity thirty miles away. Those were the kind of observations that impressed themselves very strongly on me. I want to state incidentally that perhaps I was, in the telegraph service, the first person that transmitted dispatches over a wire without breaking the circuit, and it is perhaps an incident that may be interesting. I was in West Virginia and was ordered from New Creek into the Shenandoah Valley. I left Moorefield and I had to communicate with the other end of the line. I did not dare to cut the line, and I had nothing with me but a small piece of wire and a pocket instrument, and knowing that the operator was at the other end of the line, I just threw my copper wire over the main line and used my pocket instrument to the ground. In that way I got in communication with one end of the line without cutting the line at all. When I came to Omaha I assumed the office of Manager of the Western Union. Mr. Hibbard was Superintendent there and he insisted that the thing could not be done. I insisted that it could, and eventually I had the opportunity of testing it again. There was a flood in the Platte River, and when we arrived we found the wire in the water. There were no poles, but high cottonwood trees on each side. We pulled the wire out, and as we were within ten miles of the battery we were very badly shocked, and it was impossible to hold the wire. The repairer said that he couldn't handle the wire and must cut it. I said "No; they must take the battery off." I grounded the wire and said "take this battery off." I suppose the instruments on the table almost jumped off when we grounded the wire, but the operators took the battery off, as we suggested, and we repaired the line without having to cut the wire. Some year or two later, I think it was, Stearns said, and I could account for it a great deal easier and more readily than some others, that messages could travel in opposite directions over the same wire at the same time. Telegraphy has taken a tremendous jump since that time, and electricity has gone far beyond me.

Just before I came west I had a conference with Prof. Henry, of the Smithsonian Institution, and he asked me to report from time to time such meteorological observations as would be of special interest. I think I was the first person that served under the government in keeping the record of the weather. I kept the books at Omaha for two years. The records show the temperature and direction of the wind, etc., at Omaha, Julesburg, Fort Bridges, Fort Laramie, Salt Lake City and numerous other places. Those records were all sent to Prof. Henry. They were all important, but there is one in particular that I would like to call attention to, as I think it is very interesting. It was in the winter of 1864 during a blizzard when the temperature was down to 20 degrees below zero that the operators were obliged to take the batteries off, and I sent messages both sides of Columbus without any battery, but by the atmospheric electricity. I did not know what the cause might be, but I thought it might be due to an aurora. I wrote to Prof. Henry in regard to what had happened, and he wrote back that it was caused by the small, fine particles of snow drifting through the air from the west to the east over a long distance of wire, and that was the cause of all the trouble—and there is no doubt that Prof. Henry was correct. I have drifted away from the electrical field and have not kept pace with its progress, although in 1891 I went abroad and investigated some of the Postal Telegraphs of the world. I went to London, Liverpool, Manchester, Birmingham, Paris, Prague, Berlin, Hamburg and all the large cities of Europe, and made a very thorough investigation of the methods in use there.

I appreciate very highly the compliment you have paid me in calling me before a convention of this kind, and I hope we will meet often during the progress of your deliberations. I hope you will take the time necessary to see Omaha and get a favorable impression of it, not only of the Exposition, but of the city—a city in which I have lived for 34 years.

The regular business of the meeting was then taken up, beginning with the Inaugural Address of the President, as follows:

Inaugural Address by the President at the 15th General Meeting of the American Institute of Electrical Engineers, Omaha, June 27th, 1898.

THE PRESENT STATUS OF ELECTRICAL ENGINEERING.

BY A. E. KENNELLY.

While mechanical engineering may be said to have an antiquity coeval with civilization, its latest offshoot, electrical engineering, only came into existence with the advent of the electric telegraph some 60 years ago. For the greater part of this time electrical development was confined to the telegraphic industry, but with the extended introduction of the arc and incandescent lamps, the utilization of the magnetic properties of iron and steel made rapid progress in dynamo construction, so that the magnetic properties of steel now play almost as important a part in the advance of civilization as do their mechanical properties.

By far the greater proportion of electric development has come within the last decade and a half. Looking back from the Trans-Mississippi Exposition at Omaha of to-day to the International Electrical Exhibition of Philadelphia in 1884, the birthplace of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, it is doubtful whether outside of telegraphy and telephony there was at that time in the United States a total investment of $1,000,000 in electrical applications. The words ammeter and voltmeter were just commencing to be generally recognized, and of electric traction there was none. At the present time the capitalization in electrical applications in the United States is estimated at about $1,900,000,000.

In 1884 a 50 K. W. dynamo was considered a large machine, while a 100 K. W. Edison steam dynamo was justly called a "Jumbo." At the present time the largest size of generator built or building is of 4,600 K. W. capacity. The price of dynamos in 1882 was about 20 cents per watt of out-put, while dynamos of similar running speed in comparatively small sizes without switchboards, now cost about two cents per watt. The great reduction in price represents the aggregated result of the very large amount of labor devoted to this branch of engineering in the last 15 years.

It is interesting to notice that the efficiencies of continuous-current dynamos have not made any marked nominal advance since the birth of the INSTITUTE, though their output per unit of mass has considerably increased. Thus the 50 K. W. dynamo tested at the Philadelphia Exhibition is stated to have had an efficiency of approximately 92%, and this would be considered a satisfactory performance in that size of machine to-day. But, where the output then was only six watts per pound of net weight (13.2 watts per kilo) the output of a machine of similar rating and speed to-day would be about 10 watts per pound (22 watts per kilo.) In other words, the efficiencies of the best dynamos of 1884 were already so good that it has not paid, at existing costs of power, to markedly improve them, and such improvements in material and design as have since been effected have enabled manufacturers to increase the rating or yield, and, therefore, the cheapness of the machines. It seems probable, moreover, that this will continue to be the direction of future progress. We scarcely can desire more efficient machines than the best we have now, but we shall always desire cheaper and more powerful machines, and shall welcome any improvements which lead to them.

Another evidence of the development in dynamo machinery is their improved appearance. Formerly, the only claim possessed by such apparatus was utility. More recently, grace, the expression of unconscious power, has supervened, and the modern dynamo is often pleasing to look upon as well as useful to operate.

The cost of generating a kilowatt-hour of electric energy from steam for electric lighting, appears to have been at least 7.5 cents at bus-bars in 1884. At the present time the cost of delivering a kilowatt-hour to large street railway systems from steam, is only about one cent, and the power-house operating costs are reported in some cases as low as half a cent. In municipal electric-lighting systems supplied at low pressure from steam central stations and hampered by relatively heavy distributing expenses, the retail price of the kilowatt-hour varies from 20 to about 4½ cents, according to the locality and quantity consumed. Niagara power is now sold to consumers in Buffalo at rates varying, according to the amount delivered, from two cents to slightly less than two-thirds of a cent per K. W. hour delivered.

The price of 16 candle-power incandescent lamp 16 years ago was about $1.00. Now it is about 18 cents. The best lamps at that time, under laboratory conditions, gave about 0.28 mean horizontal normal British candle-power per watt, and under commercial conditions about 0.20. The highest pressure for which they could then be obtained was about 110 volts. At the present time lamps are obtainable giving normally 0.4 mean horizontal British candles per watt, while under commercial conditions the average lamp normally develops about 0.25 candle per watt. They can also be obtained (at 0.25 candle per watt) for pressures up to 240 volts, and are frequently installed on 220-volt mains.

Arc lamps were already so far advanced in 1884, that comparatively little improvement in their effectiveness has taken place, the gain having been made in economy of operation. Thus, the carbons which cost at that time about six cents apiece, now cost about two cents apiece. The enclosed arc lamp has of recent years become popular owing to its diffused light and a carbon life of from 100 to 150 hours.

It has been estimated that about $600,000,000 has been invested up to the present time in electric lighting stations and plants in the United States.

The best storage cells tested at the Philadelphia Exhibition of 1884 gave a yield, under laboratory conditions, of 3.425 watt-hours per pound of electrodes (7.55 watt-hours per kilo) with an energy efficiency of 69.45 per cent. when discharged at the mean current density of 12.42 amperes per square foot of negative plate surface (1.34 amperes per square decimetre); while the deterioration was comparatively rapid. At the present time storage cells are in use giving under laboratory conditions, a yield of from 5 to 6 watt-hours per pound of charged cell (11.0 to 13.23 watt-hours per kilo), with an energy efficiency of about 85 per cent. when discharged at a current density of 4.8 amperes per square foot of negative plate surface (0.52 amperes per square decimetre.) There are now storage batteries installed in the United States to the aggregate capacity of about 56,000 kilowatt-hours. The largest installation has 166 cells, weighs 500 short tons and has an eight-hour discharge capacity of 22,400 ampere-hours, or 3136 K. W.-hours at 140 volts pressure.

A very great development has taken place in the direction of electric traction, by virtue of which, the horse car, once so well nigh ubiquitous in the city streets, has almost entirely disappeared, while electric locomotives of 1,500 H. P. have even made their appearance on steam railroad tracks. The introduction of soft cast steel has been very advantageous to the electric motor, enabling its output to be increased from five watts per pound of net weight in 1884, (11 watts per kilo) to about 14 watts per pound (30.9 watts per kilo) in street-car motors, at the present time. It is estimated that there are, to-day, in the United States, about 14,000 miles of electric railroad, with a nominal capital of about one billion dollars, and employing about 170,000 men.

The electric transmission of the power of falling water is a branch of engineering that has come into service since 1884, and is making rapid strides, owing to the recent successful employment of high voltages and multi-phase alternating currents. It has been estimated that about 150,000 K. W. of this class of machinery is installed in the North American continent, commercially transmitting power to various distances up to 85 miles, at various pressures up to 40,000 volts.

The alternating-current induction motor has become very popular in recent years, mainly owing to its powerful starting torque and its freedom from commutator and brushes. A burned-out armature, the perpetual source of dread in motor operations of days gone by, is practically unknown in this type of machine, even when put to severe service. Indeed its depreciation under fair conditions appears to be as low as in any class of rotating machinery.

The alternating-current transformer has been correspondingly improved, developing in large sizes, an efficiency of about 98.5 per cent., and an output, when cooled by external power, of about 100 watts per pound of weight (220 watts per kilo.)

The principal engineering value of electricity to-day, lies in its adaptation to the transmission of power, through mills or cities, or from some locality where power is cheap to another where it is dear. A steel rope, by its bodily motion, can transmit, with appreciable friction and depreciation, some hundreds of kilowatts to a distance of some thousands of feet. A bare quiescent copper rope, half an inch in diameter, and supported on poles, can, by maintaining an effective potential of 10,000 volts, by the motion of electric waves over its surface, transmit say 2,500 K. W. with an energy loss of two-thirds per cent. per mile (0.4 per cent. per kilometer), and with practically no depreciation except to the poles and supports.

The use of high pressures has thus become more frequent during the last few years. Alternating-current generators are now made to supply 10,000 volts at their terminals, and insulation-testing sets have been made for producing alternating pressures up to 100,000 volts effective.

The application of electric power to domestic use and household comforts, irrespective of illumination, has made steady progress. In the large cities, the fan-motor day load of summer is in the aggregate a perceptible quantity, while electric ranges and heaters on a small scale have found favor through their convenience.

In telegraphy, comparatively little change has recently taken place, beyond the substitution of the dynamo or dynamotor for the voltaic battery, and of copper line-wire with some five ohms per mile, for iron wire with some 13 ohms per mile. About one million miles of telegraph wire are now strung on some 200,000 miles of pole line in the United States, connecting about 25,000 offices and working a capitalization of about one hundred and fifty millions of dollars.

In the United States, the uniformity of the closed circuit Morse system simplex, duplex or quadruplex, is only varied by an occasional Wheatstone set. This crystallization of methods is not due to any lack of invention, or capability of improvement in signaling speed, but rather to the apparently settled belief that the present systems are the most economical under existing conditions of traffic. In long submarine telegraphy, the pressure of increasing traffic has made itself more distinctly felt, and automatic curb-senders have, to some extent, been introduced, but the physical difficulties in the way of attaining high speeds have as yet been obviated only in part by an increased expenditure in copper and gutta-percha, to obtain a diminished conductor resistance per mile. Wireless telegraphy has entered its experimental stage, and bids fair to enter practical service in the future, at least within a limited range. Its public use thus far in the United States seems to have been limited to blowing up at stated intervals, in the recent New York Exhibition, miniature models of the "Maine," at a distance of some 25 metres from the oscillator.

In telephony, the most notable improvement in recent years has been the general substitution of metallic circuits for ground return circuits, with great advantage to the convenience and effectiveness of the traffic. At the present time conversation is carried on commercially up to a distance of 1,800 miles, and quite frequently at distances of 1,500 miles. There are at the present time in the United States about 1,000,000 telephones connected with the telephone service of the country, employing a capitalization of about 100,000,000 of dollars, 400,000 stations and about 900,000 miles of wire. Every day about 17,000 employees make on the average more than 3,000,000 of connections. About 300,000 miles, or nearly one-third of the total length of telephone wires have, within the last few years, been made up into aerial and subterranean cables within city limits, owing to the reduction of the electrostatic capacity effected in such cabled wires to less than one-twelfth of a microfarad per mile of single wire.

At no time has a useful discovery or improvement had more chance of welcome or application than at present. As an example, the case of Roentgen rays may be cited. Professor Roentgen's celebrated paper announcing the discovery of X-rays was read in Wurzburg in December, 1895, and the particulars were not known in the United States until early in 1896. In the same year (December, 1896) radiographs were accepted as legal evidence in a United States District Court.

A considerable development has occurred in electro-thermic and electrolytic processes. More than 4,000 kilowatts of Niagara power are now employed in such processes. Among electrochemical processes are the electrolytic refining of copper to the extent of about 150,000 tons annually, the production of aluminium, the production of sodium and alkalis and the treatment of ores. Among electro-thermic processes are the production of the carbides of silicon and calcium in steadily increasing quantities.

In electrotechnical theory considerable advance has been made of recent years, particularly in the study of alternating currents. Accompanying the expansion of knowledge in the various branches there is a tendency to combine and unite them into one general theory. Thus, while the early dynamos generated a low-tension electricity which was once regarded as something so dissimilar to high tension electricity as to require separate treatment and classification, to-day the high-tensions derived from alternators through step-up transformers, so far invade the territory of so-called frictional electricity that a dividing line between the two classes can no longer be maintained. Similarly telephony and telegraphy are coming to be regarded as sub-classes of alternating current power transmission, while electricity and magnetism cannot properly be studied apart.

Although a large amount of electrical work is done in physical laboratories in the United States, a comparatively small amount of the results of this work becomes available to the science or art of electrical engineering. Each year sees more than a hundred students engaged in experimental thesis work after a laborious training and preparation for several years in the technical college. Many of these men have the time and facilities to do the best experimental work of their lives under the guidance of their instructors. Some of the men display aptitude and interest in some special line of research in which they would be best left untrammeled, but in most cases the experimental work under co-operative guidance could accomplish a great deal for the knowledge and progress of our branch of applied science. There are numerous questions concerning the various electromagnetic properties of matter and of the ether that are of great and growing importance, and there are numerous scientific subjects of immediate practical importance that it is necessary to measure and observe, so that by uniting the available experimental resources of the various colleges in this country under a common leadership, in sympathy with the college instructors, the results which now largely fill thesis books lying on neglected shelves might be incorporated into permanent results for the general advancement of our profession. The plan would involve practically no expenditure beyond the voluntary efforts of those upon whom the duty devolved of formulating and dividing the subjects of research, and classifying or comparing the results attained. Such a system of co-operation among the students through their instructors would economize a large amount of the most skilled technical labor, and accelerate progress in all branches of inquiry, application, and industry. No better work could be undertaken by our INSTITUTE than the fostering of such an organization.

The technical progress of a profession like ours is shown by the precision of which it is capable. A loose nomenclature begets looseness of observation and description, and is inconsistent with a high degree of development in a science that quickens the footsteps of every human industry. The tendency of our machinery and definitions to become standardized is apparent in the impulse which has led the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS to appoint a Committee on Standardization, the preliminary report of which is to-day laid before this INSTITUTE for consideration.

In connection with standardization it is important to observe that there has been of recent years a tendency to depart from the regular standards of dynamo machinery built by the manufacturers, in favor of special machinery of independent design. To a limited extent this is, of course, necessary under the pressure of changing methods and conditions, but there is reason to believe that much more special machinery is built than necessity can warrant. Not only is the special machinery thus ordered or specified considerably more costly than standard machinery, but the tendency, by interfering with the natural shop methods of standardizing and cheapening production, prevents regular consumers from purchasing standard machinery at as low rates as would otherwise be possible. When we consider that the industrial radius of application of electricity mainly depends upon the first cost of the apparatus it employs, it needs no homily to drive home the conviction that the unnecessary introduction of special machinery is a puncture in the tire of progress.

Our INSTITUTE may well take pride in the share which it has taken in the electric progress of the fourteen years which have elapsed since its inception. It now numbers 1100 members. Its purpose is to aid all who seek to acquaint themselves with this branch of science and art, and to set the stepping stones of progress in the sands of time for the advance of the industrial applications of electricity.

A Paper presented at the 15th General Meeting of the American Institute of Electrical Engineers, Omaha, June 27, 1898, President Kennelly in the Chair.

[ADVANCE COPY—SUBJECT TO REVISION.]

DIELECTRIC STRENGTH OF AIR.

BY CHARLES PROTEUS STEINMETZ.

To investigate the dielectric strength of air, tests were made of the striking distances in air between parallel cylinders of different diameters, between sharp points, and between spheres of different sizes. Further tests were made on the effect of inserting a conductor in or near the path of the disruptive discharge and investigating its influence on the striking distance.

As source of power, an A-8 smooth core alternator of the Thomson-Houston type was used, of about 30-K. W. capacity and a frequency of 125 cycles, giving practically a sine wave. In other tests a 60-K. W. high-frequency ironclad alternator of the Thomson-Houston type was used, giving the well known sawtooth form of wave. The alternator was driven by a direct current motor of ample capacity.

With alternating E. M. F.'s of only 125 cycles, the luminous phenomena, as brush discharges from conductors, etc., were much less marked and brilliant than observed even at lower voltages with oscillating currents of very high frequency, as given by a Thomson transformer.

For the purpose of these tests four high-potential transformers were built, of the ratio of transformation 1 : 18 and of a rating of about 7.5 K. W. each. They are of standard air-blast type, but were used when immersed in large wooden tanks filled with oil.

Each of these transformers contains two primary and two secondary coils, the two high-potential secondary coils in the center, the low-potential primary coils at the outside.

The utmost care was taken in the insulation of these transformers and it proved very successful, since over and over again the voltage has been run up to 150,000 volts and beyond and later even to 172,000 volts without ever breaking down the transformer.

The high-potential circuits of the four transformers were connected in series. To avoid the danger of a disruptive discharge taking place from the outside of the high-potential transformer at one end of the series through the low-potential coils to the outside of the high-potential transformer at the other end of the series, the low-potential primaries were not connected directly to the generator in parallel with each other, but were connected to the high-potential sides of four standard type F transformers of General Electric make of 7.5 K. W. each, and these transformers were again fed by another set of four standard type F 7.5 K. W. transformers, the latter being connected in parallel to the generator.

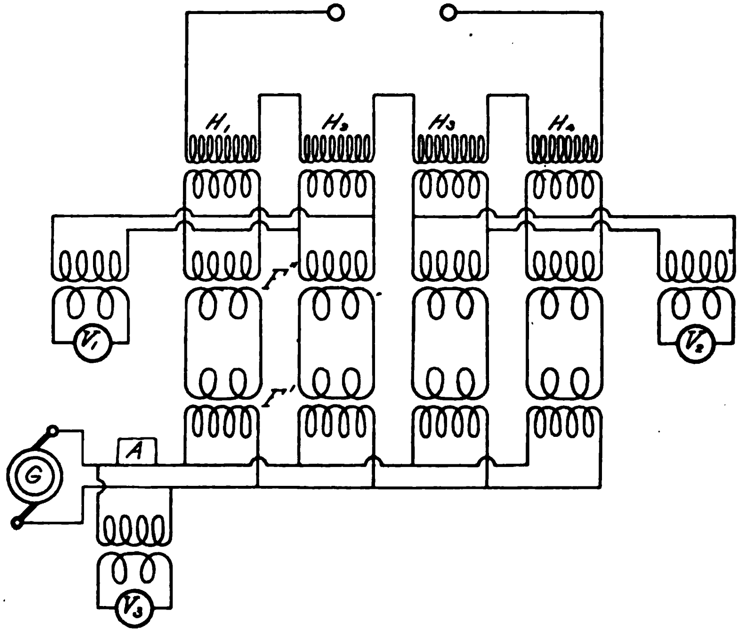


FIG. 1.

Thus the diagram of connections was as follows (Fig 1): The generator G feeds in parallel the high-potential sides of four transformers F′ which step down in the ratio 10 : 1 or 10 : .5. These transformers F′ feed four transformers F″ which step up in the ratio 1 : 10 or .5 : 10 and feed with their high potential side the low-potential coils of the four transformers H_1, H_2, H_3, H_4.

An internal disruptive discharge thus has to pierce two high-potential transformers H_1 and H_4 and four standard F transformers.

Incidentally hereby the ratio from the generator to high-potential circuit could be changed between 1 to 360, 1 to 720, and 1 to 1440 by changing the ratio of the F transformers, that is connecting their low-potential coils in multiple or in series.

The generator was driven by a direct current motor and was separately excited. The voltage was varied by varying the generator excitation, by varying the ratio of transformation of the F transformers, and by cutting more or less of the high-potential transformers out of circuit. Thus in the lowest readings only one high-potential transformer was used, in the highest readings all four. When cutting out transformers always the first transformer H_4, then H_1, and last H_3 were cut out, leaving ultimately only H_2 in circuit.

The F transformers were generally for the higher voltage used with the ratio 1 : 10 in F' and .5 : 10 in F''.

The high potential voltage was derived by the ratio of transformation, and for this purpose two Weston alternating voltmeters with 10 : 1 voltmeter transformers were inserted on the low-potential side of the transformers H_2 and H_3, as shown by V_1 and V_2 in Fig. 1. They were calibrated before and after each test. A third voltmeter was inserted into the generator circuit with voltmeter transformer, and is shown as V_3. Its readings were not used for deriving the high-potential voltage, since too many transformations were intermediate. Thus it was used merely as a check and for guidance in operating the generator field rheostat.

The tests were made in the usual manner by setting the electrodes for a certain distance, then closing the generator switch and gradually raising the generator excitation while following the rise of the voltmeter needle, until the discharge took place and the voltmeter dropped. Then the exciter switch was opened, the voltmeter reading recorded, and the electrodes reset for the next test.

For the tests between points, 2½″ sewing needles were used and for every test a new pair of needles taken, since it was not considered sufficient to re-sharpen the needles after the discharge had taken place.

For the tests between cylinders and spheres it was not considered sufficient to have the electrodes polished, since no polish can give an absolutely perfect surface without any minute unevenness. To secure a perfect smoothness, a film of liquid quicksilver was used as electrode surface, that is polished brass cylinders and spheres were used, and were immersed in a solution of mercuronitrate and afterwards wiped off with a clean cloth. The fairly thick film of quicksilver deposited on the electrode surface forms a liquid and thus perfectly smooth surface. After every discharge the electrodes were reamalgamated.

The effect of this precaution was that even with very small distances, the discharge appeared constantly at the same voltage, while with merely polished electrodes with very small distances, a more or less erratic behavior takes place due to minute unevenness of the surface.

Before undertaking the final tests, a number of preliminary tests were made to determine,

1). The constants of the generator and the transformers and the total power thus available in the discharge circuit.

2). The equality of the ratio of transformation of all four sets of transformers, since only at two out of the four transformers was the voltage measured.

3). The constancy of the ratio of transformation, since it was relied upon for determining the high potential voltage.

4). The shape of the generator wave and its variation under the conditions of test.

1st.—The synchronous impedance of the generator was found as,

$$Z_0 = r_0 - j\, x_0 = 3 - 12j,$$

that is, at an excitation corresponding to the voltage v at open circuit with a current C in the armature, the E. M. F. $C\, r_0$ is consumed in phase with the current, the E. M. F. $C\, x_0$ in quadrature with the current, thus giving the terminal voltage $V = C\, (r_0 - j\, x_0)$.

Of the transformers F′ and F″, of rating F–125–7.5–1040–104–52, reduced to the high potential or 1000-volt coils, it is:

The total impedance,

$$Z^1 = r^1 - j\, x^1 = 2.1 - 20\, j.$$

The primary admittance, that is, admittance of the exciting circuit,

$$Y^1 = g^1 + j\, b^1 = (.13 + .24\, j)\, 10^{-3}.$$

The total number of primary turns is 280, the total number of secondary turns 28, of which, as before said, two could be connected in parallel. The cross-section of the magnetic circuit is 32.4 sq. in.

Of the transformers H$_1$, H$_2$ H$_3$, H$_4$ of rating OC-125,-7.5,-27000,-1500 reduced to the low potential or 1500-volt coils, it is:

Total impedance,

$$Z_1 = r_1 - j\,x_1 = 2.5 - 8.0\,j.$$

The primary admittance,

$$Y_1 = g_1 + j\,b_1 = (.32 + .5j)\ 10^{-3}.$$

The total number of high-potential turns is 3458 per transformer, of wire No. 24 B & S, subdivided in two coils.

The total number of low-potential (1500 volt) turns is 192, subdivided in two coils also. The cross-section of the magnetic circuit is 46.5 sq. in. in the center, 72.9 sq. in. in the outside shell.

Herefrom we get for the whole system in the connection used for the highest voltage, that is with F′ connected 10 : 1, and F″ connected .5 to 10, reduced to the high-potential discharge circuit.

Total impedance inclusive generator,

$$\begin{aligned} Z &= 4 \times 18^2\,Z_1 + 4 \times 18^2\,Z^1 + 4 \times 36^2\,Z^1 + 144^2\,Z_0 \\ &= (80 - 390\,j)\ 10^3 \text{ ohms,} \end{aligned}$$

or absolute:

$$z = 398 \times 10^3 \text{ ohms,}$$

or reduced to the generator circuit:

$$Z_2 = r_2 - j\,x_2 = 3.9 - 18.8\,j \text{ ohms.}$$

Total admittance,

$$\begin{aligned} Y &= \tfrac{1}{4}\tfrac{1}{18^2}\,Y_1 + \tfrac{1}{4}\tfrac{1}{18^2}\,Y^1\ \tfrac{1}{4}\tfrac{1}{36^2}\,Y^1 \\ &= (.37 + .62\,j)\ 10^{-6} \text{ mhos.} \end{aligned}$$

or reduced to the generator circuit,

$$Y_2 = (7.7 + 12.8\,j)\ 10^{-3} \text{ mhos.}$$

Thus with 150,000 volts between the discharge terminals at the total ratio of transformation 144, the terminal voltage of the generator is about 1,100 volts and its field excitation corresponds to an induced voltage at open circuit of about V = 1,280 volts. It follows herefrom that the maximum current which can be produced in the discharge circuit is:

$$\frac{V}{144\sqrt{r_2^2 + x_2^2}} = .465 \text{ amps.,}$$

and the maximum power available in the discharge circuit is:

$$\frac{V^2}{2\,(r_2 + \sqrt{r_2^2 + x_2^2})} = 35.5 \text{ K. W.}$$

At this voltage the maximum density in the core of the transformers H is 42.5 kilo lines per sq. in., or 6,600 lines per sq. cm. In the transformers F″ it is 41.5 kilo lines per sq. in., or 6,400 lines per sq. cm., hence far below saturation.

2nd.—To determine the equality of the ratio of transformation, all four high-potential transformers were connected in parallel with their high-potential coils and in series with their low-potential coils, as shown in Fig. 2, and the voltages across the low-potential coils read. They were,

a	*b*	*c*	*d*
419	408	401	401

showing that the first transformer has a slightly higher ratio of transformation, and the last two a slightly lower ratio than the average.

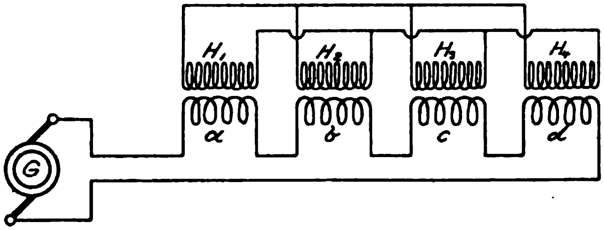


FIG 2.

Allowance therefor was made in reducing the readings. The correction in the extreme case did not exceed 1.33%.

3rd.—Since the high potential was derived indirectly by voltmeter readings on the low-potential side of the transformers, it was necessary to determine whether the voltage read in this manner was correct and whether the capacity of the discharge circuit has any effect on the ratio of transformation.

For this purpose the high-potential transformers were connected in pairs in parallel with their low-tension and in series with their high-tension sides, the one pair used as step-up transformers, the other pair as step-down transformers, and the voltage read in both low-tension circuits, as shown in Fig. 3. Then step-up and step-down transformers were interchanged, that is, the generator was connected first at *a*, then at *b*. This test was repeated after inserting an oil condenser into the high-potential circuit at *c*. This condenser consisted of twelve iron plates of about ½ sq. ft. each, separated by ¾″ of oil. Two such boxes of condensers were used in series, giving a total condenser surface of about 5½ sq. ft. per electrode and 1½″ oil distance, thus a capacity far in excess of that of any discharge circuit.

A number of tests were made, of which I give one set.

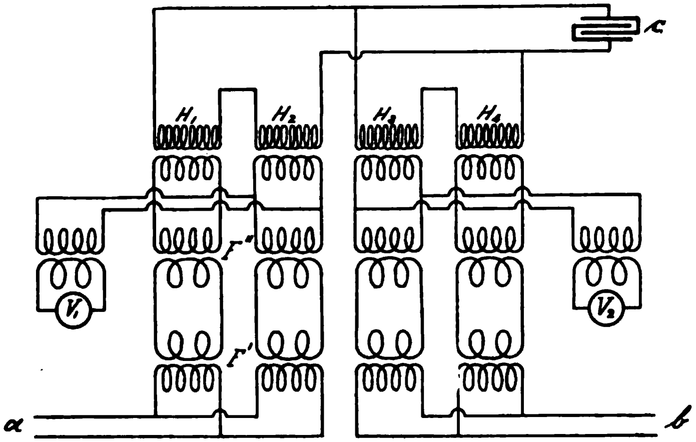


FIG. 3.

Generator at *a*: Ratio: 1 + 360.				Generator at *b*:			
No Condenser.		Condenser.		No Condenser.		Condenser.	
V_1	V_2	V_1	V_2	V_1	V_2	V_1	V_2
11.5	11.0	11.0	11.0	10.1	11.8	10.6	11.9
25.2	23.5	20.3	19.0	24 2	25 1	19.8	20.6
44.9	42.8	30 0	28.5	43.2	45.0	29.5	30.5
66.8	64.2	39.9	38.3	65.3	67.0	39.4	40.4
93.0	89.2	45.6	43 7	91 0	92.7	44.5	45.8
102.1	98.5	56.0	53.5	100.4	102.0	54.7	56.0
117.6	113.0			115.8	117.3		
128.0	123.5			126.6	128.6		
134.4	129.6			132.2	133.6		

Average ratio:

1.0405 | 1.0455 | 1.0201 | 1.03

Average without condenser, 1.0303.

Average with condenser, 1.0396.

Hence 1.0303 is the change of ratio of transformation due to three times the exciting current. Thus the correction for the exciting current is 1.01%. The relatively very large condenser inserted into the high-potential circuit does not change the ratio of transformation by as much as 1%. Thus the very much smaller capacity of the discharge circuit is entirely negligible in its effect on the ratio of transformation.[1]

To investigate the equality of the ratio of transformation of the type F transformers, the transformers were connected as in Fig. 4, that is the same way as during tests, but with the high-potential circuits disconnected, and the voltage at the low-potential terminals of the high-potential transformers read at *a*, *b*, *c*, *d* and at the generator *g*. It was found :

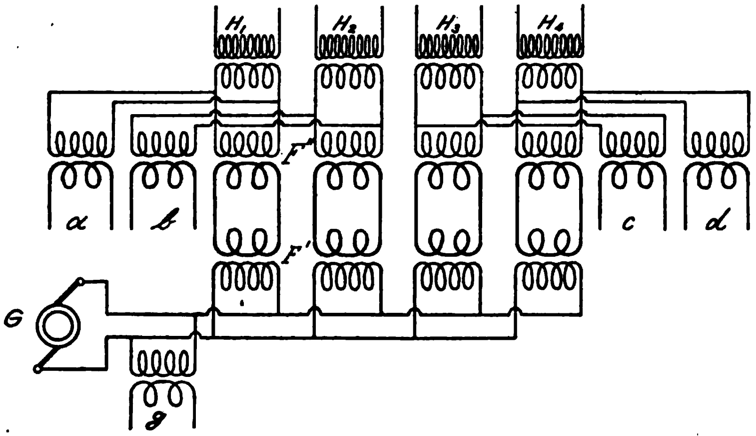


FIG. 4.

g	*a*	*b*	*c*	*d*
50.3	47.5	48.1	47.2	47.8
74.6	70.0	70.7	70.6	71.0
100.6	97.0	97.2	97.4	97.3
127.3	122.8	123.2	123.0	123.0
352.8	337.3	339.2	338.2	339.1

Average *a*, *b*, *c*, *d* = 338.45,

---

[1] This is due to the relatively very low self-induction of the step-up transformers compared with the self-induction of, for instance, a Ruhmkorff coil, etc.

Average ratio:

1.0425	.9966	1.0022	.9993	1.0019

that is, the four sets of intermediate transformers F′ and F″ are

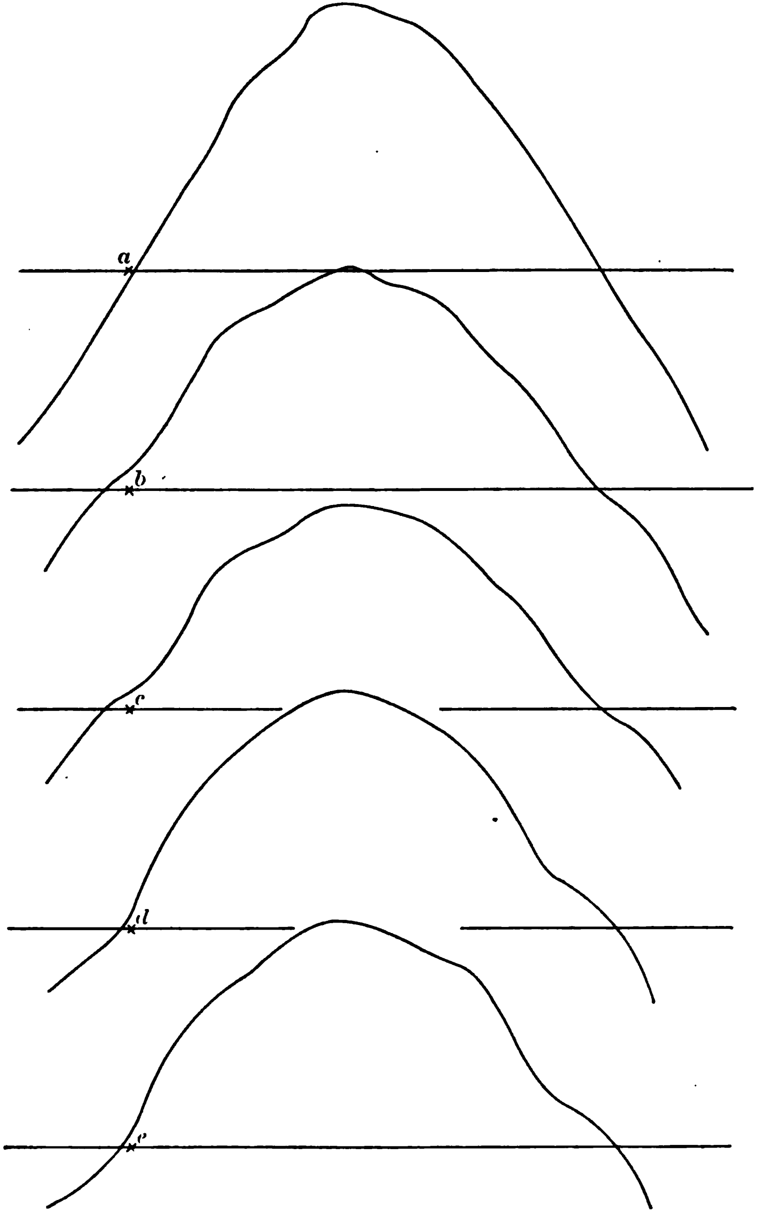


Fig. 5.

of identical ratio of transformation within a small fraction of one per cent., and the drop of voltage in them (which, however, is unessential for the test) amounts to 4.25%. Furthermore it follows that the voltmeter readings at the low-potential side of two of the step-up transformers give the high-potential voltage correct within one per cent., hence are perfectly reliable.

4th.—The shape of the generator wave was determined by instantaneous readings,

a. At open circuit. *b.* With the high-potential transformers and the type F transformers feeding them connected to the generator. *c.* With the above described condensers in the high-potential circuit.

The same connections were used as shown in Fig. 3, and the wave shape determined at the generator terminals *a* as well as at the terminals of the step-down transformer *b*, so as to investigate whether a change of wave shape takes place by the transformation. The following values were found:

Degrees.	At generator, open circuit.	At generator, no condenser.	At step-down transformers, no condensers.	At generator, condenser.	At step-down transformer, condenser
10	13	7.25	5.8	5.3	3.7
20	28.5	18	14.4	26	25.8
30	44.1	35.5	29.7	43.3	42.3
40	64.4	52.6	48.2	56.2	53.9
50	13.6	61.6	56.5	64.8	60.7
60	82.5	66.0	60.1	72.6	69.3
70	89.6	71.9	66.5	79.9	77.5
80	95.5	77.3	72.8	85.0	81.9
90	97.7	80.1	74.2	86.1	82.3
100	95	77.5	72.5	83.6	79.8
110	91.4	74.25	70.8	79.2	75.1
120	86.5	70.6	66.6	74.6	70
130	76.8	61.6	58.6	69.4	65.8
140	63.2	49.9	48.1	59	56
150	50.5	41.25	40.2	42.1	38.7
160	36.6	28.6	27.1	23.6	21.8
170	19.9	13.3	13.4	14.75	13.4
180	2.6	.6	.9	7.6	8.3
Ratio $\frac{\text{max.}}{\text{eff.}}$	1.42	1.44*	1.43	1.42	1.42

---

* As seen in Fig. 5, this particular wave has a small peak at the maximum reading which causes a slightly higher ratio, but is probably merely an error of observation of this individual reading.

that is 1.008 times the value corresponding to the sine wave.

Hence, the generator wave has within less than 1% the same ratio of maximum to effective value as the sine wave, and this ratio is not changed by transformation nor by capacity in the high potential circuit.

The maximum value of voltage can therefore be calculated from the effective value by multiplying by $\sqrt{2}$. In all the tests the effective values of voltage are given.

To conclude, we get as results of preliminary tests:

Voltmeter readings on the low-potential side of the high-potential transformers give a striking voltage correct within 1%, irrespective of the capacity of the discharge circuit, within the limits of the tests.

The wave of the smooth core alternator is practically a sine wave, and is not changed by transformation or by capacity of the discharge circuit.

Since the accuracy of the striking distance determination cannot well exceed 1 to 2%, these preliminary tests show the method as correct within the errors of observation.

In the tests all distances are given in inches, since they were measured in inches, and the reduction to cm. is omitted.

The voltages are given in kilo-volts effective, and the maximum voltages thus are $\sqrt{2}$ times as large.

In general each of the readings given in the table is the average of from two to four tests. The tests are recorded in tables I. to IX. and plotted in Figs. 6 to 17.

It is:

Table I., striking distances between sharp points with smooth core and with ironclad alternator, the latter in air, fog and steam.

Table II., striking distance between ¼″ spheres.

Table III., striking distance between ½″ spheres.

Table IV., striking distance between 1″ spheres.

Table V., striking distance between 2″ spheres.

Table VI., striking distance between parallel cylinders of .313″ diameter with smooth core alternator only.

Table VII., striking distance between parallel cylinders of .111″ diameter with smooth core alternator only.

Table VIII., striking distance between ¼″ spheres with brass disks inserted into the path of the discharge, with smooth core alternator.

Table IX., striking distance between ¼″ spheres with wet plank parallel to the path of the discharge.

Fig. 6, sharp points with smooth core alternator, observations marked by crosses.

Fig. 7, sharp points with smooth core alternator. Average of two sets of tests. Observations marked by crosses.

Fig. 8, ¼″ spheres. Two sets of tests. Smooth core alternator.

Fig. 9, ¼″ spheres. Average of two sets of tests. Smooth core alternator.

Fig. 10, ½″ spheres. Smooth core alternator.

Fig. 11, 1″ spheres. Smooth core alternator.

Fig. 12, 2″ spheres. Smooth core alternator.

Fig. 13, sharp points and spheres. Comparison of results with smooth core alternator. Sharp points showing dotted line.

Fig. 14, .313″ cylinders with smooth core alternator. Maximum electrostatic gradient marked by crosses.

Fig. 15, .111″ cylinders with smooth core alternator. Maximum electrostatic gradient marked by crosses.

Fig. 16, sharp points with ironclad alternator. Two set of tests in air, one in fog and one in steam. Smooth core alternator, curve marked by dash-dotted line.

Fig. 17, sharp points and spheres. Comparison of results with ironclad alternator. Curve of sharp points in dotted lines. Sharp points with smooth core alternator marked with dash-dotted lines.

The following has to be remarked regarding these tests:—

All distances given are net, that is, from the surface of sphere and cylinder to the surface of the other cylinder and sphere, etc. Connection of the high-potential transformers H_1, H_2, H_3, H_4 and the intermediary transformers F′ and F″ with the generator G and the voltmeters V_1, V_2, V_3, were in all the tests, as shown in Fig. 1. As stated before, the voltmeter readings of V_1 and V_2 were averaged to calculate the striking voltage, while the voltmeter reading V_3 was used merely as check. An ammeter was also inserted into the generator circuit at A as check to observe capacity effects.

Generally the intermediary transformers near the generator, F′, were connected for the ratio 1 to 10, the transformers F″ for the ratio 1 : 20.

For lower readings the high-potential transformers were gradually cut out in the order H_4, H_1, H_3, leaving ultimately only H_2 in circuit.

Under the floor of the testing room were a number of steam pipes from which some steam was escaping, so that the air in the testing room was always moderately moist.

TABLE I.

POINTS.

2½" needles. 125 cycles.

Smooth Core Alternator: A-10-30-1500.				Ironclad Alternator: A-10-60-1500.						
Distance, inches. *d*:	Kilovolts: effective.			Distance, inches. *d*:	Kilovolts: effective.					
	7-21-'96 * in air.	7-17-'96 † in air.	Average.		7-24-'96 ‡ in air	Jan. '95 in air.	Average.	Jan '95 in fog.	Jan. '95 in steam
.25	4.25			.25	4.13				
.5	10.0			5	9.0	10.0	9.5	11.0	14.5
1.0	20.4			1.0	16.9	18.5	17.7	22.0	25.3
1.5	29.3			1.5	24.3	26.0	25.1	31.0	35.5
2.0	35.2			2.0	30.5	30.5	30.5	38.0	43.0
2.5	40.4			2.5	33.9	35.0	34.4	43.5	50.3
3.0	41.6			3.0	36.3	38.0	37.1	48.0	54.5
3.5	49.4			3.5	42.2	41.7	42.0	51.0	63.0
4.0	52.5			4.0	41.3	45.0	43.2	55.5	
4.5	59.6			4.5	45.5	48.0	46.7	61.0	
5.0		61.0		5.0	48.4	50.5	49.5		
5.5		65.7		5.5	53.0	55.0	54.0		
6.0	69.8	69.5	69.65	6.0	56.1	58.8	57.4		
6.5	73.4	74.7	74.05	6.5	59.8	62.0	60.9		
7.0	77.5	79.2	78.35	7.0	63.3	64.7	64.0		
7.5	83.8	83.0	83.4	7.5	67.5	69.0	68.3		
8.0	86.8	87.3	87.05	8.0	70.9	73.4	72.1		
8.5	90.5	90.2	90.35	8.5	75.8	76.0	75.9		
9.0	95.0	93.7	94.35	9.0	79.8	70.2	79.5		
9.5	97.7	96.3	97.0	9.5	84.8	82.5	83.6		
10.0	101.5	99.0	100.25	10.0	88.8	86.4	87.6		
10.5	107.0	103.0	105.0	10.5	93.5	89.5	91.5		
11.0	111.5	107.5	109.5	11.0	97.7	93.0	95.4		
11.5	114.0	110.5	112.5	11.5	102.0				
12.0	121.0	116.0	118.5	12.0	107.7				
12.5	125.5	120.0	122.75	12.5	111.0				
13.0	133.0	123.0	128.0	13.0	117.5				
13.5	135.0	127.0	131.0	13.5	122.5				
14.0	140.0	129.0	134.5	14.0	128.0				
14.5	144.0	136.0	140.0	14.5	134.4				
15.0	150.0			15.0	138.3				
15.5	155.0								
16.0	159.5 §								

* 85° F. Weather sultry.
† 75°-80° F. Weather clear and bright.
‡ 70° F. Weather cool and cloudy.
§ Internal discharges in intermediary transformers F' F".

In most of the tests the temperature and the weather are given from the record sheets. The meteorological record of the days during which tests were made is given in Table X. To check the influence of the weather, a few readings with 1" spheres and ironclad generator were repeated on a sultry and rainy day, but found to agree with the readings taken on a clear and bright day.

With the E. M. F. of the smooth core alternator brush discharges at the electrodes were observed by the hissing noise produced by them when the potential approached the striking voltage, and at greater distance even far below this, with sharp points with smaller spheres and with parallel cylinders of smaller diameter, less pronounced with larger spheres and parallel cylinders of large diameter.

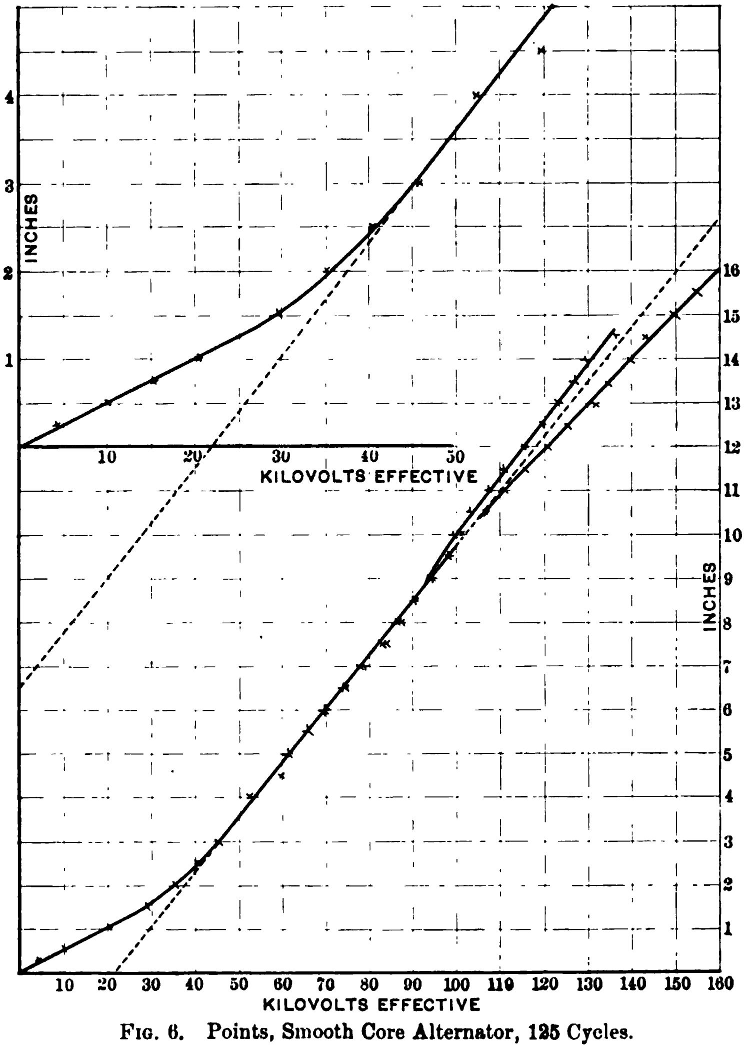


FIG. 6. Points, Smooth Core Alternator, 125 Cycles.

When approaching 160,000 volts effective with a smooth core alternator, electrostatic discharges took place inside of the intermediary transformers F′ and F″, apparently between primary and secondary. It seems the transformers acted as a system of six condensers in series, the two outside high-potential transformers H_1 and H_4 and the two sets of intermediary transformers F′ and F″ connected thereto with the insulation between primaries and secondaries as dielectric. At or near 160,000 volts the electrostatic stress exceeded the disruptive strength of the insulation between primary and secondary in F′ and F″. Since, however, the insulation between H_1 and H_2 resisted, no arc followed the discharge. Nevertheless, even at lower voltage, a number of intermediary transformers, F′ and F″, were pierced.

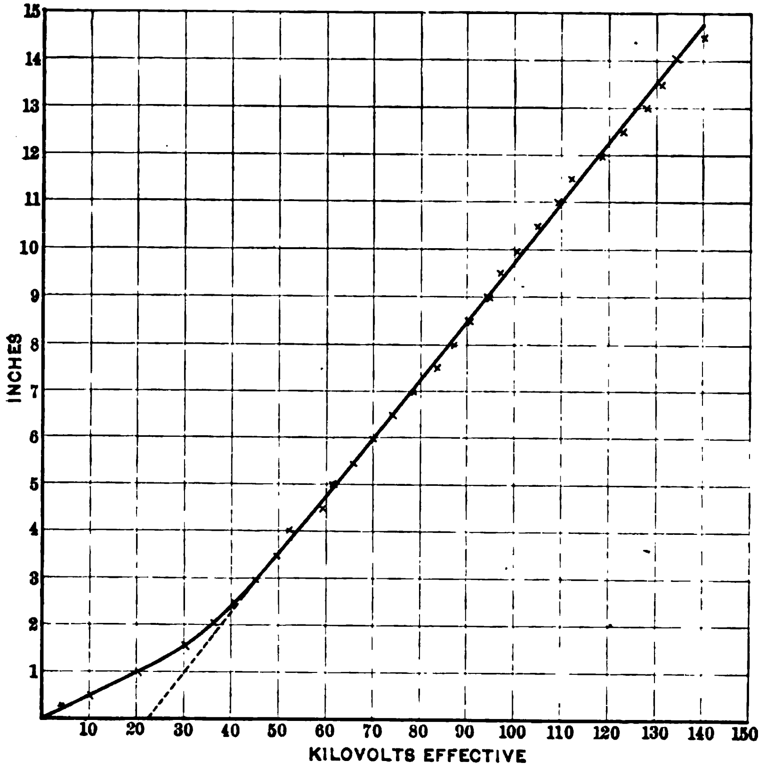


FIG. 7. Points, Smooth Core Alternator, 125 Cycles.

With the ironclad alternator with sharp points as well as with brass spheres, the breaking-down point was quite unstable.

Although the brass spheres were polished, amalgamated and rubbed smooth before each test with the same care as in the tests with the smooth core alternator, nevertheless the readings are far more erratic and in several instances the same disruptive voltage was found with a change of the striking distance of as much as 1″. In the record sheets all questionable readings are omitted.

With the ironclad alternator, at voltages of 80,000 and upward, almost always several heavy electrostatic discharges took place between the electrodes before the disruptive voltage was reached, frequently as much as 1,000 to 1,500 and even 2,000 volts below the actual striking voltage. These discharges were never observed with the smooth core alternator, but were most marked with ½″ and 1″ spheres and with sharp points. To investigate the frequency, a Thomson transformer, that is a transformer consisting of a small number of primary and of secondary turns wound in air (without iron core) was inserted in series in the discharge circuit with sharp points as electrodes, and the secondary terminals of this Thomson transformer separated by a gap of ⅜″. When approaching the striking voltage, but before the final disruptive

TABLE II.

¼″ SPHERES.

Amalgamated. 125 Cycles.

Smooth Core Alternator: A-10-30-1500.				Ironclad Alternator: A-10-60-1500.	
Distance, inches. *d*:	Kilovolts; effective.			Distance, inches. *d*:	Kilovolts; effective. 7-2[illegible]-'96. †
	7-13-'96. 7-14-'96.*	7-25-'96.	Average.		
.125	8.18			.125	6.4
.25	12.9			.25	11.3
.50	18.65			.5	13.4
.985	22.4			1.0	18.2
1.47	24.8			1.523	23.3
2.0	34.7			2.0	28.2
2.97	43.6	44.8	44.2	3.0	37.8
3.51		50.0		4.0	47.7
4.01	56.5	56.4	56.45	4.97	53.8
5.03	67.0	66.0	66.5	5.97	58.0
5.5		71.0		7.0	65.8
5.99	77.0	76.4	76.7	8.0	75.1
7.0	86.8	83.6	85.2	8.97	86.2
8.0	96.0	90.6	93.3	10.0	98.4
9.03	103.5			11.0	108.5
10.02	108.7	100.6	104.62		
11.01	111.5				

* 80°–90° F. Weather clear and bright.

† 75°–80° F. Weather rainy and sultry

discharge took place, a continuous discharge passed across the ⅜″ air-gap of the secondary circuit of the Thomson transformer, showing thus the existence of an oscillatory or very high frequency effect.

Photographic investigations of the phenomena taking place during the disruptive discharge have shown that it always consists of an oscillating electrostatic discharge with at least two or three well marked oscillations followed afterwards by an arc, as I have discussed more fully in a previous article on "Photographic Study of a 150,000-volt Power Discharge."

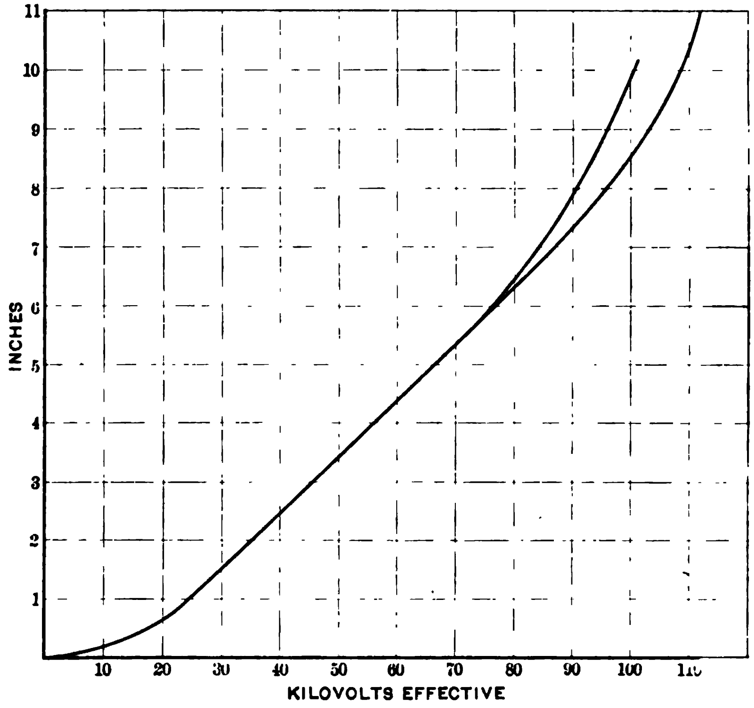


FIG. 8. ¼″ Spheres. Smooth Core Alternator, 125 Cycles.

Condenser effects were observed only once when two insulated brass disks were inserted in the path of the discharge between ¼″ spheres separated by 9⅛″, and these brass disks brought very close, within ¾″ to the discharge terminals. In this case the primary current in the generator circuit rose. As above discussed, capacity within a reasonable limit has no effect on the ratio of transformation, but would show a rise of the current in the generator circuit, and no such rise was observed, except in the above mentioned case.

Regarding the effect of frequency on the striking distance, within the range of frequency easily accessible, that is from 40 to 125 cycles, no noticeable change was observed.

Of more general interest are the tests of the striking distance made with the smooth core alternator in which the wave is nearly a sine wave and the ratio of maximum to effective E. M. F. thus constant and known. The striking distance with the ironclad alternator are of interest only in so far as they show which deviations from the sine wave curve can be expected with this type of machine most commonly in use, of sawtooth wave shape. Since, however, during the tests the voltage was varied by varying the alternator excitation and the wave shape of the ironclad changes more or less with the excitation, these curves are of comparative interest only.

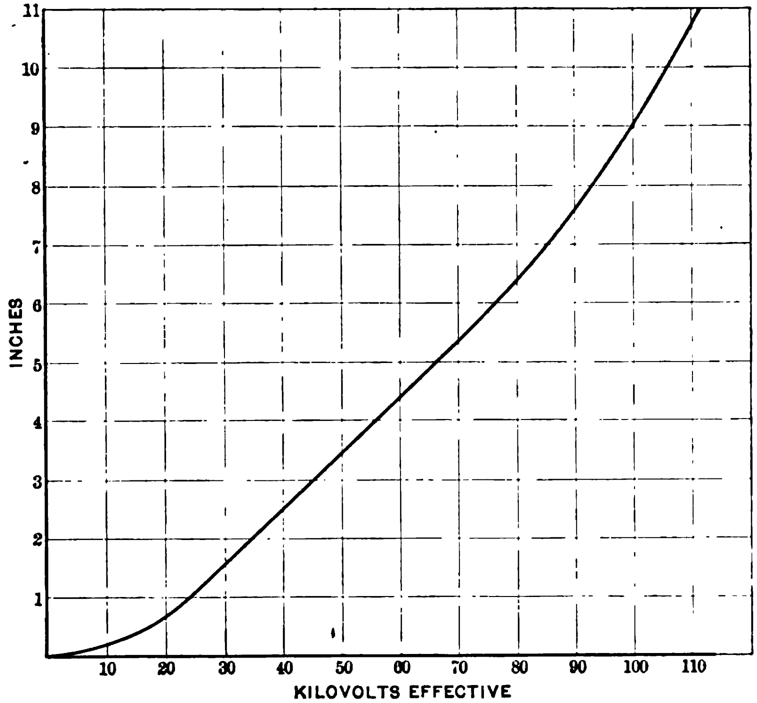


FIG. 9. ¼″ Spheres. Smooth Core Alternator, 125 Cycles.

Restricting thus at first our attention to the tests made with the smooth core alternator, we find the striking distance between parallel cylinders in Tables VI and VII and Fig. 14 and 15 represented by curved lines, the striking distance increasing faster than the voltage. The curve of parallel cylinders of larger diameter resembles the lower part of the curve of cylinders of smaller diameter in increased scale, as is to be expected.

Very interesting is the curve of striking distance between sharp points, Table I and Figs. 6 and 7. It starts in a straight line, the striking distance being proportional to the voltage at the rate of 20,000 volts per inch. At about 1¼″ distance the curve bends upward and passes into a second straight line which it follows from 3″ distance upward, the distance increasing at the rate of 1″ per 8,000 volts effective. This second straight line, however, does not pass through the origin, but through a point of the voltage of 22,000 effective.

TABLE III.

½″ SPHERES.

Amalgamated. 125 Cycles.

Smooth Core Alternator: A-10-30-1500.		Ironclad Alternator: A-10-60-1500.	
Distance, inches. *d:*	Kilovolts; effective. 7-23-'96. 7-14-'96.*	Distance, inches. *d:*	Kilovolts; effective. 7-20-'96.†
.125	8.2	.125	6.86
.25	14.6	.25	11.9
.485	22.0	.5	17.5
.94	31.3	1.0	27.9
1.5	36.1	1.5	26.5
2.0	39.4	2.0	35.4
2.5	44.4	2.97	44.0
2.90	47.2	4.0	51.2
4.0	59.4	4.95	56.1
5.0	68.0	5.94	60.0
6.06	79.0	6.97	68.8
6.97	84.0	7.97	77.5
7.97	95.0	8.97	88.0
9.0	98.3	9.97	97.3
9.93	105.5	11.03	108.8
11.0	112.0		

* 80°-90° F. Weather clean and bright.

† 75°-80° F. Weather rainy and sultry.

At very high voltages, about 100,000, the two sets of readings taken diverge from each other, the one falling below, the other passing above the straight line, as shown in Fig. 6.

The average, however, follows very closely the straight line as shown in Fig 7, where the average values of the two sets of readings are marked by crosses.

The four sets of curves representing the striking distance between spheres of various diameters have a considerable similarity with each other, the same curve repeating itself in increased scale with the increased diameter of the spheres. They differ, however, greatly from the curve of sharp points.

All the four curves start at the same slope for very small distances, of about ⅛″ per 10,000 volts. Then they bend upwards and pass into a second straight line, and the middle of the bend lies at about twice the diameter of the spheres. After the bend they follow a straight line for a certain range, but bend upwards once more for high voltages and then approach rapidly the curve of sharp points. The second upward bend is marked with ¼″ and ½″ spheres, while with 1″ spheres the curve extends only to what is probably the end and with 2″ spheres the beginning of the straight lined part. At very high voltages the ½″ and ¼″

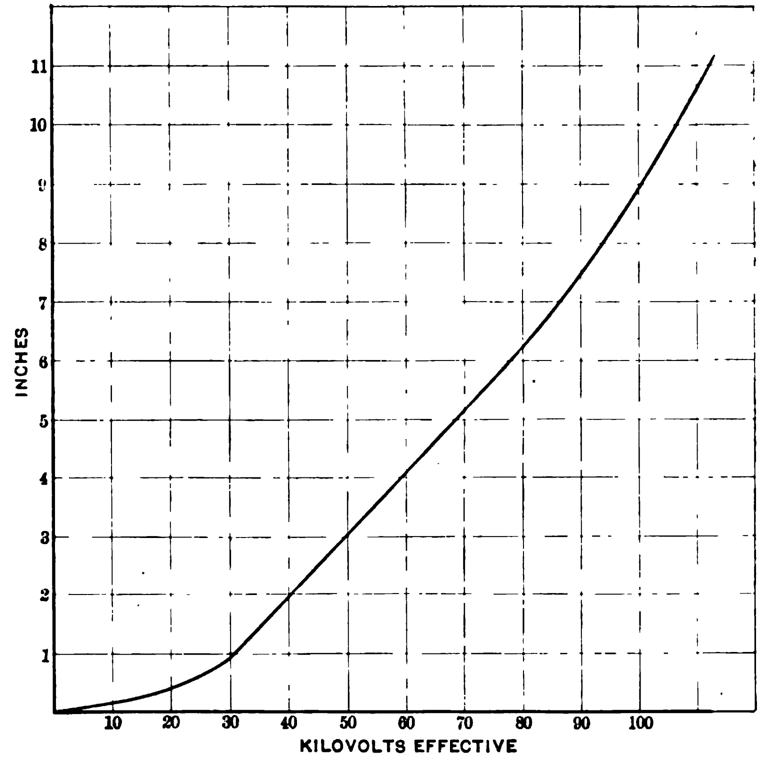


FIG. 10. ½″ Spheres. Smooth Core Alternator, 125 Cycles.

TABLE IV.

1″ SPHERES.

Amalgamated. 125 Cycles.

Smooth Core Alternator: A-10-30-1500.		Ironclad Alternator: A-10-60 1500.	
Distance, inches. *d*:	Kilovolts; effective. 7-13-'96. 7-14-'96.*	Distance, inches. *d*:	Kilovolts; effective. 7-17-'96.†
.125	8.95	.125	6.75
.25	11.9	.25	11 6
.5	26.1	.485	19.6
1.0	43.6	1 00	33.3
1.47	52.8	1.188	37.2
1.94	59.2	1.97	46.0
2.97	67.7	3.0	52 5
3.99	76.0	4 0	66.7
5.0	81 2	4 99	69.2
6.03	86.5	6 0	74.7
6.61	89.0	6.99	79 5
7.28	[illegible]0.0	8.2	86 0
7 99	99.0	8.99	92.0
8.99	104.5	10 0	97.5
9.99	108.7	10.97	107.0
10.94	124.0		

* 80°-90°. Weather clear and bright.
† 75°-80°. Weather clear.

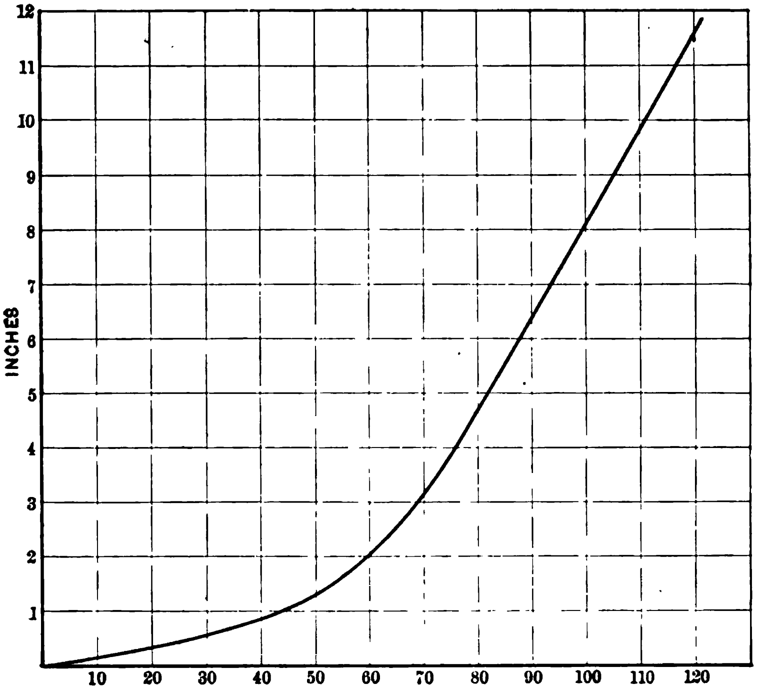


Fig. 11. 1″ Spheres. Smooth Core Alternator, 125 Cycles.

spheres have practically approached each other, the 1″ spheres are coming close to the same value, while the 2″ spheres show a bend, which as seen in Fig. 8, would bring the curve beyond the range of test up to the same value. At high voltages, however, the two sets of tests with ½″ spheres deviate from each other, the one leaving the straight line sooner than the other. Thus their average has been plotted in Figs. 2, 9 and 13.

TABLE V.

2″ SPHERES.

Amalgamated. 125 Cycles.

Smooth Core Alternator: A-10-30-1500.		Ironclad Alternator: A-10-60-1500.	
Distance, inches. *d*:	Kilovolts; effective. 7-13-'96. 7-14-'96.*	Distance, inches. *d*:	Kilovolts: effective. 7-20-'96.†
.125	8.95	.125	6.67
.25	15.9	.25	12.5
.493	26.7	.50	22.6
1.08	51.0	1.03	39.3
1.454	65.2	1.50	50.8
1.688	70.8	1.95	57.8
2.25	83.8	2.51	66.7
3.0	94.0	2.99	75.0
3.438	102.0	3.5	80.3
2.952	101.5	4.0	82.7
5.08	108.0	4.49	92.0
5.60	114.5	4.07	94.0
		5.47	96.5

* 80°-90° F. Weather clear and bright.

† 75°-80° F. Weather rainy and sultry.

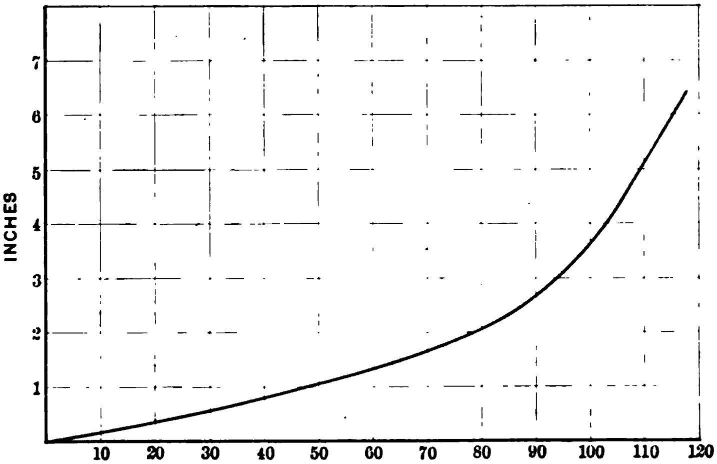


FIG. 12. 2″ Spheres. Smooth Core Alternator, 125 Cycles.

While the striking distances between spheres of different diameters are very different at intermediary voltages, they seem to coincide at very low and very high voltages, but differ essentially from the curve taken between sharp points, except at extremely high voltages.

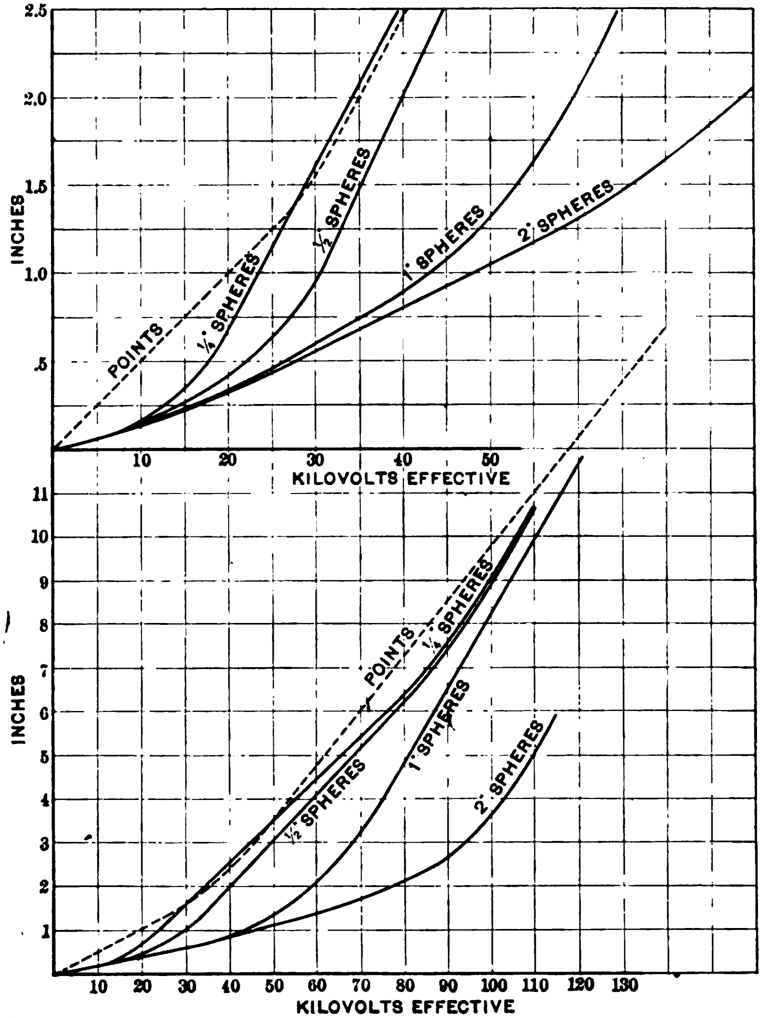


FIG. 13. Comparison of Points and Spheres. Smooth Core Alternator, 125 Cycles.

Comparing the striking distance between small spheres, and those between needle points as shown in Fig. 13, the remarkable feature is observed that the ¼″ spheres approach sharp points at comparatively low voltages, and even intersect the curve of sharp points, so that within a certain range of voltage, from 28 to 49 kilovolts, the striking distance between ¼″ spheres is greater than between sharp points, but beyond this range these curves separate again widely, far beyond the possible error of observation, and at very high voltages approach once more. The intersection of the curve of sharp points and of ¼″ spheres is very interesting and quite marked, and cannot well be due to errors of observation, since either curve represents two independent sets of tests taken at different times which coincide, and the same intersection at a somewhat lower range is strongly marked also in the tests with the ironclad alternator, Fig. 17.

TABLE VI.

PARALLEL CYLINDERS.

.318″ diameter. Radius of Curvature : 87″. Length : 24″
Amalgamated brass. 125 cycles.

Smooth Core Alternator : A-10-30-1500. 4-14-96.

Distance, inches. d:	Kilovolts, effective :	Mean Gradient. g :	$\sigma\sigma_0$ *	Maximum gradient : g_0 :	Δ :
.065	4.78	73.5	.934	78.6	+ 1.5
.080	5.7	71.2	.921	77.2	+ .1
.174	10.85	62.2	.849	73.4	− 3.7
.347	18.55	53.4	.742	72.0	− 5.1
.439	23.7	53.9	.698	77.2	+ .1
.47	22.9	48.8	.685	71.2	− 5.9
.565	23.0	40.7	.643	63.3	− 13.8
.69	30.5	44.2	.600	73.7	− 3.4
.84	34.3	40.9	.556	73.5	− 3.6
.93	33.1	35.6	.533	66.8	− 10.3
1.18	41.5	35.1	.478	73.4	− 3.7
1.44	47.3	32.8	.434	75.5	− 1.6
1.72	51.4	29.9	.396	75.7	− 1.4
2.12	53.8	25.3	.357	71.0	− 6.1
2.62	65.0	24.5	.312	78.5	+ 1.4
2.82	67.8	24.1	.298	80.5	+ 3.4
3.16	71.0	22.5	.276	81.6	+ 4.5
3.18	69.8	21.9	.275	79.6	+ 2.5
3.69	72.5	19.65	.251	78.4	+ 1.3
8.72	73.3	19.7	.250	78.8	+ 1.7
4.06	75.6	18.6	.236	79.0	+ 1.9
4.09	77.4	18.95	.234	8 .4	+ 3.3
4.34	77.3	17.8	.226	79.0	+ 1.9
4.53	77.7	17.15	.220	77.8	+ .7
4.84	80.0	16.5	.211	78.3	+ 1.2
5.28	83.5	15.8	.199	79.3	+ 2.2
5.46	83.7	15.35	.195	78.6	+ 1.5
5.84	93.6	16.0	.186	86.0	+ 8.9

Average : 76.0
Second average : 77.1

* $\sigma\sigma_0$ = ratio $\frac{\text{mean}}{\text{max.}}$ gradient, calculated.

From all these tests it should be expected that a law on the disruptive strength of air could be derived.

The disruptive electrical discharge bears a striking analogy to mechanical rupture. Thus, as the mechanical strength of a beam remains practically unimpaired up to a certain load, and at this load suddenly falls to zero by mechanical rupture, so the resistance of an air space is practically infinite up to a certain potential, at which, under disruptive discharge, it suddenly falls down to practically nothing. In looking for a physical law representing the electric disruptive discharge, it thus was to be investigated how far the laws of mechanical strength would represent the observed effects.

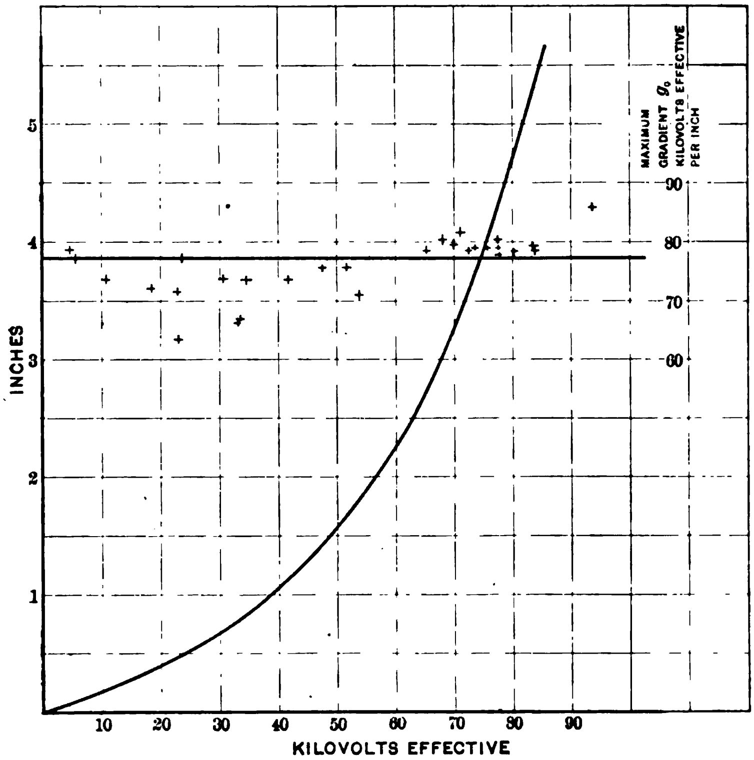


FIG. 14. Parallel Cylinder .313'' Diameter. Smooth Core Alternator, 125 Cycles.

Under mechanical stress, rupture takes place as soon as the stress exceeds the breaking strain anywhere in the material, and this breaking strain is a constant of the material. Thus I investigated whether the disruptive discharge of air takes place as

TABLE VII.
PARALLEL CYLINDERS.

1.11″ diameter. Radius of curvature: 140″ Length: 20.
Amalgamated brass. 125 cycles.

Smooth Core Alternator: A–10–30–1500. 4–6–96.

Distance, inches. d:	Kilovolts, effective.	Mean Gradient. g:	$\sigma\sigma_0$ *	Maximum gradient. g_0:	Δ:
.094	5.9	62.7	.973	64.5	+ 4.5
.109	7.02	54.4	.969	66.5	+ 6.5
.172	9.94	57.8	.951	60.8	+ .8
.188	11.6	61.7	.947	65.2	+ 5.2
.320	19.2	60.0	.914	65.6	+ 5.6
.407	21.6	53.0	.892	59.4	— .6
.492	27.0	55.0	.874	63.0	+ 3.0
.891	41.0	46.0	.797	57.8	— 2.2
1.31	52.0	39.7	.729	54.5	— 5.5
1.49	60.5	40.6	.704	57.6	— 2.4
1.78	66.2	37.2	.667	55.8	— 4.2
1.79	68.4	38.3	.666	57.6	— 2.4
2.06	74.0	36.0	.637	56.5	— 3.5
2.19	79.0	36.0	.623	57.7	— 2.3
2.37	84.6	35.7	.605	59.1	— .9
2.46	86.7	35.3	.597	59.2	— .8
2.54	93.0	36.5	.589	62.0	+ 2.0
2.90	98.5	34.0	.559	60.8	+ .8
3.19	103.7	32.5	.536	60.7	+ .7
3.72	118.4	31.8	.502	63.5	+ 3.5

Average: 60.4
Second average: 59.6
Mean: 60.0

* $\sigma\sigma_0$ = ratio $\frac{\text{mean}}{\text{max.}}$ gradient, calculated.

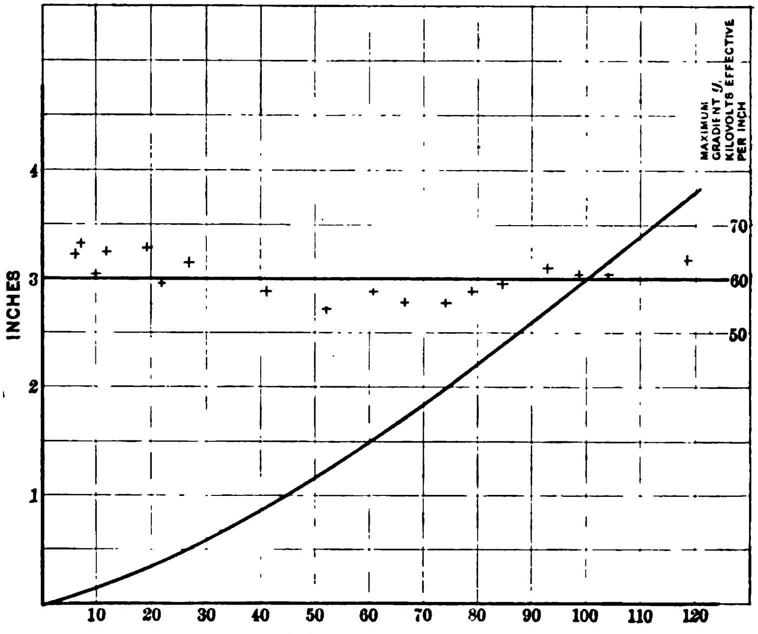


FIG. 15. Parallel Cylinder, 1.11″ Diameter. Smooth Core Alternator, 125 Cycles.

TABLE VIII.

Brass Disks of $\frac{5}{32}$' Thickness, in Path of Discharge of ¼' Spheres, at Right Angles Thereto.

Spheres Amalgamated, Disks suspended by three silk threads. 125 cycles.

<table>
<tr><th colspan="12">Smooth Core Alternator: A-1c-30-1500. 7-22-'96.</th></tr>
<tr><th rowspan="2">Number of disks</th><th rowspan="2">Diameter of disks, inches.</th><th colspan="2">Distance between spheres and disks.</th><th rowspan="2">Total distance between spheres. a:</th><th rowspan="2">Net air distance between spheres. b:</th><th rowspan="2">Air distance between spheres around edge of disk. c:</th><th rowspan="2">Kilovolts, effective.</th><th rowspan="2">Δ_a</th><th rowspan="2">Δ_b</th><th rowspan="2">Δ_c*</th></tr>
<tr><th>Inches.</th><th>Per cent</th></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">$8\frac{21}{32}$</td><td>......</td><td>98</td><td colspan="2" rowspan="6">(from Table II.)</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">$8\frac{13}{16}$</td><td>......</td><td>99</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">$8\frac{31}{32}$</td><td>......</td><td>100</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">$9\frac{1}{8}$</td><td>......</td><td>101</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">9.185</td><td>......</td><td>101.3</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">10.75</td><td>......</td><td>110</td><td></td></tr>
<tr><td>1</td><td>15</td><td>$4\frac{13}{32} + 4\frac{13}{32}$</td><td>.50 + .50</td><td>$8\frac{31}{32}$</td><td>$8\frac{13}{16}$</td><td>......</td><td>123.5</td><td>23.5</td><td>24.5</td><td></td></tr>
<tr><td>1</td><td>10</td><td>$4\frac{13}{32} + 4\frac{13}{32}$</td><td>.50 + .50</td><td>$8\frac{31}{32}$</td><td>$8\frac{13}{16}$</td><td>......</td><td>126</td><td>26</td><td>27</td><td></td></tr>
<tr><td>1</td><td>10</td><td>$3 + 5\frac{13}{16}$</td><td>.34 + .66</td><td>$8\frac{31}{32}$</td><td>$8\frac{13}{16}$</td><td>......</td><td>124</td><td>24</td><td>25</td><td></td></tr>
<tr><td>1</td><td>10</td><td>$1\frac{21}{32} + 7\frac{5}{32}$</td><td>.19 + .81</td><td>$8\frac{31}{32}$</td><td>$8\frac{13}{16}$</td><td>......</td><td>116</td><td>16</td><td>16</td><td></td></tr>
<tr><td>2</td><td>10</td><td>$2\frac{15}{16} + 2\frac{15}{16} + 2\frac{15}{16}$</td><td>.33 + .33 + .33</td><td>$9\frac{1}{8}$</td><td>$8\frac{13}{16}$</td><td>......</td><td>127</td><td>26</td><td>28</td><td></td></tr>
<tr><td>2</td><td>10</td><td>$\frac{3}{4} + 7\frac{5}{16} + \frac{3}{4}$</td><td>.085 + .83 + .085</td><td>$9\frac{1}{8}$</td><td>$8\frac{13}{16}$</td><td>......</td><td>94.3†</td><td>— 6.7</td><td>— 4.7</td><td></td></tr>
<tr><td>3</td><td>10</td><td>$\frac{3}{4} + 3\frac{5}{8} + 3\frac{5}{8} + \frac{3}{4}$</td><td>.087 + .413 + .413 + .087</td><td>$9\frac{1}{8}$</td><td>$8\frac{21}{32}$</td><td>......</td><td>94.7†</td><td>— 6.3</td><td>— 3.3</td><td></td></tr>
<tr><td>1</td><td>6</td><td>$4\frac{13}{32} + 4\frac{13}{32}$</td><td>.50 + .50</td><td>$8\frac{31}{32}$</td><td>$8\frac{13}{16}$</td><td>10.75</td><td>115.5</td><td>15.5</td><td>16.5</td><td>5.5</td></tr>
<tr><td>1</td><td>2</td><td>$4\frac{13}{32} + 4\frac{13}{32}$</td><td>.50 + .50</td><td>$8\frac{31}{32}$</td><td>$8\frac{13}{16}$</td><td>9.185</td><td>108.5</td><td>8.5</td><td>9.5</td><td>7.2</td></tr>
</table>

* Δ_a = kilovolts observed minus kilovolts required for distance *a*. Δ_b = kilovolts observed minus kilovolts required for distance *b*. Δ_c = kilovolts observed minus kilovolts required for distance *c*.

† Decided capacity effect, with increase of primary current, in generator circuit, to 8 amperes.

soon as the dielectric stress, that is the electrostatic gradient anywhere in the path of the discharge exceeds a certain constant value, which would be called the "dielectric strength of air" in analogy to the "mechanical strength" of a material. The mechanical strength of a material is tested by subjecting it to a uniform mechanical stress, the usual test of tensile strength by pulling a test piece of known cross-section to pieces. The analogous test of the dielectric strength of air would require a uniform electrostatic field, that is, parallel plates of perfect polish as electrodes. This is obviously not feasible. Thus I chose a shape of electrodes giving a relatively simple, although not uniform electrostatic field.

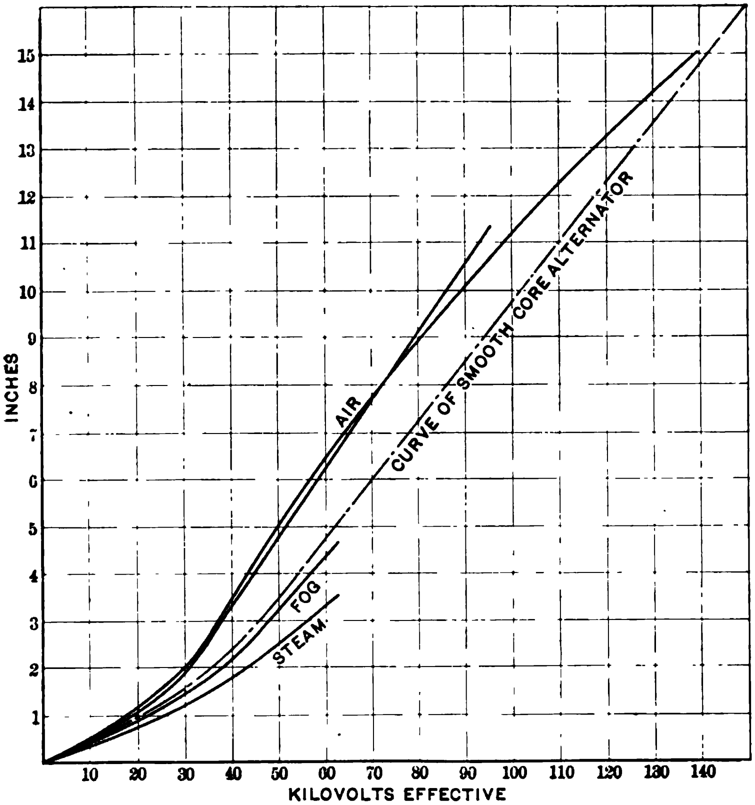


FIG. 16. Points in Air, Fog and Steam at Atmospheric Pressure. Ironclad Armature, 125 Cycles.

Between spheres, the lines of electrostatic force and equipotential surfaces are curves and surfaces of higher order. Between parallel cylinders, however, lines of force and equipotential lines are two linear systems or pencils of circles or rather cylinders, that is, all lines of electrostatic force are circles intersecting each other in two points, the fundamental points of the pencil, and all

TABLE IX.

Wet Plank Parallel to Discharge of ¼" Spheres.

Grain parallel to discharge. Mohawk river water. Spheres amalgamated.

125 cycles.

Smooth Core Alternator: A-10-30-1500. 7-22-96.							
Distance, inches, between: Spheres:	Sphere and plank.	Kilovolts, effective:	Struck to:	Average Kilovolts,* effective. 9	Δ_a:	Δ_b:	Δ_c:†
6	∞	76.5	—	—	From	Table 2.	
8	"	93	—	—			
10	"	105.6	—	—			
12	"	118	—	—			
4¼	"	58	—	—			
6⅛	"	77.7	—	—			
9	"	99.5	—	—			
10⅞	"	110.5	—	—			
6	2	67.7	plank.	69.5	7.0	11.5	18.5
"	2¼	71.3	spheres.				
"	2½	71.3	"				
"	3	71.3	"				
8	2¾	78	plank.	82.1	10.9	4.4	15.3
"	3	80.7	"				
"	3⅛	83.5	spheres.				
"	3½	86.5	"				
10	3¾	88	plank.	103	2.6	3.5	6.1
"	4⅛	102	"				
"	4½	104	spheres.				
"	4⅝	105	"				
12	5¼	116.5	plank.	117.3	.7	6.8	7.5
"	5⅜	119.5	"				
"	5½	115	spheres.				
"	5⅞	121	"				

* That is, voltage where the direct path between the spheres, and the path over the wet plank have the same dielectric strength.

† Δ_a = kilovolts of direct discharge between spheres, minus 9.

Δ_b = 9 minus disruptive voltage between spheres at twice the distance of wet plank.

$\Delta_c = \Delta_a + \Delta_b$

equipotential lines are circles intersecting the first set at right angles, and containing the cross section of the cylinders as one pair.

This being the relatively simplest case, it was chosen for the investigation. Obviously the length of the parallel cylinders could not be infinite, and therefore, to avoid the influence of the ends of the cylinders, they were given a slight backward curvature of a very large radius compared with the diameter of the cylinders and their distance, as shown in Fig. 18, which represents the relative proportions of the larger cylinders at the highest observed striking distance. The effect of this curvature was investigated and correction made therefor.

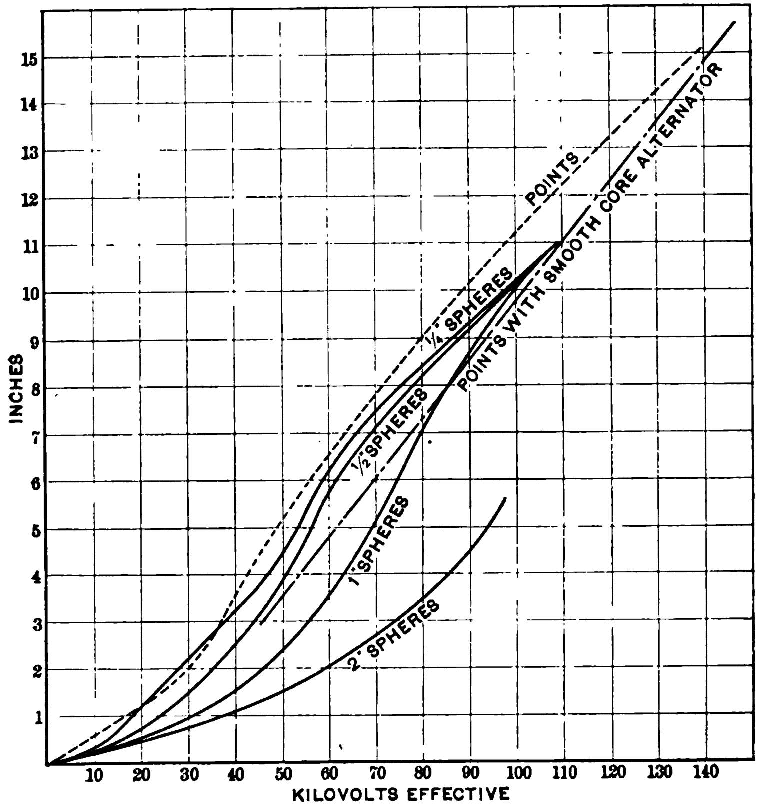


Fig. 17. Comparison of Points and Spheres. Ironclad Armature, 125 Cycles.

From the distance between the cylinders d and the striking voltage V, the mean electrostatic gradient $g = \frac{V}{d}$ was calculated and is given in the third column of Tables VI. and VII. in kilovolts per inch. From diameter and distance of cylinders, the ratio of mean to maximum gradient σ was calculated, and by

TABLE X.

METEOROLOGICAL RECORD AT DATE OF TESTS.

Date.	TEMPERATURE ° C:					BAROMETER, ":		SKY:			Tests made.
1896.	Preceding nightly minimum.	8 h morning.	Daily maximum.	9 h evening.	Following nightly minimum.	8 h morning.	9 h evening.	Forenoon.	Noon.	Afternoon.	
April 6	−2	+1.5	+11.5	+2	+.5	29.9"	29.8"	cloudless		almost cloudless	1.11" cylinders, smooth core.
" 14	—	17	25	17	—	29.55"	29.7"	cloudless	cloudy	almost cloudless	.313" " "
July 13	26	—	30	24.5	23	29.7"	29.6"	almost cloudless	cloudy	almost cloudless	¼", ½", 1", 2" spheres.
" 14	23	25	29	23	18.5	29.65"	29.65"	cloudy		almost cloudless	Smooth core.
" 17	13	17.5	26	20	15.5	29.8"	30.0"	almost cloudless			Needle points, smooth core. " spheres, ironclad.
" 20	20	21.5	25.5	23.5	21	29.9"	29.7"	rain	rain	cloudy	¼", ½", 2" spheres, ironclad.
" 21	21	25	31	25	22.5	29.77"	29.8"	almost cloudless			Needle points, smooth core.
" 22	22.5	23.5	31.5	23	19	29.8"	29.5"	almost cloudless		rain and thunderstorm	Brass disks and wet plank.
" 24	15.5	18	20.5	16	15.5	29.75"	29.5"	cloudy	rain	rain	Needle points, ironclad.
" 25	15.5	18	26.5	18.5	15	29.62"	29.8"	almost cloudless			¼" spheres, smooth core.

dividing the observed mean gradient g by the factor σ, the maximum gradient $g_0 = \frac{g}{\sigma}$ would be derived for parallel cylinders. To correct for the backward curvature of the cylinders, of radius r_0, the ratio of mean to maximum radient was calculated for the distance d but a diameter of cylinders of $2r_0$. Since σ_0 differs very little from one, being at the highest distance observed with large cylinders $\sigma_0 = .994$ and with small cylinders $\sigma_0 = 0.893$, by dividing with σ_0 the correction was far within the errors of observation.

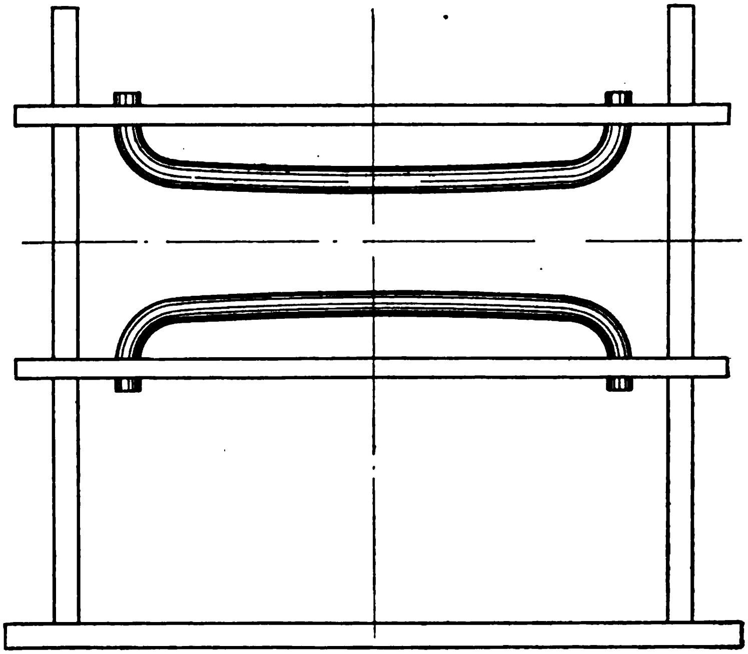


FIG. 18.

Thus the maximum gradient g_0 was derived from the observed mean gradient $g = \frac{V}{d}$ as: $g_0 = \frac{g}{\sigma \sigma_0}$.

The calculation of σ and σ_0 is as follows:

Let in Fig. 19 be represented the cross section of the two parallel cylinders of equal diameter.

Let x = abscissæ with center 0 between the parallel cylinders as origin.

y = ordinates of one line or circle of electrostatic force of radius R.

d = distance inside between parallel cylinders.

r = radius of parallel cylinders.

p = distance of fundamental points A and A^1 of cylindrical pencil (common point of intersection of all lines of force) from origin.

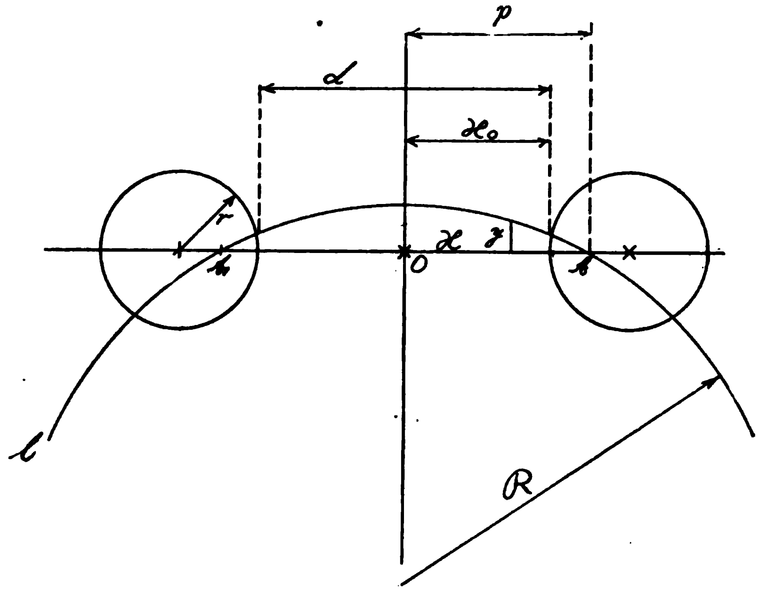


FIG. 10.

At the surface of the cylinders, it is:

$$y_0 = \sqrt{R^2 - x_0^2} - \sqrt{R^2 - p^2};$$

in general it is:

$$y = \sqrt{R^2 - x^2} - \sqrt{R_2 - p^2};$$

it is:

$$p^2 = x_0 (x_0 + 2r).$$

Let g_0 = electrostatic stress at the cylinder surface in the central line, that is at x_0; then it is:

$g_x = \frac{y_0}{y}$ = electrostatic stress at point x of central line, if the line of force 1 is infinitely near the central line, that is, if:

$$r = \infty .$$

Thus the ratio of average electrostatic stress g to maximum stress g_0 is:

$$\sigma = \frac{g}{g_0} = \frac{1}{x_0}\int_0^{x_0} \frac{y_0}{y}\, d_x .$$

Substituting, it is:

$$\sigma = \frac{1}{x_0}\int_0^{x_0} \frac{\sqrt{R^2 - x_0^2} - \sqrt{R^2 - p^2}}{\sqrt{R^2 - x^2} - \sqrt{R^2 - p^2}}\, d_x .$$

Introducing the transformation:

$$\sqrt{R^2 - x^2} = R - u x,$$

$$x = \frac{2 u R}{1 + u^2},$$

$$d = \frac{2 R (1 - u^2)}{(1 + u^2)^2},$$

$$\sqrt{R^2 - x^2} = \frac{R (1 - u^2)}{(1 + u^2)},$$

$$u = \frac{R}{x}\left\{ 1 - \sqrt{1 - \frac{x^2}{R^2}} \right\},$$

$$\sqrt{R^2 - x_0^2} = a,$$

$$\sqrt{R^2 - p^2} = b,$$

it is:

$$\sigma = \frac{2 R (a - b)}{x_0}\int_0^{x_0} \frac{(1 - u^2)\, d_x}{(1 + u^2)\{(R - b) - (R + b) u^2\}} .$$

Substituting:

$$R - b = c^2,$$

$$R + b = g^2,$$

$$\delta = \frac{2 R (a - b)}{x_0 (g^2 + c^2)}\int_0^{x} \left\{ \frac{1 + u^2}{2} + \frac{\frac{g^2 - c^2}{2 c}}{g u + c} -- \frac{\frac{g^2 - c^2}{2 c}}{g u + c} \right\} d x .$$

$$\frac{2 R (a - b)}{x_0 (g^2 + c^2)} \text{ arc tan } u + \frac{g^2 - c^2}{2 g c} \, \mathrm{l}\, g \frac{g u + c}{g u - c} \Big/_0^{x_0}$$

or substituting:

$$\sigma = \frac{R}{x_0}\left\{\sqrt{1-\frac{x_0^2}{R^2}}-\sqrt{1-\frac{p^2}{R^2}}\right\}\Big/ 2 \text{ arc tan } \frac{R}{x}\left\{1-\sqrt{\frac{x^2}{R^2}}\right. +$$

$$\left.\frac{R}{p}\sqrt{1-\frac{p^2}{R^2}}\, lg\, \frac{p\left\{1-\sqrt{1-\frac{x^2}{R^2}}\right\}+x\left\{1-\sqrt{1-\frac{x^2}{R^4}}\right\}}{p\left\{1-\sqrt{1-\frac{x^2}{R^2}}\right\}-x\left\{1-\sqrt{1-\frac{p^2}{R^2}}\right\}}\right|_{x_0} =$$

$$\frac{R}{x}\left\{\sqrt{1-\frac{x^2}{R^2}}-\sqrt{1-\frac{p^2}{R^2}}\right\} 2 \text{ arc tan } \frac{x^2}{R}\left\{1-\sqrt{1-\frac{x^2}{R^2}}\right\} +$$

$$\left.\frac{R}{p}\sqrt{1-\frac{p^2}{R^2}}\, lg\, \frac{x_0\left\{1-\sqrt{1-\frac{p^2}{R^2}}\right\}+p\left\{1-\sqrt{1-\frac{x^2}{R^2}}\right\}}{x_0\left\{1-\sqrt{1-\frac{p^2}{R^2}}\right\}-p\left\{1-\sqrt{1-\frac{x^2}{R_2}}\right\}}\right\}^{o}.$$

In the central line between the parallel cylinder it is:

$$R = \infty.$$

Substituting this, it is:

$$\sigma = \sqrt{1-\frac{x^2}{R^2}} \doteq 1 - \frac{1}{2}\frac{x^2}{R^2} - \frac{1}{8}\frac{x_0^4}{R^4}.$$

Thus:

$$\sigma = \frac{p^2-x^2}{2\,p\,x_0}\, lg\, \frac{p+x_0}{p-x_0},$$

the ratio of average to maximum strain in the central line, where:

$$x_0 = \frac{d}{2},$$

$$p^2 = x_0\,(x_0 + 2\,r).$$

Substituting this, it is:

$$\sigma = \frac{r}{p}\, lg\, \frac{p+x}{p-x},$$

and if the distance x_0 is very small compared with the radius r, it is:

$$\sigma = \frac{r}{p}\, lg\, \frac{p+x_0}{p-x_0}$$

$$= \frac{2r}{p}\left(\frac{x_0}{p}+\frac{x_0^3}{3p^3}+\frac{x_0^5}{5p^5}\right),$$

or, since:

$$p^2 = x_0 \, (x_0 + 2 \, r,$$

approximately:

$$\sigma = 1 - \frac{x_0}{2 \, r}.$$

If now

r = diameter of cylinders,

r_0 = ratio of curvature of cylinders (r_0 being very large compared with r and x_0), it is:

$$\sigma = \frac{r}{p} \, lg \, \frac{p + x_0}{p - x_0},$$

$$\sigma_0 = 1 - \frac{x_0}{2 \, r_0},$$

and

$$\sigma \, \sigma_0 = \frac{r}{p} \left(1 - \frac{x_0}{2 \, r_0} \, lg \, \frac{p + x_0}{p - x_0} \right),$$

the ratio of the maximum to the mean electrostatic gradient within the path of the discharge.

Thus, if g = mean gradient,

$g_0 = \dfrac{g}{\sigma \, \sigma_0}$ is the maximum gradient.

With the cylinders used it was:

r = .1565 and .555 respectively.

Herefrom the numerical values of correction factor $\sigma\sigma_0$ and maximum gradient g_0 are calculated and given in Tables VI and VII.

With the large cylinders, which were investigated first, the values of the maximum dielectric gradient g_0 were found over the whole range from the lowest to the highest voltage to average 60. The difference of individual values of g_0 from the average is not greater, but rather less than found under similar conditions in tests of tensile strength in mechanics. They are, however, greater than can be accounted for by the errors of observation, thus showing the existence of some secondary effect disturbing the results. The values of g_0 show no noticeable tendency of deviation from constancy for very high or very low voltages, and appear rather low in the middle, high at either end of the curve.

The tests with the smaller cylinders gave an equally good agreement between the values of the maximum gradient g_0.

However, comparing both sets of tests we found that the "dielectric strength of air" averages 60 with the 1.1″ cylinders but averages 77 with the .313″ cylinders. Thus, while the maximum gradient is fairly constant with the same size of cylinders and different distances, it differs considerably with different sizes of cylinders, or in other words the dielectric strength of air as found in this way is not a constant, as the tensile strength of mechanics, but varies with the conditions.

Some further results on the question of the constant dielectric strength of air can be derived from the tests with points and with spheres as terminals.

Between mathematical points the dielectric field of force is similar regardless of the distance. Thus with the needle points used, for all distances great compared with the radius of curvature of the needle points, that is already the smallest distance investigated, the striking distance should be proportional to the voltage if it depends upon the maximum gradient. This, however, is not the case.

Between mathematical points even with the lowest voltage the gradient at the points is infinite. Thus with needle points very small voltages should strike over great distances. This is not the case either, but the curve of needle points does not differ much from that of $\frac{1}{4}''$ spheres. This leads us to one of the phenomena obscuring the true electrostatic gradient at the moment of disruption, the brush discharge.

Long before the disruptive voltage is reached between needle points and smaller spheres or cylinders, a brush discharge issues from the terminals into the surrounding air. The space surrounding the electrodes is filled with an infinite number of violet streamers issuing from the electrodes under a hissing noise and being constantly in motion, and this space is thus more or less broken down dielectrically, so that, when the final disruptive discharge takes place, the terminals of the discharge are no longer the original metal terminals, but the whole space covered by the brush discharge is more or less to be considered as discharge terminals.

An attempt was made to investigate this phenomenon, thus: Instead of the amalgamated metal cylinders of diameter D and distance d, two cylinders were substituted of the diameter $\mathrm{D} + x$ and distance $d - 2x$ and for the latter cylinders the mean gradient $d = \frac{V}{d-2x}$, the ratio of mean to maximum gradient $\sigma\sigma_0$ and this the maximum gradient g_0 calculated for various values of x.

Representing then the length of the brush discharge by x, with constant D, d, and V, g_0 decreases with increasing x, reaches a minimum and then increases again; or inversely, at a constant maximum gradient g_0, with increasing length of brush discharge, the voltage required to give this gradient g_0 will increase, reach a maximum and then decrease again. Thus if the terminal voltage is gradually increased, as soon as the maximum gradient at the terminals exceeds the breaking strain, a brush discharge will issue and thereby enlarge the size of the terminals by the space covered by the brush discharge, but at the same time decrease the maximum gradient at the surface of the effective terminals, that is, the space covered by the brush discharge, until the critical point is reached beyond which a further expansion of the brush discharge increases the gradient at its surface again. At this point a disruptive discharge will take place.

No satisfactory results were found, however, by this method, probably for the reason that:

1st. The brush discharge at high voltage does not cover a well defined distance, but consists of an infinite number of streamers issuing from the electrodes to a greater or lesser distance and being in rapid and violent agitation.

2nd. The space covered by the brush discharge is only partially broken down, that is while not having the dielectric strength of air before the break-down, its dielectric strength has not fallen to zero yet, as after the discharge. It thus represents electrostatically a similar condition as mechanically a medium under strain exceeding the elastic limit of the material. Under mechanical stress, rupture does not always take place as soon as the strain anywhere in the cross-section exceeds the breaking strain.

Comparing, for instance, a beam of the cross-section A in Fig. 20 with that in B of the same figure, which latter differs only by the addition of the two small ribs a on top and bottom, it is obvious that B has no lesser strength than A. But at the extremities of the ribs a the breaking strain is exceeded at a load far below that which would break down beam A. The result is that in the two thin ribs a, cracks are formed or the material strained beyond the elastic limit, and only at much greater load the break-down of the beam occurs.

The tests made with spheres allows some further conclusions. The electrostatic field of force between two spheres of diameter D and distance d is similar to the field between spheres of diameter n D and distance $n\ d$. Thus the ratio between mean and maximum gradient is the same. Hence, if disruptive discharge takes place at the same maximum gradient, in the latter case n times the striking voltage would be required.

Since tests with four different diameters of spheres were made, this feature is easy to investigate. In the following a number of sets of readings are given abstracted from Tables II to V: Values are chosen in that range of voltage where the four curves differ most. The first column gives the diameter of the sphere

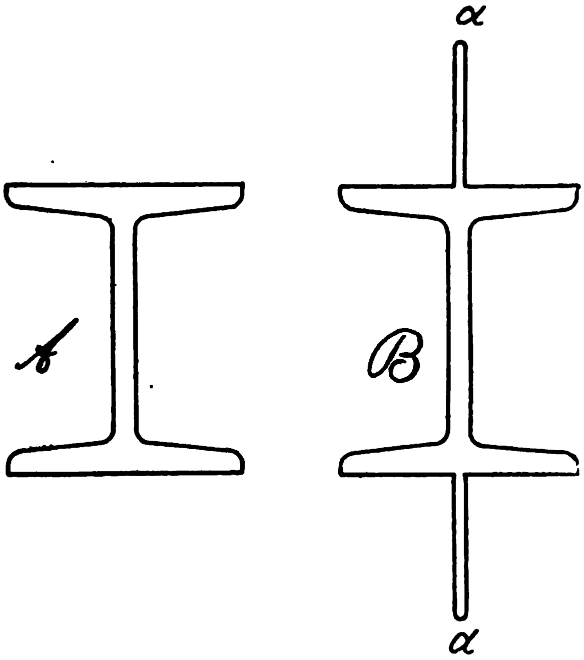


FIG. 20.

D, the second column the striking distance d chosen proportional to the sphere diameter, the third column the striking voltage, and the fourth column the ratio a of mean gradients of subsequent lines. As seen, while constant dielectric strength of air would require a ratio $a = 1$, the ratio differs herefrom. This difference could not well be accounted for by a brush discharge depending upon the electrostatic gradient, and thus some further secondary effects are probable.

Diameter of spheres, inches. D:	Distance of spheres, inches. d:	Striking voltage, kilovolts. V:	Ratio of gradients. a:
1	8	98.7	1.194
½	4	59	1.152
¼	2	34	
1	6	87	1.134
½	3	49.3	1.180
¼	1½	29	
1	4	75.4	1.060
½	2	40	1.165
¼	1	23.6	
2	6	115	1.194
1	3	68.5	1.035
½	1½	35.4	1.186
¼	¾	21	
2	4	103	1.155
1	2	59.5	1.010
½	1	30	1.154
¼	1½	17.3	
		Average........	1.155

At half the distance, the gradient is 1.135 times as great. Thus, if g_1 = gradient at distance d_1, it is, at distance:

$$d = \frac{1}{2_n} d_1,$$

the gradient:

$$g = 1.135^n g_1,$$

thus:

$$\underline{l}d = \underline{l}d_1 - n\underline{l}2,$$

$$\underline{l}g = \underline{l}g_1 + n\underline{l}1.135,$$

hence, eliminating '*n*':

$$.183\,\underline{l}d + \underline{l}g = .183\,\underline{l}d_1 + \underline{l}g_1,$$

$$g\,d^{.183} = g_1\,d_1^{.183},$$

or:

$$g = \frac{a}{d^{.183}},$$

$$V = a\,d^{.817},$$

where:

$$a = g_1\,d_1^{.183} = \frac{V_1}{d_1^{.817}},$$

or:

$$d = b\,V^{1.22},$$

where:

$$b = \frac{d_1}{V_1^{1.22}}.$$

This gives a parabolic law of striking distances in uniform field.

According hereto the curve of striking distances should approach the zero point horizontally, that is for very small voltages the electrostatic gradient should approach infinity and the striking distance zero. This, however, is not the case, since even for very small voltages the striking distance and the gradient are finite. On the contrary, in the tests with spheres the gradient for very small distances approaches 75 to 80, about the same value as the dielectric strength of air as found with small cylinders. Hence, if a constant dielectric strength of air exists it would be somewhere between 60 and 80 kilovolts per inch. Some results are in favor but some in opposition to such a hypothesis.

The curve of striking distance between sharp points has a very interesting shape. Up to 1¼″ striking distance it is proportional to the voltage, and represented by the equation,

$$d = .05\ V$$

or

$$V = 20\ d,$$

then it curves upwards and becomes a straight line again from 3″ upward to the limits of test, at 14½″.

This straight line does not pass through the origin but through a point at the voltage 22 or the distance —2¾, and can thus be represented by the equation,

$$d = .125\ V - 2.75,$$

or,

$$V = 8\ d + 22.$$

This feature points to something like a spurious "counter E. M. F. of the spark." That is, beyond 3″ distance, by assuming a potential of 22 as required for the discharge passing from the terminals to the air, the remaining voltage is proportional to the distance. For low voltages the curve leaves the straight line and slopes towards the origin, becoming straight again for still lower voltages.

This shape of curve bears a striking similarity to the volt-ampere curve of the electric arc or to that of electro-chemical polarization.

In the electric arc under constant conditions the voltage is approximately proportional to the current plus a constant value, the spurious counter E. M. F. of the arc.

In an electrolyte the current is proportional to the voltage for small voltages below the counter E. M. F. of polarization. Approaching the latter the current rises beyond proportionality, that is, the volt-ampere curve bends upwards, and ultimately turns into a second straight line, when the dissociation voltage V_0 is passed, which latter straight line does not pass through the origin, however, but through the point $C = 0$, $V = V_0$, and thus can be represented by

$$C = a\,V + V_0.$$

Thus the theoretical volt-ampere curve of the electrolyte is of the same shape as the distance-volt curve between points.

Since with alternating E. M. F. the current in the electrolyte below the dissociation potential is essentially in quadrature with the E. M. F. the current over the whole range can be represented by the theoretical equation,

$$C = \sqrt{a^2\,V^2 + b^2\,(V - V_0)^2}$$

where the latter term appears only beyond $V = V_0$. It is of interest to note that the curve of striking distance between sharp points over the whole range from the origin to the limits of observation can be represented by

$$d = \sqrt{.05^2\,V^2 + .115^2\,(V - V_0)^2}.$$

This equation represents the curve absolutely as shown in the following comparison, where the first column gives the voltages, the second the striking distance taken from test, and the third the striking distances as calculated from this formula:

$$d = \sqrt{d_1^2 + d_2^2}$$

$$d_1 = .05\ V$$

$$d_2 = .115\ (V - 27.5.)$$

V:	d calc:	d obs:
10	.5	.5
20	1.0	1.0
27.5	1.38	1.38
30	1.53	1.53
60	4.8	4.8
90	8.5	8.5
120	12.25	12.25
150	16.0	16.0

The magnitude of this spurious counter E. M. F. or transition resistance of the spark is the same as that at which the brush discharge is formed. Not the electrostatic glow of bluish color which under favorable conditions can be observed already below 1,000 volts, but the real brush discharge consisting of violet streamers issuing from the terminals into the surrounding air.

The tests with spheres show also more or less marked the appearance of straight lined parts in the curve, passing through a point differing from the origin.

The most interesting feature in connection therewith is, however, if an electric conductor as a brass disk is inserted into the path of the discharge.

A considerable number of tests were made and are recorded in table 8, by inserting brass disks of different diameters and in different positions and different numbers into the path of the discharge between ½″ spheres. The first column of table 8 gives the number of disks used, the second the diameter, the third and fourth the position of the disks between the spheres, the fifth and sixth the total distance and the net distance between the spheres and the seventh the striking voltage. The last three columns give:

As Δ_a the difference in the observed voltage and the striking voltage between ½″ spheres at the same total distance without disks between them.

As Δ_b the difference in the observed voltage and the striking voltage between ½″ spheres at a distance equal to the net air distance between spheres and disks.

As Δ_c the difference in the observed voltage and the striking voltage between ½″ spheres at the same distance as in the test, but in a line over the edge of the disk.

It is of interest to note that the insertion of an electric conductor, as a brass disk, increases the voltage required to strike between the spheres, although the net air distance is reduced by the thickness of the disk.

Thus with one 10″ disk midway between ½″ spheres at about 9″ distance, 126 kilovolts are required to strike across, while after withdrawing the disk 100 kilovolts will strike; or in other words, at voltages between 100 on 126 kilovolts between ½″ spheres and 9″ distance in air, a disruptive discharge will take place, but will not take place any more if an electric conductor as a brass disk is inserted between the spheres.

The disks were suspended and insulated by three silk threads. Between 10″ and 15″ disks, no difference seems to exist, but 6″ disks increase the striking voltage less, and still less 2″ disks. In either of the two last cases, however, the striking voltage is higher than would be required for a stroke from sphere to sphere around the edge of the disk.

This phenomenon could be explained by the fact that two sparks of half the length require a higher voltage than one spark of full length. This explanation, however, does not explain the observations on the 6″ and 2″ disks, where the voltage was higher than necessary for a single stroke through air around the edge of the disk, by 5.5 and 7.2 kilovolts respectively. If the disk is not midway between the spheres, but nearer to one side, the increase of voltage is less.

Two disks equidistant from each other and the spheres, increase the voltage by the same amount as one disk in the center, and less if they are nearer to the spheres, and disks very close to the spheres even reduce the striking voltage, under marked capacity effects. The same applies to three disks.

That means, if the disks are very close to the electrodes they are probably brought in perfect electric connection therewith by the brush, and thus form a new set of electrodes.

The increase of voltages due to the insertion of an electric conductor is from 23.5 to 27 kilovolts, that is about the same as the spurious counter E. M. F. of the spark, and would thus well agree with the assumption of such a phenomenon, since the insertion of a conductor increases the number of transitions from metal to air by two, and thus should require an increase of the striking voltage by the counter E. M. F. of the spark.

The next table, No. 9, gives tests of striking distances between ½″ spheres when an electric conductor, as a plank wetted with river water, is approached parallel to the discharge line. The effect thereof is a change of the striking voltage below that required for twice the distance between the spheres, but beyond that required for twice the distance between spheres and plank. That is, when the plank is approached so far that the single discharge between the spheres and the double discharge from spheres to plank have the same dielectric strength, the striking voltage is intermediate between that corresponding to the length of the direct discharge and a distance equal to the sum of the two discharges from spheres to plank. The difference in voltage which would be required for direct discharge between spheres and for a discharge equal to twice the distance of the plank is 18.5 and 15.3 kilovolts respectively in the first two cases, less in the last two, where probably the resistance of the plank as an imperfect conductor was noticeable. Making allowance for the latter, we find again a voltage of the magnitude of the spurious counter E. M. F. of the spark, as discussed under sharp point.

Tests with the ironclad alternator between sharp points in air, in fog and in steam, point also to such a counter E. M. F. of the spark, or lesser magnitude with the ironclad alternator, due to the greater ratio of maximum to effective E. M. F.

These sets of tests with brass disks and wet plank were suggested by some observations made three years ago with an ironclad alternator and recorded on table I.

To investigate whether the dielectric strength of air was reduced in fog, as occasionally suggested at that time, a steam pipe was arranged below the discharge circuit and steam made to escape very slowly, so as to fill the whole space between the needle points with dense fog. Against expectation it was found that a much higher voltage was required to strike across the same distance in fog as in dry air. This is seen in Fig. 16. Hence fog increases the dielectric strength of air and reduces the striking distance very markedly. This may be explained by the assumption that the discharge is by the fog broken up in an infinite number of minute successive discharges, between the conducting fog particles, requiring a higher total voltage than the direct discharge over the same total distance.

By turning full steam on, issuing from a boiler at 80 pounds pressure into the space between the needle points, the striking distance was still reduced further below that in fog, that is, live steam at atmospheric pressure has a much greater dielectric strength than dry air.

From these tests, the following results are derived:

1st. At constant voltage and constant wave shape, that is constant ratio between maximum and effective E. M. F., the striking distance is a constant, especially between sharp points, where the tests have been repeated over and over again, and independent of the atmospheric condition, the frequency, etc., to such an extent that the striking distance between needle points offers the most reliable means to determine very high voltages. For this reason, it is used in this manner as final check in all high potential insulation tests of the General Electric Company.

2nd. No physical law has been found to represent satisfactorily all the observations. Some point to the existence of a constant dielectric strength of air, analogous to the tensile strength of mechanics. Others point to the existence of a spurious counter E. M. F. of the spark or transition resistance from electrode to air.

3rd. Constant dielectric strength. Cylinders of 1.11″ diameter give an average disruptive strength of air of 60 kilovolts per inch. Cylinders of .315″ diameter, an average dielectric strength of 77. Spheres at very small distance point toward the latter value. As a disturbing factor in this case, enters the electrostatic brush discharge, which by a partial breakdown of the air surrounding the electrodes changes and increases the size and decreases the distance of the effective terminals.

4th. Counter E. M. F. of the sparks. The tests with sharp points give 22 kilovolts, or 11 kilovolts for a single transition from terminal to air. Spheres give curves pointing to a similar phenomenon. Electric conductors inserted at right angles into or parallel with the discharge, point to the existence of a counter E. M. F. of the same magnitude. The beginning of the electrostatic brush discharge is at a potential of this magnitude also.

5th. Potentials of 160,000 volts effective and even up to 170,000 volts have been experimented with. They are probably the highest voltages ever reached by man at ordinary frequencies with alternating currents of considerable power.

[COMMUNICATED AFTER ADJOURNMENT BY MR. A. VOSMAER.]

We practical men must congratulate Mr. Steinmetz for such an excellent and valuable paper as he has given. Experimenting myself in the line of high tensions it has often puzzled me how to fix minimum distances for different parts of instruments and transformers, and information was not to be had.

We can find some tables of spark lengths and potential differences, but scientific men like Baille, Paschan, Liebig, and others do not seem to have the slightest interest for alternating current, and do not generally extend their series wide enough.

It matters very little indeed to us what tension corresponds to a spark of a fifteen thousandth of a millimetre or what it is in hydrogen or at low pressures, but it is of the greatest practical value to know the spark lengths in air and for alternating current.

I would like to ask two questions, how many were the frequencies of his high frequency ironclad alternator and does Mr. Steinmetz consider a variation in the frequency from 40 to 125 large enough to permit any conclusion as to the apparent independence of striking distance and frequency, it being well known that at very high frequencies the tendency for sparking is greatly diminished.

Has Mr. Steinmetz also experimented with a specially constructed high-tension transformer, and in consequence of experience preferred four transformers in series with the complication of insulation by transformers?

We have a one kilowatt 40,000-volt transformer in constant use, it never has given any trouble, but it was specially designed for the purpose, oil insulation being used though the secondary coils were made with the utmost care.

We have had opportunity to see a 100,000-volt, 15-kilowatt transformer designed and constructed by Schneller, which does not even have oil insulation and has nothing else but air insulation; that is all high-tension parts are spaced wide enough to prevent sparking.

For ourselves we preferred oil, because the dimensions of the air-insulated transformer are rather out of proportion; which means a great deal of copper in the secondary, and oil is cheaper than copper.

Nevertheless the transformer, in constant use, has always given full satisfaction. Schneller who has made a number of lower transformers used to couple these in series, *i. e.*, two of 30,000 volts each; preferred to construct one for 100,000 and used a factor of transformation of 1000 which is a pretty good figure.

The secondary tension could be easily measured because the secondary windings consisting of ten coils in series and one thus can measure one coil for itself with a static voltmeter.

As a matter of fact we have done the same for our transformer, there being eight coils connected alternately at the center part and at the periphery, just as is done for large induction coils, each coil, after having been placed a good many hours in hot ceresin standing 10,000 volts without puncturing.

I should prefer this to the arrangement given by Mr. Steinmetz as being far simpler.

The good behavior of Schneller's 100,000-volts transformer would suggest a similar behavior for one of 200,000 volts.

As said, Mr. Steinmetz's contribution to our knowledge about very high tension alternating currents is a most valuable one, and we express our hopes that he will investigate the dielectric strength of solid and fluid dielectrics in the same thorough way as he has done for air. The future will bring us very high tensions in common use, and the value of elaborate tests is beyond doubt as regards general interests.

Haarlem, Holland, July 24, 1898.

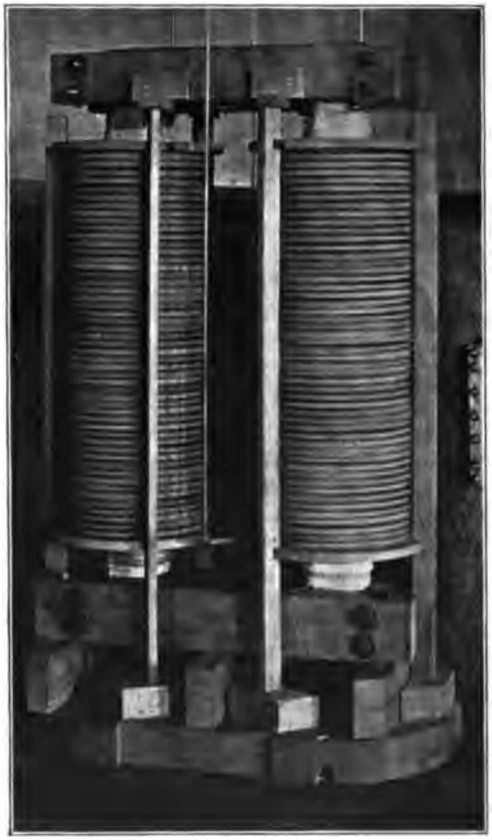
[COMMUNICATED AFTER ADJOURNMENT BY HAROLD B. SMITH.]

The valuable paper of Mr. Steinmetz has to do with work on a subject which has been under investigation during the past year by Messrs. E. B. Paine and H. E. Gough, graduate students under my direction at the Worcester Polytechnic Institute.

Their thesis on "High Potential Discharges in Dielectrics" involved the construction of a 150,000-volt transformer of 20-K.W. capacity, which is interesting in that with a *single* transformer a ratio of 1 : 1500 was secured, and the transformer has been operated to potentials above 170,000 volts without failure.

The transformer was operated from the secondary circuit of a bank of smaller transformers, the potential of which was varied as desired from a small value to as high as 115 volts. The primaries of the smaller transformers were supplied with current from a 30 K. W. Westinghouse smooth core alternator, giving practically a sine wave of E. M. F. at a frequency of 133 cycles. The accompanying cut shows the construction of this transformer which was immersed in a tank of kerosene oil, preliminary experiments proving the value of this oil under the given conditions.

The investigation of various dielectrics included a series of tests on the dielectric strength of air, and, while not as complete for this dielectric as those of Mr. Steinmetz, are of value in this connection as they entirely corroborate his results by an entirely independent investigation under nearly the same conditions as to methods of experimentation and apparatus used. There is no occasion to repeat the tabulation of our tests with sharp points



No. 1.—150,000-Volt Transformer.

No. 2.—Eighteen Inch Discharge.

No. 3.—Thirty-one Inch Discharge on String.

No. 4.—The Breaking Down of a High Potential Insulator at 90,000-Volts, Showing Material Ejected from Point of Rupture.

and spheres of small radius, as they would add nothing to results given by Mr. Steinmetz further than to add data agreeing almost exactly with that obtained by him.

Our results show a corresponding constancy and reliability of length of spark gap as a measure of high potentials.

A photograph is shown of a discharge between ¼" spherical terminals 18 inches apart which exhibits the same characteristics as those obtained by Mr. Steinmetz at shorter lengths.[1] This discharge took place at a virtual voltage of 167,000 volts, corresponding to a maximum potential of 236,000 volts, and required at the transformer about fifty horse-power during its existence.

A discharge along a moistened string 31 inches long and the breaking down of a high potential porcelain insulator at 90,000 volts are also shown.

HAROLD B. SMITH.

Worcester Polytechnic Institute, July 6th, 1898.

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[1] "Photographic Investigation of a 150,000 Volt Power Discharge" *Electrical World*, March 5, 1898.

ASSOCIATE MEMBERS ELECTED AND TRANSFERRED.

Elected at Executive Committee Meeting, New York, June 24th, 1898.

Name.	Address.	Endorsed by.
ALLEN, WALTER CUMMINGS,	Inspector of Electric Lighting, Government of District of Columbia, District Building, Washington, D. C.	O. T. Crosby. J. B. Cahoon. W. G. Ely, Jr.
ARMSTRONG, ALBERT H.	Electrical Engineer, General Electric Co., Schenectady, N. Y.	C P. Steinmetz James Lyman. Jin Tachihara.
DAMON, GEO. A.	With B. J. Arnold, Electrical Engineer, 1541 Marquette Building, Chicago, Ill.	B. J. Arnold. Henry S. Carhart. R. B. Owens.
DEXTER, FRANK H.	Student, Cornell University, residence, 51 Huestis St., Ithaca, N. Y.	Fred'k Bedell Edw. L. Nichols. Ernest Merritt. H. J. Ryan.
DOWNING, P. M.	Supt. Electrical Dept. Blue Lakes Water Co., Blue Lakes City, via Jackson, Cala.	F. A. C. Perrine. F. V. T. Lee. T. E. Theberath.
LYONS, JOSEPH.	Patent Solicitor, with Gustav Bissing, 908 G. Street, Washington, D. C.	Edw. J. Houston. A. E. Kennelly. F. L. Freeman.

Total, 6.

TRANSFERRED TO MEMBERSHIP.

Approved by Board of Examiners, May 11th, 1898.

Thresher, Alfred A.	Electrical Engineer, and Proprietor, Thresher Electric Co., Dayton, O.
Jackson, William B.	New York and Staten Island Electric Co., West New Brighton, N. Y.
Lincoln, Paul M.	Electrical Superintendent Cataract Construction Co., Niagara Falls, N. Y.
Reid, Thorburn.	Consulting Electrical Engineer, 120 Liberty Street, New York City.
Gossler, Philip Green.	Electrical Engineer, Royal Electric Co., Montreal, P. Q.
Theberath, Theodore E.	Pacific Coast Engineer, Stanley Electric Co., San Francisco. Cal.
Pedersen, Frederick M.	Assistant Electrical Engineer, Crocker-Wheeler Electric Co., New York City.
Dunlap, Will K.	Electrical Engineer, Westinghouse E. and M. Co., Niagara Falls, N. Y.

Elected at Executive Committee Meeting, New York, July 27th, 1898.

Name.	Address.	Endorsed by.
Adams, Ernest K.	Graduate Student, Columbia University; residence, 455 Madison Ave., New York City.	F. B. Crocker. S.G.F. Townsend W. H. Freedman.
Martin, John	Agent, Stanley Electric M'f'g. Co. 300 California Street, San Francisco, Cal.	J. A. Lighthipe. F. F. Barbour. F. A. C. Perrine.
Meyer, Hans S.	Electrical Engineer, General Electric Co.; residence, Hotel Edison, Schenectady, N. Y.	C. P. Steinmetz. Eskil Berg. J. Tachihara.
Pearson, Fred'k J.	Supt. of Construction, Western Electric Co., 1510 Howard St., Omaha, Neb.	R. B. Owens. W. F. White. R. W. Pope.
Wordingham, Chas. H.	City Electrical Engineer, The Manchester Corporation Electric Light Station, Dickinson Street, Manchester, England.	W. H Preece. H. F. Parshall. E. Danielson. W. M. Mordey.

Total, 5.

A Paper presented at the 15th General Meeting of the American Institute of Electrical Engineers, Omaha, June 27, 1898, President Kennelly in the Chair.

TWO WIRE DISTRIBUTING SYSTEMS AND LAMPS, 200—240 VOLTS.

BY JOHN W. HOWELL.

Distributing systems, operating at 200—240 volts with simple two-wire circuits, first attracted attention about four or five years ago. These early plants used two 110—120-volt lamps in series and were installed as a means of competing in cost of installation with three-wire plants without resorting to the alternating current system, with its disadvantages where motors are operated.

The growth of these plants was slow until the demand created by them led to the production of the 200—240-volt lamp and practical experience had shown the weaknesses of these lamps and led the makers to overcome the difficulties met in their manufacture.

What these weaknesses were, can be judged by the following extracts from previously published articles:

"The consensus of opinion at the present day of the average types of high-voltage lamps undoubtedly points to the fact that a large percentage are expected to short-circuit as soon as they are put up, and I have heard several engineers say that they expect about one in twelve to go in this way."

"There is no doubt whatever that almost all the present day 200-volt lamps are only suitable for burning in a vertical position. As soon as any other position is adopted defects become prominent. The long thin filament soon drops onto the bulb and cracks it. Also electrostatic attractions, owing to higher voltage, cannot be resisted by the long thin filament, and this is an additional cause of the filament approaching the bulb.

The effect of electrostatic attractions on long thin filaments is even noticeable with lamps burning in a vertical position."

These are extracts from a paper read by Mr. G. Bingswanger Byng before the British *Institution of Electrical Engineers* on February 24th, 1898.

These defects have been entirely remedied, and the experience of many plants operating 200—240-volt lamps during the past year proves these lamps to be just as reliable in service as are 110-volt lamps. The development of the lamp has taken considerable time, and the growth of the 200—240-volt 2-wire system in spite of the shortcoming of the early lamp is due to compensating advantages in other elements of the system.

These advantages over the three wire system are—(1) cheapness of installation and (2)—simplicity of operation.

1.—Cheapness of installation of the 200—240-volt 2-wire system, when compared with the 110—120-volt 3-wire system, arises from the use of a single large dynamo where the three-wire system requires two, each having half the capacity; with the accompanying duplication of regulating apparatus, indicators ammeters, etc. There is also a saving of the entire cost of the neutral conductor of the 3-wire system, which conductor in street mains (as distinguished from feeders) and in house wiring, should be as large as the outside wires.

Three-wire plants in cities, whose business warrants the employment of the skill necessary to operate the system to best advantage, successfully use 110—120-volt 3.1 watts per candle lamps and get very excellent results from them. The 200—240-volt 2-wire system cannot be considered a competitor of the 3-wire system under these conditions since the best 200--240-volt lamp on the market to-day is a four watts per candle lamp. But it is my opinion that in smaller installations, whose conditions call for a 3.5 watts per candle lamp when a 110—120-volt 3-wire system is used, the advantages of the 2-wire 200—240 volt system are sufficient to offset the disadvantages of a 4 as compared with a 3.4 watts per candle lamp. Under normal conditions the performance of the present four watts per candle 200—240-volt lamp as regards life and maintenance of candle power is about 25 per cent. poorer than the present 3.5 watts per candle—110—120-volt lamp, but it is my opinion that the greater irregularities in pressure ordinarily found in the 3-wire plants we are now considering, as compared with the 2-wire plants operated under similar conditions, fully counteract, by their injurious effects upon the lamps, the advantage in life and candle power which the 110—120-volt 3.5 watts per candle lamp has under normal conditions over the 200—240-volt four watts per candle lamp.

In considering the relative advantages of the two systems, in the case of moderate sized plants above referred to, we must charge against the saving effected in a 2-wire plant by its single equipment and omission of the neutral conductor, the increased capacity of machinery and conductors made necessary by a four watts per candle as compared with a 3.5 watts per candle lamp.

Considering the copper required by a 220-volt 2-wire system using four W. P. C. lamps as our unit, the copper required by the two outside conductors of a 110-volt 3-wire system using 3.5 W .P. C. lamps will be .875. The amount to be added to this for the neutral conductor will vary somewhat with location of the station with reference to the points of consumption. If we assume that one half the copper is installed for feeders and one half for the distributing mains, and that the neutral wire is one third the size of the outside wire in feeders and the same size in mains, then the total copper in the neutral conductors of feeders and mains will be 29 per cent. of the amount used in the 2-wire 220-volt system, and the total copper used in the 110-volt 3-wire system will be 16 per cent. greater than the copper used in the 220-volt 2-wire system. This comparison of the costs of copper does not consider the cost of wiring customers' premises, which is usually borne by the customer; it is, however, an advantage to the 220-volt system that this wiring will require at least 20 per cent. more copper for the 3-wire 110-volt system than for the 220-volt 2-wire system.

The 4 W. P. C., as compared with the 3.5 W. P. C. lamp, would require for the 200—240-volt 2-wire system, one seventh greater capacity of boilers, engines and dynamos than would be required for the 3-wire 110—120-volt system.

The duplication of apparatus required for the 3-wire system will only partly offset this increased cost in the 2-wire 200—240-volt system, but the cost of this duplication of apparatus, together with the increased cost of copper required, will in many cases make the cost of installation of the 3-wire system at least equal to that of the 200—240-volt 2-wire system, leaving the simplicity of operation of the 2-wire system to be balanced against the increased cost of fuel required to operate 4 W. P. C., as compared with 3.5 W. P. C. lamps.

During the time the plant is operated considerably below its rated capacity, which will probably cover even the maximum load during the first year of the plant's existence, and all but three or four hours per day at all times, I think the increased fuel consumption due to 4 w. P. C. lamps will not be appreciable because of the poor efficiency of boilers and engines with light loads, and the total increased consumption of coal during the year will, I believe, be a small consideration under most circumstances, and in my opinion not enough to balance the simplicity of operation above noted.

A few months ago I made a trip through some of our central states, visiting a number of 200—240-volt plants to get a knowlledge of the practical workings of the systems from the persons actually operating them, hoping to get from their experience, information concerning existing conditions which would be of value in the lamp factory.

Naturally, my first questions to the man who operated the plant concerned the lamps; were they generally satisfactory? were they long lived? did they ever explode? I was greatly pleased with the answers I received. The lamps were reported to be almost universally satisfactory. They were very long lived, in fact too long lived, for better service would be rendered if the lamps were renewed when they began to get dull, and not allowed to remain in service after they ceased to give a first class light.

These 4 w. P. C. 200—240-volt lamps may be used for 600 hours and still give a good light, but I think this is about the limit of their useful life. If not taken in they will keep on burning for a long time and will give an average life of over double that figure before breaking.

The reports concerning exploding were equally satisfactory. For the past year or more, exploding lamps had been practically unknown; previous to that time, however, this had been one of the most serious objections to the system.

All these plants have been installed with switches, cut-outs, and other appliances made for 110—120-volt installations, and it is remarkable how little trouble has been caused by them.

Sockets.—Ordinary key sockets have been freely used and experience has shown the Edison screw socket and lamp base to be preferable to other types. Some engineers recommend keyless sockets and good snap switches, to avoid possible failure of the key socket to break the circuit.

In order to get the desired factor of safety, the General Electric Company has recently developed a special key socket for this work, having a break-gap twice as great as the sockets designed for 110—120-volt systems, and having a fibre insulating lining between the outside shell of the socket and the screw shell which is connected with the circuit. This fibre lining projects sufficiently beyond the screw shell to prevent contact with the circuit when the lamp is in the socket. The lamps are provided with short bases designed to be completely covered by this fibre lining, so it is impossible to get a shock by touching the lamp when it is burning.

Flexible Cord.—Flexible cord has been freely used, and is all right if the best quality is used. For this purpose the conductors should be covered with rubber $\frac{1}{32}''$ thick and the outside covering should be silk, or if cotton it should be slicked with a compound which makes it non-inflammable.

Rosettes.—Rosettes designed for 110—120-volt circuits having fuses, have given a good deal of trouble, so it has become good practice to leave out the fuse wire and put copper wire in its place thus having no fuse between the lamp and the fuse block close to the switch controlling the circuit.

The General Electric Company has produced a new porcelain rosette with fuse wires over one inch long, which have been severely tested with very satisfactory results. Their use with fuses will give protection to individual lamps, which is very desirable, as it increases the safety of the wiring.

Cut-outs.—Fusible cut-outs designed for 110—120-volts, have failed in many instances, and have often proved much more fusible than their makers expected them to be.

A complete line of fuse blocks carrying special 200—240-volt fuses has been developed recently by the General Electric Company. These are fitted with the cartridge type of fuse, the fuse being contained in a tube which is provided with brass terminals which fit in spring clips on the fuse block. The fuse wire is inside the tube and is soldered to the brass terminals. The tube is then filled with a plaster compound which smothers the arc formed when the fuse blows. These fuses have been severely tested with 500 volts, and currents many times their rated capacities, and have always opened the circuits without a flash.

Switches.—Standard knife switches or quick-acting snap-switches having large break distances, should be used. Such switches specially designed for 200—240-volt installations are now being developed.

Wiring.—Standard methods of wiring for 110—120-volts are approved for 220—240-volts. Good rubber covered wire run on porcelain knobs or cleats is specified by the fire underwriters.

Arc Lamps.—Good arc lamps burning two in series on 220-volt circuits are on the market. Each lamp is provided with an automatic cut-out which throws an equivalent resistance into the circuit when one lamp is extinguished, thus permitting the use of one lamp if desired.

Future.—The future of the 200—240-volt system depends largely upon the development of a more economical lamp. All other elements of the system can be made entirely satisfactory with the means and knowledge now at our command. but the production of a more economical lamp calls for an advance in the art of lamp manufacture. That this advance will be made and a more economical lamp will be produced, I have no doubt, and hope to see such a lamp placed upon the market at an early date.

DISCUSSION.

PROF. GEO. D. SHEPARDSON said that high-voltage systems should be planned with an ample reserve of generating machinery for the following reasons: First, that high-voltage lamps are of low economy, generally 4 watts per candle-power initial, and, on account of the difficulty of getting a sufficiently high resistance, are generally of large candle-power, starting at 18 or 20 and running up to perhaps 22 C. P., making a double increment of the load. The dynamos must, therefore, not only be 25 per cent. larger because of the inefficiency of the lamp, but about 20 per cent. more on account of the increased candle-power of the lamps. He thought that the disparity between the 110 and 220-volt lamps was likely to remain, since any improvement in the one would effect a similar improvement in the other. One reason for the comparative perfection of the 220-volt was the very difficulty in manufacturing, since only the best manufacturers could solve the problem at all, while anyone could make a 110-volt lamp. The illumination of 220-volt lamps is, as a rule, steadier than that from 110-volt lamps, since, with the same voltage regulation, the candle-power varies much less in lamps of the lower economy.

MR. H. H. HUMPHREY stated that the rate of improvement of the 220-volt lamp was much faster than that of the lower voltages, and that the difference between the two would, in his estimation, soon vanish. While one year ago it was difficult to get any guaranty or even promises from the lamp manufacturers, his company has lately ordered 10,000 lamps with guaranties nearly as good as can be obtained for 3.5 watt 110-volt lamps. The guaranteed life was just as high, but the drop in candle-power was allowed to be a little greater.

A Paper presented at the 15th General Meeting of the American Institute of Electrical Engineers, Omaha, June 27th, 1898, President Kennelly in the Chair.

A CAPILLARY ELECTROMETER FOR ELECTRICAL MEASUREMENTS.

BY CHARLES FREDERICK BURGESS.

Many of the measurements made in practical engineering work require the use of a sensitive electrical instrument, and owing to the demand for such an instrument the galvanometer has reached a high degree of perfection in some of the latest and improved forms. There is still much to be desired, however, in the way of portability, rapidity of reading, simplicity, cost, and freedom from the effects of mechanical vibration and varying magnetic field. There can scarcely be a call for an instrument of greater sensitiveness and accuracy than that which the galvanometer gives us when properly constructed and used, and in fact this sensitiveness might well be reduced in many cases if by so doing some of the disadvantages in its use might be overcome.

It is my purpose to call attention to the applicability of the capillary electrometer for practical electrical measurements, as a means of overcoming some of these defects. Although the principle upon which this instrument works was discovered about twenty years ago, its use has hardly extended beyond a very limited application in scientific research, and from some of the excellent properties which it holds as a measuring instrument, this seems to be a surprising fact.

This principle is the change of surface tension of two liquids which are in contact (preferably mercury and dilute sulphuric acid) in a capillary tube, and the meniscus which is formed as the separating surface moves, upon the application of a potential difference to the two liquids in question. It is the movement of this meniscus which corresponds to the movement of the galvanometer needle, in using it as a measuring instrument. I do not propose to enter upon a scientific discussion of the phenomena of surface tension, capillarity, and the change of surface tension under the influence of electrical potential which are here utilized, as this has been completely done in a number of scientific publications,[1] but will give a description of a certain form of this instrument and enumerate some of its principal characteristics.

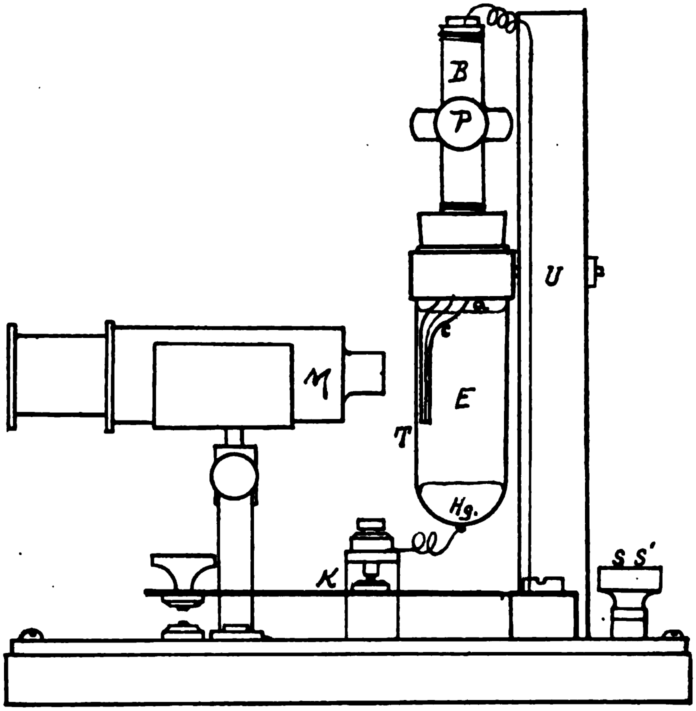

Fig. 1.

The only reasons for the comparatively limited use to which the capillary electrometer has been put, appear to be that it has not been made into a portable form, as glass and two liquids enter into its construction, and that great care is necessary to keep it in good condition. The form of instrument herein described was designed with the view of overcoming these objec-

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[1] The Capillary Electrometer, George J. Burch, Lond. *Electrician*, '96, "Lehrbuch der Allgemeinen Chemie."—Ostwald, Vol. II., p. 485.

tions. Fig. 1 illustrates the construction, T being a rather thick glass tube having a platinum wire sealed in the lower end. A layer of mercury covers the platinum wire, and the tube is nearly filled with the electrolyte E, which consists preferably of a dilute solution of sulphuric acid. A capillary tube C, made by drawing out a piece of thermometer tubing, rests against the side of the glass, and is held firmly in place by a tightly fitting rubber stopper inserted in the top of the large glass tube, enclosing an air space A above the electrolyte. A piece of flexible rubber tubing is fitted on the upper end of the capillary and wrapped tightly to prevent leakage. This tube, being filled with pure mercury is closed by a piece of glass into which platinum wire is sealed, and again wrapped tightly with copper wire. On compressing the pinch-cock P, mercury is forced through the capillary and upon slightly releasing the pressure the mercury is drawn back, being followed by the electrolyte. The instrument is then ready for use. A microscope M containing a micrometer eye-piece is held on an adjustable support, and is used for noting the movement of the meniscus. The glass tube is held firmly by a brass collar attached to an ebonite upright. Two binding posts, S, S, form the terminals of the instrument, K being the key which short-circuits it when not in use and connects the electrometer with the binding posts when depressed. The connecting wires are placed in grooves between the two parts of the base.

This instrument is one which may be tipped in any position without injury, it is as portable as any instrument made partly of glass can be, and it may readily be taken apart for the purpose of cleaning or renewing its parts. It will respond to a difference of potential of one one-thousandth of a volt, though with proper attention to its construction and by use of a suitable microscope its sensibility may be increased ten-fold or even greater. If a pressure over a volt is applied to the terminals an electrolytic action will occur, with the liberation of a bubble of gas or the formation of a cloudy precipitate at the meniscus, depending upon the polarity. This will destroy the sensibility, but the defect can be easily remedied by compressing the rubber tube until a drop of mercury flows through, and on releasing the pressure the instrument is again ready for use. The adjustment of the meniscus on the micrometer scale may be made either by moving the microscope or by means of the pinch-cock.

The direction of movement of the meniscus depends upon the polarity, and the extent is approximately proportional, through a limited range, to the potential. This is not absolutely so, for it would entail the use of a capillary of absolutely uniform bore, which would be difficult to attain. For this reason it is almost essential to use it as a zero instrument.

The meniscus moves, not by reason of a passage of current through the instrument, but by the application of a potential difference which gives it a certain electrostatic charge. In other words, it may be said to be a condenser which automatically registers the amount of charge which it holds. An addition of resistance in circuit will in no wise decrease its degree of sensitiveness, though it will make the movement of the meniscus somewhat slower. With the instrument described, an application of a pressure of .005 volt produced a deflection of eight divisions on the scale whether this pressure was applied direct or through a resistance of 100,000 ohms.

On pressing the electrometer key the meniscus may move very rapidly if a potential difference exists at terminals, and again on closing the short-circuit key it will quickly return to its zero point without vibration. It may be subjected to almost any amount of mechanical vibration without moving the position of the meniscus on the scale.

The principal characteristics may be summed up as follows: The instrument is of very simple construction and can be made by any one fairly expert in glass manipulation. It is very light and compact, and requires little space for its operation. The instrument described weighs two pounds and occupies a space of 7″ x 5″ x 6″. In the way of portability little more can be desired. It may be quickly set up for use, requiring no leveling, and the adjustment may be rapidly made. No serious damage such as a burnout can occur by the accidental application of even a very high pressure. The breakage of any of its parts can be repaired with little trouble and at slight expense. One of these instruments has been in use for nearly a year and the only repairs necessary on it was in once refilling the rubber tube with mercury. The entire absence of the effect of mechanical vibration and varying magnetic field will especially recommend this instrument. On the other hand, it can hardly be made with the degree of sensitiveness which may be given the galvanometer, and it has to be used as a zero instrument.

Measurement of Insulation Resistance.—Having had occasion to measure the insulation resistance of a large number of samples of rubber covered wires in lengths of 500 feet, I attempted to make the measurements with a four-coil Thomson astatic galvanometer, using the well-known direct deflection method, and encountered all the difficulties which are attendant upon the measurement of such high resistances, and was unable to obtain satisfactory results, owing to the mechanical vibrations in the building in which the work was to be done, and to the constantly changing magnetic field produced by electric machinery operating in the room below. When trouble was not experienced from this last source, the movement of cars on an electric railway several hundred yards away caused a decided swing of the galvanometer needle. An improved and sensitive form of D'Arsonval galvanometer was then used, by means of which these influences were greatly reduced, though not entirely eliminated. The tendency of the suspension wire to take a set if the swing of the coil was somewhat large, made a frequent determination of zero necessary, and this, together with the length of time required for the mirror to come to rest made the measurement of a large number of resistances slow and tedious work.

To use a battery of chloride of silver cells for such measurements may well be objected to for testing insulated conductors, and especially those which are to be used on high-tension working, on account of the comparatively low electromotive force which is necessarily used, and the internal resistance of the cells which is a greatly varying quantity and may sometimes reach an enormous value. It is desirable in such measurements that the wire shall be tested under actual working conditions, and a pressure even greater than that for which it was designed is preferable. For this reason, a one K. W. dynamo to be operated at a pressure of 1,000 volts was obtained. This was belt-driven from a motor, and it operated at a fairly constant pressure, but upon attempting to employ the galvanometer for the measurement of the current flowing through the insulation, it was found that even the slight variations of pressure, combined with the electrostatic capacity of the cable under test, caused disturbing currents to flow through the galvanometer, thus preventing the needle from taking a steady deflection.

The attempt was then made to employ the capillary electrometer in place of the galvanometer, and the results obtained were so satisfactory that I feel justified in describing the method used and the results obtained. On account of the electrometer being a zero instrument, the direct deflection method cannot be used, and a compensation method is employed; the method of operating being as follows. Fig. 2 shows arrangement of connections for the test.

A known resistance R (preferably 1,000,000 ohms) is placed in series with the generator and the insulation to be measured. The electrometer C is employed in measuring the fall of potential across R by the compensation method of introducing a pressure in series with the electrometer which shall just neutralize the pressure across R. When this has been effected, the depression of the electrometer key will produce no movement of the meniscus. It is therefore necessary to have an electromotive force which may be varied at will. A convenient method of obtaining this pressure is the following:

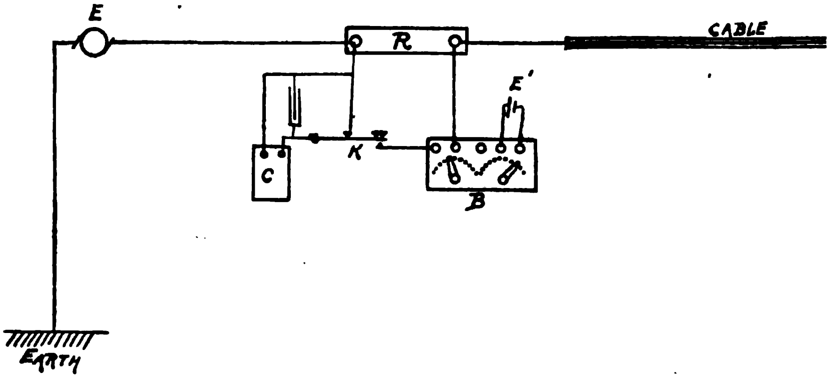

FIG. 2.

Fig. 3 represents plan of resistance box, the terminals of which are binding posts A, B, C, D, E. Between D and E are connected coils of german silver wire arranged in series, and giving a resistance of 1,000 ohms. This resistance is subdivided into nine 100-ohm coils and ten 10-ohm coils, the ends of which are connected to brass terminals and numbered as shown. Two brass arms which are connected with wires to binding posts A and B make contact with the resistance terminals. It is by noting the position of these arms that the pressure between A and B is determined, that pressure being the resistance included between the two arms X a constant pressure at terminals D E, ÷ 1,000. When the balancing pressure requires that the contact be made between the terminals of one of the ten-ohm coils, the resistance which would produce an exact balance, may be calculated by interpolation with a fraction of an ohm, this being done by noting the distance of movement of the meniscus of electrometer. A 9,000-ohm coil between C and D enables the pressure across D E to be one-tenth of the pressure of the battery or other sources of constant pressure connected to C and E.

The data necessary to derive the value of insulation resistance then is the value of the compensating E. M. F. which may be obtained directly from the reading of the box B when a balance has been effected. Any ordinary form of primary or secondary cell may be used for pressure E¹. The expression for insulation resistance is

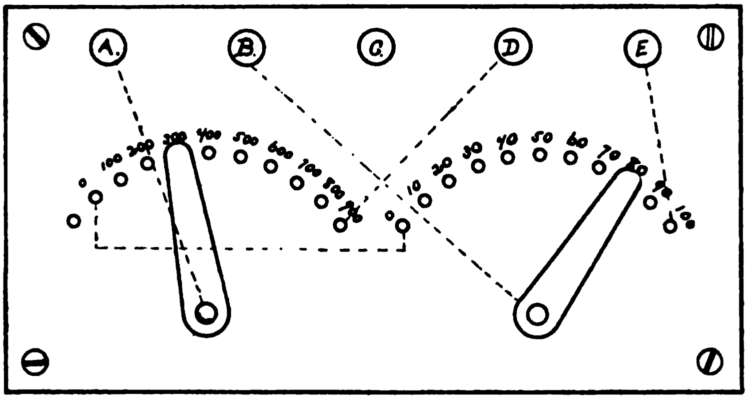

FIG. 3.

$$\text{Resistance} = \frac{E \times 1{,}000{,}000{,}000}{E^1 \times B} - 1{,}000{,}000.$$

The constant is 1,000,000,000 E/E¹, and the ratio E/E¹ may be derived by means of a voltmeter, or if such instrument is not available, by balancing the smaller pressure in circuit with the electrometer and terminal A B against the larger pressure connected to C E, the volume being 1,000 ÷ box reading.

When dynamo pressure is used for testing, the variations in current flowing through R caused by slight but rapid fluctuations of applied pressure and the electrostatic capacity of the cable, will produce a very rapid movement of the meniscus which will interfere seriously with its use unless suitable precautions are taken. The influence of this variable current upon the electrometer may be reduced to an unnoticeable amount by placing a condenser across the terminals of the electrometer. To effect this, however, a comparatively large condenser capacity is necessary, ten microfarads being used in the apparatus which I employed. The following arrangement proved much more satisfactory however than the ordinary form of condenser first used.

Fig. 4 shows an H tube of glass closed at the lower ends in which platinum wires are fused. These wires are covered with mercury and the tubes then nearly filled with an electrolyte, very dilute sulphuric acid being suitable. The platinum wires are connected to electrometer terminals and the appliance entirely absorbs the fluctuations which would otherwise cause violent movements of the meniscus. It will be seen that this is really a modified form of the electrometer in which the surfaces of contact of electrolyte with mercury is rather large. Using tubes .5″ in diameter a condenser of 100 microfarads capacity may readily be obtained. If this capacity is too great however, the movement of the meniscus in the capillary tube may be so slow as to consume considerable time in waiting for it to come to rest. The capacity may be varied by varying the amount of mercury surface exposed, or by changing the density of the electrolyte.

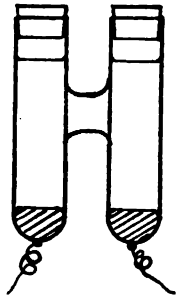

FIG 4.

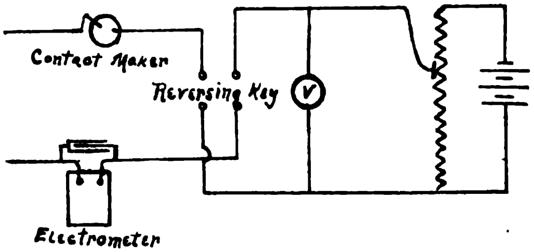

FIG. 5.

By such an arrangement the pressure from any ordinary direct current dynamo running at a reasonably constant voltage may be utilized in the testing of insulation resistances.

Values for insulation resistance may be obtained with considerable accuracy and speed, and values as high as 20,000 megohms have been measured. The limit may be made very much greater by increasing the sensitiveness of the electrometer or by increasing the value of R.

A portable testing set which I have been using for some time consists of the following parts:—Chloride of silver testing battery of about 50 volts; capillary electrometer with microscope and short-circuit key; graphite resistance of one megohm; thousand ohm subdivided resistance box; a 1.5-volt dry cell. The weight of set, exclusive of 50-volt battery is six lbs., the chloride of silver cells weighing 10.5 lbs. The range is from 0 to 5,000 megohms.

Measurement of Electromotive Force.—The electrometer with subdivided resistance box may be used for the measurement of direct pressures up to 150 volts with an accuracy of one-tenth of one per cent., provided resistance is accurate. The standard for comparison is the standard cell of known E. M. F. The pressure to be measured is placed across terminals D. E. if less than 15 volts and between C. E. if greater. The balance is effected with standard cell in series with electrometer and connected to terminals A. B.

As the cell in series with the electrometer is not called upon to furnish an appreciable current, this affords an excellent apparatus for electrolytic measurements such as polarization pressures and contact electromotive force set up between metals and electrolytes, where the passage of an appreciable current would cause a variation in the pressure. If the pressure to be measured is of such a nature, the voltage at D. E. must be known, which may be furnished by any of the ordinary forms of cells which will not polarize appreciably when connected through 1000 ohms.

Values of current may be obtained by the use of standard resistances of large current carrying capacity, the drop through such standard being measured by connecting it in electrometer circuit.

The calibration of direct current ammeters and voltmeters may be conveniently and rapidly carried out with the above arrangement.

This form of electrometer is especially suited for use in the dynamo room or in the neighborhood of moving machinery, on account of the small amount of space necessary for its operation, the rapidity with which measurements may be taken, and the entire freedom from external influences. It has been used to a considerable extent in the laboratories of the University of Wisconsin in obtaining current and pressure curves on alternating current machinery, and has proved satisfactory where other forms of measuring instruments had failed. The method of using this instrument for tracing alternating current curves is in substituting it for the galvanometer or the telephone receiver in the method proposed by Mershon[1], Fig. 5. It is superior to the telephone receiver from the fact that its readings depend upon the eye rather than the ear; the direction in which the slider must be moved to effect the balance can be detected immediately by noting the direction of movement of the meniscus; in addition, the telephone receiver is difficult to work with on account of the noise of belts and machinery and the induction which is set up when used in the neighborhood of alternating current apparatus. The degree of accuracy is considerably greater as is also the rapidity with which curves can be taken. For use in this work a microscope is unnecessary, and when the movement of the meniscus is too rapid and of a fluctuating nature due to unsteadiness of the compensating pressure or other causes, a condenser similar to the one described above may be used as a damper. A resisttance placed in series with the electrometer will also serve to increase the period of movement of the meniscus.

The above are some of the measurements in which the use of the electrometer has been tested, and the many advantages which have been found for it leads me to believe that it might be advantageously used in many other measurements in practical engineering work, especially in those where a great degree of sensitiveness is not required. In any of the modified forms of Wheatstone bridge methods for the measurement of resistance, induction and capacity it should prove a serviceable instrument. For use on shipboard it would be the ideal instrument as far as the rolling, and the jars due to moving machinery are concerned.

Another property of this instrument, and one which might be utilized to advantage, is the great rapidity with which the meniscus may move under a variation of pressure. It has been shown that alternating curves of a frequency of 120 per second may be obtained by a photographic record of the excursions of the meniscus, as well as the currents of much greater frequency which the telephone line transmits.[2]

In reply to an inquiry by Prof. Shepardson as to what extent inertia would enter in using the capillary electrometer for tracing alternating current waves, the author replied that the capillary electrometer may be made so that the effect of inertia of the mercury column, under the influence of an alternating pressure, will be inappreciable. This is well illustrated by the fact that Burch, in the work referred to, succeeded in reproducing the curve of a telephonic current having a frequency of about 600 alternations per second.

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[1] "Alternating Currents and Alt. Current Machinery," by D. C. and J. P. Jackson, p. 597.

[2] "The Capillary Electrometer," George J. Burch, Lond. *Electrician*, '96.

A paper presented at the 15th General Meeting of the American Institute of Electrical Engineers, Omaha, June 28th, 1898, President Kennelly in the Chair.

A MODERN ELECTRIC CENTRAL STATION.

BY GEORGE A. DAMON.

The plant of the Imperial Electric Light, Heat and Power Company, of St. Louis, Missouri, is interesting at this time, as it is a good example of the present tendency in electric power station practice.

The designers of this installation were not burdened at the outset with the complication of an old system of distribution, nor were they confronted with the necessity of adapting a new station to the use of generating machinery already on hand. Everything was to be modern, and the engineers in charge of the work were free to adopt the plans which seemed best suited to the existing conditions. The territory to be supplied with electrical energy was a down-town district, and the character of the load to be expected, included arc and incandescent lighting as required in stores, hotels, office buildings, and theatres, with more than the ordinary amount of motor work for elevators and light manufacturing establishments.

In planning an installation for a commercial enterprise of this character two conditions are imposed upon the designer. First, the service supplied the customer must be absolutely reliable. The earning capacity of the whole enterprise depends primarily upon the ability to furnish a continuous electric service, and any impairment or interruption would be a serious drawback to the success of the undertaking. After reliability has been secured, the second problem is to deliver to the customer electrical energy at the least possible cost, considering interest upon first investment, maintenance, and all other factors which enter into operating expenses. The engineering success of the enterprise, viewed from a commercial standpoint, will be measured in the proportion that the completed work meets these two requirements of maximum reliability and of economy, consistent with minimum investment.

The system which has been adopted as the one best fulfilling all the conditions in this particular case, involves the use of the direct current 220-volt incandescent lamp; the location of the station as near as possible to the center of distribution; the operation of generators capable of delivering current at a potential of 500 volts, a special arrangement of the generating units, and the installation of a storage battery in the plant to act as an accumulator, and also to operate in parallel with the generators as an equalizer. The generators are run at a potential enough greater than 440 volts to overcome the line loss, and the motor circuits are at present operated at this potential. The storage battery across the outside mains allows 220-volt incandescent lighting feeders to be distributed over the district.

It is not the purpose of this paper to discuss the 220-volt lamp question, any more than to indicate that the adoption of this lamp, after a careful investigation, for a central station of this size and importance, shows considerable faith in its possibilities. The greatly reduced investment required for copper distributing feeders for a 220-volt system from that required by the usual direct current 110-volt system, the enlargement therefore of the territory which could be supplied, as well as the better quality of light and the possibility of operating small 220-volt motors on the same circuits, were the main advantages which led to the adoption of the 220-volt lamp. The lower efficiency and the higher first cost of the lamp as compared with the 110-volt type was recognized, but these points are yielding to development, and it is thought that the difference between the two lamps in respect to efficiency and price is sure to become much less as the demand for the new lamp increases.

Local conditions made the location of the plant a much simpler problem than is usually the case. To have secured free water for condensation purposes would have removed the plant much too far from the center of distribution. The difference between drayage charges on the coal delivered to the station on its present site, and the cost of bridge tolls and switching charges which would have been necessary if the coal had been delivered directly from the cars, is only 15 cents per ton in favor of the latter plan, and this is not enough to justify the extra expense in feeders which would have been required to have located the plant on a railroad switch. No doubt, therefore, was entertained in regard to the advisability, in this particular case, of carrying the fuel of the plant in wagons from the railroad to the station at the center of supply, rather than transmitting the product of the plant over copper conductors the same distance.

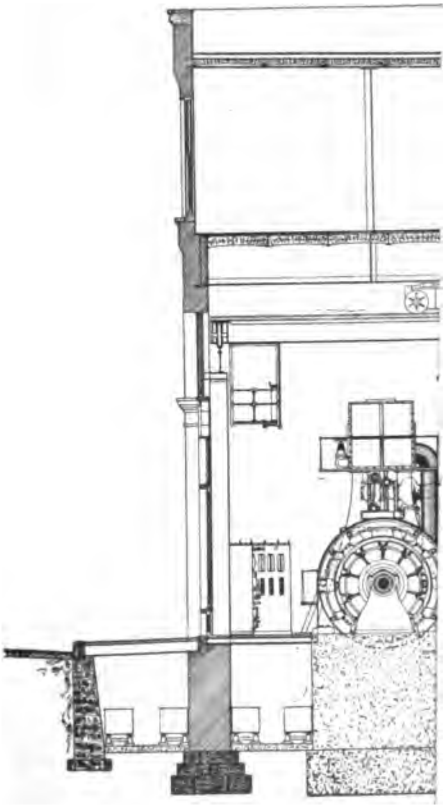
The advantages of supplying all classes of service from one type of generator, thus simplifying the distribution circuits as well as the arrangement of the station, and at the same time increasing the economy of the plant by reducing the amount of both fuel and labor required were not forgotten. At periods of light loads it is possible to furnish the entire output for incandescent lamps, arc lights and motors from one generator, while during the hours of minimum demand the load may be carried by the accumulator. The recent rapid progress of the storage battery in this country has been brought about only after a discussion which has made the economic advantages of a battery auxiliary in connection with a central station system, matters of common information, and therefore they need not be discussed at great length at this time.

The battery in this case is to be used in the ordinary manner. During periods of light loads it will accumulate a charge to be given out again at times of sudden demand, or in order to carry the plant over the peak of the load. The ability of a battery to respond immediately to unexpected demands, is one of the most advantageous features of an accumulator auxiliary. The necessity of carrying a sudden increase in the load arises continually in central station operation, and usually this condition requires that a reserve of boilers, engines and generators be held always in readiness under steam. Many central station managers keep a generating unit turning slowly over, ready to take its share of the load at a moment's notice, greatly increasing what may be called the "stand-by" losses of the plant, and thus sacrificing the economy of operation of the station to the integrity of its service. An accumulator of proper proportions will take care of these extra unexpected loads with much better fuel economy and at considerable saving in labor and worry.

The battery acts in the same manner in carrying the peak of the load. This peak usually extends over a period of from one to three hours. and in an ordinary plant the equipment which is necessary to supply the extra demand at this time, is inoperative during the remainder of the day. The interest on the investment, the fixed charges and the allowance for depreciation on this part of the plant are the same, whether the machinery is running for two hours or for the entire twenty-four hours of each day. The interest factor in the cost of producing the amount of energy required to carry the extra demand at the peak of the load, is thus greatly increased over the corresponding factor in the cost of the remaining average output of the station. Add to this the fact that the plant is necessarily working at low efficiency on account of a constantly varying load of short duration, and the effect of the peak of the load upon the earning capacity of the station may be appreciated. The storage battery auxiliary improves these unfavorable conditions, first, by evening up the load line, and thus increasing the efficiency of the generating plant, and second, by decreasing the total amount of investment required. The advantages of convenience and reliability of an accumulator in a central station cannot be questioned. Whether or not it will improve the efficiency or decrease the total amount of required investment in any particular case is influenced by local conditions, principally the character of the load line. In the plant being considered the peak of the load is expected to extend over a period of little more than one hour, which is a condition especially favorable to the use of a storage battery, though the "factor of safety" which the battery adds to the plant is an advantage of nearly sufficient importance to justify the investment.

Coming to the generating station proper, it is found that every precaution known to modern practice has been adopted to deliver at the switchboard as much as possible of the energy originally contained in the fuel. A central station is at its best a very wasteful institution, delivering to the distributing circuits, under its best working conditions, but from five to seven per cent. of the energy originally supplied to it from the fuel. Where the evident possibilities of increasing efficiency are so great, the study of the economics of a modern electric plant is an imporant one.

Fig. 1 shows a cross-section of the station and indicates the general compact arrangement of the plant equipment, which was made necessary on account of the cost of real estate in the vi-



cinity of the site. The engine-room and the boiler-room are upon the ground level, which arrangement ensures plenty of light, good ventilation, and convenience in operation. The engine-room basement is used for the storage batteries, while in the boiler-room basement is located the coal-storage bin, the ash-handling apparatus, the piping, pumps, hot-well and condenser. A second floor is added to the building for the offices of the company, for the storage of supplies and for a machine and repair shop.

The furnaces of the boiler are of the down-draft type, thus securing the advantage of skilful hand firing, and at the same time avoiding the cooling of the gases, by the frequent opening of the furnace doors. The water-cooled grates furnish some additional heating surface to the boiler and the general arrangement ensures a better combustion of fuel than is ordinarily obtained. This results in reducing the amount of ash and preventing the production of smoke, the latter feature being absolutely essential in a city installation. Considerations of availability and cost, limit the fuel supply to coal from Southern Illinois mines, which produce a bituminous slack containing about 11,000 B. T. U. per pound. As the wagons deliver the coal directly on the boiler-room floor, automatic coal-handling machinery was not thought to be a good investment.

Horizontal water tube boilers were adopted on account of their quick steaming properties, the comparatively small amount of floor space occupied by large capacities, their economy of fuel, and their safety under high steam pressures, the pressure adopted for this plant being 175 pounds. In determining the size of the boilers, due allowance was made for the fact that they were to be operated in conjunction with economizers, and their capacity was reduced accordingly. The question of economizers was thoroughly considered, and they were adopted only after careful estimates had been made, which demonstrated that the probable saving of fuel effected by their use would be sufficient to cover the usual allowance for depreciation, insurance, etc., and yet leave a very good margin for interest on the investment. As no steam-driven auxiliaries are used in the plant, there is consequently no other feed-water heater besides the economizer. The economizer for each battery of two 375 H. P. boilers consists of 320 pipes, and the heavy weight is carried on special iron framework which places the economizer at the back and above the boilers as shown in the figure. The flue passages, and stack connections, are so arranged and fitted with dampers that the flue gases can pass either directly to the stack, through the economizer to the stack, or in series through the mechanical draft fan and economizer.

A mechanical draft fan is now considered by many engineers, a necessary adjunct to a power station, and especially is this true if economizers are used, as in this case the flue gases escaping from the boilers can be robbed of nearly all their latent heat without impairing the draft. To the fact that a saving is thus effected in the usual large waste due to a chimney, the mechanical draft fan has the further advantage of furnishing a ready means of controlling the draft according to the load upon the plant, so that the boilers may be worked with comparative economy at light loads, or may be forced far beyond their rated capacity without too seriously affecting their economy. Unfortunately in this particular plant, the city ordinances required a stack which would carry the gases up above the surrounding buildings. For this purpose a steel chimney has been built, but it is a disadvantage rather than a benefit as far as the question of draft itself is concerned.

The engines are compound-condensing, and are the only steam using parts of the entire station equipment, all auxiliary apparatus being operated by means of electric motors. The steam thus passes directly from the boilers into the engines with a minimum amount of steam piping exposed for radiation losses. The steam from the engines exhausts into a surface condenser placed in the basement below the boiler-room, from which it is pumped into the hot-well and through the economizers back into the boilers.

The condensing water which flows through the tubes of the condenser is taken from the bottom of a cooling tower located upon the roof at an elevation of 50 feet above the condensing apparatus. After this water passes through the condenser it is forced back to the top of the cooling tower by means of centrifugal circulating pumps. The water circuit is arranged so that the weight of the descending column is used to balance the weight of the ascending column of water. The work actually required of the circulating pump, therefore, is represented by the amount of power required to raise the water through the height of the tower, or about 30 feet, and the net result is the same as if the tower had been located on the ground level.

The plans for the completed station contemplate a total capacity of 5,000 K. W. There are at present, however, installed in the station but two engines, one of 750 H. P. and the other of 1,500 H. P. capacity. These engines are of the cross-compound marine type of massive design and run at a speed of 150 R. P. M. They are expected to develop an indicated horse power hour on less than 14 pounds of water. Each engine is designed, however, to stand a continuous overload of 100 per cent. This will be developed by means of admitting high pressure steam directly into the low pressure cylinder. The conditions under which it is expected to operate the engines in this manner will be referred to later. The cylinders are placed side by side, each piston acting upon a separate crank. Between the cylinders is located the receiver which is provided with copper reheating coils. The high-pressure cylinder is steam-jacketed on the barrel, and both cylinders have a steam-jacket on the heads. Both receivers and cylinders are protected with a non-conducting covering over which there is a steel jacket held in place by bands. Each engine is provided with a heavy fly wheel located in the center of the frame between the cylinders. The throttle-valve is of the flanged lever type and is operated from the starting platform. The speed is regulated by a shaft governor operating an eccentric connected to the cut-off valves of the high-pressure cylinder, and in addition to this governor, each engine is provided with an additional automatic safety-valve, designed for the protection of the engine in case the speed should be abnormally increased for any reason. The engines also have a speeding device attachment by means of which they may be brought to the same rate of speed under frictional load as under full load.

The engines are directly connected to three 500 K. W. generators and two 50 K. W. boosters. These dynamos are of the multipolar type with ironclad bar wound armatures. Provision is made for sliding the field casting parallel with the shaft a sufficient distance to allow the field coils to be removed and the armatures reached for repairs. The brush holders are carried in a circular iron frame, arranged to be moved by means of a threaded rod and a hand-wheel, so that the position of the brushes may be adjusted. An additional hand-wheel is provided for lifting the brushes from the commutator.

The engines and generators are connected by means of the "Arnold System" This system of power station design is well known, but its application to this particular station will be of interest. The general idea of the system is to improve upon the usual direct-connected unit principle by mounting each genertor in such a manner that it can be operated by more than one engine. Fig. 2 shows partly in cross-section and partly in elevation, the line of engines and generators as they will eventually appear as the output of the station is increased. Three engines are shown, the capacity of the center engine being 1,500 H. P. and double that of either end engine. Each of the four large generators is rated at 500 K. W. while each of the small central dynamos, shown located between the larger machines, is a low-voltage booster of 50 K. W. capacity. The central engine therefore has a capacity sufficient to operate two of the generators when running at its most economical load, while either end engine is proportioned to supply but one generator with power under normal working conditions. The use of the boosters in this plant is incidental, and occurs at periods of light loads only, so that no additional engine capacity over that demanded by the main generators is required for their operation. Under all ordinary running conditions the units of this plant are manipulated as usual, an effort being made to vary with the load the number of engines running, so as to keep those in operation at any one time working as nearly as possible at their rated capacity. In this respect the operation of the plant follows general practice. In a station containing independently-direct-connected units, however, if any piece of the generating machinery gets out of order, it disables the entire unit and thus the commonly accepted principle which underlies the selection of the size and number of units for a direct-connected station is to have in reserve and always ready to be put into immediate service, engine and generator capacity sufficient to take the place of the largest single unit in operation. Thus, with a station containing five generating units of equal size, the station capacity which may be safely relied upon is the combined output of but four of the units, the fifth unit being either held in reserve or undergoing repairs. An additional investment of 25 per cent. in station equipment over that actually required by the demands of the service is necessary, therefore, in this case, in order to ensure reliability. Where less than five independent units are required, the percentage of the investment which may be charged up to the account of reliability is increased. Thus, with three units, the reserve is seen to require an investment of 50 per cent. over that actually needed by the demands of the service. It has already been pointed out that one of the greatest drawbacks to central station work is the amount of equipment which must be provided in order to take care of the

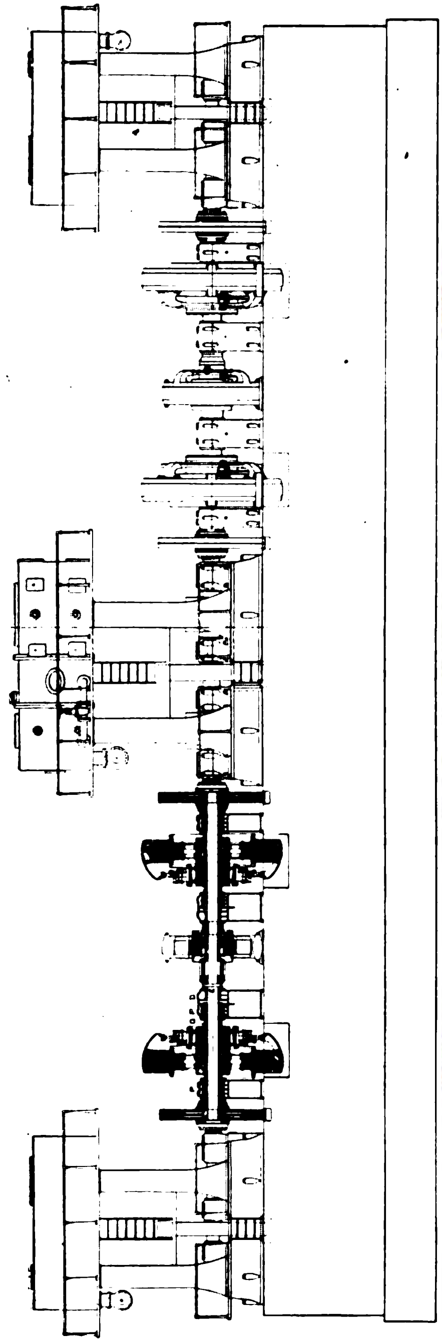


Fig. 2.—Arnold System.

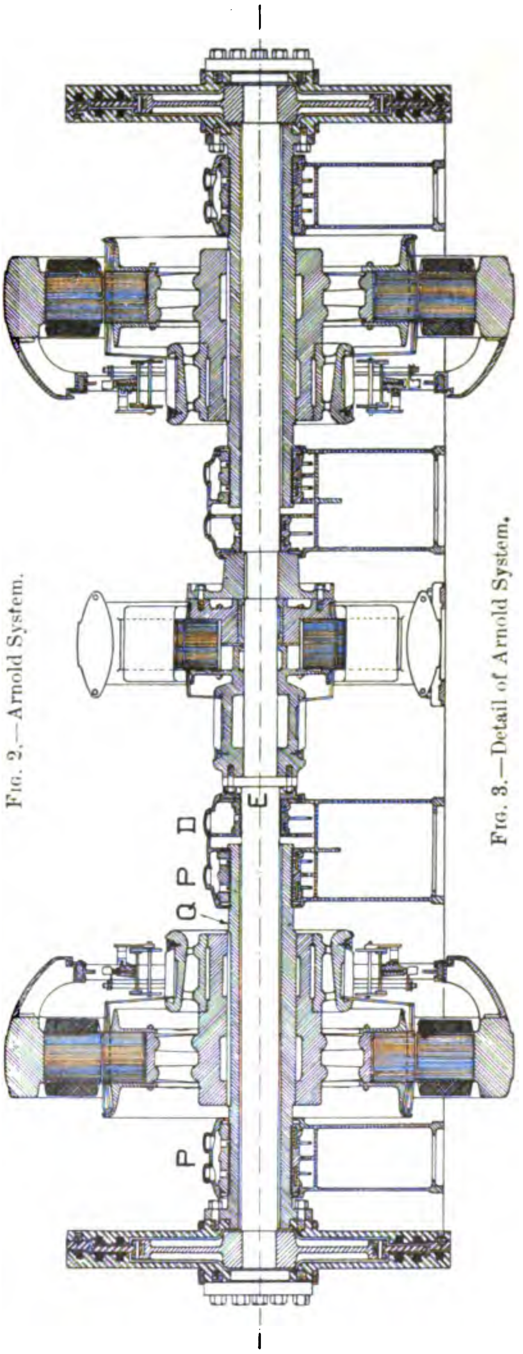


Fig. 3.—Detail of Arnold System.

occasional maximum demand. When to this burden is added an additional investment of from 25 to 50 per cent. in order to secure reliability, it is easily seen that the earning capacity of the station may be seriously affected. One of the advantages of the "Arnold system" of power-station construction is that the extra reserve unit is not required. Each generator is not rigidly connected to its corresponding engine but is mounted in such a manner that it may be operated by more than one prime mover. Thus in Fig. 2, the central engine may run either one or all four of the generators as well as the two boosters, while the smaller end engines can reach either or both of two generators and also one booster.

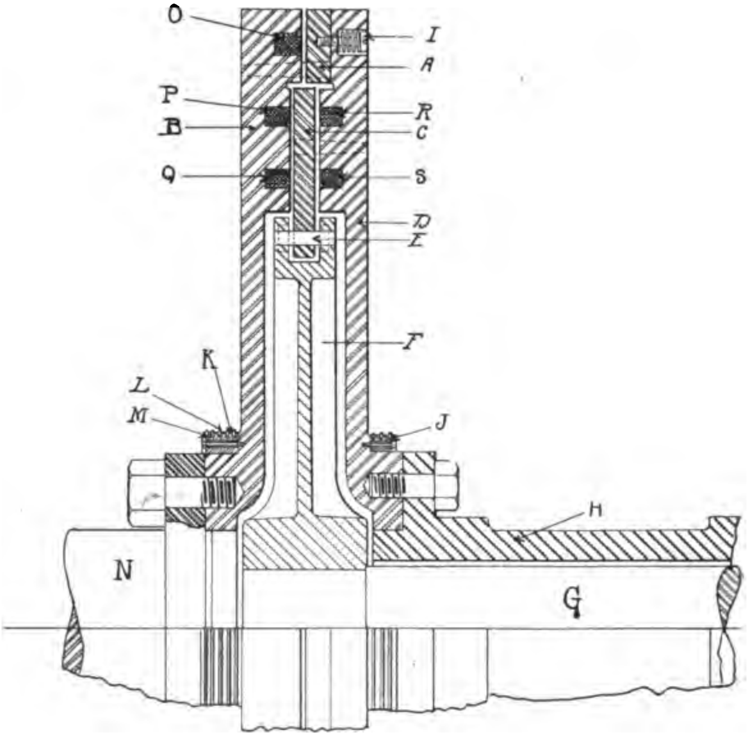


FIG. 4.—Detail of Magnetic Clutch.

The method of mounting and connecting the dynamos which makes this flexible arrangement possible is shown more clearly by Fig. 3. Each generator armature is mounted on a hollow shaft or quill Q, which is carried independently in the bearings P P. The booster armature is attached to the solid shaft E. This shaft is made of forged steel and extends through the hollow generator quills but without touching them, so that it is free to revolve in the bearings D. It is by means of this shaft that any engine can reach the generators not contiguous to it, but under all normal operating conditions, this shaft does not turn, so that this system of connecting involves no more friction and requires no more lubrication than the ordinary arrangement. The coupling on the end of the shaft permits of three combinations: the engine may be directly connected with the quill of the adjacent generator allowing the interior shaft to remain idle; or the solid shaft may be attached to either the engine flange or to the generator quill, the latter two combinations allowing the transfer of power peculiar to this system.

The coupling or clutch is of particular interest as it is said to be the first magnetic clutch applied upon a large scale to power station work. Fig. 4 shows a cross-section detail of this clutch. One part, B, is bolted to the engine flange, N. A corresponding part, D, is bolted to the generator quill, H, and this part carries an annular armature, A. Radial arms F, keyed to the solid shaft O, carry an interior armature C. Each coupling is provided with five circular coils of magnet wire O. P, Q, R and S. These coils are electrically connected to contact rings J, K and L, carried on insulating bushings bolted to the hubs of the clutch. Stationary brushes which are connected through a system of switches to the storage battery omnibus bars make it possible to send a current around any coil. The parts of the clutch containing the coils are made of cast-steel of high permeability so that when a current is sent around any coil, the surrounding metal becomes a magnet and the armature facing the coil is immediately magnetically attracted. The two surfaces of the clutch parts being held in contact by a pressure of at least 80 pounds per square inch, it becomes possible to transmit power from one to the other. Thus to connect engine shaft N to generator quill H, a current is sent through coil O in that part of the clutch B attached to the engine shaft. Armature A which is attached by means of strong studs to that part of the clutch B which is securely bolted to the generator quill, is immediately attracted and overcoming the small resistance of the spring I, the two parts become firmly attached to each other, making it possible to run the generator from the engine. If it is desired to revolve the interior shaft by means of the engine, the current is sent through coils P and Q in parallel, attracting armature C, while if the solid shaft is being turned by the other engine and it is desired to connect the shaft to the generator quill, then the coils R and S are energized and the armature O is attracted in the other direction. The circuits to these coils are all controlled by means of switches on the main switchboard. These switches are so arranged that when the circuit of any coil is broken, the discharge of the extra current is taken up through a carbon resistance, and the insulation of the coil is therefore protected from the liabitity to puncture. When the current in any coil is discontinued, spiral springs have been provided to overcome the residual magnetism and bring the armature back to its original position.

If both parts of the clutch which are to be connected are stationary, the connection becomes an easy matter, but if one part is revolving, it becomes necessary to put the other part in motion before the current is sent through the coils. This is accomplished by starting the dynamos as motors and bringing them up to speed before closing the magnet coil switch. For this purpose, regular starting-boxes have been installed, one for the boosters and the other for the generators, so that any machine may be thrown into or out of service directly from the switchboard. The result of the whole arrangement is, that a number of combinations between the engines and the generators becomes possible. Under all normal running conditions, the center engine will run its two adjacent generators and the outside engines will operate the end generators. Each booster may be run when necessary, from either of two engines. The entire line of machinery may be connected together, so that all the engines and generators operate in unison as one large unit, the speeding attachment on the engines making it possible to operate them satisfactorily in this manner.

In case of accident to any generator, that particular machine may be stopped without stopping its corresponding engine, and the electrical load will be immediately taken up by the other generators, but without overloading the engines. In case of accident to any engine, the ability of the other engines to carry an overload of 100 per cent. may be taken advantage of, if necessary, without overloading any of the generators. Thus the center engine is capable of carrying all four of the generators fully loaded while the smaller end engines can operate two of the generators, if necessary, in case of a break-down on the larger engine. The plant may, therefore, operate at period of maximum load, at its full rated capacity, depending entirely upon the advantages of the system of arrangement for a reserve in case of accident to any part of the equipment.

The flexibility and the reliability of the system may be compared to that of a belted plant and this has been secured without the use of an unsightly arrangement of belts or the complicated system of levers and pivots necessarily connected with mechanical clutches. The advantages of the belted plant have thus been combined with the advantages of economy and compactness of the direct-connected plant and many of the disadvantages of both arrangements have been eliminated.

All the variable speed motors operating the auxiliary equipment of the plant are designed to run at two voltages, the maximum being 440 volts, and the other voltage being one-half the maximum. Further speed regulation is obtained by changing the field excitation by means of a small resistance in the field circuits. The use of armature resistance is thus entirely done away with. A switchboard containing the switches and controlling apparatus for the pumps and fan motors has been placed conveniently in the boiler-room and another auxiliary board has been placed in the engine-room to control the circulating pump and cooling-tower motors as well as the circuit leading to the crane which spans the engine-room. The use of economically controlled electric motors for running the pumps, fans and other auxiliaries of the plant is expected to result in a considerable saving of fuel.

The storage battery is located in the basement and has a capacity of 2,000 ampere-hours at the normal rate of discharge, but is capable of standing a discharge at the rate of 500 K. W. for one hour. The station, therefore, as it now stands, can carry a maximum of 2,000 K. W., three quarters of which can be taken care of by the generators, and the remaining quarter being supplied by the battery. The battery consists of 280 cells, 100 of which are end or regulating cells, by means of which the potential may be varied, the voltage depending, of course, upon the number of cells in circuit.

Fig. 5 shows a diagram of the electrical connections of the station. The generators are compound-wound, but are so designed that they will give a potential of 500 volts with shunt excitation only, as it is desirable when operating with storage batteries to run the generators as shunt dynamos. An extra switch has been added therefore to each generator panel which is used to cut out the series winding and connect the equalizer lead directly to to the positive omnibus bar. Referring to the diagram: when switches 6 and 8 are closed, and 7 and 9 are open, the generator

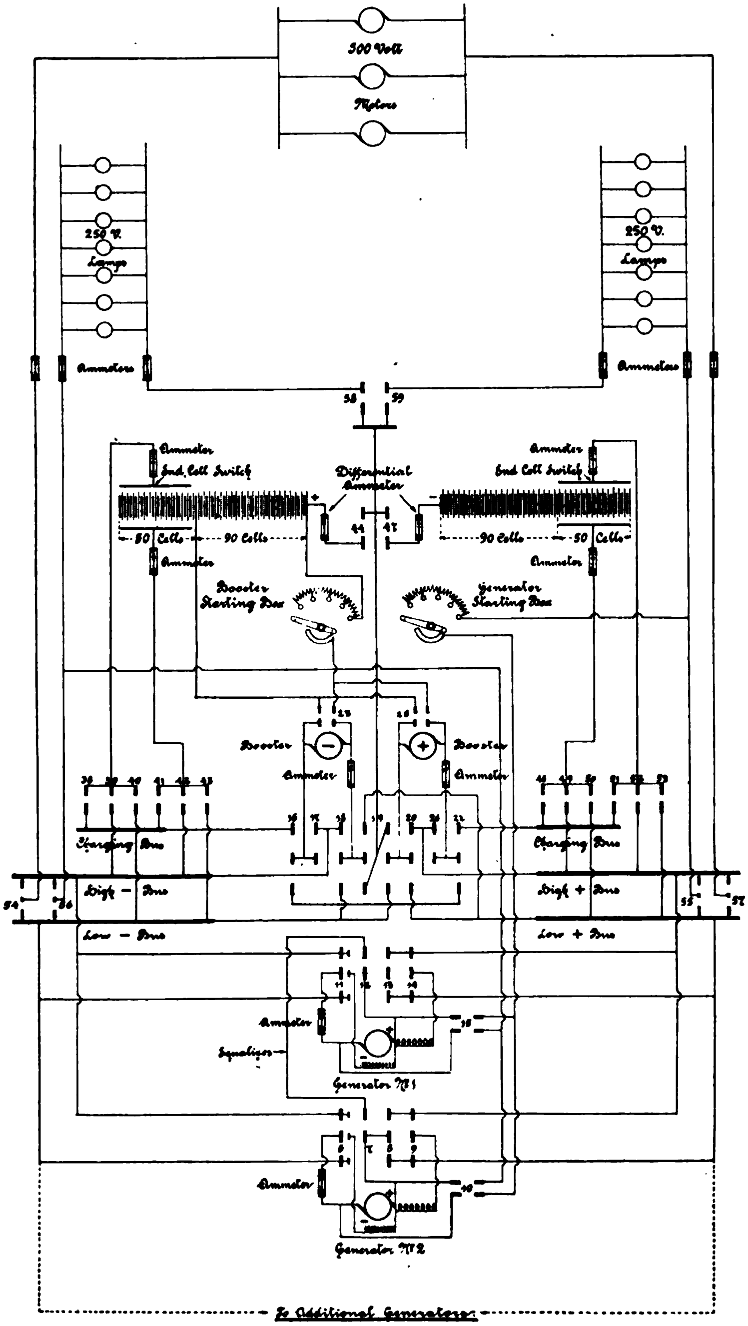

500 Volt
Motors
250 V.
Lamps
250 V.
Lamps
Ammeters
Ammeters
58
59
Ammeter
End Cell Switch
Differential Ammeter
Ammeter
End Cell Switch
50 Cells
90 Cells
90 Cells
50 Cells
Ammeter
Ammeter
44
47
Booster Starting Box
Generator Starting Box
Booster
Booster
Ammeter
Ammeter
Charging Bus
Charging Bus
High − Bus
High + Bus
Low − Bus
Low + Bus
54
56
55
57
Ammeter
Equalizer
Generator No 1
Ammeter
Generator No 2
To Additional Generators

FIG. 5.

is running as a straight shunt machine, while with 6 and 9 closed, but with 8 open, the dynamo is connected to the omnibus bars as a compound generator, and may be thrown in multiple with the other dynamos of the plant by closing equalizing switch 7.

When starting up a dynamo, the shunt fields are excited directly from the omnibus bars through a special field switch. When the generator is taken out of service, this field switch is automatically opened, leaving the field coils connected as in a shunt machine, and thus avoiding the discharge of the coils.

The switchboard is a double potential board so that the feeders extending to the outlying districts of the territory may be supplied with current at a higher potential than the shorter feeders. All switches on the generator and feeder panels are arranged so that when thrown up they connect with the high potential omnibus bars, and when thrown down, they connect with the low potential bars. All positive switches are placed on the right of the panels.

The battery is connected in two independent parts and is provided at each of the two outside ends with two end-cell switches. These end-cell switches may be connected through suitable knife switches to either the "high" or to the "low" omnibus bars or to a charging bar. Combinations of switches numbered on the diagram (Fig. 5) from 16 to 22, allow the boosters to be connected between either bar and also to the charging bar. The boosters in the plant are used to charge the batteries when it is desired to give them a heavier charge than they would ordinarily receive when working in parallel across the mains at the regular voltage. Without in any way interfering with the performance of the battery as an equalizer across the system, the boosters can be placed in series with the batteries and thus any amount of current can be forced through the cells. The condition for this operation occurs at periods of light demand upon the station, which is the time the battery can be most econominally charged. The voltage of the boosters ranges from 0 to 130 volts. The two boosters may be placed in series and can thus be substituted for either leg of the battery, allowing the replaced half of the battery to either accumulate an extra charge in case the two sides of the system have become so badly unbalanced as to have discharged one side of the battery excessively, or the replaced portion of the battery may be entirely cut out for repairs. In fact, the boosters may take the place of the entire battery if necessary, acting as an equalizer across one leg of the system, giving or taking current, as occasion requires.

The switchboard consists of eleven panels of black enamelled, polished slate. The three generator panels are each provided with the usual complement of switches, a rheostat, a cutting-in galvanometer, a circuit-breaker, an ammeter, and a voltmeter. One booster panel and two battery panels are necessary for the manipulation of the battery auxiliary. The battery panel is provided with hand-control wheels which connect to the end-cell switches so that the potential of the battery can be charged from the front of the board. It is also possible to operate each end-cell switch by means of a small motor directly attached to the switch spindle. This motor is controlled by a push button on the front of the battery board, and an indicator shows how many cells are in service at any time. Low-reading voltmeters and voltmeter switches allow the potential of the end cells to be ascertained conveniently from the front of the board. A wattmeter panel contains four station wattmeters which register the total output of the plant. Three feeder panels are at present employed to distribute the current, and these panels each contain six feeder-switches and six corresponding ammeters. A regulating voltmeter panel is located at the end, and at right angles to the rest of the board in a position where it can be easily seen by the switchboard attendant.

The design of this station has been described to show the latest solution worked out by conservative engineers of the problem of the generation and distribution of electrical energy. It is thought to be of interest because it presents a combination of the following widely discussed features of modern central station practice: (1) Improved furnaces; (2) Water-tube boilers; (3) Mechanical draft; (4) Fuel economizers; (5) Electrically-driven auxiliaries; (6) Cooling-tower condensing system; (7) Arnold system of power station construction; (8) Battery auxiliary; (9) Combined lighting and power distributing system; (10) 220-volt lamps.

DISCUSSION.

In answer to Prof. F. B. Crocker's criticism of the reduction of the necessary reserve capacity by the Arnold coupling system, Mr. B. J. Arnold explained that there is no such reduction in generators, but that the engines are so made that they can run at 100 per cent. overload by using live steam in both high and low-pressure cylinders, and the necessity of an engine reserve is thus done away with. This effect could not, of course, be obtained with ordinary direct-coupled units, as the generator would not stand the overload.

Replying to a criticism by Mr. Steinmetz on the difficulty of aligning such a long shaft, Mr. Arnold said that each shaft or quill is supported in but two bearings, and only when they are coupled together is there any likelihood of difficulty, and then but little, as the coupling arrangements give some radial flexibility.

In case of a hot bearing in the middle of the line, Mr. Arnold stated that the boxes are readily removable without disturbing the shaft and that they are all water jacketed.

A Paper presented at the 15th General Meeting of the American Institute of Electrical Engineers, Omaha, June 29, 1898, President Kennelly in the Chair.

SOME PHASES OF THE RAPID TRANSIT PROBLEM.

BY ALBERT H. ARMSTRONG.

The rapid transit problem, in congested districts, has to deal with the transportation of passengers at a high average speed with frequent stops, and even in suburban traffic where the stops are less frequent, the schedule speeds have been so increased by the ability of the electric motor to accelerate rapidly, that trains hardly reach full speed before it is necessary to apply the brakes. As running at a constant speed does not occur in rapid transit service where stops are at all frequent, it becomes of the greatest importance to carefully investigate the subject of train acceleration in order to determine the method of running a train from station to station with the least expenditure of energy.

Problems in train acceleration may be divided into two broad classes: 1.—Where the road is level and

2.—Where grades exist or where an artificial profile is made in order to take advantage of down grades at starting.

Modern passenger cars demand a dead weight of approximately 550 lbs. for each passenger carried, or, in other words, only 20 per cent. of the total weight of a loaded motor car is a paying load. When it is considered that in rapid transit service with frequent stops, over 80 per cent. of the total energy output of the motive power on level roads is required to accelerate the train, it is evident that in this class of service the rolling stock requires the greatest attention.

To avoid undue complication, the following discussion has assumed that train friction is a constant quantity at all speeds, as at the low maximum speeds—20 to 30 miles per hour— reached in practice with frequent stops of two or more per mile, the error introduced by assuming a constant friction rate will be small and will not at all alter the conclusions arrived at.

The following constants have been assumed as representing average operating conditions:

Length of run, 2000 feet.

Length of time train is in motion, 75 seconds.

Schedule speed, 16.05 miles per hour, including 10-second stops, or 85 seconds total time.

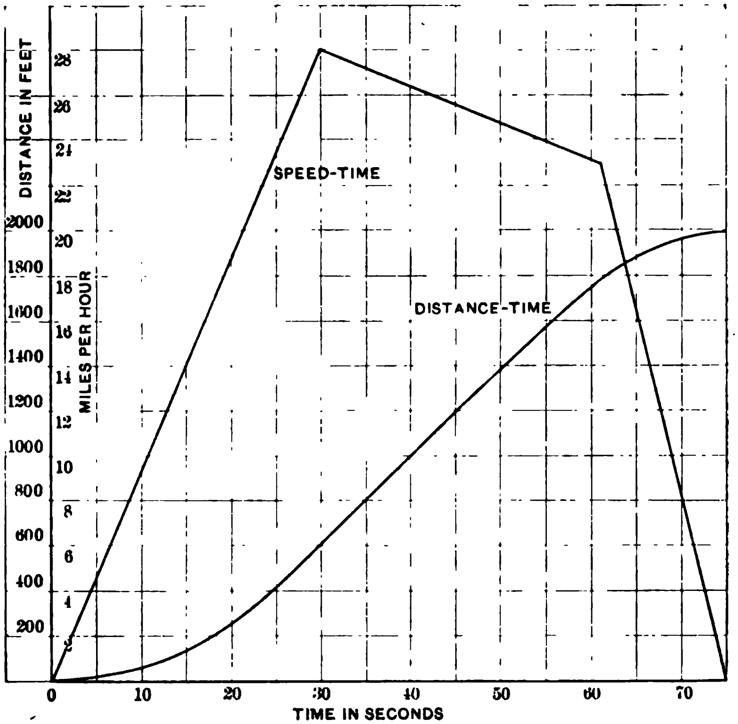


FIG. 1.—Acceleration Curves.
Distance, 2,000 feet. Time, 75 seconds. Tractive Effort, 100 lbs. per ton. Friction, 15 lbs. per ton. Braking Effort, 150 lbs. per ton.

Tractive effort, 100 lbs. per ton total, to be maintained uniform during acceleration of the train.

Braking effort, 150 lbs. per ton constant throughout the period of braking.

The train friction being 15 lbs. per ton, reduces the effective accelerating force from 100 to 85 lbs. per ton, corresponding to a rate of .927 miles per hour per second.

With this data a simple acceleration curve, as in Fig. 1., may be calculated, the train reaching a maximum speed of 28 miles per hour in 30 seconds, when power is shut off and the train allowed to coast with a retardation due to friction of .1635 miles per hour per second for 31 seconds to the braking line, when it is retarded at a uniform rate of 1.635 miles per hour per second and comes to rest in 75 seconds from time of starting.

Owing to the greater efficiency of the run, the train is allowed to coast after reaching its maximum speed rather than to allow it to continue at a uniform speed with just sufficient power supplied to overcome the train friction loss.

It is obvious that the train could be accelerated at a different rate than that corresponding to 85 lbs. per ton and still make the same length of run in the same time, the length of time occupied in coasting depending upon the rate of acceleration, being a maximum with an infinite rate, that is, with the train starting with a certain initial velocity. A minimum rate of acceleration is reached when no time is left for coasting, that is, when brakes are applied as soon as power is shut off.

In Fig. 2 such a set of curves has been prepared showing a train covering a distance of 2000 feet in 75 seconds, as before, but accelerating at various rates from that corresponding to 62.8 lbs. per ton as a minimum up to an infinite rate, or starting with an initial velocity of 25.2 miles per hour.

As the area enclosed by time as abscissæ and speed as ordinates represents the distance covered, this will be a constant quantity for the fixed distance of 2000 ft. assumed, and curves of Fig. 2 are thus constructed with the same enclosed area for each rate of acceleration. The fact is plainly brought out that with a low rate of acceleration a much higher maximum speed is demanded than would be the case if the rate had been increased, and a curve may be plotted by joining the maximum speeds reached for different accelerating rates, as shown.

A friction of 15 lbs. per ton has been chosen as being that of an average train composed of a motor car and three or four trailers and weighing about 120 tons. With heavier and longer trains this rate may be reduced to as low as 7 or 8 lbs. per ton, while for a motor car alone, the rate may be as high as 30 lbs. per ton, due to friction of motors and gearing. The braking effort of 150 lbs. per ton is also chosen as representing what can be done on an average by a train equipped with air brakes and operating at half the slipping coefficient of the wheels.

It is advisable in rapid transit service to keep the maximum speed reached by the trains as low as possible, as this class of work generally calls for a short time-interval between trains

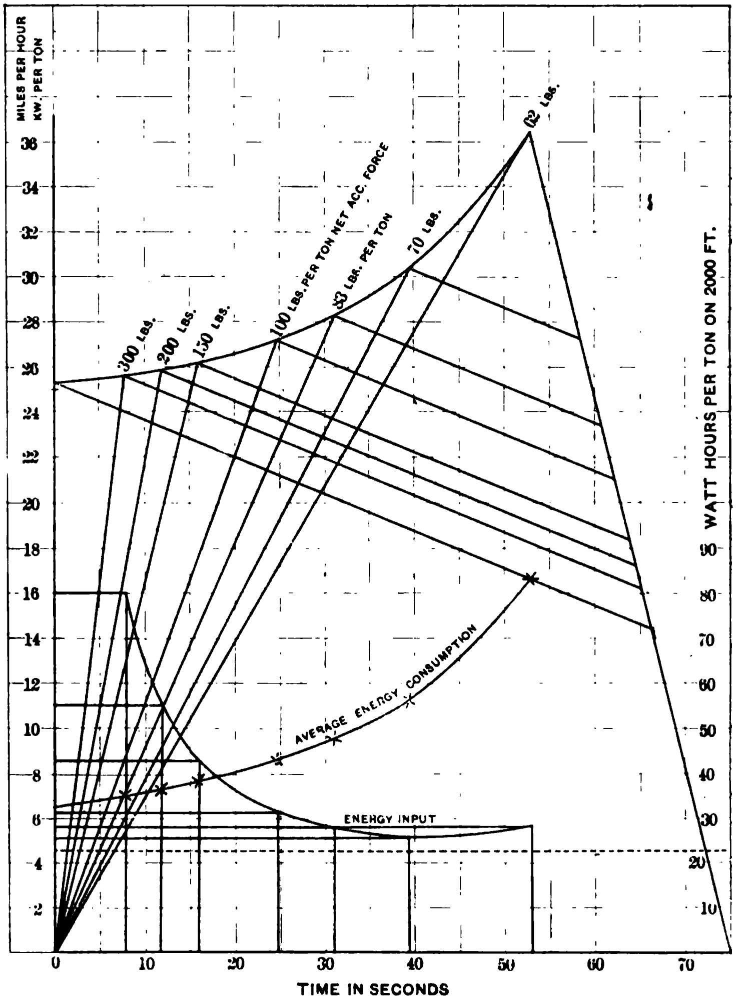


FIG. 2.—Speed and Energy Curves.
Distance, 2,000 feet. Time, 75 seconds. Friction, 15 lbs. per ton. Braking Effort, 150 lbs. per ton.

where the utmost precautions are necessary to keep the trains a safe distance apart. In fact, the maximum speed required for a given run practically determines the time-interval between trains, as the train headway should be at least five or six times the length of time required to bring a train to rest from its maximum speed with normal braking force applied.

A second reason for higher rates of acceleration lies in the fact that with rates of acceleration approaching the minimum no margin is left for errors of judgment of the motorman, as little or no time is left for coasting, and the rate of acceleration per ampere input is continually varying with the changing passenger load and hence with an overload it becomes difficult to maintain schedule speed.

A third and most important objection to the use of a low rate of acceleration lies in the saving of energy for the run by the use of a higher rate.

Neglecting $I^2 R$ and core losses of the motors, a set of energy input curves per ton weight of train may be plotted as in Fig. 2, assuming for simplicity that motors are series wound, operate all in multiple and are so geared that starting resistance is entirely cut out at the various maximum speeds reached in the various runs, that is, that no accelerating is done on the motor curve. A constant impressed E. M. F. is assumed, and starting resistance is supposed to be cut out proportional to the motor speed, thereby keeping the current and torque constant.

Thus it is seen that accelerating a train with the minimum rate calls for the highest maximum speed, demands nearly the least current input and also demands the greatest waste of energy in the brakes, as the speed is a maximum when brakes are applied.

The areas enclosed by the various energy time curves represent the comparative amounts of energy required for the run for the different rates of acceleration, and these are plotted in Fig. 2, which compares the energy input and the average energy consumption for the run of 2,000 feet in 75 seconds for all rates of acceleration from the minimum corresponding to 62.8 lbs. per ton up to infinity.

For convenience the average energy rates are plotted in terms of watt hours, and the curve shows that while the minimum rate of acceleration corresponding to 62.8 lbs. per ton calls for an expenditure of 83.5 watt hours per ton weight of train, this is reduced to 56.5 watt hours by accelerating with a rate corresponding to 70 lbs. per ton, to 42.7 watt hours with 100 lbs., and finally reaches a minimum value of 32.5 watt hours if the accelerating rate is pushed to infinity.

Thus the energy required for the run of 2,000 feet in 75 seconds may vary from 83.5 to 32.5 watt hours per ton of train weight, a decrease of over 60 per cent., depending upon the rate of acceleration used.

The curves in Fig. 2 are worthy of careful study, and similar curves afford a means of determining the proper rate of acceleration and hence motor equipment, gearing, etc., to use for a given set of conditions. The limiting factor in the more rapid rate of acceleration of a train is the current input required. Thus, if the rate of acceleration be carried to abnormally high values, the local demand for current becomes so great that either the loss in the feeders more than offsets the reduction in energy consumption at the train, or else the interest on the increased feeder investment is not offset by this energy reduction.

There are other limiting factors governing the rate of acceleration in the size and weight of motors, which are limited in the current they can carry without undue sparking and heating. Thus it will be found that the rate at which a train accelerates, largely determines the cost of feeders, size of motors and generators, both in regard to current and thermal capacity, and also fixes the safe headway between trains.

The error made in accelerating at or near the minimum rate is clearly brought out. For example, the current consumption per ton is the same for 62.8 lbs. per ton or 85 lbs. per ton; as, although 85 lbs. calls for the greater tractive effort, the torque per ampere is so increased by the lesser maximum speed demanded, that the current input is the same in each case, hence the feeder considerations are the same in both cases, while the energy consumption shows a reduction from 83.5 watt hours per ton with 62.8 lbs. to 47.5 watt hours, or about half, with 85 lbs. per ton.

Referring again to Fig. 2, it is obvious that a similar set of curves may be plotted for a run of 2,000 feet for any other length of time than 75 seconds, and Fig. 3 gives such a set of curves plotted for lengths of time ranging from 41 seconds, as a minimum possible, up to 210 seconds. The minimum time in which it is possible to make a run of given length is determined by the braking effort, in this case assumed to be 150 lbs. per ton, the train reaching a maximum speed of 66.5 miles per hour in zero seconds with an infinite accelerating force, and being retarded throughout the entire running time of 41 seconds at the rate of 1.635 miles per hour per second, corresponding to a force of 150 lbs. per ton braking effort.

The constants assumed in these curves are the same as before, 15 lbs. per ton friction rate, and 150 lbs. per ton braking effort applied uniformly until the train comes to rest at a distance of 2,000 feet from the start. While the braking effort determines the minimum length of time for the run, the friction rate imposes a limit upon the maximum rate of acceleration possible for

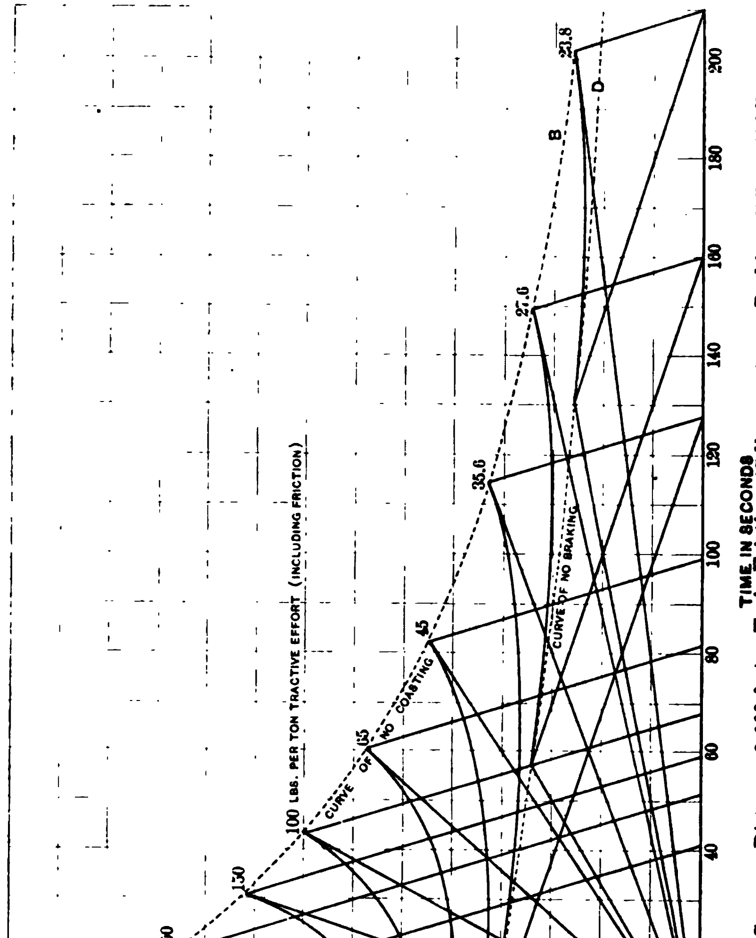


Fig. 3.—Speed Curves. Distance, 2,000 feet. Train Friction, 15 lbs. per ton. Braking Effort, 150 lbs. per ton.

lengths of time greater than 128 seconds for 2,000 feet run. That is, a train accelerating with an infinite rate and coasting the entire length of 2,000 feet would come to rest in 128 seconds with no energy loss in the brakes, and any longer interval of time occupied in the run would require some finite rate of acceleration at a maximum. This is pointed out in Fig. 3, where for a run in 210 seconds the maximum rate of acceleration possible is .175 miles per hour per second, corresponding to 24 lbs. per ton. No train in practice would require such a long time as 210 seconds, nor would it be possible to make a run of 2,000 feet in 41 seconds, but these curves have been carried out to show the limits for a given set of conditions.

As the energy lost in braking is proportional to the square of the speed when the brakes are applied, the curve A–B, Fig. 3, being the locus of the minimum rates of acceleration, that is, with no coasting, is thus the curve of maximum input for a run of 2,000 feet for any length of time. Also the curve C–D, being the locus of the various coasting lines, that is, of no braking effort, is thus the curve representing the minimum possible input.

To compare the amounts of energy required for rates of acceleration other than the maximum and minimum, a set of curves has been prepared in Fig. 4 giving the energy consumption for a run of 2,000 feet on a level track for any rate of acceleration and for any length of running time, the constants being 15 lbs. per ton friction rate and 150 lbs. per ton braking effort. For convenience in comparison, the energy consumption is reduced to watt hours per ton mile, and speed is expressed as average speed in miles per hour while train is in motion or equaling schedule speed if the train loses no time in stopping. The dotted curve A–B is the maximum energy curve corresponding to the curve A–B of minimum rates of acceleration in Fig. 3, and the curve C–D represents the minimum amount of energy possible for the different speeds and is described by an infinite rate of acceleration.

The curves of maximum and minimum energy consumption approach each other and coincide at a speed of 33.3 miles per hour, corresponding to an energy consumption of 298 watt hours per ton mile, this value being the greatest amount of energy that can be expended on the run with 150 lbs. per ton braking effort.

All energy values are net, that is, they represent the amount of energy required to accelerate the train plus energy lost in overcoming friction, and hence take no account of any losses occuring in actual operation in the motors, rheostats, gearing, etc.

Fig. 4 shows the economy resulting from properly proportioning the accelerating rate to the schedule speed and distance traveled. For example, a train accelerating with a tractive

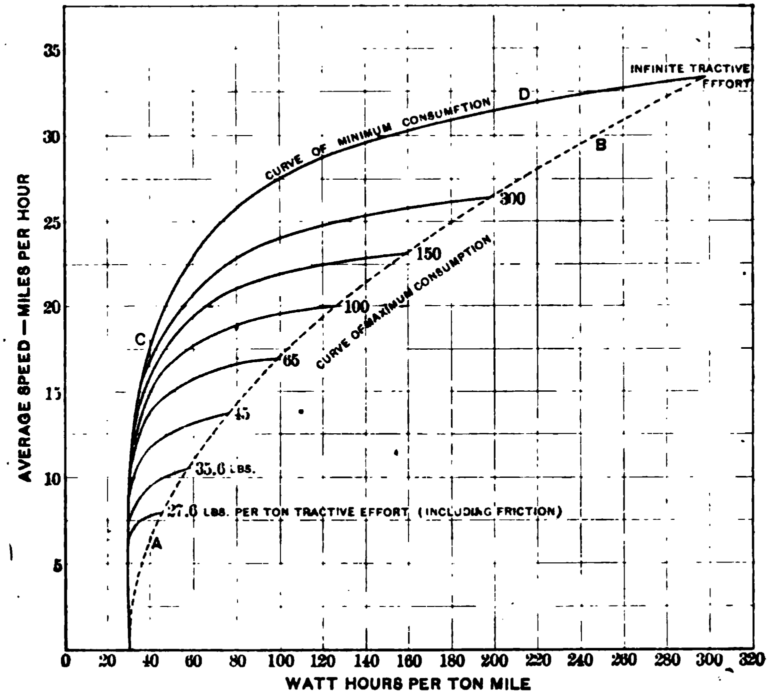


FIG. 4.—Speed-Energy Curves.
Distance, 2,000 feet. Friction, 15 lbs. per ton.

effort of 100 lbs. per ton and making 20 miles per hour average speed, not including stops, will require 127 watt hours per ton mile, which would be reduced to 65 watt hours per ton mile if the tractive effort had been increased to 150 lbs. per ton, or, in other words, the generator capacity would be but half as large for the same service.

The curve of 300 lbs. per ton tractive effort is interesting as it represents about the maximum speed attainable with modern apparatus for a distance of 2000 ft. with the assumed constants of friction and braking effort. Assuming the entire weight of the car to rest upon drivers, about 300 lbs. per ton would be available for traction without slipping the wheels on an average track, so that an average speed of 26½ miles per hour is the highest that could be obtained over a distance of 2000 ft., not allowing any time whatever for coasting.

All previous curves have been based upon the assumption that trains are allowed to coast after reaching maximum speed, and also that acceleration is carried on at a perfectly uniform rate until power is shut off, but in practice this assumption may be modified somewhat, the starting resistance being cut out before the maximum speed is reached, and the latter part of the acceleration carried on at a constantly decreasing rate upon the motor curve.

Another method would be to accelerate at a constant rate until maximum speed is reached, then continue this speed constant by supplying motors with just sufficient power to overcome train friction. This latter method of train acceleration, however, demands such a considerable increase in the amount of energy required for the run that it has not hitherto been considered.

The three methods of acceleration are illustrated in Fig. 5, showing the three forms of speed curves, *a–a* accelerating at a constant rate and coasting after maximum speed is reached until brakes are applied, *b–b* accelerating at a constant rate and continuing at full maximum speed until brakes are applied, and *c–c* accelerating at a constant rate until starting resistance is cut out and further acceleration allowed to continue at a constantly decreasing rate with constant full line potential at motor terminals until maximum speed is reached, when train coasts until brakes are applied.

Curve *a–a* reaches the highest maximum speed but wastes the least energy in the brakes, and hence is the most efficient run mechanically, curve *b–b*, the constant speed method, being the least efficient.

As these three curves were plotted from the speed torque curves of an actual motor, it is instructive to compare the watt hours consumed for each run with series parallel control, operating two motors in series, then in multiple. To this end a set of energy input curves have been plotted in Fig. 5, showing that curve *c–c* requires the least maximum energy input, while curve *a–a* requires the greatest amount.

The area enclosed by the energy time curves is a measure of the average energy consumption for each run, and their respective values reduced to watt hours are:

a. Constant current and coasting, 147 watt hours per ton,
b. Constant current and no coasting, 160 watt hours per ton.
c. Constant current and acceleration on motor curve, 126 watt hours per ton.

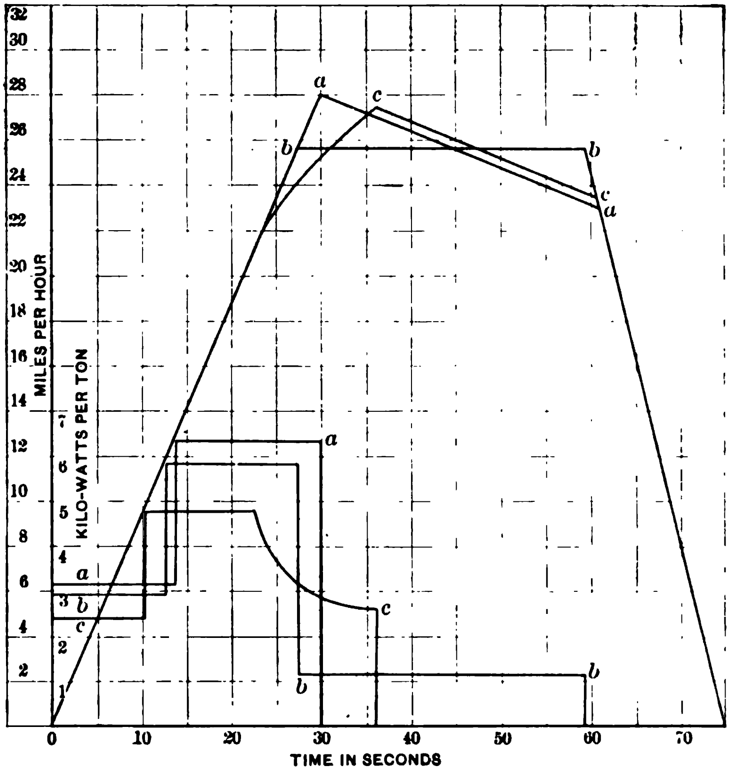


Fig. 5.—Speed Curves.
Distance, 2,000 feet. Time, 75 seconds. Friction, 15 lbs. per ton. Braking Effort, 150 lbs. per ton.

Hence, of the three methods, curve *c*, making use of the acceleration due to a series motor curve, not only requires the least maximum current input, but also requires the least average energy input to the motors for a given run and hence is the form of curve used in the majority of actual runs. Although the energy given out by the motors in run *c* is greater than in run *a*, as evidenced by the higher speed at which brakes are applied, yet this extra work is done so much more efficiently, owing to the smaller starting resistance loss, that the total watt hours input becomes less.

Whatever form of acceleration curve be used, the results arrived at in Fig. 4 will not be greatly modified if similar forms of curves are compared, and, being expressed in terms of actual work done, may be used for any run with a factor expressing the efficiency of acceleration: that is, the ratio of actual work done to the total energy input.

It will be noted that all curves of Fig. 4 approach a minimum value of 30 watt hours per ton mile, that is, the minimum energy expressed in watt hours per ton mile expended for a given run will be double the friction rate. The actual factor is 1.98 and forms a very convenient method of determining the net energy consumption for any speed and train weight if the friction rate be known. Thus, assuming the light load efficiency of a railway motor, including gear loss, to be 75 per cent., a friction rate of 15 lbs. per ton would demand an input of 40 watt hours per ton mile, corresponding to an input of 1200 watts per ton weight of train at, say, a constant speed of 30 miles per hour.

A number of interesting conclusions may be made from the foregoing investigation of the operation of trains upon a level track.

1st. The rate of acceleration determines the energy consumption for a given run, and since this energy consumption decreases with increased rate of acceleration, the train should be brought up to speed as quickly as possible and allowed to coast to secure the minimum energy input.

2nd. The maximum current input during acceleration increases with the rate of acceleration, and hence limits the rate at which a train can be accelerated with a given feeder loss or feeder investment.

3rd. In order to reduce the average energy consumption and also the maximum current input to a minimum for a given run, a due amount of acceleration should take place on the motor curve after starting resistance is cut out, hence a motor should be carefully proportioned for the work it has to do.

4th. A normal amount of coasting should be permitted after power is shut off, partly to provide a margin to allow for errors of judgment of the motorman, but largely because this is the most efficient method of accelerating a train. On no account should the maximum speed be continued by supplying the motors with just sufficient current to overcome train friction, as this method of accelerating is extremely wasteful and inefficient.

Having discussed various methods of accelerating, it is interesting to follow out the problem, and determine the actual efficiency of transporting passengers by our modern methods of travel. It has been pointed out that only from 15 to 20 per cent. of a fully loaded train consists of a paying load, and with an average load as carried throughout the day this percentage will be reduced to 10 per cent. or less, that is, nine-tenths of the energy consumed in moving this train at a constant speed is wasted. But in rapid transit work a train seldom attains a constant speed, due to the frequent stops and high schedule speed, and at least ten times the energy required to overcome friction alone must be expended in accelerating the train, only to appear as heat in the brake shoes when bringing the trains to rest. That is, considering the friction work of the train as the only useful work done, an efficiency of only 10 per cent. is reached in the average run. But only 10 per cent. of this friction work is useful in moving passengers, hence the actual passenger efficiency is reduced to less than one per cent. of the total energy delivered to the train during acceleration.

When it is considered that further losses occur in operation in the motors and their method of control, in the transmission lines and generators of an electric traction system, it will be appreciated that the present method of transportation, with its efficiency of a fraction of one per cent., opens a wide field for improvement. This applies with greater force to rapid transit service using steam locomotives as a motive power, as the dead weight carried per passenger is greater with a steam locomotive than with a motor car, and the efficiency from the coal pile is much less. Hence some means of reducing the large loss, due to accelerating the train is desirable, and this is found in the adoption of an artificial profile, as followed out in a large underground road now building, using down-grades in starting, and up-grades to retard the train when stopping.

The ideal profile would provide for a down-grade at starting sufficient to do the work of acceleration and with an up-grade to do the entire braking required, thus leaving only the friction energy to be supplied by the motive power. Such a road would operate at 100 per cent. efficiency, neglecting the dead weight of train carried and considering total friction work as useful work.

Reduced to practice, this ideal grade must be modified considerably. The per cent. grade used is limited partly by the rapidity of acceleration that may be imparted to the train without discomfort to the passengers and partly by the available tractive effort of the motive power, which must be sufficient to haul the train up the grade in case of necessity.

A second modification occurs in the necessity of having stations placed on a level track, and since a train has an appreciable length, it must travel its own length before the last car is off the level and the full effect of the grade is felt. Thus, during the first period of acceleration the rate is comparatively small and must be furnished by the motors, resulting in a material reduction in the energy gain in the theoretically ideal profile. An artificial profile can only be secured on elevated or underground roads, and a double track road necessitates two separate overhead structures and the underground road must consist of two separate tunnels with unlike profiles.

Assuming two stations to be on the same level, there are two forms of profile that may be assumed with a given maximum difference in levels, as shown in Fig. 6. Profile A consists of a down-grade with a level track at each terminus equal to the length of train operating over the road, while profile B consists of a down-grade and up-grade equal in length and percentage with a level track connecting them, and also a level track at each station equal to a train length.

In practice a perfectly symmetrical profile, as in B, will not be possible, as the level tract connecting grades must be replaced by a slight grade to provide for drainage in tunnel roads, this grade preferably opposing the direction of movement of the train.

In order to ascertain the behavior of a train upon the two forms of profiles and to determine the most efficient form of grade, a series of curves have been plotted upon the following assumptions:

Length of run total, 2,000 feet.

Train friction, 15 lbs. per ton constant.

Braking effort, 150 lbs. per ton during time brakes are set.

Running time, 75 seconds.

Length of train, 200 feet, corresponding to an average train of four to five cars.

Tractive effort, as supplied by motors, 100 lbs. per ton. (This effort being supplied irrespective of added effort due to grades.)

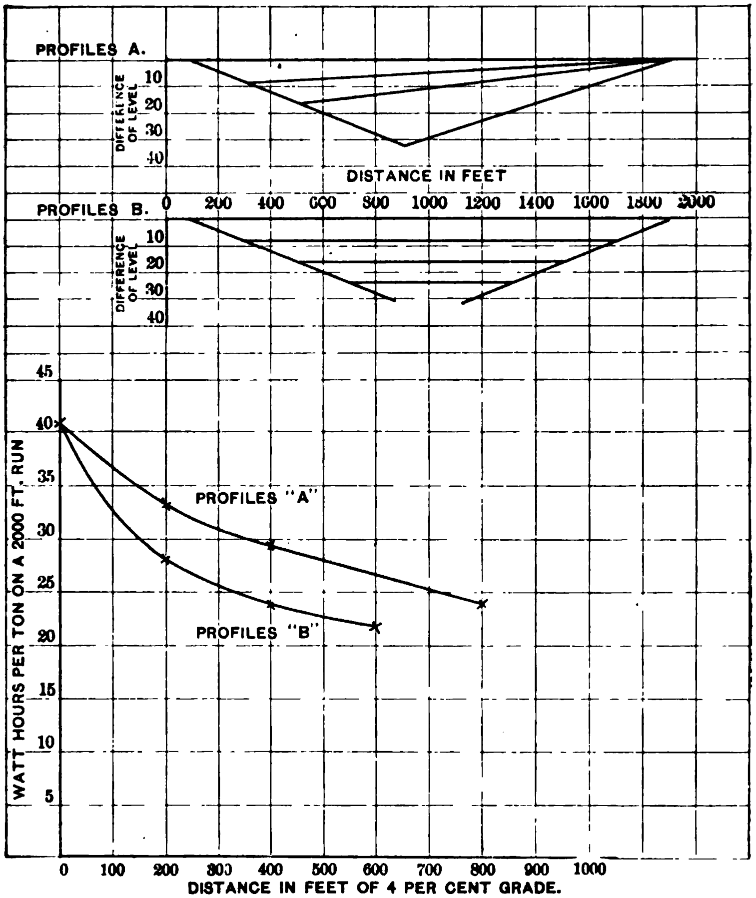


Fig. 6.—Energy Curves on Artificial Profile.
Distance, 2,000 feet. Time, 75 Seconds. Starting Grade of 4%. Tractive Effort of Motors, 100 lbs. per ton. Friction, 15 lbs. per ton, Braking Effort, 150 lbs. per ton.

No running is assumed to take place on the motor curve, and train is supposed to coast after reaching maximum speed.

Motors are controlled by the ordinary series-parallel method, starting with two motors in series and throwing them into multiple, the starting resistance being supposed to be cut out uniformly so that 100 lbs. per ton motor effort is maintained constant while current is on.

Due regard is paid to the fact that the tractive effort due to grade depends upon the proportional length of train off the level track at the stations, and hence is a constantly increasing quantity until the entire train is on grade.

A grade of four per cent. has been chosen for the down-grade in A, and for both down and up grades in B; and energy consumption plotted in Fig. 6 for different lengths of grade.

Thus for a run of 2000 feet in 75 seconds, the energy input with series parallel control is 40.75 watt hours per ton for a level track, which is reduced to 27.8 watt hours in curve A with a length of 500 feet, 4 per cent. grade and 22.6 watt hours per ton in C, with the same length of 4 per cent. grade, that is, with the same vertical fall.

A length of 500 feet of 4 per cent. grade calls for a vertical fall of 20 feet, which is not excessive in practice, hence by the use of a profile similar to B, Fig. 6, the energy consumption for a given run may be reduced as much as 40 to 50 per cent. from that required on a level track.

With proper proportioning of the gear ratio of the motor allowing some acceleration on the motor curve, this saving in energy consumption could even be exceeded, so that a rapid transit road, especially a tunnel road, properly laid out with an artificial profile, could operate with a very much less energy consumption than an existing surface road.

In conclusion it may be pointed out that the electric motor is eminently adapted to rapid transit service, owing to its ability to accelerate rapidly; and for tunnel work especially, it has no rival, adding to its high efficiency of operation and its perfect immunity from smoke and gases.

Schenectady, May 31, 1898.

A paper presented at the 15th General Meeting of the American Institute of Electrical Engineers, Omaha, June 29th, 1898. President Kennelly in the Chair.

POWER TRANSMISSION AND DISTRIBUTION FOR RAILWAY WORK.

BY ERNST J. BERG.

When electric power was first applied to railway work, the distances of transmission were comparatively short, so that one generating station usually located in the center of distribution was sufficient to furnish all power at a reasonable loss.

As the plants were extended it was soon evident that even disregarding the question of efficiency, the distances were very limited for commercial and practical reasons, and boosters connected in series with the line so as to raise the voltage proportional to the load were introduced. By their use it was possible to cover considerable distance and yet keep the potential up without too excessive an amount of copper. Since, however, any booster system must be very inefficient, such installations are not very common, and their field of usefulness limited to cases where considerable power is taken and at the end of a long line for a short time only. The next step towards extension was the introduction of power stations located in various places in the network, but the complication and inefficiency of such an arrangement was apparent, and the possibility of transmitting the power by alternating currents was brought out.

The first suggestion was to generate alternating current power in one station and transmit it at a reasonably high voltage to various sub-stations placed where the steam stations would have been located under former conditions, and there converting it to direct current by means of synchronous motors driving direct current generators. This method of transmitting and converting electrical power was applied in a few cases but was soon superseded by the converters which not only gave a simpler means of converting alternating current to direct current, but which are more

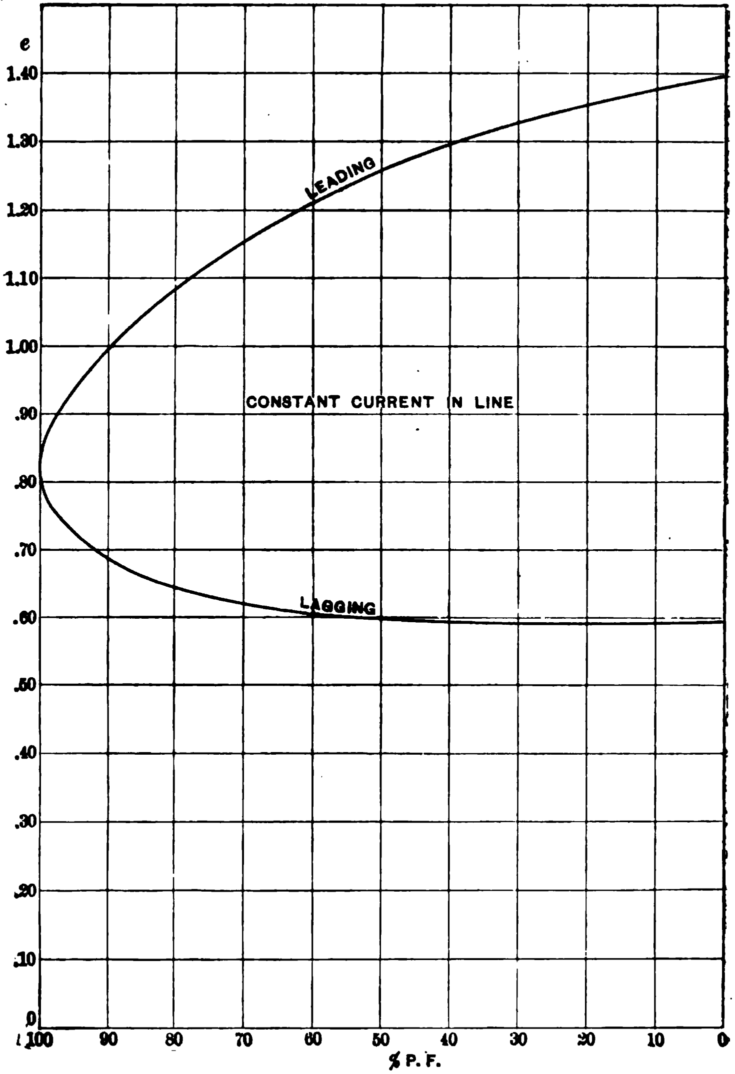


Fig. 1.—Curve Showing how the Generator Voltage Depends upon the Power Factor of the Receiving Circuit. Constant Line Current. Voltage at Receiving End of Transmission Assumed as 1. $Z = .1 - .4j$.

efficient and permit of automatic potential control. Thus in 1894 large and representative converter systems were installed.

Since, with the introduction of long distance transmission the generators were placed far away from the converters and connected to them by lines of considerable resistance and self-induction, it was apparent that potential control could hardly be effected in the power station, at least a control of sufficient sensitiveness to follow the greatly fluctuating loads in a railway circuit, the more so as the voltage does not vary in the same proportion as the load.

To illustrate the variation in voltage at the receiving end of a line of considerable resistance and reactance as function of the phase relation in the current, in Fig. 1 is plotted a curve giving as abscissæ the power factor of the load, that is cos ω and as ordinates the voltage at the receiving end. The line current is the same in all cases, the generator voltage is constant and assumed as unity, the resistance is 10 per cent. and reactance 40 per cent. The upper part of the curve gives the voltage with leading current, the lower with lagging current.

It is readily seen from this diagram how impossible it would be to control the potential at the generating station under these conditions, as, for instance, with a load of 90 per cent. power factor the voltage at the receiving end would be 69 per cent. of the generator voltage with lagging current, and the same as at the generator with leading current. Thus, if the generator should be controlled by the amount of current taken, it is evident that no indications whatever would be made by the current itself, since it is the same under these two conditions.

But even if a wattmeter were in the circuit at the power station, this would not help matters, since under the conditions referred to, the watts, that is the power, is the same, and yet the voltage so widely different.

In Fig. 2 this is demonstrated in a slightly different way. It is assumed that the voltage impressed upon the converter shall be constant at all loads, and shows how the generator voltage has to be varied in order to keep this constant at rated output with different power factors, and consequently at a variable line current. It is equally evident from this curve how unfeasible voltage control from the generating station would be.

It was therefore necessary to develop some means by which the potential could be controlled, not at the generator station, as is done in direct current railway circuits, but in the con-

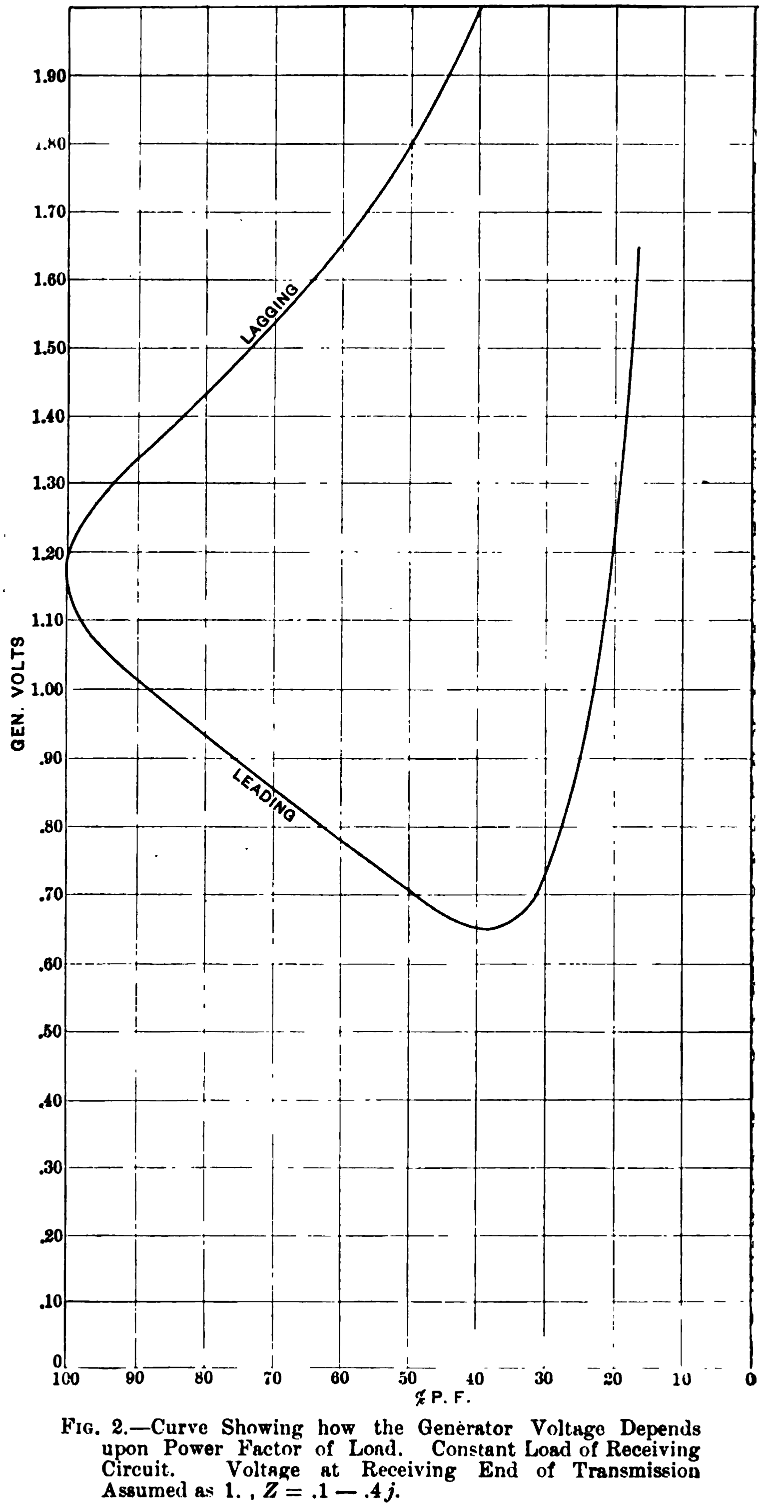


FIG. 2.—Curve Showing how the Generator Voltage Depends upon Power Factor of Load. Constant Load of Receiving Circuit. Voltage at Receiving End of Transmission Assumed as 1., $Z = .1 - .4j$.

verter station. This means of regulating the potential was found in changing the phase relation of the current taken by the converter by means of a change of field excitation, raising or lowering the impressed alternating voltage, and consequently the direct current voltage by means of this current passing through lines of considerable self-induction, or through special reactive coils inserted in the circuit.

In the following I shall endeavor to explain this method of control, and discuss its effects on the operation in general.

In a synchronous converter system we have to distinguish between three E. M. F's.; the impressed E. M. F., that is, the E. M. F. at the collector rings of the rotary converter; the counter E. M. F., which is the E. M. F. induced in the rotary converter by the armature revolving in the magnetic field, and consequently proportional to the field excitation; and the E. M. F. of impedance or the E. M. F. consumed by impedance, which is that caused by the current flowing through the reactance and resistance of the converter.

The first mentioned E. M. F., that is the impressed E. M. F., is entirely dependent upon the generator voltage; the counter E. M. F. is entirely dependent upon the field excitation of the converter, and is constant regardless of the load on a machine, and the E. M. F. consumed by the impedance changes with the load and is proportional to the current.

To explain the phase relations between these E. M. F's. let us for the sake of simplicity consider the converter running light or doing no work. Since the work done by a synchronous converter rotary is the product of the current taken by the rotary and the projection of the counter E. M. F. on this current at no load the current must be in quadrature, that is, at right angles to the counter E. M. F. Since, furthermore, the input of a rotary converter is expressed by the product of the impressed E. M. F. and the projection of the current on the impressed E. M. F. under the assumption that no energy is consumed. the current is also in quadrature or at right angles to the impressed E. M. F. Consequently the impressed E. M. F. and the counter E. M. F. must be in phase and in opposition to each other. Let, then, the field excitation of the converter be reduced, so that the counter E. M. F. is less than the impressed. Since only three E. M. F's. are acting in the system and their sum must always be zero, that is, the impressed E. M. F. must at any time be equal to the counter E.

$z = r - j\,x$ the total impedance between e_0 and e, that is the total impedance of transmission system and generator in the case of a generator with constant excitation, and the impepedance of the transmission line[1] if the generator voltage is constant.

We have the following equations:

$$e_0 = e + (i_1 + j\,i_2)\,(r - j\,x) \text{ or} \tag{A}$$

$$e_0{}^2 = (e + i_1\,r + i_2\,x)^2 + (i_1\,x - i_2\,r)^2 \tag{B}$$

At non-inductive load $i_2 = 0$

$$\text{therefore } e_0{}^2 = (i + i_1\,r)^2 + i_1{}^2x^2 \tag{C}$$

At no load $i_1 = 0$

$$\text{therefore } e_0{}^2 = (e + i_2\,x)^2 + i_2{}^2r^2 \tag{D}$$

Usually it is required that the converter voltage shall remain constant or increase with the load, when the generator voltage or excitation is kept constant. If each converter is operated from its own generator, it is preferable to leave the generator field excitation constant and thereby use the generator reactance for phase control and avoid any necessity of regulation in the generating station. If, however, many converters are operated from one generator, or if all generators in the power station are operated in multiple, it is preferable to keep the generator terminal voltage constant, and control the converter voltage by outside reactances in a low reactance transmission, or by the line reactance in a highly inductive transmission.

In either case equation B applies, if it is borne in mind that the impedance $Z = r - j\,x$ includes the generator in the first case and only refers to the transmission system between generator and converter in the latter. Furthermore, if it is desired to have overcompounding, that is, converters which increase their voltage with the load, the converter voltage e should be expressed by $e = e + p\,i_1$ where e is the no load E. M. F. and $p\,i_1$ gives the increase in E. M. F. at a load of i_1 amperes.

Thus the general equation of phase control becomes

$$e_0 = e + p\,i_1 + (i_1 + j\,i_2)\,(r - j\,x) \text{ or}$$

$$e_0{}^2 = (e + p\,i_1 + i_1\,r + i_2\,x)^2 + (i_1\,x - i_2\,r)^2 \tag{E}$$

where $p\,i_1$ is 0 in a rotary with constant voltage at all loads. As seen, the overcompounding enters the equation in essentially the same way as a resistance and can therefore in most problems be assumed as such.

---

[1] Including transformers and other intermediary apparatus.

Looking over equation A, we find that it is the relation of E. M. F.'s and currents in an alternating current transmission line, indeed, the usual equation for determining line drop, etc., and corresponds to equation $e_0 = e + i\,r$ in a direct current line.

Since a converter can be made to take leading or lagging current by changing its field excitation and thus its counter E. M. F., such an installation gives the most favorable opportunity to study the fundamental principles of alternating current.

It may perhaps seem as if it would be rather a delicate operation to accomplish this potential control in commercial circuits where available instruments, etc., would prohibit the determination of leading or lagging currents necessary for the control with any degree of accuracy, yet the problem is perfectly simple and resolves itself to adjusting the shunt excitation for a given running light current which is predetermined by calculation, and afterwards to adjust the series field so that the converter takes minimum current, that is, runs non-inductively at the desired load.

It will then follow that the potential control for all intermediate loads is perfect, at least within very close limits, as I shall show later.

The running light current is readily determined from equations (B) and (C).

Let $i_1 = i_n$ at non-inductive load where $i_2 = 0$

$i_2 = i_0$ running light where $i_1 = 0$

then $e_0 = (e + e_n\,r)^2 + i_n^2\,x^2$ which substituted in equation (C) gives $(e + i_n\,r)^2 + i_n^2\,x^2 = (e + i_0\,x)^2 + i_0^2\,r^2$ which solved in reference to i_0 the running light current gives

$$i_0 = \frac{e\,x}{z^2} + \sqrt{\frac{e^2\,x^2}{z^4} + i_n^2 + \frac{2\,e\,i_n\,r}{z^2}} \qquad \text{(F)}$$

denoting the converter voltage $e = 1$

The converter full load current $i_1 = 1$

and assuming the converter non-inductive at full load we get the equation of running light current.

$$i_0 = -\frac{x}{z^2} + \sqrt{\frac{x^2}{z^4} + 1 + \frac{2\,r}{z^2}}$$

The magnitude of this current is calculated and plotted in Fig. 4 for different conditions of resistance and reactance.

Curve *a* shows the conditions at 15% energy loss.
" *b* " " " 10% " "
" *c* " " " 5% " "

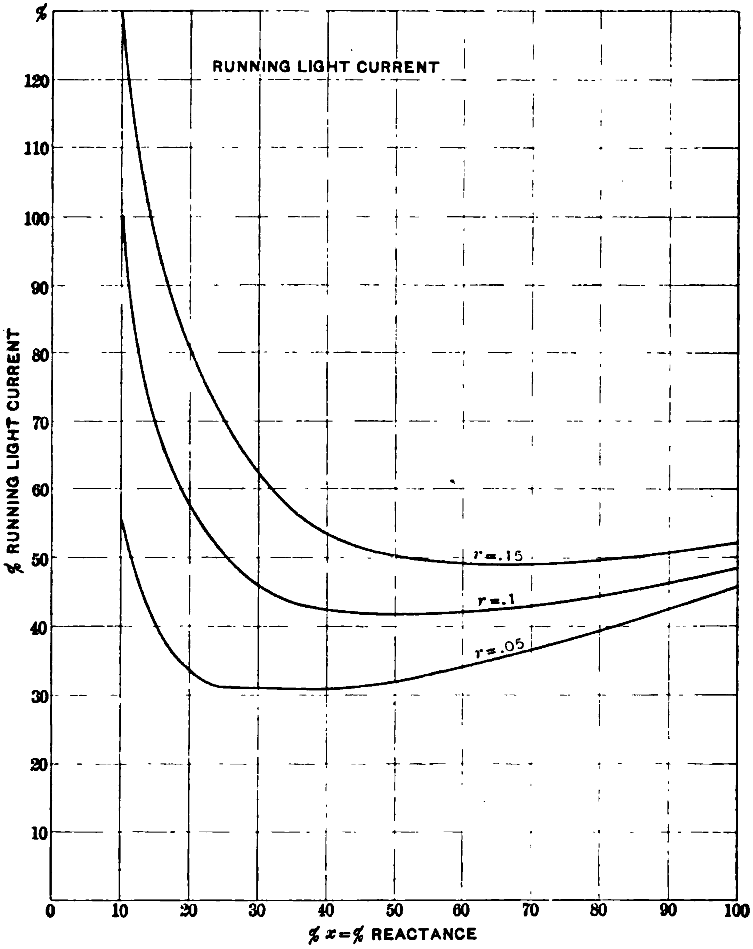


Fig. 4.—Dependence of Running Light Current on the Reactance and Resistance of the Circuit. Converter Adjusted to Run Non-Inductively at Full Load.

It shows plainly that the lesser the loss the lesser is the running light current and the lesser reactance is necessary. In a system of 5% loss 30% reactance, that is such a reactance should be inserted as gives 30% of rated voltage at full load current. In a system of 15% loss, however, 50% reactance would be about as low as we would go, and yet the running light current is 50% of full load current.

It is evident also that the more energy loss, the higher should the generator voltage be relative to the converter voltage as shown by the equations.

In the above case we assumed that the converter should run non-inductively at full load; usually, however, it is preferable to run it non-inductively at a somewhat lighter load, say ¾ load. Under these conditions substituting in equation F for $i_n = .75$ the equation of the running light current and non-inductive load at ¾ load becomes,

$$i_0 = -\frac{x}{z^2} + \sqrt{\frac{x^2}{z^4} + .56 + \frac{1.5}{z^4}}$$

In this case with 40% reactance, the running light current is only 20% of full load current at 10% energy loss, and with 50% reactance only 34% at 15% energy loss. Therefore it would indeed seem as if it always were more favorable to run with non-inductive load at ¾ load. This is still more evident, when investigating the power factor curves with these adjustments, yet there are some reasons why sometimes converters are adjusted for non-inductive load at full load as will be seen.

The maximum output of a converter is practically unlimited provided the generator voltage can be increased, and there is sufficient capacity behind the generator.

With the best arrangement of reactance, resistance and generator voltage, this is limited only by the resistance in the transmission and is expressed by equation $i_1 = \frac{e_0^2}{4\,e\,r}$ as will be shown later. Usually, however, the maximum output is less than this, so that only the maximum value can be obtained by this equation, so that the above equation should be written $i_1 = \frac{e_0^2}{4\,e\,r}$ where i_1 is the limit of energy current, that is output, e_0 and e the generator and converter E. M. F.'s respectively and r the resistance in the system.

To obtain the maximum possible output with a given line impedance, the converter should run non-inductively at higher outputs as the generator voltage increases, so that for instance, if the system has 10% energy loss and 40% reactance and the generator voltage is kept 12½% above the converter voltage, the maximum output is 2.12 times rated output and the converter should run non-inductively at ⅔ of rated load. If the generator voltage were 18% higher than the converter voltage, the output would have been 2¼ times the rated, and the converter would run non-inductive at full load and finally, if the generator voltage were 30% higher than the converter voltage the maximum output would be 2.55 times the normal output but the non-inductive load would have been 1½ times full load. In other words the converter should run with lagging current up to 50% overload.

In commercial installations, however, where there is always a limit to the generator voltage, which limit is caused by saturation of the machine, or outside conditions which do not permit of excessive voltage in the power station, the output of a converter is by no means unlimited, and thus some care has to be taken, to get the proper reactance, since with a given difference in generator and converter potential, the output changes as we change the reactance and resistance.

Referring again to equation (B).

By solving the equation in reference to i_2, it is

$$i^2 = -\frac{e\,x}{z^2} + \sqrt{\frac{e^2 x^2}{z^4} - i_1^2 - \frac{2\,e\,i_1\,r}{z^2} + \frac{e_0^2 - e^2}{z^2}}$$

i_2 becomes maximum for

$$\frac{e^2 x^2}{z^4} - i_1^2 - \frac{2\,e\,i_1\,r}{z^2} + e_0^2 - \frac{e^2}{z^2} = 0$$

or

$$i_1 = -\frac{e\,r}{z^2} + \sqrt{\frac{e^2 r^2}{z^4} + \frac{e^2 x^2}{z^4} + \frac{e_0^2 - e^2}{z^2}}$$

where c_1 is the limiting current which directly represents the limit in output.

Solving this equation in reference to z the impedance, the following expression gives the impedance corresponding to a given maximum output:

$$Z = + \frac{1}{e_1\,\sqrt{2}} \sqrt{e_0^2 - 2\,e\,r\,i_1\,\sqrt{e_0^4 - 4\,i_1\,r\,e\,e_0}}$$

for maximum output

$$e_0^4 = 4\,i_1\,r\,e\,e_0^2 \text{ or } i_1 = \frac{e_0^2}{4\,e\,r}$$

as given above.

Inserting this value we get,

$$Z = \frac{e_0}{2\, i_1}$$

or if

$$\frac{e_0}{e} = k,\ z = \frac{2\, r}{k}$$

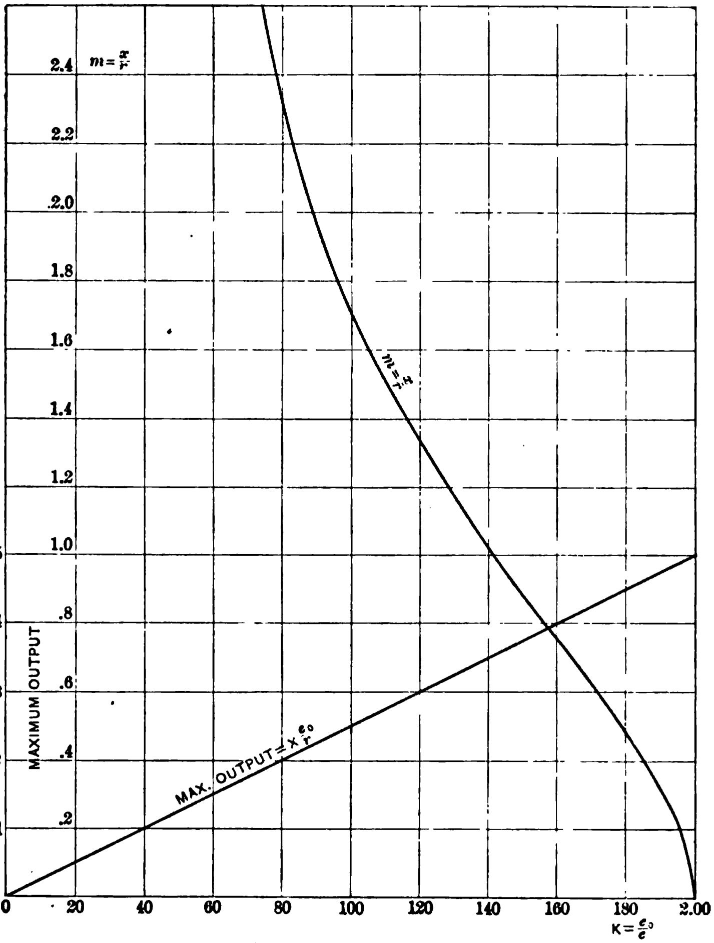


FIG. 5.—Curve Giving Maximum Possible Output and Corresponding Ratio of Reactance and Resistance for Given Ratios of Generator and Converter Voltages.

and

$$x = \frac{r}{k} \sqrt{4 - k^2}$$

or to get maximum output for a given ratio of generator and converter voltage the ratio of reactance and resistance is fixed by equation

$$\frac{x}{r} = \sqrt{\frac{4 - k^2}{k}}$$

thus

$\frac{e_0}{e} =$	1	1.1	1.15	1.2
$m = \frac{x}{r} =$	1.73	1.52	1.42	1.33
max. output =	$.25 \frac{e_0}{r}$	$.275 \frac{e_0}{r}$	$.2875 \frac{e_0}{r}$	$.302 \frac{e_0}{r}$

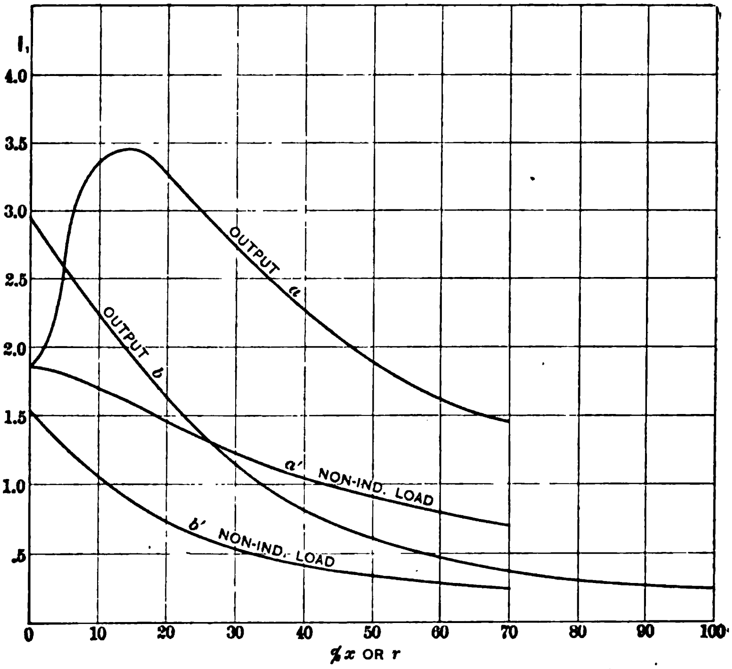


FIG. 6.—*a* and *a'* are Curves Showing How the Maximum Output of a Converter Depends Upon the Reactance in the System. Full Load Assumed to be 1. Energy Loss 10%. Generator Voltage 19% Higher than Converter Voltage. *b* and *b'* show how Output Depends upon the Resistance at 40% Reactance.

$E_0^2 = 1.4$ $E = 1$.

$r = .1$ and Variable x = curve *a*.

$x = 4$ and Variable r = curve *b*.

Curve *a'* = Position of Non-Inductive Load Variable x.

Curve *b'* = Position of Non-Inductive Load Variable r.

It must, however, be borne in mind that this limiting value by no means represents the best "all around" condition. Indeed by choosing the reactances from results obtained from this equation and Fig. 5, the power factor of the system would in general be very poor, therefore it would be better either to sacrifice some in output and increase the reactance, or raise the generator voltage some and thus keep the output with the greater reactance.

In Fig. 6 a couple of curves a and a_1 are given showing the relation between reactance in the transmission line and the maximum output of a converter for given energy loss, and also at which load the converter should run non-inductive under those conditions. These particular curves are figured out for a generator voltage 19% higher than the converter voltage and 10% energy loss in transmission.

As seen, the maximum output would be 3.45 times rated output with a reactance of only 15% and with the converter so adjusted as to run non-inductively at about 1.6 times full load current. This condition is of course rather absurd, since it means a very large running light current with consequent very low power factors at all loads up to full load or thereabouts. The curve also shows that if it was desired to run the converter non-inductively at full load, a reactance of 42% should be chosen and the maximum output would be 2.2 times full load output.

Fig. 7 shows similar curves with a lesser difference between generator and rotary voltage. The generator voltage is kept ten per cent. higher than the rotary voltage and the energy loss is the same as in previous case, that is, ten per cent. It is shown that the maximum output is three times rated output, and that this is obtained by a reactance of about 15 per cent. Also that the converter then should run non-inductively at 95 per cent. of rated load. With this small reactance the running light current will be quite large and the power factors comparably low at lighter loads, so that although the power factor is high at full load, it is really not as good a feasible arrangement. If, under these conditions, that is with ten per cent. higher generator voltage than converter voltage, it was desired to get a maximum output of double rated output of the converter, a reactance of 42 per cent. would be suitable, and the converter should run non-inductively at 65 per cent. of full load, which gives very good general characteristics as far as power factors are concerned.

The output of the converter depends also necessarily upon the resistance in the line. To illustrate this another set of curves is plotted in Fig. 6 denoted by b and b_1, b showing the maximum output for different values of energy loss with a reactance in the system of 40 per cent., and b_1 at which load the converter should run non-inductively under those conditions.

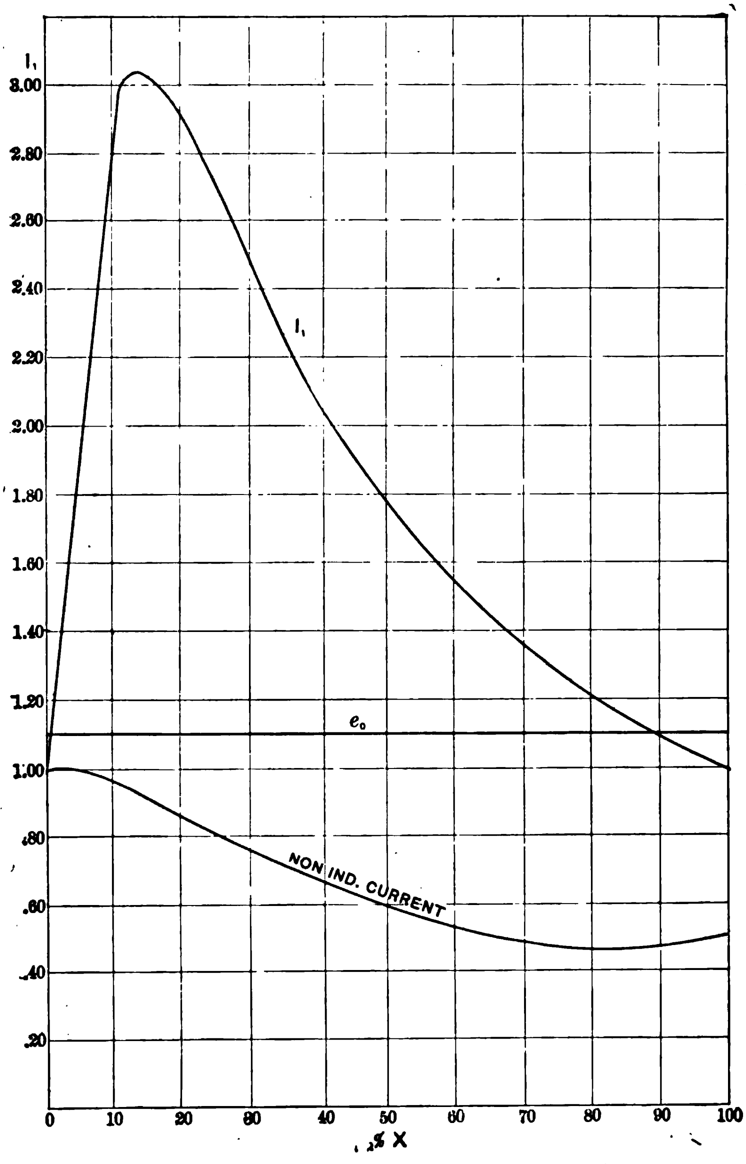


FIG. 7.—Curve Showing How the Maximum Output of a Converter Depends Upon the Reactance in the System. 10% Energy Loss, Generator Voltage 10% Higher than Converter Voltage, and Full Load Output of Converter Assumed as 1.

As seen, the output increases very rapidly as the energy loss decreases at least within commercial conditions, that is between five and 20 per cent. loss. The maximum output with 40 per cent. reactance and zero resistance would be three times rated output.

With five per cent. energy loss the maximum output would be 2.6 times rated output, and the converter should be adjusted for non-inductive load at 1¼ full load.

The condition which is to be met with in a commercial installation is, that the generator is limited to a certain value, that the converter voltage shall be maintained constant at all loads or increase with the load, and that that there shall be a certain margin in maximum output and the highest power factors at all loads.

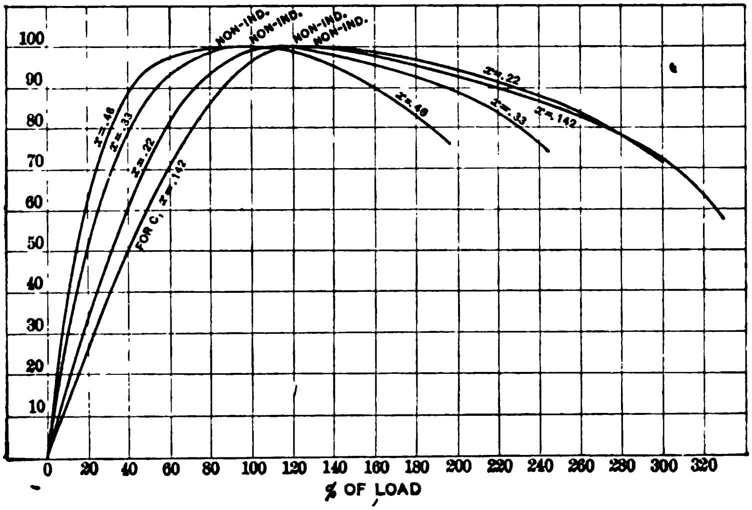


FIG. 8.— $E_0 = 1.15$ $E = 1.$ $r = .1$ x variable.
Power Factors for various Reactances. Maximum Output for $x = .142$ is 330% of full load.
Power Factor Curves of Converters Operated from Generator with 15% Higher Voltage than the Converter Voltage. Energy Loss 10%.

As an illustration, in Fig. 8 is plotted a number of curves giving the power factors at the converter under the assumption that the generator voltage is constant and 15 per cent. higher than the converter voltage, that the full load E. M. F. and current is unity, and the resistance or rather the energy loss is ten per cent. for different values of reactance.

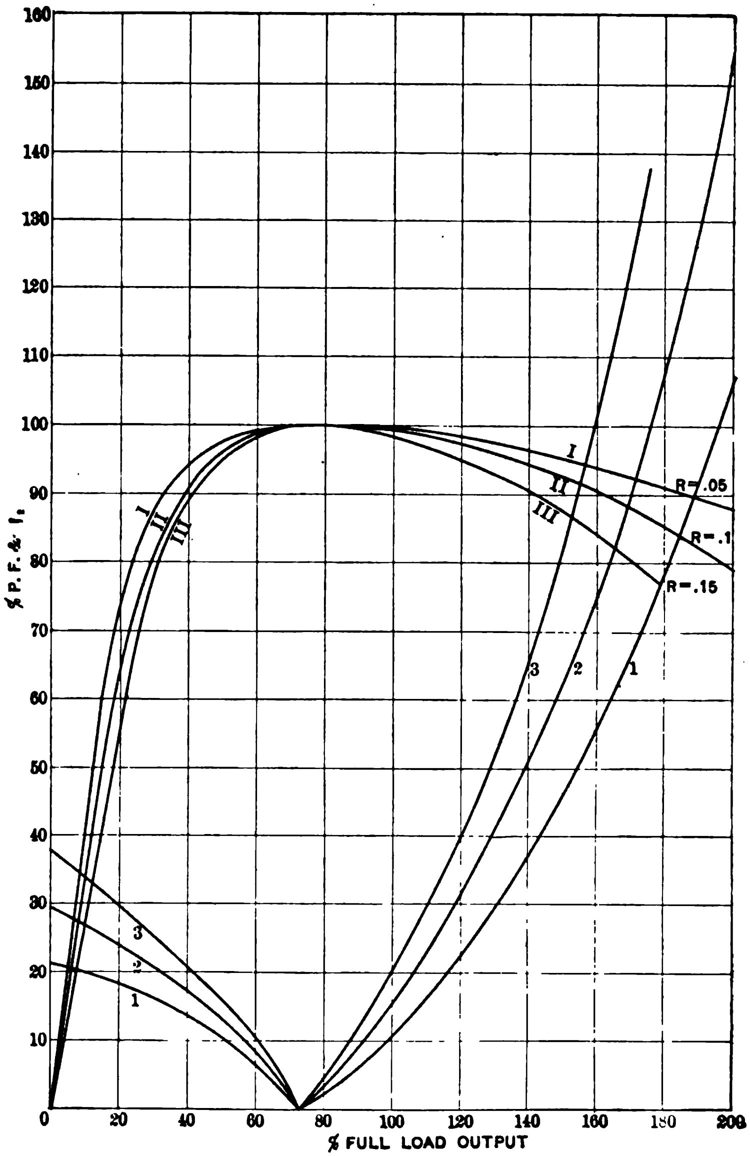


FIG. 9.—

$$x = .4,\quad r = \begin{cases} .05 & \text{Curve I.} \\ .10 & \text{`` II.} \\ .15 & \text{`` III.} \end{cases}$$

$e = 1$ Non-ind. at ¾ load.

$$\text{Wattless Current given} \begin{cases} \text{Curve 1.} \\ \text{`` 2.} \\ \text{`` 3.} \end{cases}$$

Curves Showing Power Factors of Converters adjusted to run non-inductively at ¾ load on a Circuit of 40% Reactance, and 5, 10 and 15% Energy Loss, and Constant Voltage at Converter at all loads.

As can be ascertained by equations given above, the maximum output that could be obtained under such circumstances is 3 3 times rated output with a reactance of 14.2 per cent. The power factor under these conditions is as seen, exceedingly unsatisfactory. The converter would have to run non-inductive at 140 per cent. load, and the power factor at ¼ load is 20 per cent., ½ load 60 per cent., at ¾ load 82 per cent. Apparently, judging from the power factor curve the most satisfactory reactance would be about 46 per cent. The converter is practically non-inductive at full load, has 95 per cent. power factor at ½ load and 71 per cent. at ¼ load with an output of over 2.5 times rated load.

In general it may be quite satisfactory to decide upon a certain reactance and load at which the converter shall run non-inductively, and let the generator E. M. F. correspond thereto. In Fig. 9 are plotted some curves under a similar assumption with a reactance of 40 per cent., resistance of five per cent., 10 per cent. and 15 per cent. respectively, and assumption that the non-inductive load should be ¾ of full load. As seen, the power factor is better the lower the resistance is, yet even over this range of energy loss there is very little difference around loads between half and full load. The running light current, however, depends greatly on the line loss, and is, as seen, 20 per cent. with five per cent. energy loss, 30 with 10 per cent., 38 with 15 per cent. energy loss. The current is necessarily lagging up to ¾ load and then becomes leading.

If the converter were to be over-compounded the power factors would have been somewhat poorer, since as stated above, over-compounding acts in essentially the same way as increased energy loss.

This is illustrated in Fig. 10 where corresponding curves are plotted for a converter of ten per cent. over-compounding, that is, for a converter where the terminal voltage is expressed by $i = e + p\, i_1$.

The power factor at the generator will be slightly poorer at light load and slightly better at heavy load than at the converter, assuming that the transmission line has considerable self-induction.

In Fig. 11 is plotted in a different way the wattless current in the line corresponding to condition given in Fig. 9. Here it is plainly seen how the amount of lagging or leading current is not proportional to the load, consequently the magnetizing or demagnetizing effect of the armature current is not proportional thereto.

In practice the shunt field is so adjusted that the converter takes the required lagging current running light, and the series field is made to increase the excitation so as to give the required field strength at non-inductive load. Since, however, the series excitation is proportional to the load, it is evident that without

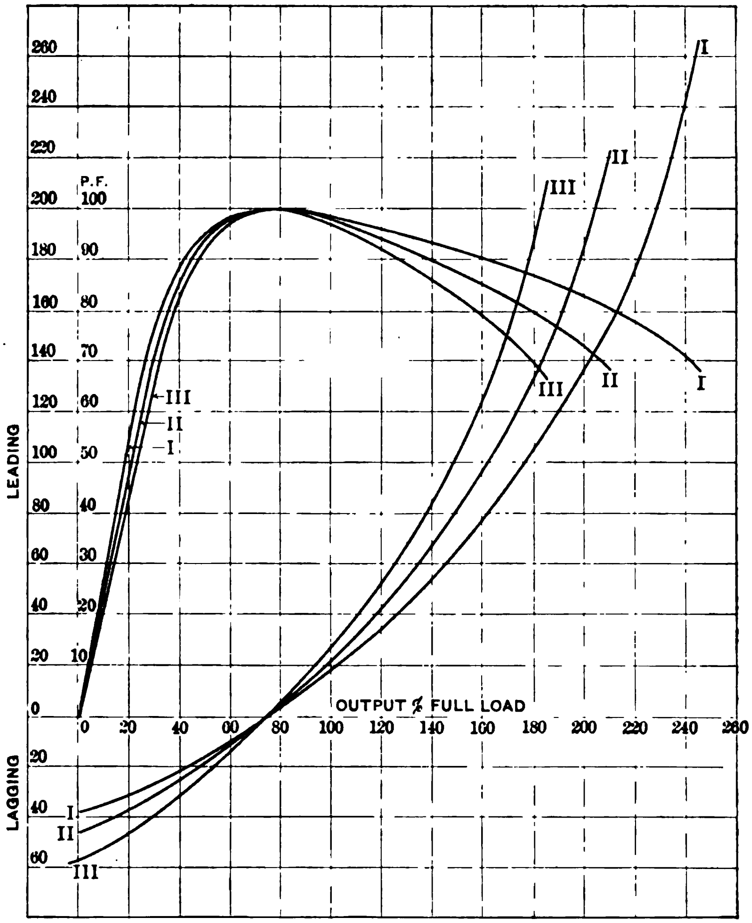


FIG. 10.—

$$x = .4, \quad r = \left\{\begin{array}{lll} .05 & \text{Curve} & \text{I.} \\ .10 & \text{"} & \text{II.} \\ .15 & \text{"} & \text{III.} \end{array}\right.$$

$e = 1 + .1\, i_1$ non-ind. at ¾ load.

Curves giving Power Factors of Converter. Reactance is Assumed as 40%, Energy Loss, 5, 10 and 15% respectively. Converter Runs Non-inductively at ¾ Load, and Over-compounded 10%.

hand adjustment, it would be theoretically impossible to accomplish perfect phase control; or rather, it would be impossible to have constant voltage at the rotary converter with constant voltage at the generator. The difference, however, is exceedingly small, the series field being slightly too strong at light load and too weak at overload, in other words the voltage will be slightly increased at the converter up to non-inductive load and will drop slightly at overload.

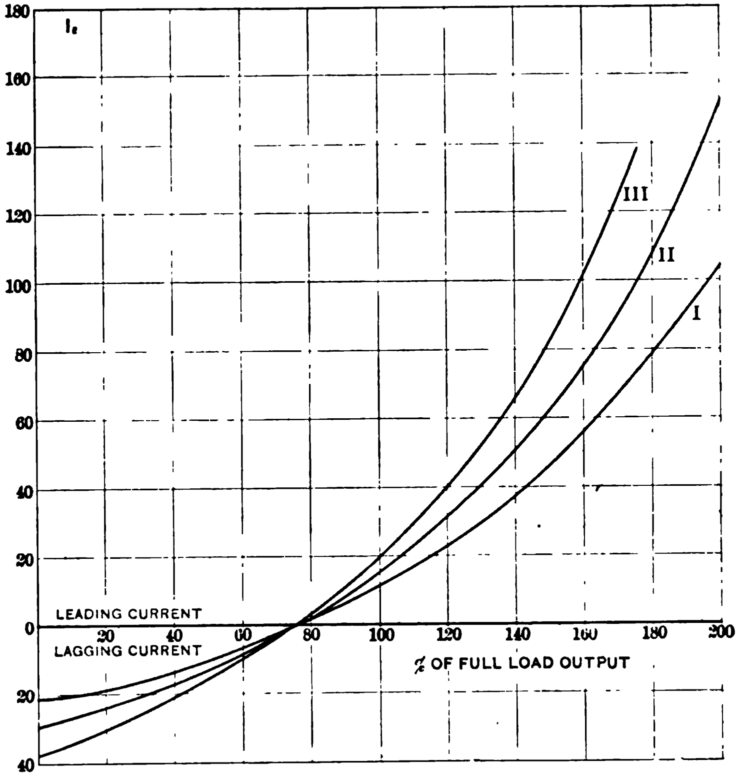


Fig. 11.— $x = .4, \quad r = \left\{\begin{array}{l} .05 \text{ Curve I.} \\ .10 \text{ `` II.} \\ .15 \text{ `` III.} \end{array}\right.$

Curve Showing amount of Leading and Lagging Current in Line in order to get perfect Phase Control. 40% Reactance. 5, 10 and 15% Energy Loss.

In the preceding we have not considered this point and have assumed that the theoretical loading or lagging current can be obtained at any load. Consequently the values which we have given of maximum output of the converter are not quite true in practice but the output is always less. The amount of this decrease in output depends upon the magnetic characteristic of the machine and can readily be determined in practice.

Before closing the paper it might be well to discuss the conditions which govern the amount of reactance, etc., in the machines. As stated in the beginning of the paper, in plants where one converter is operated from one generator it is convenient to use the generator reactance for phase-control. Since, however, as seen, it requires considerable self-induction to do this at high power factors, it means a generator of high armature reaction and self-induction, in other words a generator with rather limited output with constant field excitation. This is not objectionable, since by leading or lagging currents the output can really be made as high as desired, even if the armature reaction is high. Yet when considering that it is often desirable to start the rotaries from the generator and therefore its voltage may be reduced greatly at the starting moment when the converter necessarily takes a large lagging current, it may not always be the best policy to use the generator reactance alone for phase control.

Often, however, converters are started from the direct current side and sometimes by auxiliary motors. Under these conditions the generator might conveniently be made with very high armature reaction.

In plants where several converters are operated from one generator, or from a number of generators in parallel, control by generator reactance is not to be recommended, since it involves the change of series field adjustments with the change of generator capacity. The generators may be made of any armature reaction since several of them are used in parallel in starting, yet it must of course be borne in mind even then, that if the armature reaction is too high, the large current taken in starting a converter from the alternating current side, may cause the voltage to drop so far as to seriously disturb the system in general.

Regarding converters themselves, it is obvious from the preceding discussion that they must be of composite type, that is, they must have shunt and series excitation.

Shunt wound converters do not permit of automatic phase control, but at constant adjustment of the field will always run at the same wattless current at all loads, so that, for instance, if the field is adjusted for non-inductive load at one load, the converter will run non-inductively at all loads, and therefore the drop in voltage at full load will correspond to the energy loss in the system, and the converter voltage will be higher at lighter loads than at heavier loads, therefore will vary as the load varies, and phase control is thus feasible only by hand regulation, that is, in systems where the load varies only slowly as in lighting circuits.

Reaction converters take lagging currents at all loads and thus are in general objectionable, the more so as they do not allow any automatic potential control.

[COMMUNICATED AFTER ADJOURNMENT BY CHARLES P. STEINMETZ.]

The striking distance is constant from 40 to 125 cycles, and probably for some range outside thereof. At zero cycles, that is, continuous electrostatic stress, a deviation may occur, due to a difference of the mechanical motion set up in the medium.

Of very high frequency as 100,000 cycles or so, nothing can be said, since no means exist to measure voltages at such frequencies. Calculation from the constants of the circuit is not possible, since these constants may be entirely changed at very high frequency. The ratio of transmission gives entirely wrong results, due to capacity and self-induction, and no instruments that I know of can measure the maximum values of very high frequency oscillations.

The only means of producing very high frequency is the condenser discharge, and this does not give constant potential, but is a limited power method in which the potential depends upon the conditions of the circuit.

There appears to me no reason, however, why the striking distance for a given voltage, with sufficient power behind to maintain this voltage, should be different at very high frequency, and in the absence of any satisfactory means of measuring voltages at such very high frequency, I should rather be inclined to estimate voltages from the striking distance, even at such frequencies, and do not believe that such estimates would be very far wrong.

Regarding the reason for choosing the arrangement described, of four separate transformers, it was done for safety, and considered desirable when these transformers were built, four years ago. Since that time single transformers for 100,000 volts have become a standard article of manufacture, for testing purposes, and are at this writing no great curiosity. But still, a great difference exists in the electrostatic stress at 100,000 and 160,000 volts.

Schenectady, N. Y., Sept. 18, 1898.

A Paper presented at the 15th General Meeting of the American Institute of Electrical Engineers, Omaha, June 29th, 1898, President Kennelly in the Chair.

THE COMMUTATED CURRENT WAVE OF A COMPOSITE-WOUND ALTERNATOR.

BY DUGALD C. JACKSON.

The accompanying curves were taken by Mr. H. S. Webb, one of my graduate students, during a relative study of the current and pressure waves in the various branches of a 50 kilowatt alternator with composite winding. The normal pressure of the alternator is 1,100 volts, and the frequency is 125 periods per second. The machine was built several years ago by the Thomson-Houston Electric Co., and has the usual construction

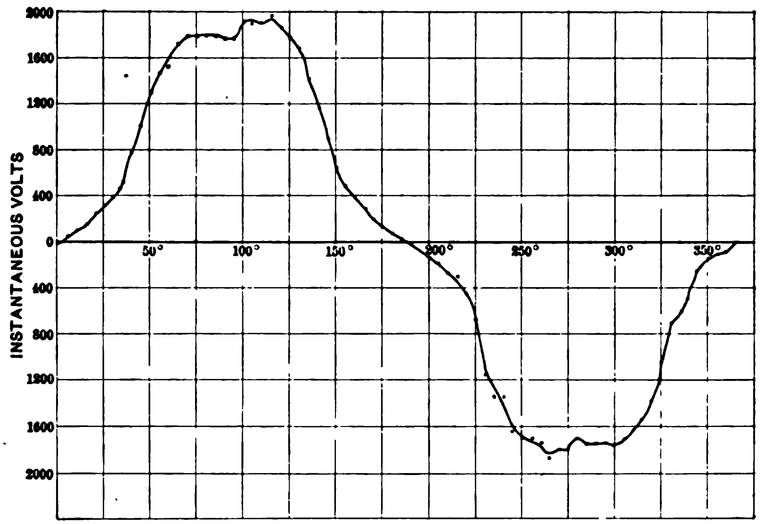


Fig. 1.—Open Circuit Pressure Wave.

of the old belt-driven alternators with ten field-poles and a toothed core, ribbon-wound armature. The driving speed during the tests was quite unsteady, as the machine was driven by the same engine that drove two street railway generators, and this resulted in irregularities which are evident in the curves.

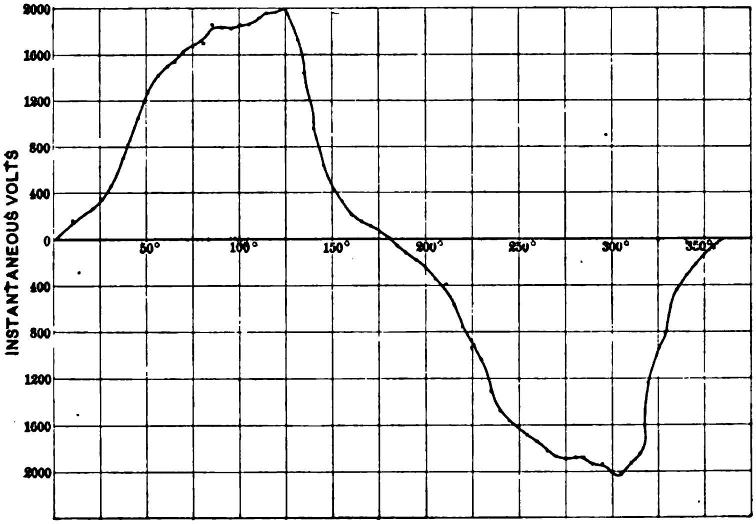


FIG. 2.—Pressure Wave with Load of 22 Amperes.

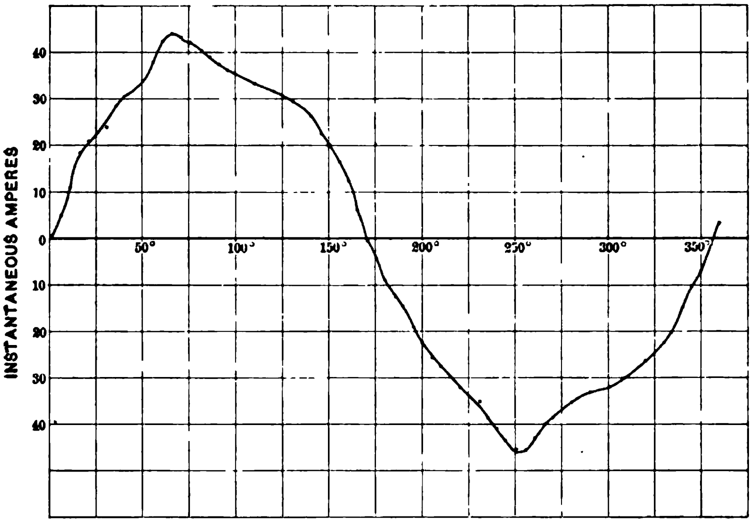


FIG. 3.—External Current Wave with Load of 24 Amperes.

I am not acquainted with any results which have heretofore been given in the TRANSACTIONS of the INSTITUTE or elsewhere, which show the characteristic form of the commutated current waves in the series field of an alternator, and I therefore present these curves. The question of the form of the commutated current wave is mentioned in two or three text-books, but experimentally determined waves do not appear.

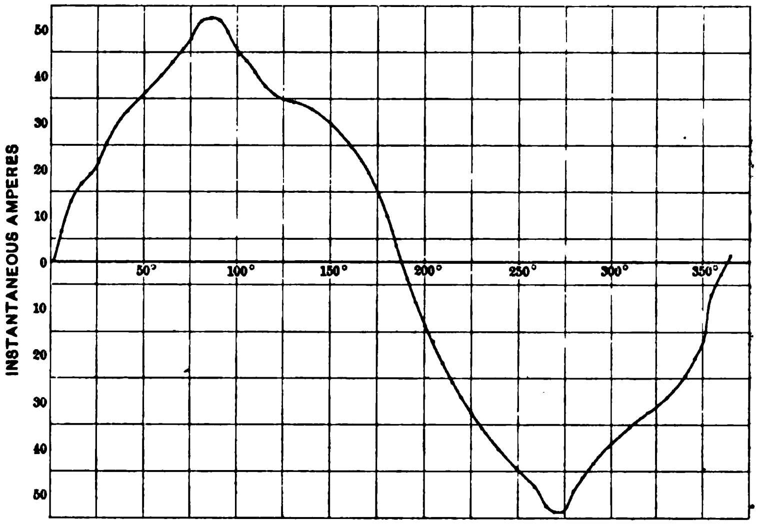


FIG. 4.—External Current Wave with Load of 28 Amperes.

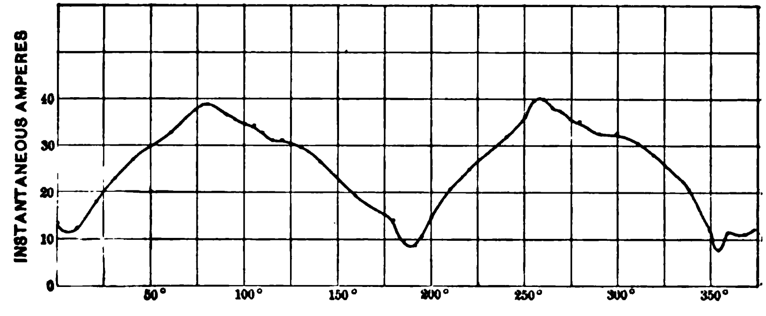


FIG. 5,—Commutated Current Wave with Load of 22 Amperes.

In the series of curves presented herewith, Fig. 1 is the pressure wave at open circuit, and Fig. 2 is the pressure wave when the armature current equalled 22 amperes. A comparison of these gives an idea of the extent of the effect of armature reactions on the form of the wave. Figs. 3 and 4 respectively, show the waves of external current when the load amounted to 24 and 28 amperes, the machine being worked upon an incandescent lamp load through partially loaded transformers. Fig. 5 shows the wave of commutated current in the series field when the external current equalled 22 amperes. Fig. 6 shows a similar wave when the load averaged 24 amperes but varied somewhat, and Fig. 7 shows a similar wave during a period in which the load on the machine was dropping rapidly. At the beginning of this period the load was 28 amperes. Fig. 8 shows the pulsation of current set up in the circuit of the continuous current external exciter, by the pulsations of the magnetism in the fields of the alternator when the load is respectively 23, 25 and 28 amperes.

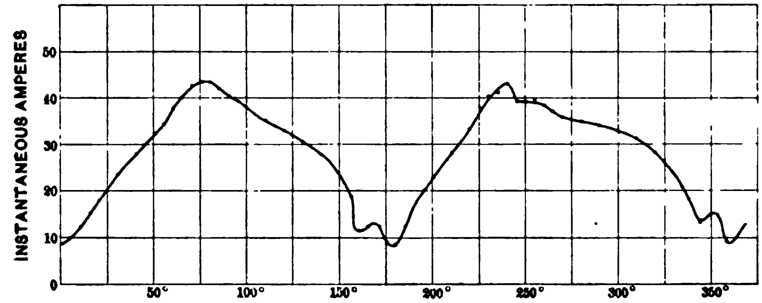


Fig. 6.—Commutated Current Wave with Variable Load averaging 24 Amperes.

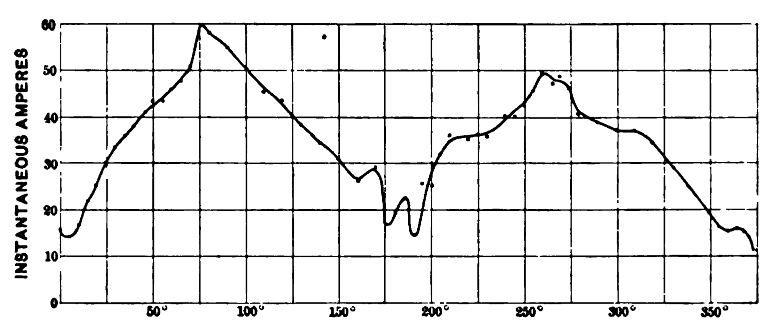


Fig. 7.—Commutated Current Wave with Load Falling from 28 Amperes.

A comparison of the external current waves, such as are shown in Figs. 3 and 4, with the commutated waves such as are shown in Figs 5 and 6, shows that the commutated waves have practically the same form as the original waves of current (with alternate loops inverted) except in regions occupying about 25 degrees on either side of the zero points of the original waves. Within these regions the commutated waves do not come to zero and they take a characteristic toothed shape, as is to be expected from the effect of the self-induction of the field windings when they are short-circuited by the brushes on the commutator. There does not appear to be any immediate connection in this machine between the pulsations of the series field current and of the current in the separately excited field. The latter pulsations are, in fact, sufficiently accounted for through the effect of the rotation of the toothed armature and the effect of armature reactions.

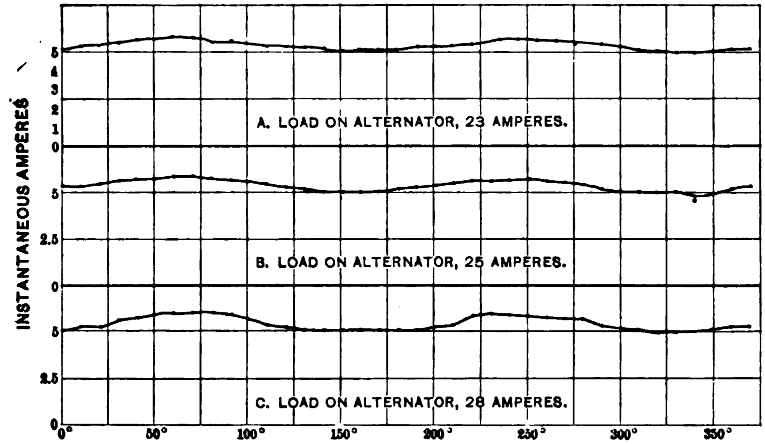


FIG. 8.—Curves Showing Pulsation of Current in Separate Exciter Circuit with Various Loads on Alternators.

The points on these curves were located by a balance or potentiometer method similar to that described on pages 296 and 297 of Jackson's "Alternating Currents," but, instead of the usual galvanometer or telephone receiver, Mr. Burgess' portable form of capillary electrometer (which is described by him in a paper presented to this meeting) was used to indicate the point of balance. This instrument has been used in tracing alternating current curves by quite a number of my students, and it is the unanimous verdict that the instrument greatly increases the convenience, the accuracy, and the speed of the method. We have had a number of the instruments in use during the past winter and have found them perfectly portable, difficult to injure, and practically unaffected by external influences.

A paper presented at the 15th General Meeting of the American Institute of Electrical Engineers, Omaha, June 29th, 1898, President Kennelly in the Chair.

SOME TESTS WITH AN INDUCTION GENERATOR.

BY A. F. MC KISSICK.

It has been pointed out by several engineers, especially by Mr. Charles P. Steinmetz, that an induction motor, driven mechanically at a speed above synchronism, will act as a generator, and that for its operation as a generator there must be connected to it either an alternator or a synchronous motor.

In an article published in the *Electrical World*, Jan. 21, 1893, by Mr. E. Danielson, the following experiment is described: "A three-phaser A of 50 volts (as measured from the neutral point to each of the brushes), and with a current capacity of about 60 amperes, sent current to a motor B, with inductive winding of about the same capacity. The motor, by means of a belt, ran a continuous current dynamo, C of 330 volts and 16 amperes. The matters were reversed so that dynamo C, fed from a 330-volt circuit, ran the motor B as a generator, sending a rotary current to the three-phaser A, which then became a motor. The belt was then thrown off of A, and trials were made to break it out of step with the current, but without success."

Again in the excellent paper of Mr. Charles P. Steinmetz on "Induction Motors" presented before the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS on July 26, 1897, the use of an induction motor as a generator was referred to as follows: "As generator the induction machine differs from the synchronous alternating current generator, or generator with constantly excited field, in-so far as the latter can yield current and output at any power factor, that is, any phase displacement corresponding to the load, while in the induction generator at given terminal voltage to every value of current output a certain power factor of load corresponds. That is, to derive a certain value of current from the induction generator, the total load put on it must have the particular power factor corresponding to this current, and besides leading current or if the power factor of the load changes, current and voltage of the induction generator will change accordingly. In consequence thereof, in general the induction generator is stable only, if at least a part of the load consists of synchronous motors."

In the discussion that followed this paper, Mr. Steinmetz speaks further of the induction generator as follows: "The induction generator is a very important piece of apparatus, I believe. It is, however, somewhat restricted in its application, due to the necessity of having as load a circuit of leading current. But whenever the conditions are such that it can be used, as for operating synchronous motors or rotary converters, this type of machine has the great advantage of the absolute absence of continuous current exciting circuits, collector rings, or any other parts requiring attention. The voltage is generated in a stationary structure and the revolving part is a solid structure of iron and copper bars. Furthermore, as soon as the circuit is opened or short-circuited, the power is gone and the machine is dead, so that you get here a type of alternator requiring no attention whatever. Besides you can run it at different speeds and still get the same frequency out of it. There is another interesting feature noticeable when comparing the induction motor curves and the induction generator curves. The same machine as induction generator gives a considerably larger output electrically than as induction motor mechanically. In a future paper I shall dwell more particularly on the induction generator, and may mention here only that I have operated synchronous motors from an induction generator, the mechanical output from the synchronous motor driven by the induction generator was larger than the maximum mechanical output which could be derived from the same induction machine as induction motor."

The results of the tests made, show close agreement with the theory as given by Mr. Steinmetz.

APPARATUS.

The tests described in this paper were made with a General Electric 5-H.P., 3-phase 220-volt, 6-pole, 60-cycle induction motor (with starting resistance in secondary rotating element), driven by a 10-H.P. 110-volt Thomson-Houston direct current motor.

The machine used as an alternator and synchronous motor in the tests was an "Ideal" 5-kilowatt 3-phase, 60-cycle, 10-pole, 220-volt machine, and could be belted either to a jack-shaft or to a 3-kilowatt-Edison-125-volt dynamo.

The curves in Fig. 1 show the operation of the induction machine as a motor with varying output.

PART I.

In the tests under this head, the belt connecting the Ideal alternator to the jack-shaft was in each case thrown off after starting and the alternator run as a synchronous motor, either empty or driving the 3 kilo-watt-Edison dynamo.

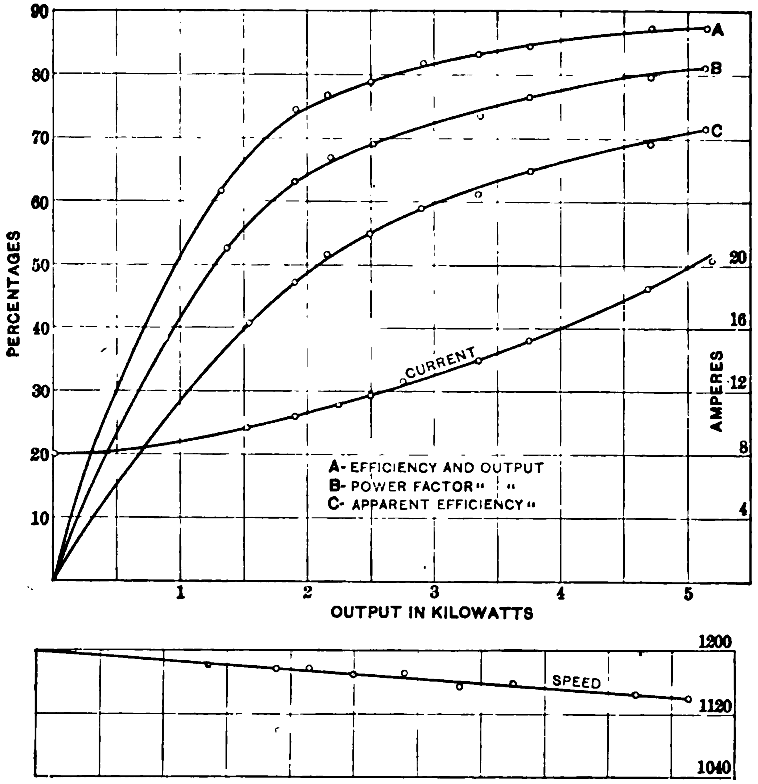


FIG. 1.

Curve of Magnetization.—The method of making this test is as follows: Start induction motor from Ideal alternator, the 10-H. P. direct current motor being belted to the induction machine, when up to speed, supply current to 10-H. P. direct current motor, driving induction machine near synchronism, and throw off belt connecting alternator to jack-shaft. This alternator will then run as a synchronous motor, receiving its current from the induction machine, which is now being driven as a generator by the 10-H. P. direct current motor belted to it.

By varying the exciting field current of the synchronous motor, the voltage of the induction generator is varied, and from the readings of field current in synchronous motor and voltage at terminals of induction generator, the curve, marked "Induction generator" in Fig. 2 is obtained.

The magnetization of the Ideal alternator is also given in Fig. 2, which is almost identical with the magnetization curve of the induction generator.

Test With Induction Generator Driving Synchronous Motor Loaded.—In this test the alternator was made to run as a synchronous motor by the induction generator as before, and then belted to the 3-kilowatt-Edison, driving this machine as a dynamo.

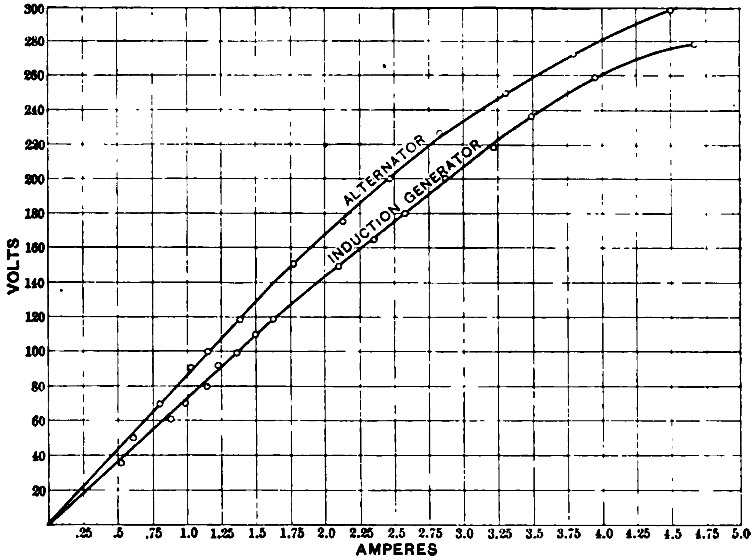


Fig. 2.

The results of this test are shown in Fig. 3.

In making the calculations for efficiency, the energy required for the excitation of the synchronous motor fields was charged up against the synchronous motor.

Fig. 4 gives the results of the following test: With the connections the same as in the preceding test, and the load on the 3 kilowatt Edison maintained constant, the voltage of the induction generator was varied, and corresponding current, watt and speed readings recorded.

The voltage was varied from 260 to 125, the synchronous motor falling out of step on attempting to lower the voltage to 100.

Curve A gives the variation of supply current with field current, curve B variation of supply current with voltage of supply, and curve C is plotted between power factor and voltage of supply.

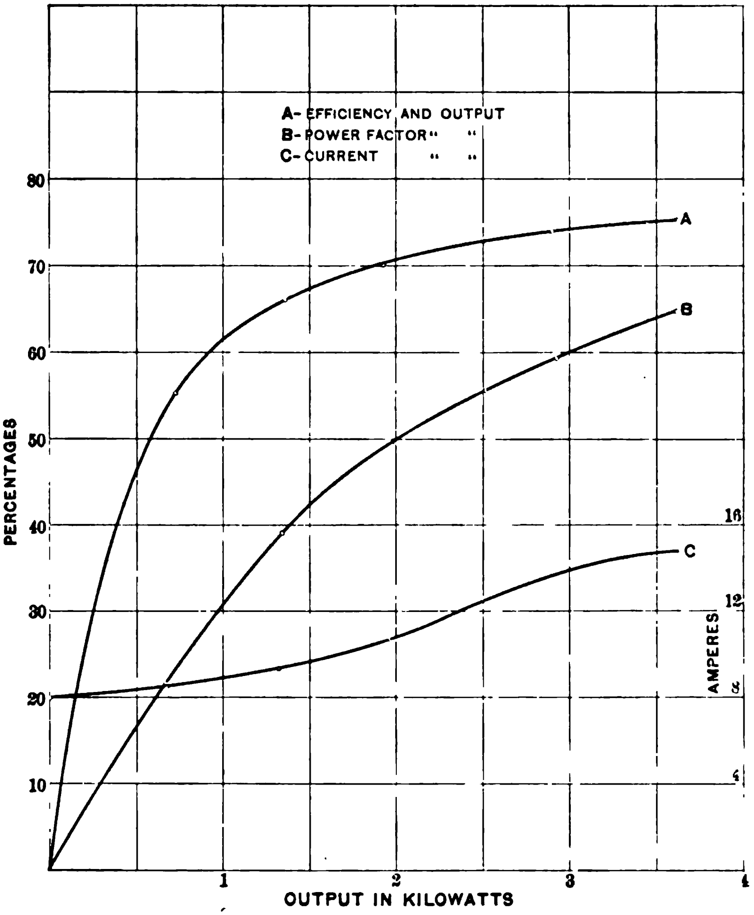


FIG. 3.

It is interesting to note the similarity between the general shape of curve A and the curve plotted between the same co-ordinate values as curve A, obtained from a synchronous motor with constant load, supplied with alternating current at a

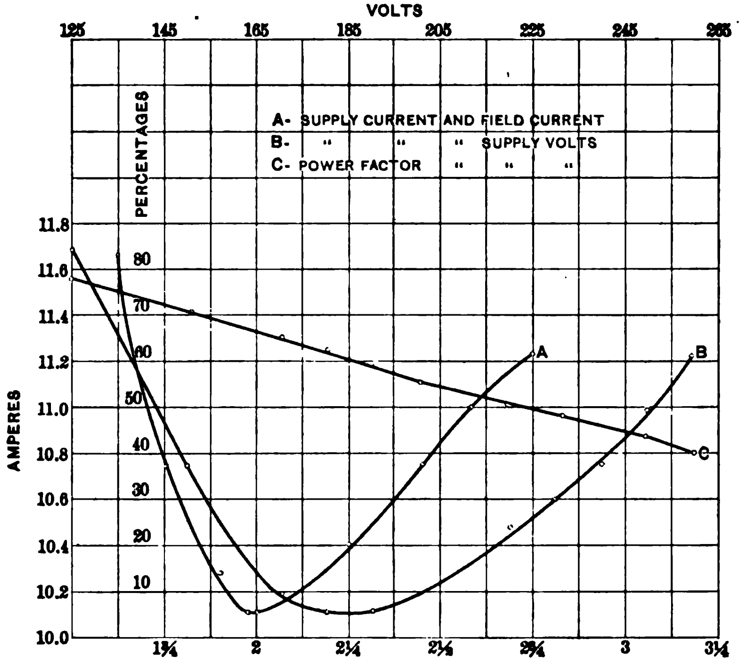

VOLTS
125
145
165
185
205
225
245
265
PERCENTAGES
A- SUPPLY CURRENT AND FIELD CURRENT
B- " " " SUPPLY VOLTS
C- POWER FACTOR " " "
AMPERES
11.8
11.6
11.4
11.2
11.0
10.8
10.6
10.4
10.2
10.0
80
70
60
50
40
30
20
10
A
B
C
1¾
2
2¼
2½
2¾
3
3¼
FIELD CURRENT

FIG. 4.

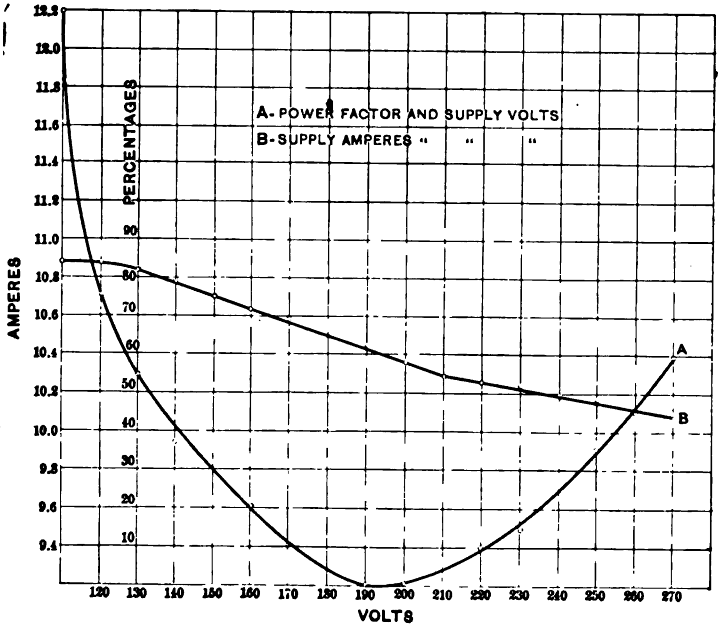

12.2
12.0
11.8
11.6
11.4
11.2
11.0
10.8
10.6
10.4
10.2
10.0
9.8
9.6
9.4
AMPERES
PERCENTAGES
90
80
70
60
50
40
30
20
10
A- POWER FACTOR AND SUPPLY VOLTS
B- SUPPLY AMPERES " " "
A
B
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
VOLTS

FIG. 5

constant pressure, and also the similarity between the curves in Fig. 4 and those in Fig. 5, which were taken with the induction machine run as a motor, the load being kept constant on the motor, but the supply voltage varied.

It will also be noted that in both tests the power factor increased uniformly with decrease of voltage.

Test of Induction Generator with Lamp Load.—The induction generator was started as before, and a lamp load that could be varied, put on, it of course being necessary to run the synchronous motor empty.

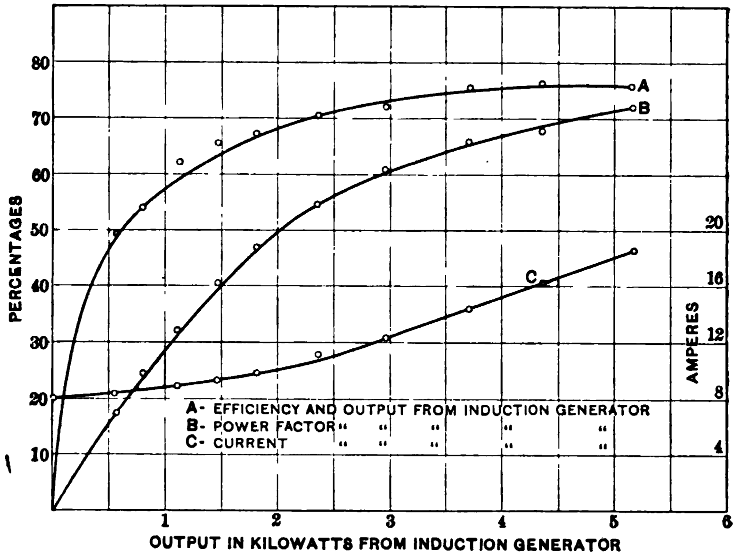


FIG. 6

The load in lamps was varied from zero to the full load of the induction generator, with the results as shown in Figs. 6 and 7.

In calculating the results shown in Fig. 6, the watts supplied to the alternator running as a motor, and to the lamps, was taken as the output of the induction generator, the efficiency being this output divided by the input to the induction generator, and the power factor, this output divided by the total apparent watts from the induction generator.

In Fig. 7 the fact that the energy delivered to the alternator, and that required for the excitation of the alternator fields, does no useful work, is taken into account. So in calculating the results in Fig. 7, the watts supplied to the lamps were considered as the output, the efficiency being this output divided by

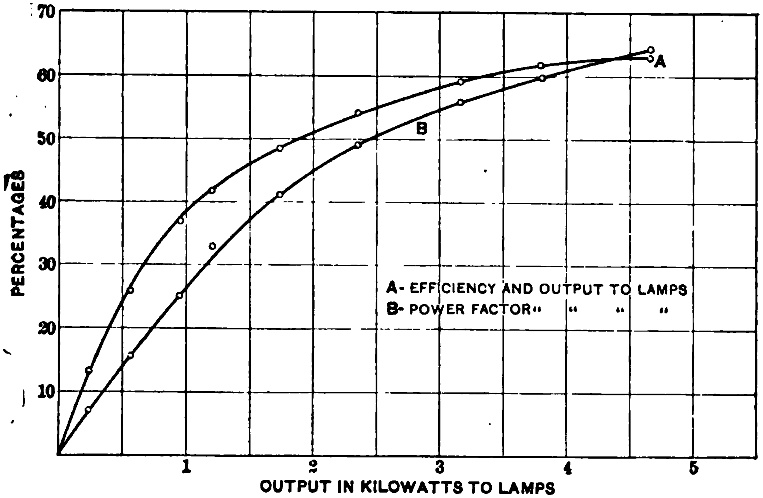


FIG. 7.

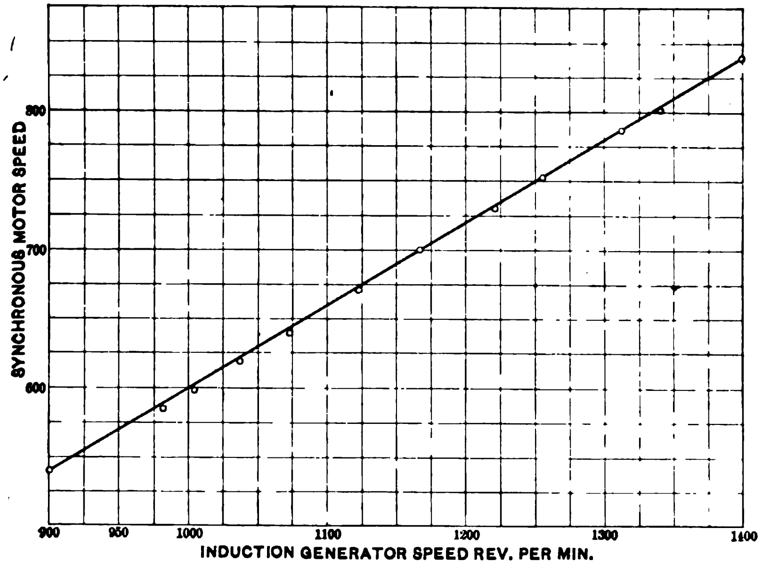


FIG. 8.

the input, and the power factor this output divided by the total apparent watts from the induction generator.

Synchronous Operation of Alternator.—The speed of the induction generator was varied, the voltage of supply being maintained constant, and corresponding readings of speed taken on alternator running as a synchronous motor, which showed that motor ran in synchronism with induction generator. The results are shown in Fig. 8, the full line representing the synchronous speed line, the small circles the points found from readings.

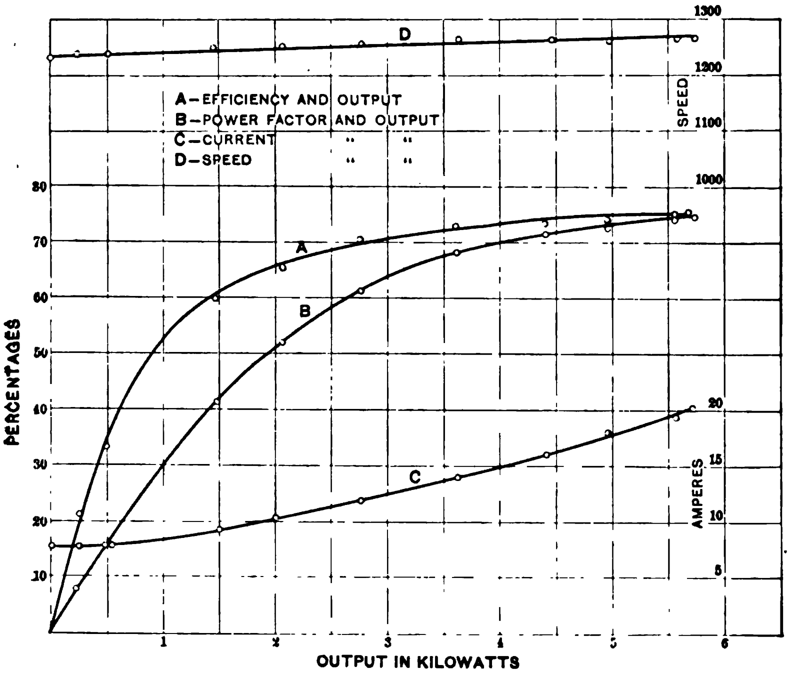


Fig. 9.

In this test, and all preceding tests, the belt connecting alternator to jack-shaft was thrown off, after the starting up of the induction generator.

Part II.

In the tests under this head, the belt connecting the Ideal alternator to the jack-shaft was not removed.

Test of Induction Generator, furnishing current to alternator.—The induction generator was started up as usual, and its speed gradually increased from below synchronism to about six per cent. above synchronism, readings taken as usual. The alternator was therefore run as a motor and helped to drive the jack-shaft.

The results are plotted in Fig. 9, which will be found by comparison to resemble the curves constructed by Mr. Steinmetz.[1]

It is interesting to note in connection with this test the readings on the two wattmeters, as shown in Fig. 10.

At the beginning of the test before the induction motor was speeded up, readings were taken on the two wattmeters, and as the power factor was below 50 per cent., the reading on one wattmeter (No. 2) was negative, hence its connections had to be reversed, and while its connections were reversed, the difference of the two wattmeter readings represented the total true watts. As soon as current was turned on the shunt motor (insufficient however to make this machine act as a motor and

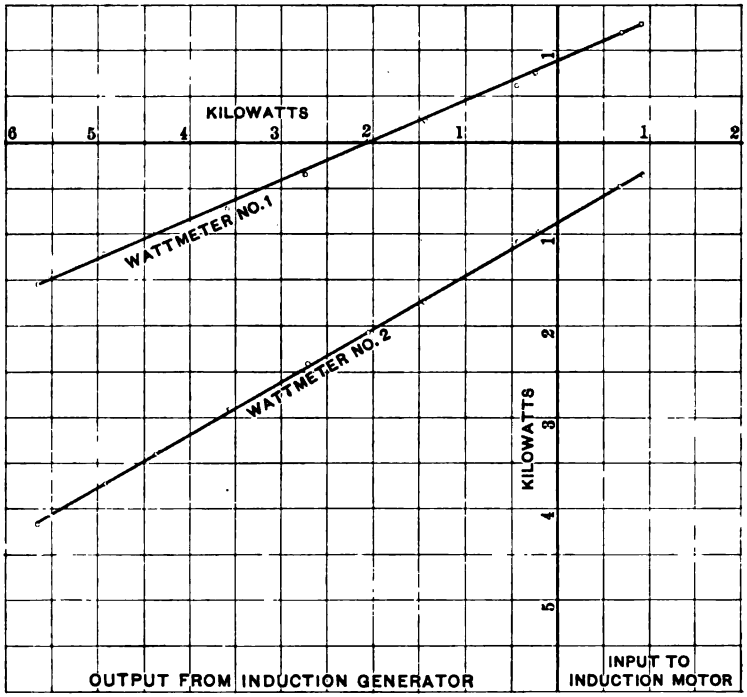


Fig. 10.

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[1] Transactions, vol. xiv., p. 203.

drive the induction machine), the load on the induction motor was decreased, the power factor decreased, and the corresponding wattmeter readings are shown in Fig. 10.

On furnishing sufficient potential to the shunt motor to make it act as a motor, and drive the induction motor as a generator, the readings on wattmeter No. 1 diminished and finally became negative (necessitating a changing of its connections), while the readings on wattmeter No. 2 continue to increase as shown, and always negative. Under these conditions, the total watts will be the sum of the two wattmeter readings, and as the sum is negative, the induction generator is supplying energy to the Ideal alternator.

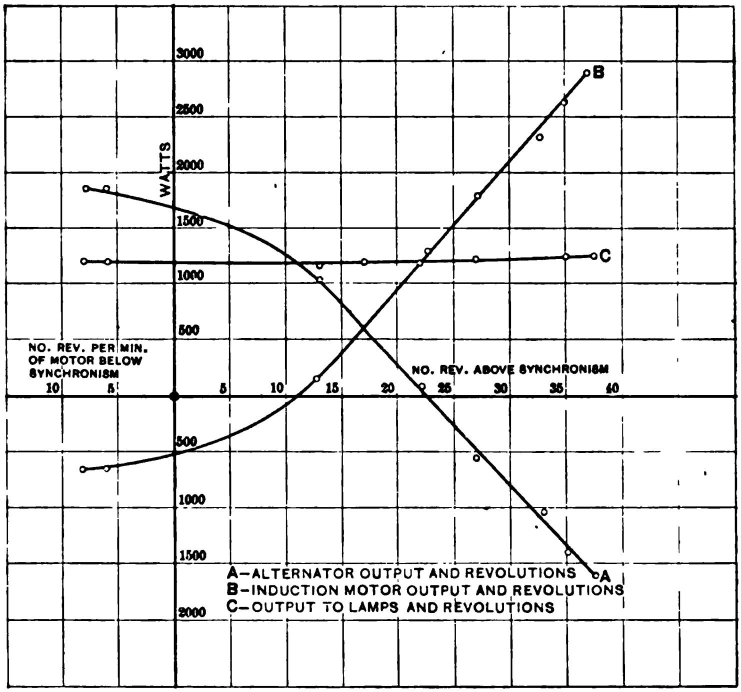


FIG. 11.

Test with Induction Generator furnishing Current to Ideal Alternator and to a Bank of Lamps.—This test is the same as the preceding one, except that a bank of lamps is connected to the three-phase terminals. At the beginning of the test, the alternator furnished current to both induction motor and lamps, when on speeding up, the induction motor, now running as a generator, supplied current to both lamps and alternator, which acts as a motor helping to drive the jack-shaft.

The results of these tests are shown in Fig. 11.

Curve B is plotted with induction motor output as ordinates and number of revolutions per minute above synchronism as abscissæ. At first the output is negative, which indicates that the motor is receiving energy from the alternator; at 11 revolutions per minute above synchronism it commences to act as a generator, and at 22 revolutions it is furnishing energy to both alternator and lamps.

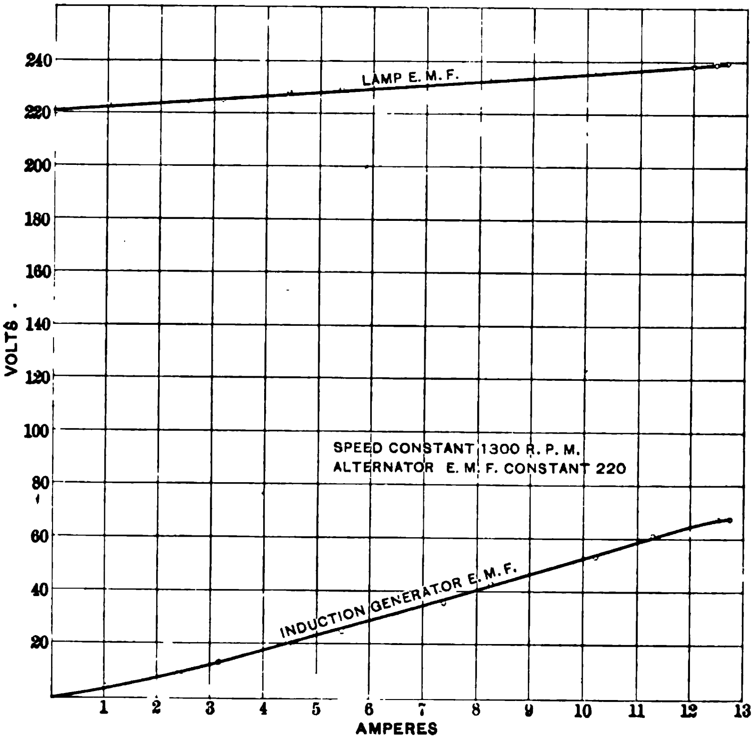


FIG. 12.

As pointed out by Mr. Steinmetz, the induction generator can be run at different speeds and still the same frequency obtained from it. For proof of this, a small induction motor was connected in the above test to the three-phase mains and run with no load. Variation of the speed of the induction generator from synchronism to 20 per cent. above synchronism, did not in any way affect the speed of the little induction motor, its speed remaining constant, which was almost synchronous with the Ideal alternator.

Of course the above will not hold true when the conditions are as described in Fig. 8.

On attempting to make some tests with this induction generator as a single-phase instead of a three-phase machine, it was found that the current required by the motor when running as a synchronous motor (with belt connecting alternator to jack-shaft thrown off) was excessive, so that this test had to be abandoned.

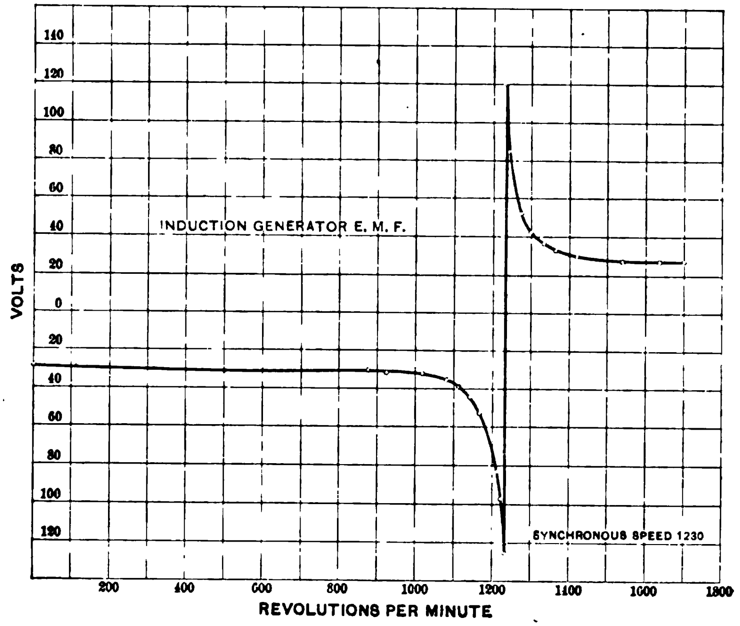


FIG. 13.

Uses of Induction Generator.—The most probable use of the induction generator will be for boosting. Mr. Kelly has discovered (*Electrical World*, March 20, 1897), that an induction generator, having its field coils in series with the mains, will act as a booster or feeder regulator, and that this action as a booster at any particular speed above synchronism, will depend upon the amount of current supplied to the field magnets.

In order to use an induction generator as a booster, the fields are connected in series with the main line, and the induction generator driven above synchronism. With no current flowing, there will be no boosting action, but as soon as current flows, the boosting action commences, its amount depending upon the current flowing in the mains, and this amount for a given current may be varied by varying the speed of the induction generator. So that by the use of an induction generator as a booster, we get a machine with no brushes, collector rings or commutator.

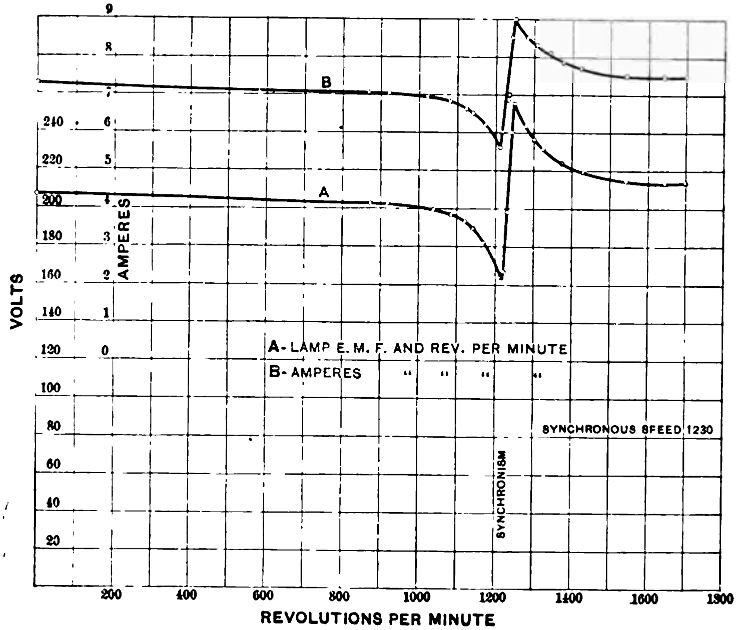


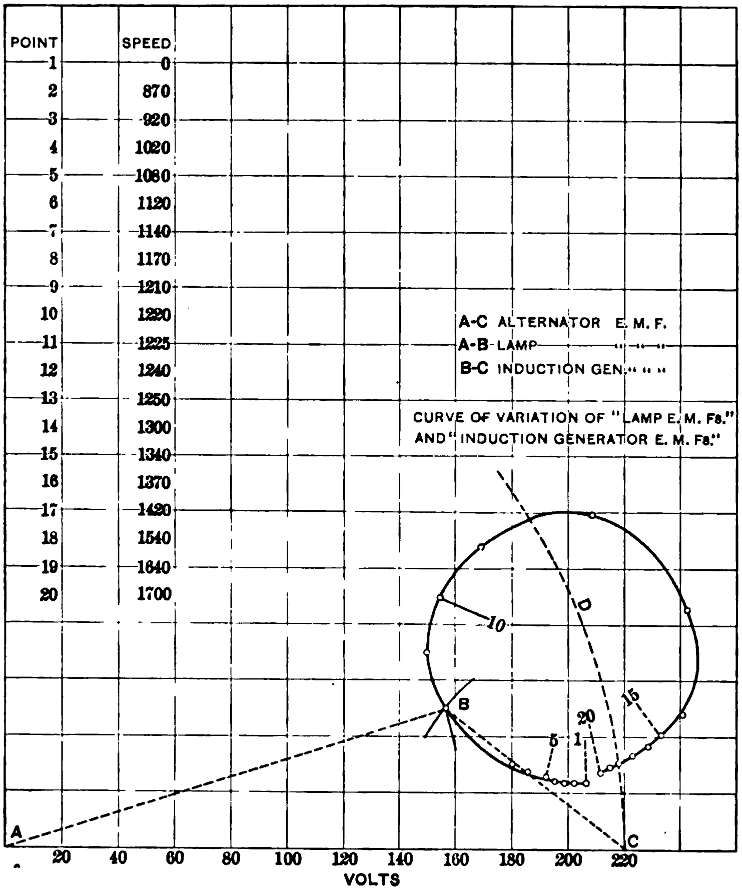
FIG. 14.

In case the induction motor should ever be used for the propulsion of street cars, its action as an induction generator, when driven above synchronism, could be taken advantage of in descending grades, thus pumping back energy into the line, doing away with braking to a great extent.

Test of Induction Generator as a Booster.—The induction generator and alternator, used in the above experiments, were connected in series as single-phase machines, with a bank of lamps and readings taken to determine its boosting action.

In the first test as a booster, the speed was maintained constant at 1,300 revolutions per minute (synchronous speed 1,230) and the current flowing in the mains varied from zero to the full load current of alternator, by adding lamps in lamp board. The results obtained are shown in Fig. 12.

In the second test the speed of the induction generator was varied between wide limits, the alternator E. M. F. being maintained constant, and also the number of lamps connected in series with the two machines.



POINT	SPEED
1	0
2	870
3	920
4	1020
5	1080
6	1120
7	1140
8	1170
9	1210
10	1220
11	1225
12	1240
13	1250
14	1300
15	1340
16	1370
17	1420
18	1540
19	1640
20	1700

FIG. 15.

The results are shown in Figs. 13, 14 and 15.

In Fig. 13, the results show that the potential difference around the induction generator terminals increased from 28 volts at rest, to 125 volts at a speed of 1,235 revolutions per minute, and that a slight increase in speed caused the machine to supply E. M. F., in other words, to act as a generator. This change, it will be noticed, is very sudden, going from a negative maximum to a positive maximum in about 10 revolutions. Several attempts were made to get intermediate points between these two maxima, but without success.

Fig. 14 gives the curves of amperes and "lamp E. M. F's.," this last expression being the potential difference around the lamp terminals.

Fig. 15 shows the variation of the "lamp" and "induction generator E. M. F's.," polar co-ordinates being used. For all points within the dotted arc D, the induction generator causes a drop in potential, and for all points without this arc the induction generator supplies potential to the system. The method of construction of this curve is simply the location of the vertices of the different triangles of E. M. F's. In this figure the points of the curve are numbered and the corresponding speed readings given in table.

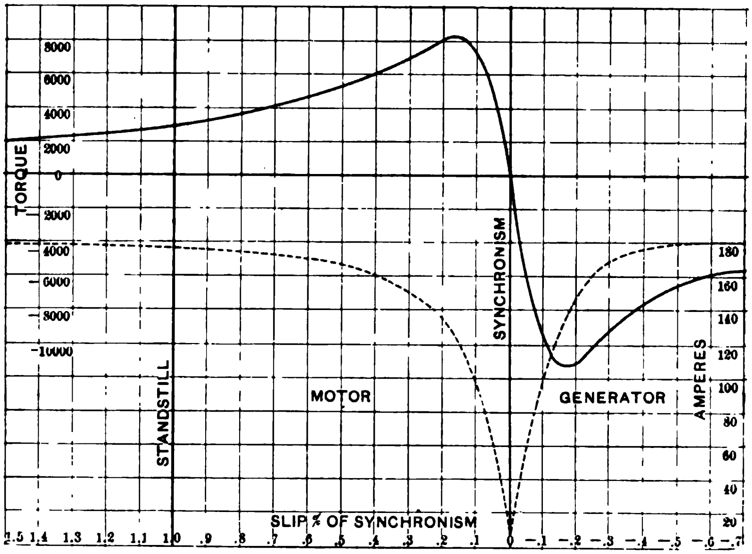


FIG. 16.—Induction Motor. Speed Curves. $Z = .1 - 8j$. $Y = .01 + .1j$.

It is interesting to note the similarity between the curves in Figs. 13 and 14 and the one for torque and slip, given in Fig. 16, taken from Mr. Steinmetz's paper on "Induction Motors." While the results, shown in these curves, were taken under somewhat different conditions, still the action, when the motor is driven near synchronism, is strikingly similar.

A Paper presented at the 15th General Meeting of the American Institute of Electrical Engineers, Omaha, June 29, 1898, President Kennelly in the Chair.

THE EVOLUTION OF THE LINE SIGNAL.

BY ARTHUR VAUGHN ABBOTT.

A careful observer at the first great American Exposition, the Philadelphia Centennial, might have noticed a fine wire running along a gallery in Machinery Hall, terminating at either end of the building in a small closet. Continued investigation would have disclosed a curious trumpet shaped apparatus into which the wire extended. whereby an attentive listener could, with the aid of a vivid imagination, distinguish articulated sentences delivered at the other extremity of the wire. Such was the first public exhibition of the telephone, whereby the transmission of speech by electricity became a fact, and in the quarter of a century which has since elapsed, electrical arachnids have been so industriously spinning a copper web that upwards of 600,000 miles of telephone wire now cover this continent, placing some 400,000 persons in talking relations with each other, and annually transmitting about 900,000,000 messages. But the invention of the telephone.was only half the solution of the transmission problem, for the instrument itself was useless without the necessary connecting circuit. Receivers and transmitters are now much the same that they were twenty years ago, but a vast amount of skill and ingenuity has been expended upon apparatus for rapidly, effectually and economically placing subscribers in talking relations with each other and the telephonist of to-day is essentially a "Transmission Engineer."

When telephonic communication is limited to two persons, it is simplicity itself to connect them by the requisite circuit, and provide proper signals to attract attention to the reception of messages, but when the correspondents in a single municipality are to be numbered by thousands and tens of thousands, it is physically and financially impossible to erect a line from each station to all of the others, so early telephone undertakings developed the idea of the "central office," to which lines from all subscribers in the immediate vicinity converge, equipped with the necessary paraphernalia for interconnecting at pleasure any pair of circuits. To carry out the exchange system, the first requisite is to provide each circuit with some form of apparatus whereby the person desiring to send a message may gain the attention of the central office attendant. As the early telephonists comprised many recruits from the "locksmith and bell-hanger school," to which the degree of "electrician" had recently been added on account of a supposed familiarity with the installation of electric bells, it is not surprising that the earliest line signal was the then crude form of hotel annunciator. It consisted, as is shown on the left of Fig. 1, of a pair of bulky spools wound with cotton covered wire, over which an armature was pivoted, carrying a catch that normally retained in a vertical position a door, or shutter. Electrical excitement of the spools released the catch and allowed the shutter to fall forward, disclosing a name

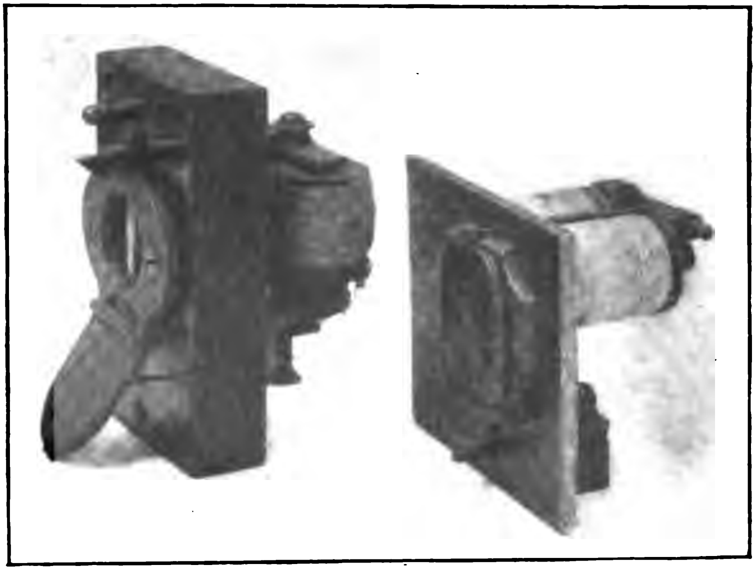


FIG. 1.

or number painted upon its inner surface. From the falling shutter, this piece of apparatus obtained the euphonious name of "drop," and as originally designed it was exceedingly clumsy, occupying a space of 2″ x 3 ½″, so but a very slight exhibition of mechanical skill sufficed to refine and compact it to a notable degree, developing the form shown upon the right-hand of Fig. 1. When it was attempted, however, to set annunciators of this description in sufficient proximity to each other to place before a single operator such a number of lines as it was possible for one person to adequately serve, much difficulty was experienced, due to the cross-talk developed by magnetic leakage between the spools of adjacent signals.

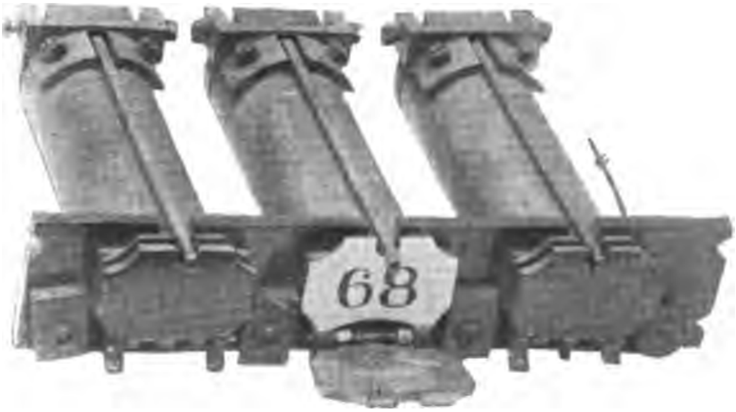


Fig. 2.

Increased mechanical skill and electrical knowledge obviated the cross-talk difficulty by ironcladding as shown in Fig. 2, and in this form, known as the "tubular drop," the line signal remained *in statu quo* for a number of years, and is still very widely employed. But in spite of improved mechanical and electrical details the tubular drop proved itself to be anything but an efficient signal. The falling shutter frequently did not attract the notice of the operator, even though the latter were careful and attentive. Accumulation of dust, either around the trunnions supporting the armature, or under the shutter hook, prevented the shutter from falling, and if adjusted for maximum sensitiveness, the slightest earth current, or the discharge from a summer thunder shower was often sufficient to display the signals of an entire switchboard. It is necessary to manually restore the shutter every time it falls, thus necessitating a considerable expenditure of time and energy for this purpose, and so the next step was the so-called self-restoring drop shown in Fig. 3.

Here great skill has been displayed in mechanically designing and constructing the signal. The head of the drop is provided with a double shutter, one thick and heavy of iron, retained in its place by a lever catch connected to the rear armature; the other, a thin outer flap of aluminium that normally conceals the number painted upon the iron disk. Electrically, as shown in Fig. 4, there are two spools. The right-hand winding is designed for the calling circuit, and when excited attracts the rear armature of the drop, lifting the catch and allowing the heavy iron shutter to fall forward, thus raising the aluminium flap and disclosing the number. The other winding comprises the restoring circuit consisting of a smaller spool which may be excited by a battery controlled by the operator in front of whom the drop is placed, the magnetism thus developed being sufficient to pull the heavy iron shutter back into its place, allowing the aluminium flap and catch to return, thus restoring the drop to its calling position.

Fig. 3.

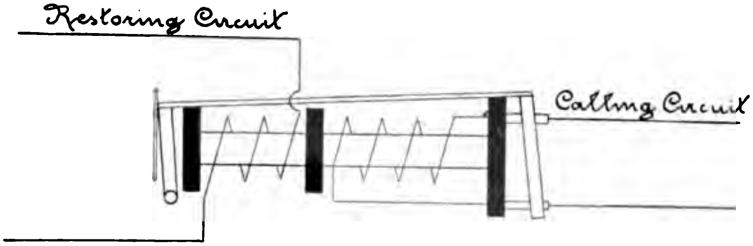


Fig. 4.

Line signals should possess five characteristics.

1st. Certainty in operation.

2nd. Ability to immediately attract attention.

3rd. Positiveness in the information conveyed.
4th. Compactness.
5th. Automatic Operation.

The attempt to simultaneously attain all of these features has given rise to hosts of devices which, for purposes of classification, may be roughly divided into three groups:

1st. Electric Signals.
2nd. Electro-Mechanical signals.
3rd. Luminous Signals.

The self-restoring drop is the best illustration of a signal of the first class. The excitation of the tripping coil by the subscribers' ringing current exhibits the signal, while with the second circuit the operator electrically restores the signal to its normal position. The second division is exemplified by the devices shown in Figs. 5 and 6. The contrivance illustrated in Fig. 5 is a particularly successful one, as it is reliable, compact and automatic. It consists of a spool surrounded by a pivoted sheet iron armature. Normally, the armature occupies the position shown at the right-hand of the illustration and is out of sight, but on exciting the spool the magnetization induced causes the armature to rise into the position shown at the left of the illustration, displaying the number painted upon the face of the armature. From the method of operation, this signal has received the suggestive cognomen of

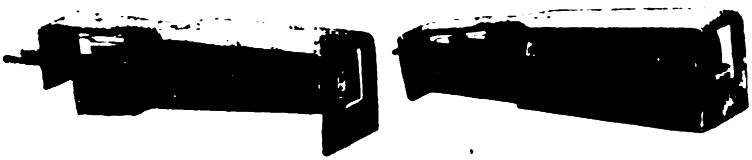


FIG. 5.


FIG. 6.

"tip-up." Unfortunately this signal is only well adapted for use where battery currents are employed, as it is not so effective with alternating currents, and in order for the signal to remain visible the magnet must be continuously excited. The arrangement shown in Fig. 6 is ingenious and seems to possess much merit, but has never received a wide application. The usual exciting spool is supplied with a pair of projecting pole-pieces which surround a slightly inclined tube. In this tube a silvered steel ball is placed and the tube so inclined that normally the ball rolls out of view. When the spool is excited the magnetization developed causes the ball to roll forward and to project through a plate covering the orifice of the tube, which also prevents it from being expelled and lost.

Many forms of luminous signals have been suggested but the only one in successful operation at present is the miniature incandescent lamp which has, on the whole, proven itself of the greatest value. So far as the writer can ascertain, the idea of employing incandescent lamps for signal purposes arose with Mr. J. J. O'Connell of the Chicago Telephone Co., who suggested in 1888, the employment of an incandescent lamp upon burglar alarm circuits in order to permit the legitimate occupant of a protected room to send to the alarm office an identification signal whereby his entrance to the premises could be made known.

In the latter part of the summer of 1890 some of the trunk lines in use in Chicago were provided with disconnect signals using miniature incandescent lamps. At the receiving office the trunk lines terminated in the ordinary cords and plugs used upon a telephone switchboard, in front of each of which an incandescent lamp was located. So long as the line was in use a relay in conjunction therewith was excited by battery current flowing over the line, and its armature drawn up. As soon as conversation was completed the operator at the originating office withdrew the plug from the trunk line jack at that office. thus opening the battery circuit and causing the relay to be de-energized; the release of the relay armature completed a local battery circuit, illuminating the incandescent lamp. The operator at the receiving office noticing the illumination of the lamp was thereby informed that conversation was completed and instructed to remove the trunk line plug. As the local lamp circuit was carried through the operator's listening key, the placing of this key in the testing position extinguished the lamp. A very short experience served to demonstrate the superiority of incandescent lamps over any other form of signal, for the illuminated lamp was at once so positive and distinct as to instantly attract the attention of the operator, thus markedly accelerating switchboard work. As a result of this experience, most of the trunk lines in the main office of the Chicago Telephone Company were rapidly supplied with lamp signals.

In the spring of 1893 it was proposed to re-equip a large multiple board in the Chicago exchange with self-restoring drops, but the expense and difficulty of this change caused the management to hesitate, and at this time the writer suggested the employment of incandescent lamps as subscribers' line signals on the ground of greater economy in space, and in installation, as well as improved signal efficiency. More conservative telephonists doubted the wisdom of such a recommendation, fearing that the numerous relay contacts would be a perpetual source of trouble, and no further steps were taken with this project. In the winter of 1894 a new type of switchboard known as the "express board" was introduced. As this board was designed to meet the wants of metallic circuit subscribers, particularly those whose telephonic business was large, it was decided to provide incandescent lamp line signals. The circuit of this board was so arranged that on the removal of the subscriber's receiver from its suspending hook, the movement of the hook closed the circuit and allowed battery current to flow through the line. This current actuated a relay at the exchange, in the local of which the signal was placed, situated behind a ground glass shade upon which the number of the subscriber was painted. The illumination of this disk displayed a very distinct and conspicuous signal that immediately attracted the operator's attention. Notwithstanding some apprehension as to the possibility of trouble with relay contacts the service given by the lamp signal was, on the whole, so satisfactory as immediately to concentrate telephonic attention upon the use of lamps, and within the four years that have since elapsed, the superiority of the incandescent lamp for this purpose has been so fully demonstrated that nearly all of the large switchboards which are at present being constructed are completely supplied with signals of this description.

As the service to which the incandescent lamp when used as a signal is subjected is peculiar, the employment of lamps upon telephone switchboards has afforded lamp manufacturers a new

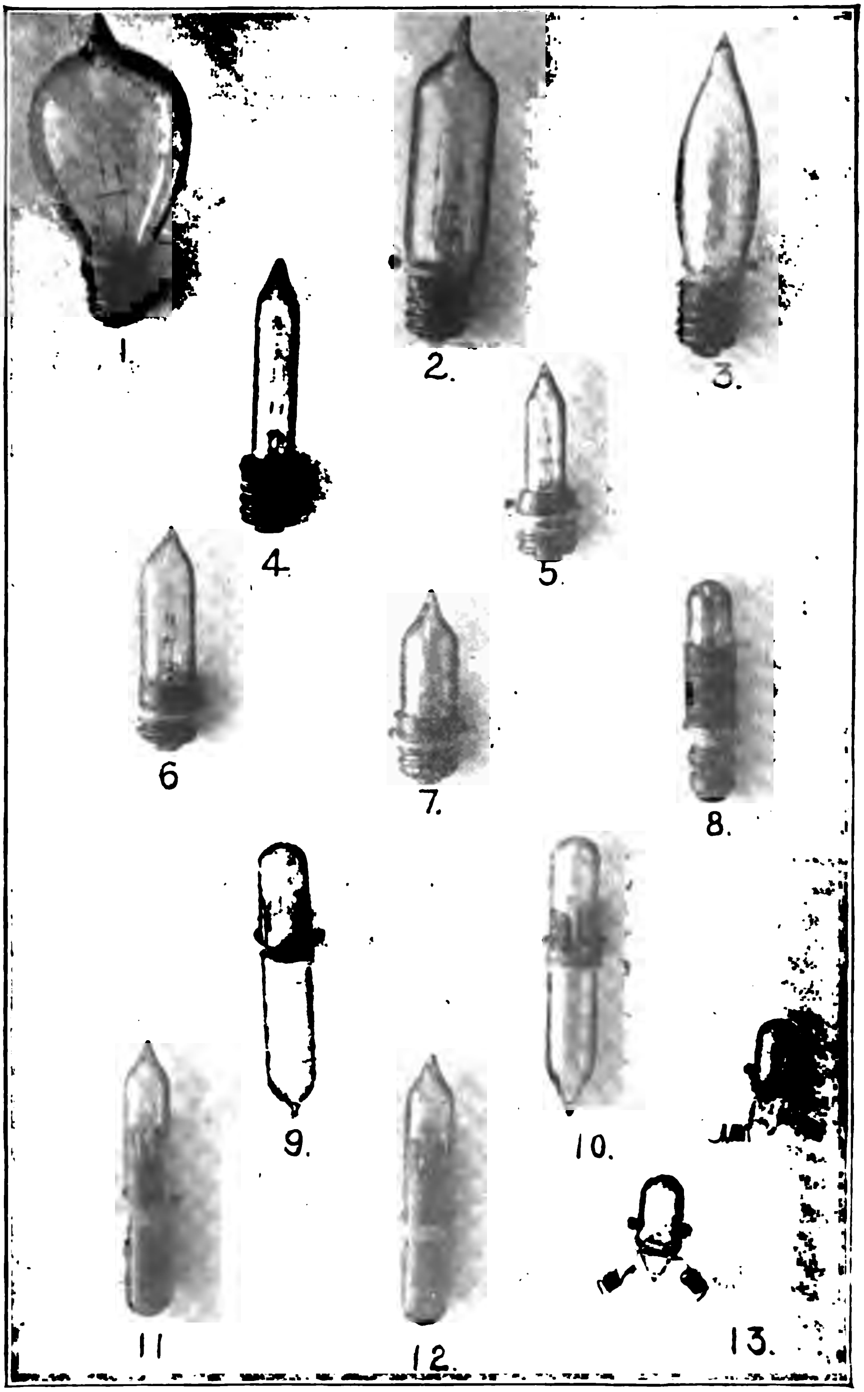


Fig. 7.

problem. In the early experiments ordinary miniature lamps of low voltage were employed. As these lamps were bulky and consumed a large amount of current, the first attempts at improvement were directed to obtaining a smaller and more economical lamp. The various changes through which the lamp has passed are illustrated in Fig. 7, in which No. 1 is the original type of lamp employed, Nos. 11 and 12 are those which experience has now demonstrated to be the most successful. Lamp No. 1 had a bulb about one inch in diameter and was about two inches long. Electrically it was designed for a four-volt circuit requiring over one-half ampere, and giving about two C. P. Lamps Nos. 11 and 12 are 1¾ inches long with a bulb ¼ inch in diameter. They are designed for a 24-volt circuit, consume about .1 ampere and yield over ¼ C. P. The early lamps were designed entirely to fit a socket supplied with a screw thread, as exemplified in Fig. 8.

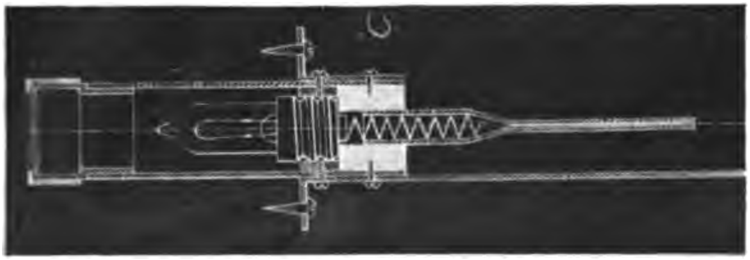


FIG. 8.

The socket consisted of a brass tube, in the bottom of which a screw base was placed matching the thread upon the lamp. A cap carrying a ground glass shade covered the front end of the tube, while from the rear two conductors extended, one fastened to the thread of the socket, thus connecting with one of the lamp leading-in wires, while the other was arranged to make contact with the other leading-in wire in the center of the lamp base. This conductor was supplied with a spiral spring, the pressure of which it was expected would lock the lamp in its place and constantly maintain good electrical contact. This expectation was not fulfilled, for one of the greatest troubles encountered has been the loosening of the lamp in its socket, due to the almost inappreciable jarring to which all buildings are subjected. Lamps in sockets of this description will gradually unscrew, opening the electrical circuit. They are then incapacitated as signals and considerable complaint will arise. Lamp sockets of this kind were designed for lamps Nos 4 to 7, inclusive (Fig. 7), and could be placed on wooden strips for mounting in the switchboard on one inch centers. The various changes in form through which the lamp bulb has passed are illustrated in Fig. 7, showing the gradual steps whereby the size of the bulb has been reduced until, as shown in Nos. 11 and 12, the present lamp occupies no greater volume than that required by a spring-jack and may be inserted into sockets composed of pairs of springs arranged on a rubber strip. Such sockets so closely resemble standard spring-jacks that they are called "lamp-jacks," for they occupy the same space, and may be secured in the switchboard in the same manner. By placing alternate strips of lamp sockets and jacks, the subscriber's line signal and answering jack may be more closely associated than has previously been possible; space economized in the switchboard and service accelerated.

At first it was considered desirable by lamp manufacturers to preserve a large volume in the bulb of the lamp in order to secure an adequate vacuum. To attain the desired compactness, the bulbs of the lamps were made smaller and longer, as is shown in Fig. 7, numbers 2 and 7 inclusive. Gradually, improvements in manufacture were sufficient to reduce the bulb of the lamp to a smaller diameter than that of the screw base, and it at once became apparent that some other method of securing the lamp in its socket would still further contribute to compactness. The next step was the construction of an exceedingly small bulb lamp, shown in Fig. 7, No. 13, which was secured to a wooden base carrying two metal rings to which the leading-in wires of the lamp were soldered, the complete lamp being shown in Fig. 7 No. 8. Whether the theory that the small sized bulb militates against a sufficient vacuum is correct, or not, it has been impossible to definitely ascertain, but experience has shown that lamps having bulbs as small as is indicated in No. 13 were not so successful as large ones. In order to retain the compactness thereby attained, a long and slim bulb was made, as shown in Nos. 9 and 10. In this lamp an additional advantage was secured by placing the filament at the end of the glass opposite the seal. This end could be blown hemispherically and quite thin, thus allowing a maximum of light to be transmitted. Lamps of this description were chiefly made for four-volt circuits, the filament consisting of a very thin thread of carbon stretched between two platinum wires. These leading-in wires were fused through the sides of the bulb and soldered to two bits of thin copper forming the contact strips that were cemented to the glass tube. Some difficulty was experienced in the peeling off of these pieces, and, in addition, the amount of platinum in the leading-in wires was so great as to considerably increase the cost of such lamps. So, from motives of economy, a partial reversion toward earlier forms has taken place in the present standard lamp, as shown in Fig. 7, numbers 11 and 12. The bulb is a glass tube about ½″ in diameter and 1⅛″ long. For four-volt lamps a straight filament is used, but for all others a horse-shoe shape. Only sufficient platinum is employed in the leading-in wire to pass through the glass, and in other respects the general details of manufacture correspond closely to the best practice in standard lamp construction. The base of the lamp is a bit of boxwood, so shaped as to readily enter the springs forming the socket, and arranged to prevent the lamp from turning as it is pushed into place.

The earliest lamps were all designed for low voltage circuits, rarely more than four volts. Presently it became apparent that lamps of longer life, together with an economy in conducting circuits could easily be attained by the use of higher voltages, and the next advance was secured by making lamps for 10 and 20 volts, while at present 12 and 24 volt lamps are standard.

When first used as signals, the lamps were placed in the local of a relay actuated by current passing over the line to which the signal was attached. In the early attempts the ordinary telegraph relay was employed, armed with extra heavy platinum contacts to prevent burning. It seemed possible to obviate the expense of installing and maintaining this relay by an appropriate lamp directly in series with the subscriber's line, so placed that the removal of the telephone from its hook should close the circuit and light the lamp. This experiment was first tried in the Chicago express office and, on the whole, worked passably well, there being a comparatively small mortality of lamps due to short-circuits and other accidents. A continuation of this experiment was attempted in another office but resulted disastrously as the lamps were burned out so rapidly as to cause an excessive maintenance expense. The occasion of this failure is to be ascribed to a preponderance of ærial lines in the last case.

A wind-cross occurring near the office on a long line would subject the lamp to an abnormal voltage and either injure or immediately destroy it. In an express office where the lines were chiefly underground, little or no trouble was experienced from this cause, and in an office in St. Louis, similarly equipped with lamp line signals placed directly on the subscriber's line, the use of a very heavy filament lamp obviated the difficulty experienced with injury to lamps. But while economy in installation due to the omission of the relay is eminently desirable, present experience decidedly indicates that the relay is essential to the successful lamp signal.

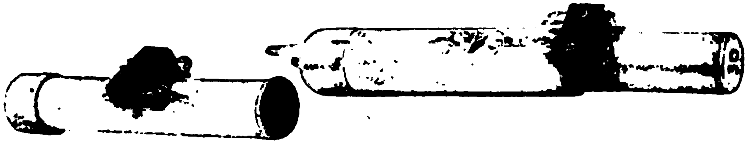


FIG. 9.

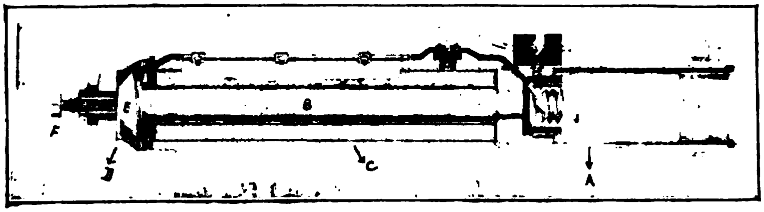


FIG. 10.

For this purpose rather an interesting type has been evolved in an attempt to consolidate the relay, lamp and socket into a single piece of apparatus and at once obtain a device which should be absolutely dust-proof and free from trunnion trouble. A general view of this relay which was developed largely with the assistance of Mr. M. A. Edson of the Chicago Telephone Company, is shown in Fig. 9 and a section in Fig. 10.

From the latter illustration it will be seen that the front end of the " lamp relay," as it is termed, consisted of a brass tube A, forming the lamp socket, carrying the screw at the bottom, supplied with round glass cap, carrying the subscriber's number. From the rear of the socket extends a core B, of soft iron sursounded by an iron tube C, between which the winding space was obtained. A hemisperical brass cap D covered the end of the iron tube, retained in its place by an appropriate set screw. The inside of this cap was hollowed out, containing a piece of soft iron E, in the form of a frustrum of a cone, that constituted the armature. As this piece of apparatus was set horizontally the armature rested upon its edge in an unstable position, tending to settle backwards and rest against the back of the cap. The excitation of the windings magnetizes the core and attracting the armature, draws it up sharply. A thin platinum spring placed on the front face of the armature serves to make contact with a corresponding platinum point set in the center of the core. As the core is insulated from everything but one lamp wire, while the other is connected to the cap, the excitation of the relay lights the lamp. By this device a relay was obtained, the moving parts of which were completely dust-proof. All trunnions or hinges were obviated and the armature merely resting upon a sharp edge secures a minimum amount of friction. Notwithstanding the compactness and completeness of this piece of apparatus, it has been found desirable to disassociate the relays and lamps, placing the relays in a case by themselves, away from the switchboard.

Probably the most gratifying feature in the evolution of the line signal has been the improvement in the life of miniature lamps. When the luminous signal was first proposed the question of cost of lamp renewals was at once raised. As each lamp was only illuminated for a few seconds at a time the service seemed equivalent to constant flashing, and ominous prophecies were plenty as to the short life to be expected. It was confidently asserted that such small lamps would either immediately burn out, or else so rapidly become dim as to be valueless as signals. Some tests were immediately instituted in the hope of eliciting information on these points. There was no question but that the candle power of the lamps gradually declined, and photometric measurements showed that when a lamp failed to emit at least .05 candle power, it became of no value as a signal.

To determine the resistance to flashing, a number of lamps were connected in circuit with a clock pendulum and flashed at intervals one second for nearly a month, with no signs of serious injury. During this test the lamps were illuminated more than a million times, so it seemed certain that a reasonably long life could be expected. Experience has since shown this conclusion to be justified, for in the main office switchboard in Chicago, there are now lamps at work that have been in service for upwards of three years and seem still to be in fairly good condition. Observation has further shown that accidental injuries rather than old age, is the cause of most lamp failures.

Much delay was experienced in obtaining the first lot of switchboard lamps, so on reception they were immediately placed in service without inspection. The rapid failure of a large number of these caused no small degree of consternation and it was determined to initiate a systematic inspection. As a result, all lamps are now examined: 1.—Mechanically, to see if they will fit the sockets. 2.—Electrically, to determine if they have the proper voltage and consume current within the specified limits. 3.—Optically, to ascertain if they emit the required candle power, and absorb the proper watts per candle. Also a certain number of lamps from each lot are placed on life test and burned to destruction.

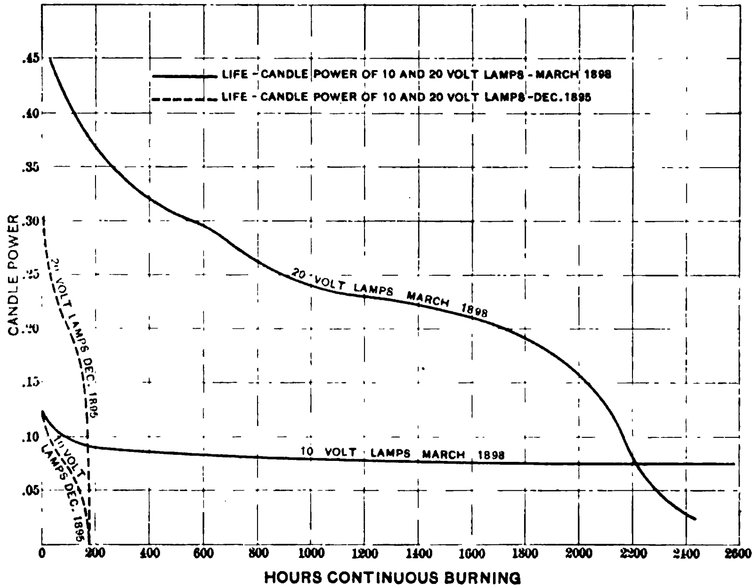


Fig 11.

In Fig. 11 four curves are given that show at a glance the improvement that has taken place in lamp life. The dotted lines are curves of life and candle power of ten samples, each of 10 and 20-volt lamps tested in 1895, while the full lines are the results from twenty samples of 10 and 20-volt lamps of the present date. In 1895, only 200 hours' life could be expected, while from the latest tests the 20-volt lamps show 2400 hours' life before failure, and the 10-volt lamps show 2500 hours, and are still burning with indications of considerable additional life.

In Fig. 12 is an interesting comparison of the rate of failure of sample lamps tested in 1897, and at the present time. Curves 1, 2, 3 and 5 are for 20-volt lamps of different makers, while curve 4 is for four-volt lamps. The ordinates are the number of lamps on test at the various times represented by the abscissæ in hours, so that the life of each lamp is plainly shown. The four-volt lamps failed almost immediately, only yielding upwards of 50 hours. The 20-volt lamps, curves 1, 2 and 3, tested in 1897, gave upwards of 600 hours life as an average, those indicated by curve 1 showing the greatest uniformity. In curve 5, the results of ten 20-volt lamps tested this spring are plotted; one lamp failed after 40 hours, but the filament was manifestly defective at the start. Nineteen lamps lasted over 1900 hours and one lamp over 2500 hours.

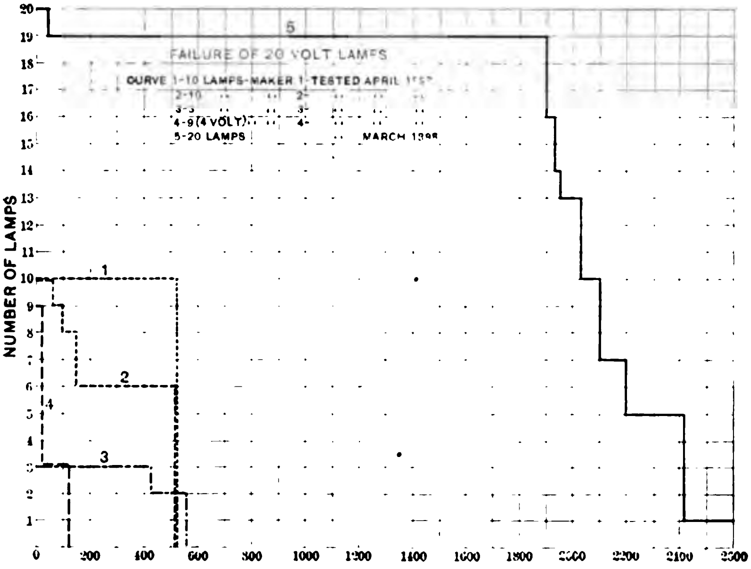


FIG. 12.

In Fig. 13 the curves of 10-volt lamps tested in a similar manner are shown. These results indicate a much greater irregularity for the 10-volt lamps. The lamps of curve 3 make a bad showing, only one lamp lasting over 40 hours; those of curves 1 and 2 are much better, indicating a life of 400 hours, but still are much below the life shown by the 20-volt lamps. Curve 4 represents the results of tests upon twenty 10-volt lamps recently manufactured. This curve is a straight line for 2500 hours, showing that so far no failures have occurred, and from the appearance of the filament, it is reasonable to expect several hundred hours more life.

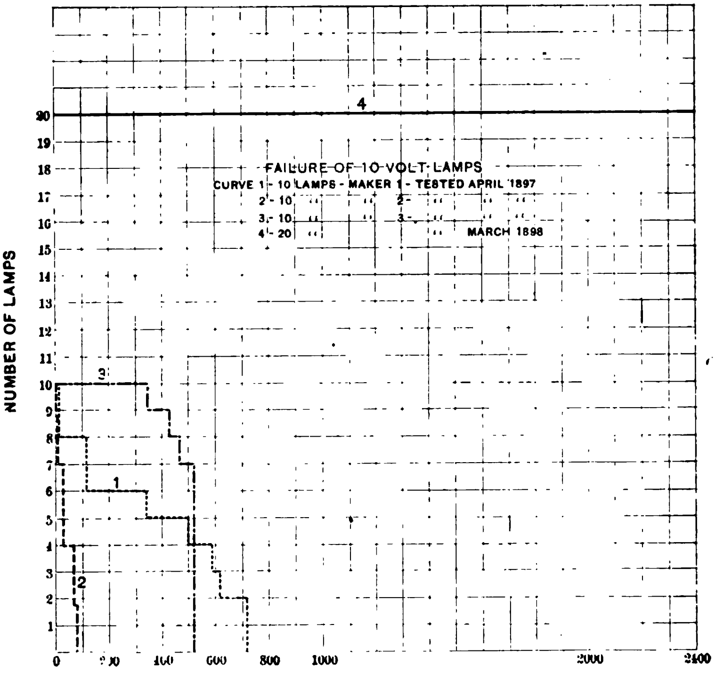


FIG. 13.

In Fig. 14 some information is plotted relative to candle-power, life and voltage of 20-volt lamps. Curves 1, 2 and 3 show the relation between the life and candle-power of 20-volt lamps when placed upon circuits of respectively 21, 20 and 18½ volts. The left-hand scale in candle-power applies to these lines. Curve No. 4 is a life-voltage curve, for which the scale of volts on the right-hand should be used. For all these curves the abscissæ are in hours. These lines strikingly illustrate the relation between life and candle power. As switchboard lamps are usually sup-

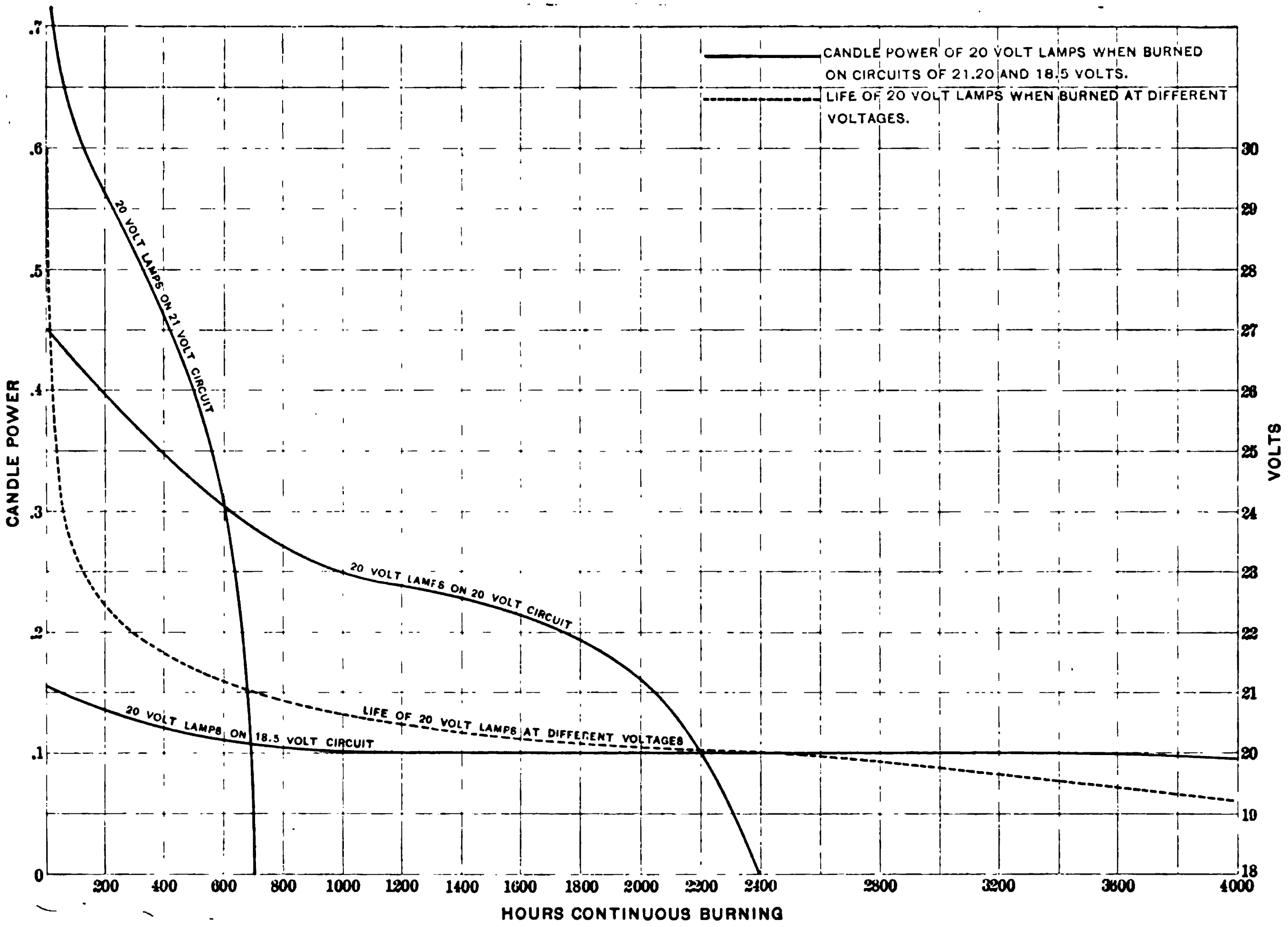

CANDLE POWER OF 20 VOLT LAMPS WHEN BURNED ON CIRCUITS OF 21.20 AND 18.5 VOLTS.
LIFE OF 20 VOLT LAMPS WHEN BURNED AT DIFFERENT VOLTAGES.
20 VOLT LAMPS ON 21 VOLT CIRCUIT
20 VOLT LAMPS ON 20 VOLT CIRCUIT
LIFE OF 20 VOLT LAMPS AT DIFFERENT VOLTAGES
20 VOLT LAMPS ON 18.5 VOLT CIRCUIT
CANDLE POWER
.7
.6
.5
.4
.3
.2
.1
0
VOLTS
30
29
28
27
26
25
24
23
22
21
20
10
18
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2800
3200
3600
4000
HOURS CONTINUOUS BURNING

FIG. 14.

plied by 10 cells of storage battery, it is impracticable to always maintain them at precisely a constant potential, for the pressure is likely to vary one or two volts from that of full charge to that of discharge and regulating resistances are more expensive than decreased lamp life. Even at the highest pressure, it is interesting to note that the lamps at present show a life of over 1400 hours.

Lamp experts will at once infer that improved life is obtained by a lamp of low efficiency and will urge the cost of the current as an insuperable objection. The total cost of a luminous signal is evidently the cost of the lamp, plus the cost of current consumed during its life, and it is easy to show that this is a minimum when the cost of the energy consumed is equal to the cost of the lamp. Switchboard lamps now cost in the neighborhood of 45 cents each. With a life of say 2,000 hours, the cost of energy is about 60 cents, but it has been shown that accidental causes tend to reduce the actual life in the switchboard far below that shown by laboratory tests and it is doubtful if the average lamp lives for 1,200 hours. Unless accidental destruction can be greatly reduced below the present amount, the cost of the lamp is now considerably above the cost of energy during its life and a still lower efficiency could profitably be employed, for it must be remembered that the thick heavy filament in the low efficiency lamps is the best insurance against accidental injury. Theoretically, subscribers' line lamps should last 25 years; cord supervisory lamps from one to two years; trunk line lamps the same length of time, and pilot lamps from three to six months. Such a life as this has been obtained in the cord and pilot lamps, but it is doubtful if the theoretical limit for the line lamps will ever be closely approximated.

Even in the present probably only partially developed state of the luminous signal, some 20,000 subscribers are now served upon boards thus equipped, and switchboards for as many more are in process of construction. Already the adoption of this form of signal has materially modified the arrangement and design of switchboard apparatus, and has been so efficient a factor in the improvement of telephonic service that it is difficult to prophesy the end of its effect.

In conclusion, the writer is only too glad of an occasion to express his appreciation of the promptness with which the various lamp manufacturers have taken up the problem of the line lamp signal, in the solution of which they have spared neither pains nor expense.

A Paper presented at the 15th General Meeting of the American Institute of Electrical Engineers, Omaha, June 29, 1898, President Kennelly in the Chair.

SOME TELEPHONE DISTURBANCES FROM ELECTRICAL GENERATORS.

BY GEORGE D. SHEPARDSON.

The modern tendency toward concentration of power plants and the use of larger units has caused some unexpected secondary results. In one of our western cities the street railway company recently built a modern power-house with seven directly connected generators, two direct current generators of 700 K. W. capacity which feed directly into the trolley lines, and five three-phase 700 K. W. alternators which drive five rotaries located at three sub-stations. The rotaries displace three steam equipments with a number of 175 K. W. generators. At about the same time in the same city the principal lighting company displaced the steam equipment in one of its direct current constant potential stations by rotaries driven by three-phase currents from its main station. When the rotaries were put into service, the telephones of the city were at once greatly disturbed by a loud roaring noise which seriously interfered with their satisfactory operation and which even made many telephones useless. While the telephone company was attempting to locate the cause and find a remedy for the troubles, the lighting company found that it also had troubles of its own, as the constant potential arc lamps which had been burning quietly, now began to hum and roar as if operated by alternating currents.

The subject promised to be of much interest, and was studied from an independent standpoint at the University of Minnesota by Instructor F. W. Springer and the writer. While the ground has not yet been entirely covered, enough of interest has developed to warrant a preliminary report with the hope that others may find opportunity and interest to carry on further studies along the lines suggested.

No doubt much of the work here reported has been done before in the company laboratories, but such work seems not to have been published.

In order to work more intelligently, a preliminary search was made to discover the disturbances that had been met by telephones before, and their names were found to be legion.

The marvelous sensitiveness of the telephone, exceeded only by that of the galvanometer, has made it unusually subject to disturbing influences. Coming into public use at about the same time as the electric light, its lines were extended more rapidly at first and many towns boasted of telephone exchanges long before the advent of electric lighting plants. When the lighting plants were put into operation later, the telephone lines theretofore operating in blissful peace and quiet, were now seriously menaced as one of their engineers aptly quoted[1] by a "pestilence that walketh in darkness" and by "destruction that wasteth at noonday." Hardly had the lines been freed from the disturbing influence of the direct current incandescent and the more troublesome arc circuits, when the alternating current system took the field with its widely scattered lines and its wider range of induction and the way of the telephone manager was thereafter indeed as hard as that of the transgressor should be. Hardly had the telephone adjusted itself to the new source of disturbance when still another enemy arose in the shape of the electric railway, which, metaphorically speaking, demanded that the telephone, like the Chinaman, should "get off the earth." Many legal battles have been fought with varying success, but the general conclusion seems to be that no one interest owns the whole earth, and that in case of interference the weaker must look out for its own protection. The remedies that have been proposed for obviating or neutralizing telephonic disturbances are too many even to catalogue in a paper treating principally with causes. As early as 1883, there were 200 or more patents for preventing induction, and the later years doubtless have been even more prolific.

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1. Lockwood, National Telephone Exchange Association, Sept., 1883. *El. World*, 12: 142. Lon. *El. Rev.*, 23: 441. West. Electrician, 3: 149. N. Y. *El. Engineer*, 7: 485. Walker, Lon. *El. Rev.* 12: 278. *El. World*, 1: 344. See also Lon. *El. Rev.*, 34: 345. 32: 692. N. Y. *El. Engineer*, 15: 474.

Telephone engineers have devoted much time and attention to the various causes for the noises that disturb the telephone and have specified them somewhat as follows: Long telephone lines are subject to the same disturbances[2] that affect the less sensitive telegraph. Some of these are of more or less constant strength and do not make a noise in the telephone, but only alter its sensitiveness by strengthening or weakening the permanent magnet. Such are the regular earth currents caused by the rotation of the earth, or those caused by electro-chemical action due to the differences in the soil at the ends of the line, or to differences in the composition or cleanness of the earth-plates, or thermo-electric currents due to differences of temperature at different parts of the line. The irregular currents that sometimes affect telephones may be caused by induction from the earth's magnetism as the wires swing back and forth in the wind, from induction as wires of different circuits approach and recede while swinging in the wind, by differences in the height above the earth in different parts of the line, by static charges from passing clouds or rising vapors, by changes in the electric state of the atmosphere, possibly by electromotive forces due to earth tremors, by mechanical vibrations of the wires, by a sort of microphonic action at loose joints, by changes of resistance of line due to temperature. Such disturbances seem to become less when the insulation of the line is low.

Disturbing currents from other wires are found to come by leakage and by induction, both electro-static and electro-dynamic, those being overcome by careful insulation and transposition of circuits. The disturbing currents are found to be greater from alternating or arc light circuits than from constant potential direct current circuits; open circuit arc machines are worse than closed coil machines, the noise becoming less as the number of bars in the commutators increases, and becoming greater[3] as the voltage increases.

That much of the trouble from other circuits comes by electrostatic induction was proved by Mr. J. J. Carty in his papers before the New York Electric Club[4] and before this[5] body. His

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[2] Lockwood, National Conference of Electricians, Sept. 12, 1884. Proceedings, p. 226. *El. World*, 4: 169.

[3] *El. World*, 19: 274.

[4] Carty, New York Electric Club, Nov. 21, 1889. *El. World*, 14: 361. Lon. *El. Rev.*, 25: 651. Lon. *Electrician*, 24: 122. N. Y. *El Engineer*, 9: 12. *West. Electrician*, 5: 282. *Elek. Zeit*, 11: 144.

conclusions have been substantiated by other experimenters, such as [6]Pierard, [7]Kennelly, [8]Bennett, [9]Dresing and Gulstad [10]Dunbar, and others. That much of it comes by leakage is a matter of daily observation.

The trouble from electric railway lines is generally considered as coming primarily and principally from the use of the ground return. If the railway currents were perfectly smooth and of uniform strength, it is generally agreed that they would not cause noises in the telephone, but would make them less sensitive. The irregularities and fluctuations in the railway current have been attributed to various causes, such as imperfect commutation[11] at the dynamos, imperfect connection between the trolley wire and supports, variable contact between the trolley and wire or between[12] the wheels and rails, lubrication[12] of the trolley, sparking at the motor[13] brushes or trolley or rails, variable speed of cars, motion of track[14] due to passage of car, to the motion[13] of the car, to noisy gearing[15], to vibration[13] of the motor. Strecker[16] says the noise varies with the voltage. Cardew[13] says it varies with the winding of the armature. There is probably more or less of disturbing influence from each of these alleged sources.

At first thought, the ordinary trolley of the American pattern would seem to give as certain contact as the shoe or harp used

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5. Carty, TRANSACTIONS, March 17, 1891. *El. World*, 17: 241, 276. Lon. *Electrician*, 26: 685, 705. Lon. *El. Review*, 28: 462. N. Y. *El Engineer*, 11: 366, 451. *West Electrician*, 8: 181, 210. N. Y. *El. Rev.*, 18: 82.

6. Pierard, *L'Eclairage Electrique*, 2: 121, Jan. 19, 1895, 10: 355. Feb. 20, 1897. *El. World*, 25: 181; 29: 362.

7. Kennelly, *El. World*, 17; 277. Lon. *Electrician*, 26: 763. Lon. *El. Rev.* 28: 747. N. Y. *El. Engineer*, 11: 450, 511, 547.

8. Bennett. Lon. *Electrician*, 26: 768.

9. Dresing and Gulstad, Lon. *El. Rev.*, 28: 589, 643, May, 1891.

10. Dunbar, *El. World*, 23: 83, 115.

11. Lon. *Electrician*; 36: 725; 37: 52. *El. World*, 12: 324. Lon. *El. Rev.*, 34: 339.

12. Wietlisbach, Lon. *Electrician*, 36: 725. N. Y. *El. Engineer*, 21: 388, 414, 440. *El. World*, 27: 438, 578. *Elek. Zeit.*, 17: 252. Perry, N. Y. *El. Engineer*, 9: 244. Van Vloten, *L'Eclairage Electrique*, 12: 415.

13. Cardew, Lon. *El. Rev.*, 33: 742. Lon. *Electrician*, 32: 236.

14. West, *Elek. Zeit.*, 17: 263. April 30, 1896. Lon. *El. Rev.*, 38: 640. Lon. *Electrician*, 37: 52.

15. Preller, Lon. *Electrician*, 36: 338, 557. *El. Railway Gazette*, Feb. 1, 1896. *El. World*, 27: 132, 293. *L'Eclairage Electrique*, 6: 411. Perry, N. Y. *El. Engineer*, 9: 244.

16. Strecker, *Elek. Zeit.*, 13: 128, Mar. 4, 1892. *El. World*, 20: 19.

on certain roads, yet eminent engineers, such as Wietlisbach[12], claim superiority for the sliding harp or bar, and appeal to experience. Lord Kelvin[17] states as his opinion that two or three wheels or a brush would obviate much of the difficulty. The most plausible explanation for the observed fact that roads using harp or bars disturb telephones less than those using wheels for contact with the trolley wire, seems to be that with the harps or bar trolleys the trolley wire need not be so accurately centered above the track as when a trolley wheel is used, therefore the line need not be supported at so frequent intervals and need not be drawn up so tightly. The tighter wire more easily gets thrown into rapid vibration, which in turn causes a considerable variation in the pressure between the trolley and the wire, hence setting up a microphonic action that affects the telephones. The lubricant on the trolley probably acts in a similar way. Experiments by West show that there is quite a considerable variation in the resistance between the car wheels and the track, even with a comparatively clean rail; and he infers from this that some of the telephonic disturbance is due to microphonic action at the wheel as well as at the trolley. The noise also depends upon the nature of the track, being greater on a hard roadbed than on one cushioned. This is thought to be due to variations in the surface resistance between the rails and the surrounding earth as the car passes. Experiments by Behn-Eschenburg[18] seem to show that the noise is not due to such action at the rail, wheel or trolley, for by cutting out the motors and sending current from the trolley through a rheostat he found an entire absence of noise; this simply proves, however, that such source of noise is very small as compared with that from the motors. Another source of microphonic action that seems at least as important as the two preceding is that due to the vibration of the brushes of the motors on account of the commutator not being truly cylindrical, or on account of the brushes being set too nearly radial with insufficient pressure so that they chatter. The great telephonic disturbances noted when the brushes of generator or motor are sparking, may be microphonic or may be due to another cause to be noted later. That the noise varies with the speed of the motor is evident to all who have had occa-

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[17] Kelvin, Lon. *El. Rev.*, 33 : 742. Lon. *Electrician*, 32 : 236.

[18] Behn-Eschenburg, *Elek. Zeit.*, 17 : 173, July 16, 1896. *El. World*, 28 : 158, 173.

sion to use telephones with earth or common return in cities with electric cars. Following out this lead it seems reasonable that noisy gears disturb telephones more than quite ones, because quiet gears allow a more uniform motion of the motors, while noisy gears involve an uneven rate of transmission and hence an uneven speed of armature. A similar reason may account for the claim[14] that motors with chain connection create less disturbance to telephones than those having gears for transmission.

That a large share of the disturbance is caused by the motors themselves, is seen from the well-known fact that the starting of a car is accompanied by a distinct rumble that increases in pitch as the car comes up to speed until the noise becomes blended in the general confusion at the higher pitch. The noise is directly connected with the brushes and commutator, as is evidenced by the uniform pitch of the sound in the telephone and that heard directly from the singing of the brushes. That it is affected also by the design of the motor is shown by the well remembered action of the early railways; when the early Sprague railway motors were changed from 56 to 72 armature coils, the noises in the telephone were greatly reduced and one could easily tell what kind of motor was on an approaching car. Various reasons have been assigned for the cause of the noise from the brushes. The most common one is that the resistance of the motor changes as commutator bars come under the brushes, so that one or more coils are short-circuited and cut out of the circuit. Others think it may be due to "feathering" of the brushes[19], which allows a continual and uncertain change in the number of armature coils actually in the circuit.

When the street railway company referred to at the beginning of this paper changed over to the new arrangements for power, the great increase in the noises in the telephones was attributed to the fact that the new generators and rotaries had toothed armatures, whereas the old armatures had smooth cores and were surface wound. The greater self-induction in the toothed machines was supposed to cause irregularities or "wiggles" in the current. Some thought that the speed varied slightly in different parts of each revolution, while others thought that in some way part of the alternating current managed to get over into the direct current circuits without being transformed.

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[19] Wietlisbach, Lon. *Engineering*, Aug. 14, 1896. *Elek. Zeit.*, 17: 532. *El. World*, 28 : 283, 3.3.

In order to learn the truth of the matter, a number of experiments were tried. That no considerable part of the noise came from any lack of uniformity in the speed of the rotaries was proved by the absence in the telephone of any tone of a pitch equal to the product of revolutions by poles of the rotaries. A variation of speed with load was noticeable when each alternator was driving its own rotary, but this was largely obviated when the alternators were operated in parallel. In order to discover whether by any means part of the alternating current could or did get over to the direct current lines, observations were made upon the constant potential arc lamps operated by the rotaries of the lighting company. It was found that the hum of the arc lamps did not at all correspond with the frequency of the current, but that it did correspond exactly with the hum of the brushes, the pitch of which was equal to the product of revolutions by commutator bars. The cause of the noise in the telephones and arc lamps seemed therefore to be connected in some way with the commutation of the current at the direct current brushes.

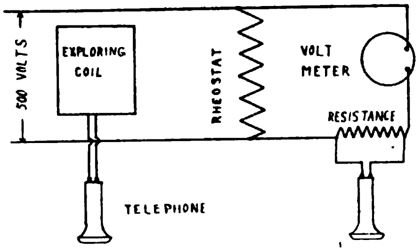

FIG. 1.

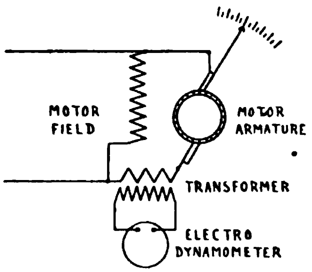

FIG. 2.

In order to work with greater facility and without incurring liability of interfering with the regular working of the commercial plants of the railway, lighting or telephone companies, further experiments were carried on in the electrical engineering laboratories of the University of Minnesota, where most of the conditions could be accurately reproduced and modified one at a time.

Preliminary experiments were first tried with a telephone receiver connected to an exploring coil of 150 turns, wound on a rectangular frame approximately 8″ long and 7″ wide, with a groove 1″ wide. This exploring coil was hung between the two main service wires leading to a 500-volt 40 H. P. motor connected with the power station. When a current of seven amperes from the power circuit was sent through a water rheostat, Fig. 1, a clear singing noise was noted in the telephone, which noise was attributed to the generators at the power-house. To make sure that the noise was not due to the water rheostat, a second test was made by shunting the receiver around a small resistance in series with a high-resistance voltmeter. The same noise was heard, and in addition definite beats could be distinguished at the rate of about two per second. These were thought to be due to interference between the generators at the power-house, where there were four power machines, one of which was of different make from the others.

The receiver was then connected with the exploring coil between the service wires, and the motor started. The original sound from the generators was now entirely obscured by a loud noise which was in unison with the singing of the motor brushes and which rose in pitch as the motor came up to speed. The brushes were now shifted to various positions, and the noise from the motor was found to be least for the position of least sparking, suggesting a means for finding such best position. The coarse coil of a 30-light transformer Fig. 2. was then inserted in the armature circuit, when the noise in the receiver attached to the exploring coil was greatly reduced, suggesting a possible means for reducing the fluctuations or "ironing out the wrinkles" in the current from the generators. In fact the lighting company found that the humming of its constant potential arc lamps was greatly reduced by the insertion of a choke coil in series. (The noise was also reduced by tightening all loose parts of the lamp in order to reduce mechanical vibration.) This suggests that the choke coils wound on heavy iron cores formerly used in Sprague railway power-houses between the lightning arresters and the 'bus bars were more useful in reducing the pulsations of the current than they were for choking back the lighting.

A Weston A. C. voltmeter was then connected to the fine wire coil of the transformer, and it was found to read seven volts when the armature current was 18 amperes. In order to make sure that there was no mistake, two sets of readings were taken while the brushes were shifted to various positions, one set with the motor armature taking about six amperes and the other with about 18 amperes, it being difficult to keep the current and speed.

exactly constant while shifting the brushes. A scale was attached to the brush-yoke and divided so that one division represented a shifting of the brushes equal to the width of one commutator bar. A number of readings were then taken, the means of which are given in Table I. The voltmeter readings are not very accurate, since they all come on the lowest part of the scale where it is not closely divided.

TABLE I.

Effect of Current Strength upon Fluctuations Through Transformer With Iron Core. 500 Volt-Motor.

Position of Brushes.	Volts on Secondary.		
	3 Amperes.	6 Amperes.	18 Amperes.
3	—	—	12.5
3½	—	15	8.5
4	—	6	5.5
4⅝	11	7	3
5	9	6	2.5
6	8	6	4.5
7	8	7	5
8	8.5	8	7.5
8⅛	—	11	9
9	11	—	—

In Table I. the brushes have forward lead in position 3, and backward lead in position 8. It is seen that for every position of the brushes the voltage on the secondary is higher with the smaller current than with the larger. This did not seem right, and another test was made with the telephone and exploring coil. In this case the noise in the telephone was directly proportional to the current in the armature, as would have been expected. The contrary results with the transformer were then attributed to the fact that the iron core of the transformer was so highly saturated by the current of 18 amperes that the pulsations had less effect than those of the six-ampere current and still less than those with the three-ampere current, although the former were actually much greater. Similar results were obtained with other transformers and it was found misleading to have any iron in the transformer. Two coils were then wound on a cylindrical wooden core 14″ in diameter, one coil of 28 turns of No. 10 B &

S G and one of 342 turns of No. 20 B & S G. These were arranged so that the coarse coil in series with the armature remained stationary, while the other was movable along a pine stick parallel to their common axis. The telephone receiver was then connected to the fine wire coil, and the armature current was sent through the coarse wire coil. By moving the fine wire coil along the stick it was intended to find the position where the sound in the telephone would disappear. But the arrangement proved to be too sensitive even when only one turn of the coarse wire was left in circuit and the fine wire coil was moved 100″ away, the sound from the motor still being quite distinguishable. As at that time the writer did not recall the differential method of opposing the action of the first coil by that of a third, in which a uniform alternating current might be sent from an independent source, and as later it was questioned whether the balance would be reliable because the pulsations at the armature were not sine functions, it was decided to make use of a sensitive electro-dynamometer for measuring the currents induced in the secondary of the air-core transformer. After some preliminary work the two coils were arranged on a common axis, being separated by the distance of one inch. The fine wire coil was connected to an electro-dynamometer having a resistance of 100 ohms and being free from metallic masses near the coils.

The 500-volt machine was then operated as a motor, and two sets of readings were taken with the air-core transformer and electro-dynamometer to compare with those taken with the iron-core transformer and the Weston voltmeter. The averages of ten readings taken at each position of the brushes are given in Table II., from which it is seen that except for the extreme forward position of the brushes, the pulsations in the current are greater with 13.3 amperes than with 6.3 amperes, as might naturally be expected. From later experience it is believed that inaccuracy in setting the brushes or a possible slight displacement of the index would account for the apparently greater deflections by the smaller current at positions of forward lead.

While the iron-core transformer was in series with the armature, another experiment was tried to discover the effect of staggering the brushes. The load on motor was kept constant and two runs were made, one with the brushes set normally, all leaving commutator bars simultaneously; while in the second run, the positive brushes were left in their usual position while the negative brushes were blocked out so that their toes were at the middle of a bar when the toes of the positive brushes were just leaving a bar. The brush-yoke was then moved to different positions and corresponding readings were taken on the voltmeter in the secondary circuit. The readings given in Table III. show that staggering the brushes effects a considerable reduction in the irregularities of the current. In the machine under experiment the carbon brushes spanned two whole bars of the commutator, so that displacing one set only a half bar had less effect than would be expected if the brushes covered only the width of one bar. That the pressure upon the carbon brushes has a considerable effect upon the smoothness of the current from the generator is shown by an experiment in which the electro-dynamometer gave a deflection of 53.5 millimeters when the pressure against the carbon brushes was only moderate, while it was reduced to 7.4 by tightening the springs, the current remaining 6.6 amperes in both cases. The time at our disposal did not allow further tests along this line, but it suggests an interesting field for studying how the smoothness of the

TABLE II.

Effect of Brush Position upon Fluctuations Through Transformer With Air Core. 500-Volt Motor.

Position of Brushes.	E. M. F. on Secondary.	
	6.3 Amperes.	13.3 Amperes.
4	—	30.3
4⅜	26.6	(22)
4½	(22)	20
4⅝	19.1	(17.5)
5	14.1	12.5
5½	12.4	14.1
6	11.3	14.2
6½	9.2	12.9
7	12.8	13.4
7½	12.8	15.2
8	13.4	18.7
8½	15.4	20.7
9	22	26.1
9⅜	37.3	—

current is affected by width of brushes, by various kinds of brush such as carbon, copper, leaf, gauze, and the various anti-sparking high resistance materials on the market. It seems probable also that the best pressure and best angle for the carbon brushes might be studied to advantage by the telephone or electro-dynamometer method.

TABLE III.

Effect of Staggered Brushes upon Fluctuations Through Transformer With Iron Core. 500-Volt Motor. Taking 5 Amperes.

Position of Brush-Yoke	Volts on Secondary.	
	Brushes Opposite.	Brushes Staggered.
2½	—	20
3	20	8
3½	11	—
4	8	6.5
5	7	6.5
6	7	6
7	7	7
8	—	7
8½	9	8

In the experiments with the 500-volt motor it was thought that perhaps the fluctuations of the generators were affecting the results, so that it was decided to examine a generator working on loads of various kinds and amounts. As at that time the University lighting plant had shut down for the summer, it was impracticable to drive the 500-volt machine as a generator by one of the other machines, and it was therefore used as a motor to drive an Edison generator upon which further experiments were made. This machine has a smooth armature core and so is not strictly comparable with the toothed machines whose pulsations disturbed the telephones referred to at the outset, but it was believed that from its study, results could be obtained that would throw some light upon the general subject of the disturbances.

The Edison dynamo was run at a speed of 1265 revolutions per minute, so that the product of revolutions by commutator bars, 1265 x 50, would equal a similar product for the 500-volt motor which had 96 bars and ran at 660 revolutions per minute. The results with the two machines are not strictly comparable, because one was operated as a motor and the other as a dynamo, the motor operating at 500 volts and the dynamo at 93 volts with one current, and at 67 volts with a larger current. The normal voltage of 110 could not be maintained on account of the low speed adopted in order to keep the frequency the same. Sets of readings were then taken with the Edison dynamo delivering 6.3 and 12.6 amperes through a non-inductive resistance, while operating with the fields excited first by a storage battery, then as a shunt machine, then as a highly over-compounded machine.

TABLE IV.

Effects of Field Excitation and Armature Current upon Fluctuations Through Air Core Transformer. Edison Dynamo. On Non-inductive Load.

Position of Brushes.	Field Excited by Battery.		Self-Excited, Shunt.		Self-Excited, Compound.
	6.3 Amperes.	12.6 Amperes.	6.3 Amperes.	12.6 Amperes.	12.6 Amperes.
3	—	157.6	319	—	214.5
3½	—	118.7	310	—	228.5
4	47.1	65.7	170.4	357	131.3
4½	29.2	36.1	114.2	130	55.2
5	7.5	15.3	37.9	62.8	20
5½	1.8	7.6	6	20.6	5.5
6	1.5	5.1	0	3.9	2
6½	1.4	2.0	0	2.1	1.5
7	3.5	2.8	1.4	17	4
7½	9.4	11.9	13.6	34	12.4
8	26.9	13	41.3	74.3	27
8½	30.6	31	145	208	34.1
8¾	—	—	—	292	—
9	43.7	91.3	228	?	54.3

The electro-dynamometer readings given in Table IV. are the means of from 4 to 14 readings taken at the various positions. Examination of the figures shows that for the same current, the pulsations with the low-voltage Edison smooth core dynamo are always less than those with the 500-volt with toothed armature. It is a source of regret that no machines were readily available having similar voltage and capacity and differing only in the armature core. It is hoped to obtain access to such similar machines for further study. It will be noted further that with a given excitation of field, the fluctuations of current are always greater with the larger current. Generally speaking, the fluctuations are less with the fields excited by current from the storage battery than when self-excited, also the fluctuations are much more with the shunt machine than with the compound. During the experiments, a periodic wavy sound was noted in the telephone. This was traced to the slight end motion of the armature and was stopped by adjusting the thrust bearing.

A preliminary experiment with the fields separately excited showed that an inductive load had the effect of smoothing out the fluctuations so that they became insensible. When the current was sent into the fields of an alternator (whose armature was at rest), the electro-dynamometer gave no deflection whatever for any safe position of the brushes. The telephone receiver was then substituted for the electro-dynamometer in the secondary circuit of the air-core transformer whose primary was in the main circuit, and no sound was perceptible until the brushes were moved to the extreme forward "position 2," where the sparking was vicious.

The smallness of the pulsations when the dynamo was excited by the battery current, suggested that the fluctuations affected the field current. A telephone receiver without any connections was placed near the pole-pieces of the dynamo, and immediately a roaring noise was heard which was in exact unison with that of the brushes. This noise in the receiver seemed to be of the same intensity whether the machine was delivering 12 or 6 amperes or whether the external circuit was entirely open. The only difference one could detect in the telephone was a slight lowering of pitch corresponding with the lowering of the speed of the dynamo when the load was thrown on. The brushes were then raised and the fields excited by the battery; no noise was heard. But as soon as one brush was lowered upon the commutator, the familiar roaring was heard. This noise was greater when the one brush was moved toward the sparking position. The noise was also increased when a second brush was lowered upon the opposite side of the commutator. For any given position of the brushes, the volume of the noise was entirely unaffected by the conditions of the outside circuit. In order to learn whether this disturbance by the current in the coils short-circuited by the brushes was simply electro-dynamic or whether it was electro-magnetic, the telephone was moved to various positions. In each case the noise was greater in positions where the ordinary magnetic leakage from the pole-pieces was known to be greatest. The sound from the short-circuited armature coil alone could not be distinguished near the head of the armature. A high-resistance galvanometer coil was next connected with the telephone and moved to various positions about the dynamo. The results uniformly corroborated those obtained with the telephone directly. The currents in the coils short-circuited by the brushes therefore affect the magnetism of the iron of the field magnet, although one would hardly expect that sluggish cast-iron and solid wrought-iron would respond to 1054 complex cycles per second. To make sure that the magnetism of the whole circuit did actually pulsate, the external circuit of the dynamo was opened, all the brushes were raised, battery current was sent through the field coil, and the telephone was shunted around part of the regulating rheostat in the field circuit. The telephone remained quiet until one brush was lowered, when the same roaring was noted again, showing that the field current was caused to pulsate by the short-circuited armature coils. This phenomenon is akin to that noted with alternators whose armature reaction causes the field current from the exciter to pulsate in unison with the alternating current.

The previous experiment seems to show that the fluctuations in the current do indeed come from some action of the brushes and commutator; but further, that it is not due entirely, perhaps not at all, to the simple cutting of an armature coil out of the main circuit. It is due rather to the more roundabout action of the current through the short-circuited coil, causing pulsation in the strength of the whole field and so affecting the total E. M. F. induced in the whole armature. In the case of the shunt dynamo, the magnetic field fluctuates not only from direct influence of the current in the short-circuited coil, but also from the fact that this in turn affects the current in the field and thereby again affects the total magnetization. Later measurements of the instantaneous values of the external current at different epochs of the pulsation seem to indicate such action. The effect of the series coils seems to be a smoothing out of the fluctuations, the self-induction of the coil having more effect upon the current passing than upon the magnetization.

The pulsations are greatly affected by the condition and the setting of the brushes. To such an extent is this true that it is difficult to obtain two consecutive curves which coincide. The slight wearing of the brushes during a run of less than an hour when they are outside the non-sparking region, will introduce changes that entirely mask the variables which it is sought to examine. In fact, the condition of the brushes seems to have more effect on the pulsations than anything else, so that the suggestion has arisen that operators could readily check the setting of the brushes by introducing a coil and electro-dynamometer into the circuit of each machine at such intervals as might be desirable.

TABLE V.

Effects of Field Excitation and Armature Current upon Fluctuations Through Air Core Transformer. Edison Dynamo on Non-Inductive Load.

Position of Brushes.	Shunt Machine.		Compound Machine.	
	6.4 Amperes.	12.8 Amperes.	12.8 Amperes.	6.4 Amperes
4	267	?	377	203
4½	152	348	193	93
5	59	203	257	105
5½	87	264	100	25
6	30	85	53	20
6½	28	97	79	19
7	26	94	88	17
7½	56	89	24	10
8	56	192	88	49
8½	130	257	57	28

To show how largely the fluctuations of current are affected by the setting of the brushes and the brush-yoke, Table V. is given for comparison with Table IV., all the conditions being apparently the same except a small difference in the current. The readings in Table IV. were obtained by going through the whole curve for different positions of brush-yoke with one arrangement of the circuits; for example, as a simple shunt machine giving 6.3 amperes, and then changing the circuits and taking readings for another series of brush-yoke settings. The readings for Table V. were taken by keeping the brushes and yoke in a constant position, while the corresponding readings for the four curves were obtained with the help of switches that changed the circuits and currents. From an inspection of the two tables it is seen that the same general relations exist among the four corresponding curves, although corresponding curves for the same arrangements of circuit on the two different days do not at all coincide. Some irregularities from undiscovered sources affected the readings so that they are not of best value, yet they illustrate the point that apparently small matters may greatly affect the relative amount of fluctuation in the current.

It was planned to carry on next, a series of experiments to determine the relative pulsations in the currents supplied from a number of individual machines, and a current of equal strength supplied from the same machines working in parallel, but a mishap in the laboratory delayed such work until too late to report at this meeting. It is believed, however, that when a number of machines are operating in parallel, the fluctuations from the various machines combine so as to form a resultant fluctuation less than that from any one machine. This is believed to be one of the two principal reasons why the fluctuations in the current from the rotaries now used by the lighting and railway companies referred to above, are much greater than they were when each company was using a comparatively large number of small machines in parallel.

The other principal reason for the greater pulsation is believed to be the fact that the rotaries now used, have toothed armatures and laminated pole-pieces, while the machines formerly used had solid cast-iron pole-pieces and had smooth body armatures. In the case of the rotaries the magnetic circuit has less reluctance, and the self-induction of the coils is greater, and the current in the short-circuited coil therefore reacts more strongly upon the field, which responds more readily, and so causes the total voltage to vary to a greater extent than occurs with the smooth body machine. It is desirable to test two machines which are identical except that one has a toothed armature while the other has a smooth core armature.

With so many elements liable to change, it seemed at first impossible to obtain the instantaneous values of the current so as to plot curves for the pulsations. The whole pulsation is so small a part of the total, one per cent. or less, that the common methods of getting the curves by fall of potential seemed unpromising, since the voltage on the power fluctuated circuit through quite a range. It was suggested that the pulsations of voltage might be measured directly by putting a battery in the condenser circuit so as to oppose the principal E. M. F. of the circuit, leaving the condenser to be charged only by the pulsating difference between the E. M. F. of the battery and that of the line. Time did not permit trying this method. Another method contemplated was to use two standard condensers, one of which should be connected into the circuit at a fixed instantaneous point, while the other should be connected into the circuit at different points. Thus one would be charged with the whole voltage at one part of the fluctuation, while the other would be charged at some definite interval from the first. By connecting the two condensers through a ballistic galvanometer, a kick would be caused by the difference between the two charges. Upon obtaining two standard mica condensers from two different well-known firms, the two were found not to agree within two per cent., and so that method was temporarily laid aside. By the two condenser method, the curve could be obtained in a way similar to a common method for obtaining curves of potential around a commutator, either by the single or double brush method. For this purpose, ordinary paraffin condensers are of little use, since with a water jet device the actual time of contact is a small fraction of a second, even though the condenser be kept charging for a whole minute for each reading.

A number of attempts were made to obtain curves of the instantaneous values of the pulsations of the current, but none gave entirely satisfactory results. A number of curves were obtained, each of which showed a high sharp peak at the point where a commutator bar left the brush. There is in each case another but less marked peak at a point corresponding to the middle of each bar. The exact cause of the second peak has not yet been definitely located, it being probably due either to the entering of a bar under the brush, or to the delayed effect of the fluctuation in the field current.

As stated at the outset, these experiments are only preliminary and incomplete, but they suggest an intensely interesting field for further experiment.

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THE GRAPHICAL TREATMENT OF ALTERNATING CURRENTS IN BRANCHING CIRCUITS

WITH SPECIAL REFERENCE TO THE CASE OF VARIABLE FREQUENCY.

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1. Let a simple harmonic E. M. F. whose constant maximum pressure is E volts be applied to the common terminal of the two branches of the split circuit shown in Fig. 1.

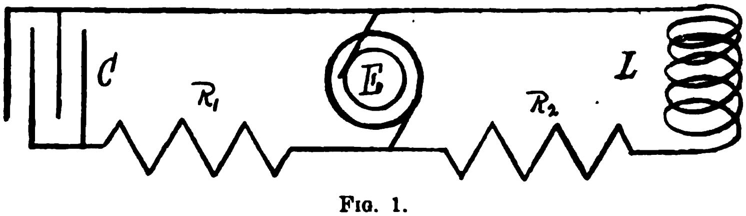


FIG. 1.

Each of the branches, designated as 1 and 2, is taken to have in it either a condenser or a self-inductive resistance in series with an ohmic resistance of R_1, or R_2, ohms; but no mutual induction between the branches is supposed to exist. After treating the special cases in which there is one kind of resistance only in each branch, besides ohmic resistance, viz: either a condenser in one branch, and a self-induction in the other; or a condenser alone in each branch; or self-induction alone in each branch; the general case in which both branches have in series condensers and self-inductive resistances as well as ohmic resistances will be made to depend upon the special cases first treated.

In case the pressure E acts between the terminals of branch 1, having a resistance of R_1 ohms and a capacity of $C = 1 / K$ farads, the maximum current of I_1 amperes may be found from the clock diagram, Fig. 2, in which I_1 is the chord $O\ P_1$ of the semi-circle whose diameter is $O\ E_1 = E/R_1$, and θ_1 the lead of I_1 is given by the equation.

$$\tan \theta_1 = \frac{K}{R_1\ \omega} \tag{1}$$

in which $\omega = 2\ n\ \pi$ is speed or angular velocity, and n is frequency or number of complete alternations per second.

Now

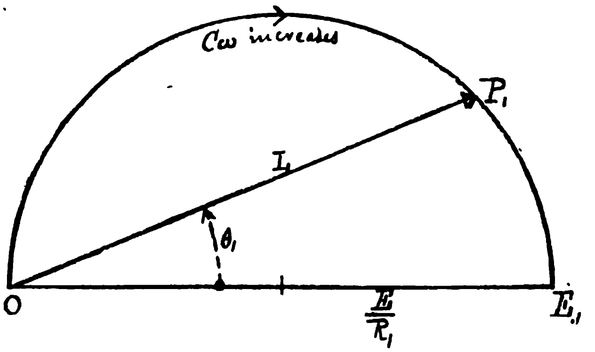


FIG. 2.

$$I_1 = \frac{E}{R_1} \cos \theta_1 = \frac{E}{R_1}\ \frac{1}{(1 + \tan \theta_1)^{\frac{1}{2}}} \tag{2}$$

Hence I_1 increases from the value zero to E/R_1 as ω and the frequency increases from zero to infinity.

It will be convenient in treating variable frequency to speak of ω as the measure of the frequency.

Similarly, in a second branch having a resistance of R_2 ohms and self-induction of L henrys, the pressure E causes a maximum current of I_2 amperes shown in Fig. 3 as the chord $O\ P_2$ of the semi-circle whose diameter is $O\ E_2 = E/R_2$, and the lag θ_2 is given by the equation

$$\tan \theta_2 = \frac{L\ \omega}{R_2}, \tag{3}$$

But

$$I_2 = \frac{E}{R_2} \cos \theta_2 = \frac{E}{R_2} \frac{1}{(1 + \tan \theta_2)^{1/2}} \tag{4}$$

hence I_2 decreases from the value E/R_2 to zero as the frequency increases from zero to infinity.

The semi-circles in Figs. 2 and 3 are the loci of the extremities of the vectors representing the maxima values of the currents I_1 and I_2 in case R_1 and R_2 remain constant, while $a = \tan \theta_1$ and $\beta = \tan \theta_2$ are made to vary from zero to infinity or *vice versa*, either by varying ω alone, or K and L alone, or by varying these all at once.

It is convenient to regard a and β as a kind of coordinates for expressing the properties of split circuits.

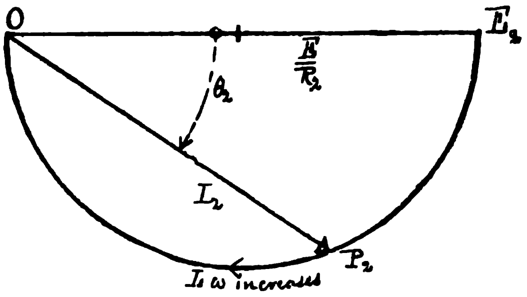


FIG. 3.

2. For example, in the case represented in Fig. 1, of a capacity C in branch 1, and a self-induction L in branch 2, take one coordinate constant, as for instance let $a = \tan \theta_1 = 2$, while $\beta = \tan \theta_2$ is variable. Then if we lay off in Fig. 4 $O\,E_1 = E/R_1$ and $O\,E_2 = E/R_2$ we have $I_1 = O\,P_1$ which vector will be fixed in magnitude and position, so long as a is constant. But P_2, the extremity of the vector $I_2 = O\,P_2$ will describe the semi-circumference $O\,E_2$ from O to E_2 as β decreases from infinity to zero through the successive values shown on Fig. 4.

Hence P, the extremity of the vector $O\,P = I$ which represents the total current produced by E in both branches, or the resultant of I_1 and I_2, describes a semi-circumference whose diameter is equal and parallel to $O\,E_2$, and beginning at the fixed point P_1 the extremity P describes the complete semi-circumference while β decreases from infinity to zero. In like manner are

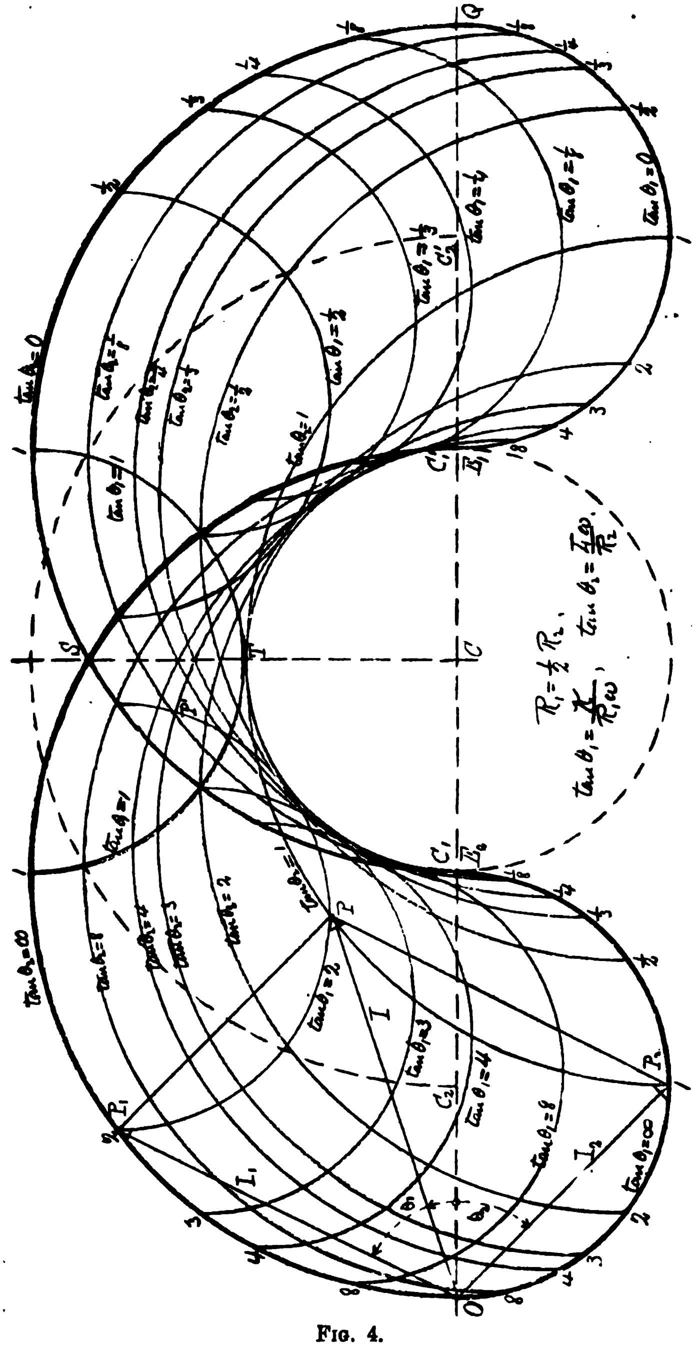

Q
O
S
C
P
P1
P2
I
I1
I2
C1
C2
C'2
B1
B0
tan θ1 = 0
tan θ1 = 1/8
tan θ1 = 1/4
tan θ1 = 1/3
tan θ1 = 1/2
tan θ1 = 1
tan θ1 = 2
tan θ1 = 3
tan θ1 = 4
tan θ1 = 8
tan θ1 = ∞
tan θ2 = 0
tan θ2 = 1/8
tan θ2 = 1/4
tan θ2 = 1/3
tan θ2 = 1/2
tan θ2 = 1
tan θ2 = 2
tan θ2 = 3
tan θ2 = 4
tan θ2 = 8
tan θ2 = ∞
R1 = 1/2 R2,
tan θ1 = k/(R1 ω), tan θ2 = kω/R2
1/8
1/4
1/3
1/2
1
2
3
4
8

FIG. 4.

to be located the other semi-circumferences along which α has the successive constant values shown in Fig. 4. They are each to be constructed by locating P_1 upon the circumference of the semi-circle $O\ E_1$ in such successive positions that $O\ P_1$ will cause the corresponding co-ordinate $\tan \theta_1 = \alpha$ to assume the required constant values. Their centers all lie on the circumference of the semi-circle $C_2\ C_2^1$. A set of semi-circles whose diameters are equal and parallel to $O\ E_1$ and whose centers lie on the semi-circle $C_1\ C_1^1$ will likewise begin at successive fixed points P_2 along the semi-circle $O\ E_2$ and will show the locus of the extremity of the vector $I = O\ P$, for successive constant values of $\tan \theta_2$ while $\alpha = \tan \theta$ decreases from infinity to zero, as shown also in Fig. 4. From this point on, we shall for the sake of brevity use the terms circle and semi-circle to designate circumference and semi-circumference.

When both these series of semi-circles have been drawn upon a diagram, for a set of successive numerical values of the co-ordinates lying near together, we then have in effect a table from which the value of $O\ P = I$ can be found by observing at what point the semi-circles intersect for any given values of the co-ordinates. For example in Fig. 4 we have represented the current $I = O\ P$ for $\alpha = 2$ and $\beta = 1$, which may be expressed in abbreviated notation more conveniently by designating this point P as the point (2, 1).

In case the semi-circles of each set are drawn for successive values of the co-ordinates at small numerical intervals, interpolation for intermediate values will be readily effected.

Different diagrams will be required for different ratios of R_1 to R_2; all other changes require a change of scale only in order to measure I.

Fig. 4 has been constructed for $R_1 = \frac{1}{2}\ R_2$. Were $R_1 = 2\ R_2$ while C and L remained unchanged in their respective branches, the diagram would be turned upside down, and be in effect, a reflection of Fig. 4 in $O\ Q$.

Now the two sets of semi-circles are so situated with reference to each other that some of the semi-circles of one set may apparently intersect certain ones of the other set in two points. But if the matter be rightly considered, such double intersections do not really occur; for the area we are considering, is enclosed by the five semi-circles whose centers are at $C_2\ C_1\ C\ C_1^1\ C_2^1$. Hence $S\ E_1$ and $S\ E_2$ are portions of its bounding edges just as truly as $S\,O$ and $S\,Q$. In fact the area consists of two equal parts or leaves which partially overlap: the first leaf bounded by the three semi-circles whose centers are $C\,C_1\,C_2$, and the second leaf by the three whose centers are $C\,C_1^1\,C_2^1$. These two leaves are joined along the semi-circle $E_1\;T\;E_2$ which thus forms an *edge of junction* and our tabular diagram would be correctly constructed, were it actually made of two leaves united along this semi-circle and not elsewhere. It will be noticed that every semi-circle of each set touches this semi-circle $E_1\,T\,E_2$ which is therefore the envelope of both sets. Every semi-circle of either set begins at P_1 or P_2 at the edge of the first leaf, and if a point P start at P_1 or P_2 and move along one of these semi-circles, it traverses the first leaf, reaches the point of tangency on the edge of junction, then enters upon the second leaf, and finally reaches the edge of the second leaf. Considered in this way, as it must be, no semi-circle of one set has more than one intersection with any semi-circle of the other set. But any point of the first leaf within the area $S\,E_1\,T\,E_2$ falls upon a point of the second leaf having $O\,P = I$ identically the same for both. In other words, there are two perfectly distinct ways of producing the same total current in case P falls within this area. In case however that P fall within either leaf and outside this area, there is one way only of producing the current $I = O\,P$, while no possible variations of frequency can make P fall outside both leaves.

Consider some point (α_1, β_1) in the first leaf, say (2, 3); then P^1 the corresponding double point at the apparent second intersection of these semi-circles is numerically very near $(\frac{8}{10}, 3)$ in the first leaf, and $(2, \frac{1}{8})$ in the second leaf; while the point (α_2, β_2) in the second leaf to which this double point corresponds is very near $(\frac{8}{10}, \frac{1}{8})$. In other words the double point (α_1, β_2), (α_2, β_1) corresponds to both (α_1, β_1) and (α_2, β_2). It also bisects the distance between them, for the center of the semi-circle α_1 ($= 2$, say) must be moved the same distance in the same direction to change it to α_2 ($= \frac{8}{10}$, say) as the center of the semi-circle β_1 ($= 3$, say) to change it to β_2 ($= \frac{1}{8}$, say), viz: the distance from one of these points to the double point.

According to this way of viewing the subject, any point, as $(2, \frac{1}{8})$ is regarded as located by starting from O and following successively two of the arcs which form the sides of the curvilinear parallelogram, whose angular points are $(\infty, \propto)$ at O, $(\infty, \frac{1}{8})$,

$(2, \infty)$ and $(2, \frac{1}{8})$ by a geometric addition of sides. It will be noticed that the order of the addition is unimportant, and that the point arrived at, is in the second leaf, whichever order be followed. The actual parallelograms of currents are the chords of sides of the curvilinear parallelogram.

Every possible value of the total current I lies between $O\,Q = E/R_1 + E/R_2$ and zero. There is a minimum value of I for each given value of either of the co-ordinates. For example let $a_1 = \tan\theta_1 = 2$, then the nearest point of this semi-circle to O, may evidently be found by drawing a straight line from O to the center of the semi-circle $a = 2$, and similarly for any semi-circle of either set. The distance from O to the intersection is the required minimum. The corresponding value of the other co-ordinate can be read from the diagram.

For each given value of either co-ordinate there is no maximum value of I, but there is a greatest value at the extremity of each semi-circle farthest from O.

For each given value of either co-ordinate, there is a value of I, giving a minimum lead (or lag), to be found by drawing through O a line tangent to the given semi-circle; but there is no maximum lead (or lag); its greatest value however, is to be found by drawing a straight line from O to that extremity of the given semi-circle which lies nearest to O.

It will be shown later, that for any pair of points situated at the same height above or below $O\,Q$ and at equal distances to the right and left of $S\,T$, the values of their co-ordinates are respectively the numerical reciprocals of each other:—for, example, $(2, 3)$ and $(\frac{1}{2}, \frac{1}{3})$ are so situated.

3. Next consider the case of two branches each of which contains a condenser only, or each a self-inductive resistance only, in addition to its ohmic resistance.

In Fig. 5 each branch is supposed to contain a condenser, and it is assumed that $R_1 = \frac{3}{5} R_2$. Were both branches to contain self-inductions instead of condensers, the semi-circles would all lie below $O\,Q$. The construction is like that of Fig. 4, except that both θ_1 and θ_2 are on the same side of $O\,Q$.

The semi-circles of both sets are tangent to the semi-circle OTQ which forms the edge of junction in this case. The other boundaries of the area within which P must fall are the four circles whose centers are $C_1\;C_2\;C_1^1\;C_2^1$, while $S\;O\;T\;Q$ is the portion of the area, where the first leaf which is bounded by three

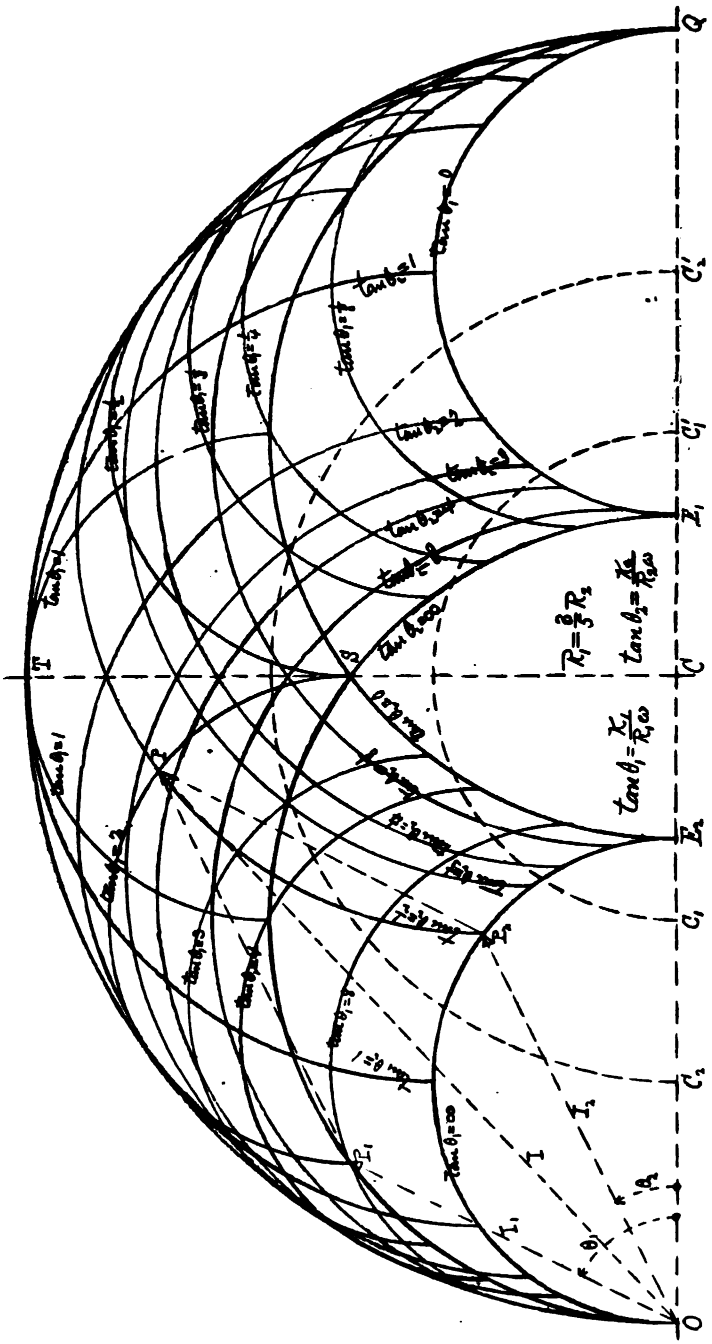

Q
C'_2
C'_1
E_1
C
E_2
C_1
C_2
O
T
S
P
P_1
P_2
I
I_1
I_2
θ_1
θ_2
$R_1 = \frac{3}{5} R_2$
$\tan\theta_2 = \frac{X_2}{R_2\omega}$
$\tan\theta_1 = \frac{X_1}{R_1\omega}$
$\tan\theta_2 = 0$
$\tan\theta_2 = 1$
$\tan\theta_2 = 2$
$\tan\theta_2 = \infty$
$\tan\theta_1 = 0$
$\tan\theta_1 = 1$
$\tan\theta_1 = \infty$

FIG. 5.

semi-circles whose centers are $C_2\ C\ C_1^1$, overlaps the second leaf, bounded by the three semi-circles whose centers are at $C_2^1\ C\ C_1$.

Every semi-circle along which $\beta = \tan\theta_2$ has any given constant value, starts in the first leaf from the initial semi-circle whose diameter is $O\ E_2$ and ends at the semi-circle in the second leaf whose diameter is $Q\ E_1$ as $\alpha = \tan\theta_1$ decreases from infinity to zero; while every semi-circle along which $\alpha = \tan\theta_1$ has any given constant value starts in the second leaf from the initial semi-circle whose diameter is $O\ E_1$ and ends in the first leaf at the semi-circle whose diameter is $Q\ E_2$ as β decreases from infinity to zero. Since the semi-circles belonging to any pair of given values of α and β, start in different leaves, their point of intersection (α, β) lies on one of the semi-circles further from the starting point than its point of contact with the edge of junction, and on the other semi-circle nearer its starting point. In Fig. 5, the point $P = (2, \frac{1}{2})$ lies in the first leaf, and on $\alpha = 2$ it lies further from the starting point P_1 than the point of contact with the edge of junction, while P lies on $\beta = \frac{1}{2}$ nearer P_2 than its point of contact. The point of the second leaf which coincides with P is approximately the point $(\frac{8}{10}, \frac{7}{2})$. Any double point (α_1, β_2), (α_2, β_1) lies midway between the points (α_1, β_1) and (α_2, β_2), and the point P in Fig. 5 lies midway between the two points whose numerical values are approximately $(\frac{8}{10}, \frac{1}{2})$ in the first leaf and $(2, \frac{7}{2})$ in the second. The proof of this statement is the same as that given in Fig. 4.

There is a maximum value of I for each given value of α or β, and it may evidently be found by drawing a straight line from O through the center of the semi-circle for that given value until it intersects the semi-circle. But there is no minimum value of $I = O\ P$ for each given value of α or β, though there is a smallest value when P is at the initial point of the semi-circle nearest to O.

For each given value of α or β there is a value of I giving a maximum lead (or lag), which is to be found by drawing from O a tangent to the given semi-circle. In Fig. 5, $O\ P$ is very nearly tangent to $\beta = \frac{1}{2}$. The least value of the lead (or lag) is found by drawing a line from O to the farthest extremity of the given semi-circle, this value is however not a minimum. Any pair of points whose respective co-ordinates are numerical reciprocals of each other lie at equal distances to the right and left of $S\ T$ and at the same height above (or below) $O\ Q$, as will be shown later.

The special case of $R_1 = R_2$ would cause E_1, E_2 and S to fall at C, and so make the two leaves cover precisely the same area. Also in this case the semi-circles $\alpha = \beta$ having equal numerical values coincide, and every point is a double point in which the numerical values of α and β exchange places, *e. g.* (2, 3) and (3, 2) would refer to the same double point. The constructions in Figs. 4 and 5 are specially suited to discuss cases in which the capacity or self-induction of a single branch is made to vary, for then, one or other co-ordinate only varies.

4. Having thus shown the boundaries and contour lines of the two-leaved plane surface within which P, the extremity of $I = O\,P$, the total current must lie in case of a split circuit, it will be specially useful in case of variable frequency to discuss certain loci obtained by assuming fixed relations between the co-ordinates. These relations arise naturally from the algebraic form of their values as expressed in equations (1) and (3), viz:—By multiplying (1) and (3) together we have

$$\tan \theta_1 \tan \theta_2 = \frac{K\,L}{R_1\,R_2} = G^2, \text{ say,} \tag{5}$$

which is independent of the frequency, *i. e.* the products of co-ordinates for the same value of the frequency is independent of the frequency and is the same for all frequencies.

It is possible to construct the locus for any given value of G, (*i. e.*, when K and L are known) in a convenient manner, as follows: Introduce two auxiliary angles φ_1 and φ_2 such that

$$\tan \theta_1 = G \tan \varphi_1, \text{ and } \tan \theta_2 = G \tan \varphi_2,$$

$$\therefore \text{ by (5),} \qquad \tan \varphi_1 \tan \varphi_2 = 1, \tag{6}$$

$$\therefore \varphi_1 + \varphi_2 = 90^\circ. \tag{7}$$

It is evident that the magnitudes in these equations are related to each other in the manner represented in Fig. 6, in which $D\,A\,F$ is a right angle, and

$$G = \frac{A\,B}{O\,B}, \tag{8}$$

for, $\qquad \overline{O\,B} \tan \theta_1 = A\,B \tan \varphi_1$

and $\qquad \overline{O\,B} \tan \theta_2 = \overline{A\,B} \tan \varphi_2.$

$A\,D$ and $A\,F$ may be drawn at right angles by making them pass through the extremities of the diameter of any circle through A whose center is on $A\,B$. In this way it is possible to construct with ease the lead θ_1 and the lag θ_2 of any pair of branch currents I_1 and I_2 that belong together, *i. e.*, that are produced at the same frequency. Should the value of the frequency be required, it can be found from equation (1). In Fig 6 we have taken $G = \frac{1}{2}$. Let us proceed to construct the required locus as shown in Fig. 7, in which lay off $O\ E_1 = E/R_1$, and $O\ E_2 = E/R_2$; and taking any convenient point B, assume A in such a

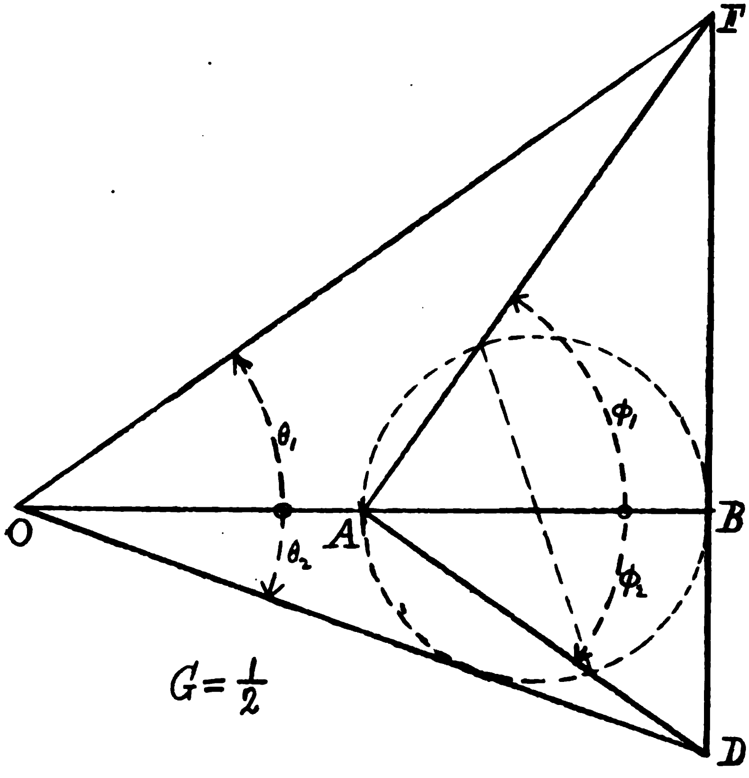


Fig. 6

position as to make the ratio $A\ B/O\ B = G$ assume any particular value desired. In Fig. 7, $G = 2$. Construct θ_1 and θ_2 as was done in Fig. 6, then $O\ P_1 = I$ and $O\ P_2 = I_2$ are the components of the total current $O\ P = I$.

By taking successive positions of lines at right angles to each other through A, the points P_1 and P_2 will traverse the semicircles whose centers are C_1 and C_2, and the point P will traverse a curve consisting of a single spire reaching from E_1 to E_2. The spire shown in Fig. 7 is the locus corresponding to $G = 2$, in case $3 R_1 = 4 R_2$.

The fact that $R_1 > R_2$ causes the upper part of the spire to be the smaller, since the diameter E/R_1 of the semi-circle C_1 is less than the diameter E/R_2 of the semi-circle C_2, and each spire approximates to some extent in its shape to that of the two semicircles. In fact, when G is infinite the curve consists of these two semi-circles themselves, and for other values of G those lying nearer infinity have spires closer to the semi-circles, while for

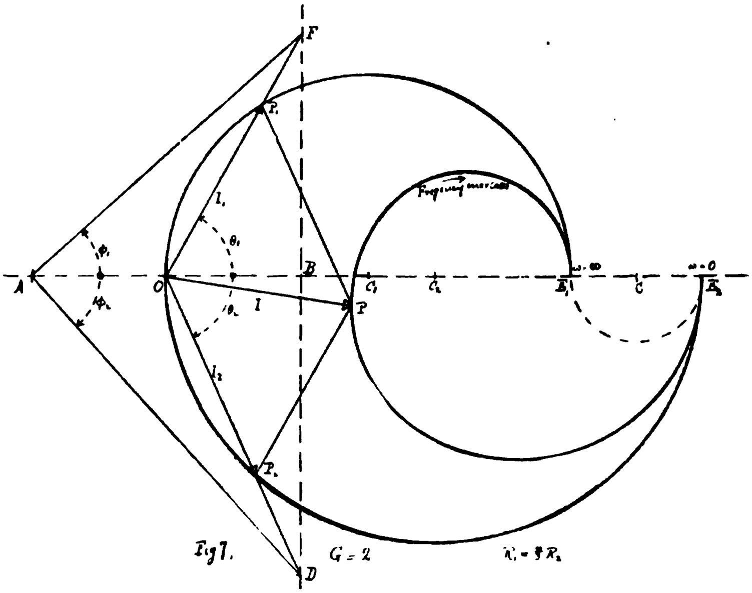


FIG. 7.

$G = 1$ the spire reduces simply to the semi-circle whose diameter is $E_1 E_2$. Spires for various intermediate values of G are shown in Fig. 9 on the left.

The truth of these statements may be shown as follows:

In case G is infinite, either K or L must also be infinite by equation (5). But, K infinite makes $I_1 = 0$ by eqs. (1) and (2), in which case I coincides with I_2, and the semi-circle on $O\,E_2$ is the locus. While L infinite makes $I_2 = 0$ by eqs. (3) and (4), and the semi-circle on $O\,E_1$ then becomes the locus. In case $G = 1$, the locus is the semi-circle on $E_1\,E_2$, for resolving I_1 and

I_2 into their working and wattless currents, and noting that in this case $\theta_1 + \theta_2 = 90°$ by eq. (5), we have on taking the origin of rectangular co-ordinates at O, and putting $E/R_1 = a_1$, and $E/R_2 = a_2$,

$$I_1 \cos \theta_1 = x_1 = a_1 \cos^2 \theta_1,$$
$$I_2 \cos \theta_2 = x_2 = a_2 \cos^2 \theta_2 = a_2 \sin^2 \theta_1,$$
$$I_1 \sin \theta_1 = y_1 = a_1 \sin \theta_1 \cos \theta_1,$$
$$I_2 \sin \theta_2 = y_2 = a_2 \sin \theta_2 \cos \theta_2 = a_2 \sin \theta_1 \cos \theta_1.$$

But if x and y be taken as the co ordinates of P reckoned from C as origin, we have, since $O\,C = \frac{1}{2}(a_1 + a_2)$,

$$\left.\begin{aligned} x + \tfrac{1}{2}(a_1 + a_2) &= x_1 + x_2 = a_1 \cos^2 \theta_1 + a_2 \sin^2 \theta_1 \\ y &= y_1 - y_2 = (a_1 - a_2) \sin \theta_1 \cos \theta_1 \end{aligned}\right\} \quad (9)$$

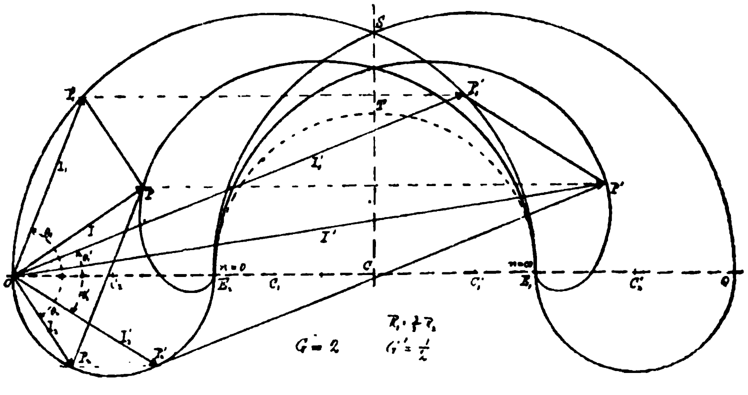


FIG. 8.

$$\therefore x = \tfrac{1}{2}(a_1 - a_2) \cos 2\,\theta_1$$
$$y = \tfrac{1}{2}(a_1 - a_2) \sin 2\,\theta_1$$
$$\therefore x^2 + y^2 = \tfrac{1}{4}(a_1 - a_2)^2 \qquad (10)$$

and the locus of P in this case is therefore the semi-circle on $E_1\,E_2$.

Before proceeding to construct the locus of P for cases in which $G < 1$, it will be first proven that reciprocal values of G give pairs of loci which are equal right and left spires such that they are simple reflections of each other in $C\,S$ of Figs. 8 and 9. For, in Fig. 8, let P_1 and P_1^1 be such that I_1 and I_1^1 have equal wattless currents, as also $I_2\,I_2^1$; then the total currents I and I^1 must have equal wattless currents. Hence P and P^1 are equidistant from $E_1\,E_2$.

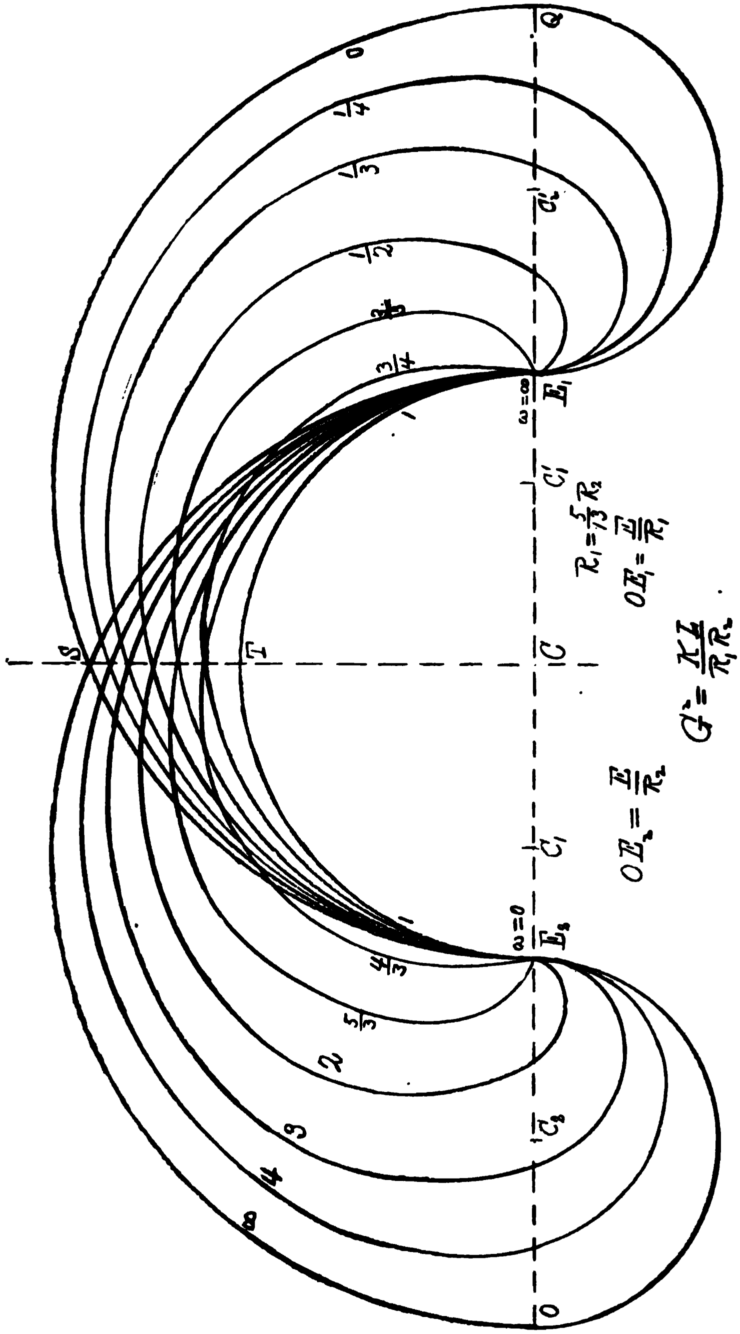

Q
0
1/4
1/3
1/2
2/3
3/4
1
a₁
ω=∞
E₁
C₁'
R₁ = 5/13 R₂
OE₁ = E/R₁
S
T
C
G² = KL/R₁R₂
OE₂ = E/R₂
C₁
ω=0
E₂
1
4/3
5/3
2
3
4
∞
C₂
O

Fig. 9.

$$\therefore y_1 = y_1^1, \; \therefore \sin \theta_1 \cos \theta_1 = \sin \theta_1^1 \cos \theta_1^1,$$

$$\therefore \sin 2 \theta_1 = \sin (180^\circ - 2 \theta_1^1),$$

$$\therefore \theta_1 + \theta_1^1 = 90^\circ, \text{ and } \theta_2 + \theta_2^1 = 90^\circ \qquad (11)$$

$$\therefore \sin \theta_1 = \cos \theta_1^1, \text{ and } \cos \theta_1 = \sin \theta_1^1 \text{ etc.}$$

By eq. (9),

$$x + x^1 + a_1 + a_2 =$$

$$a_1 \cos^2\theta_1 + a_2 \sin^2\theta_1 + a_1 \cos^2\theta_1^1 + a_2 \sin \theta_1^1$$

$$\therefore x + x^1 = 0 \; \therefore x = - x_1 \qquad (12)$$

from which it appears that P^1 is as far to the right of C as P is to the left of it. Hence the loci of P^1 and P correspond point by point in case eq. (11) holds. But in that case G and G^1 have numerically reciprocal values, for we then have

$$\tan (\theta_1 + \theta_1^1) = \frac{\tan \theta_1 + \tan \theta_1^1}{1 - \tan \theta_1 \tan \theta_1^1} = \infty$$

$$\therefore \tan \theta_1 \tan \theta_1^1 = 1, \text{ and } \tan \theta_2 \tan \theta_2^1 = 1$$

$$\therefore \tan \theta_1 \tan \theta_2 \tan \theta_1^1 \tan \theta_2^1 = 1 \; \therefore G \, G^1 = \pm 1, \text{by eq. (5)}$$

Hence the loci of P and P^1 constructed as in Fig. 8, so that their components have the same wattless currents are equal right and left spires, symmetrically situated with reference to $C\,S$, and the values of G and G^1 are numerical reciprocals. In Fig. 8, $G = 2$, $G^1 = \frac{1}{2}$ and $R_1 = \frac{3}{8} R_2$ nearly, and this last causes the upper part of the spire to be the larger.

The fact of the symmetrical disposition of the spires in pairs essentially diminishes the labor of preparing a sheet containing spires for various successive values of G such as is represented in Fig. 9; for, when any one spire has been constructed, its reciprocal spire may be readily traced without further construction. Thus it will be seen that all spires for values of G between infinity and unity lie in the first leaf, and all spires for values of G between unity and zero lie in the second leaf, while $G = 1$ is the edge of junction: $G = \infty$ is the external boundary of the first leaf; and $G = 0$ the external boundary of the second leaf.

When spires have been constructed for a comparatively small number of properly chosen successive values of G, intermediates may be readily interpolated by estimation, and then such a diagram as Fig. 9 furnishes a table of values of I and its lag or lead for a given ratio of the resistances, with a single spire in it for each value of G, the different points along the spire corresponding to different values of the frequency. That part of the total area where the two leaves overlap furnishes apparent intersections of the set of spires in which $G > 1$ with the set in which $G < 1$ but the sets are on separate leaves and do not really intersect. Every point of $S\ E_1\ T\ E_2$ is a double point with identically the same current I_1 but produced by very different values of L, K, and ω. The only possible way by which any one of these equal values of $I = O\ P$ could be gradually changed to the other would be by gradual variations of frequency etc., by which P should move to the edge of junction in one leaf and back on the other leaf to the same position. The relative positions of E_1 and E_2 depend upon the ratio of the resistances R_1 and R_2; in case $R_1 > R_2$ then E_1 is situated at the left of C as in Fig. 7, and *vice versa*.

A diagram for the case of $R_2 = \frac{5}{13} R_1$ would be that of Fig. 9 reflected in $O\ Q$, or revolved 180° about $O\ Q$. The same is true of any diagrams for reciprocal values of the ratio of the resistances. It is to be noted that for each value of $G > 1$ there is a mimimum value of $I = O\ P$ less than either a_1 or a_2, while for each value of $G < 1$ there is a maximum value of I greater than either a_1 or a_2. Also for each value of G there is in general a maximum value of both lead and lag other than zero. Moreover there is in general a value of I in consonance of phase with E, *i. e.*, it has neither lead nor lag, which differs in magnitude from both a_1 and a_2, and consequently occurs at a frequency lying between infinity and zero. This value of I is less than either a_1 or a_2 if $G > 1$, but is greater than either a_1 or a_2 if $G < 1$. These statements appear from inspection of Fig. 9. As is evident from what has preceded, the loci which are thus obtained are specially useful in tracing the manner in which the total current through two parallel branches varies as the frequency varies from infinity to zero in case the resistances are given and one branch has in it a condenser of known capacity while the other contains a known self-inductance resistance; and the effect on the total current of variations in the capacity of the condenser or in the self-inductance resistance may also be traced by their help though not so readily as variations of frequency. One convenience possessed by these loci is that as we pass from one value of G to another we take steps that begin with the boundaries of one leaf and end with the boundaries of the other, while the common boundary between them is an intermediate locus. For, in case $G = \infty$ the locus consists of the two exterior bounding semi-circles of the first leaf, in case $G = O$ the locus is the locus that bounds the second leaf in the same manner, and $G = 1$ is the edge of junction, while intermediate values give intermediate loci. The case of $R_1 = R_2$ is worthy of notice, for in that case the spires become circles as shown in Fig. 10, which truth may be demonstrated as follows: Take E in Fig. 10 as origin of the rectangular co-ordinates x and y, but using the other symbols x_1 etc., with meanings already defined, we have, since in this case $O\,E = a = a_1 = a_2$

$$x + a = (x_1 + x_2) = a\,(\cos^2\theta_1 + \cos^2\theta_2)$$

$$y = y_1 - y_2 = a\,(\sin\theta_1 \cos\theta_1 - \sin\theta_2 \cos\theta_2)$$

$$\therefore x = \tfrac{1}{2}\,a\,(\cos 2\,\theta_1 + \cos 2\,\theta_2)$$

$$y = \tfrac{1}{2}\,a\,(\sin 2\,\theta_1 - \sin 2\,\theta_2)$$

$$\therefore x^2 + y^2 = \tfrac{1}{2}\,a^2\,[1 + \cos 2\,(\theta_1 + \theta_2)] = a^2 \cos^2 (\theta_1 + \theta_2)$$

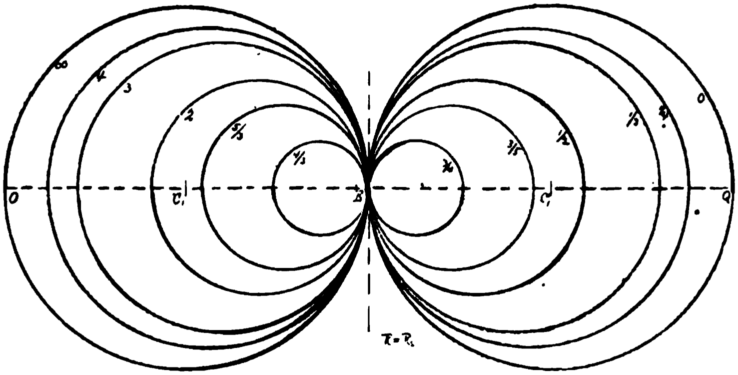


FIG. 10.

$$\text{Also, } \frac{y}{x} = \frac{\sin 2\,\theta_1 - \sin 2\,\theta_2}{\cos 2\,\theta_1 + \cos 2\,\theta_2} = \tan\,(\theta_1 - \theta_2)$$

$$\therefore \frac{x^2}{x^2 + y^2} = \cos^2 (\theta_1 - \theta_2)$$

$$\therefore \frac{a^2\,x^2}{(x^2 + y^2)^2} = \frac{\cos^2 (\theta_1 - \theta_2)}{\cos^2 (\theta_1 + \theta_2)} = \left(\frac{1 + \tan\theta_1 \tan\theta_2}{1 - \tan\theta_1 \tan\theta_2}\right)^2 = \left(\frac{1 + G^2}{1 - G^2}\right)^2$$

$$\therefore x^2 + y^2 = \pm \left(\frac{1 - G^2}{1 + G^2}\right) ax \qquad (13)$$

which is a double set of circles having a common tangent at E and lying inside the circles for which G is zero and infinity.

Though the equations of the loci are in this special case expressible in algebraic form in rectangular co-ordinates, such is not generally the case.

5. Consider next the set of loci for the case in which the two branches both contain condensers only, or self-inductions only, in addition to ohmic resistances, and let the product of the tangents of lead (or lag) be assumed constant.

For example in Fig. 11, let

$$\tan \theta_1 \tan \theta_2 = \frac{K_1 K_2}{R_1 R_2 \omega^2} = G^2 \tag{14}$$

i. e. θ_1 and θ_2 both lie on the same side of $O Q$. If in this case also we take $\tan \theta_1 = G \tan \varphi_1$ and $\tan \theta_2 = G \tan \varphi_2$, then eqs. (6) and (7) likewise hold true. The construction is readily followed in Fig. 11 where the point P on the locus $G = \frac{1}{2}$ is constructed by making θ_1 and θ_2 any two complimentary angles, by the simple device of drawing from A lines to the extremities of any chord parallel to $A B$, and making $G = A B / O B$ as in Fig. 7. We have made $\tan \varphi_1 = 3 \therefore \tan \varphi_2 = \frac{1}{3}$, so that $\tan \theta_1$ $\frac{3}{2}$ and $\tan \theta_2 = \frac{1}{6}$.

By suitable variations of these angles under the condition expressed by (14), the locus may be traced for this and other values of G. But along each locus K_1 and K_2 must be regarded as variable as well as the frequency, though the frequency is constant in case the product $K_1 K_2$ is also constant.

Each locus of the set terminates at E_1 and E_2, having vertical tangents at those points, and it has also one tangent line in common with the semi-circle whose diameter is $O Q$, *i. e.* that semi-circle is the envelope of the set. The point of contact of each locus with this envelope is such that for that point,

$$\tan \theta_1 = \tan \theta_2 = \tan \theta = G \tag{15}$$

and

$$I = (a_1 + a_2) \cos \theta = \frac{a_1 + a_2}{\sqrt{1 + G^2}} \tag{16}$$

and at this point the locus passes from one leaf to the other.

Those loci for which $G > 1$ have one or more maximum values of I. Others may have a maximum value of I near that given by eq. (16); but for small values of G there is no maximum value of I. For small values of G there may be one or more maximum values of θ. Others may have θ a maximum not far from that given in eq. (16), but for large values of G there is none.

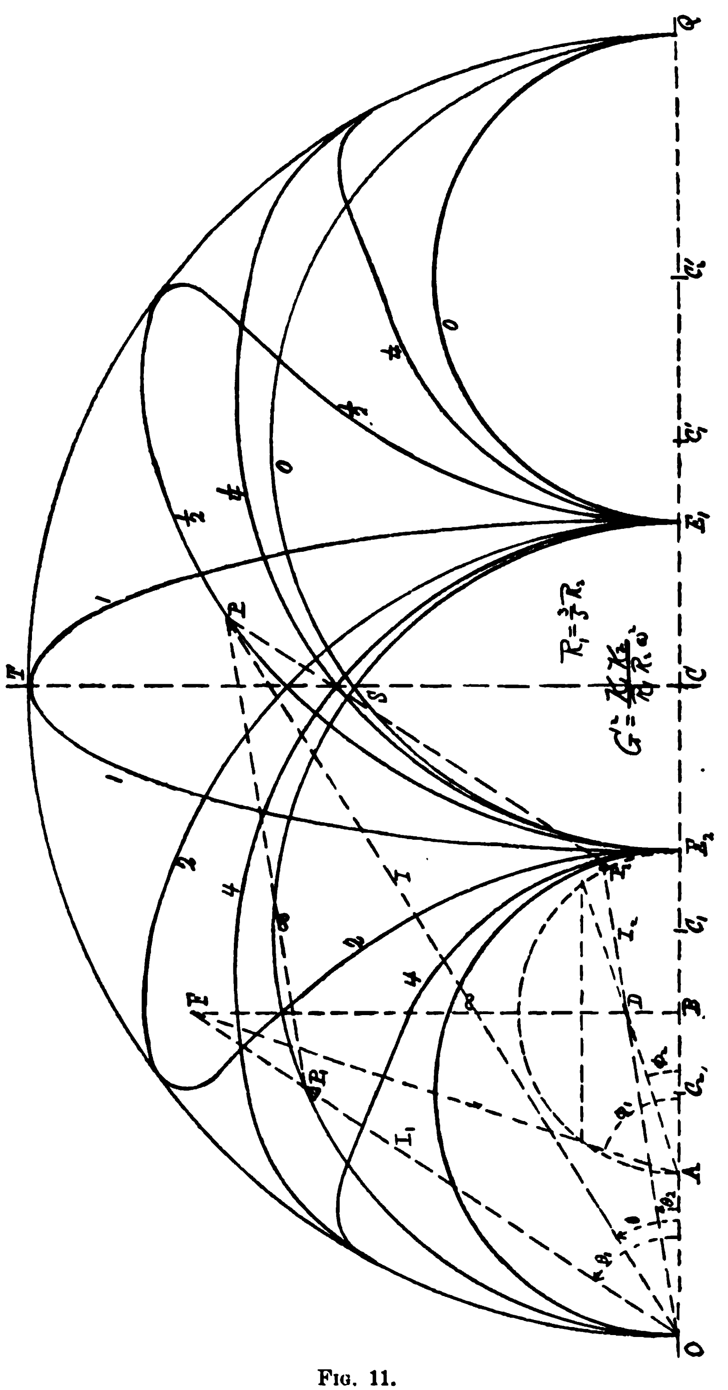

Q
C_2'
C_1'
E_1
C
E_2
C_1
B
C_2
A
O
P
S
D
I_1
I_2
$R_1 = \frac{3}{5} R_2$
$G' = \frac{L_1 L_2}{R_1 R_2 \omega^2}$
0
1
2
4
$\frac{1}{2}$
$\frac{1}{4}$
∞

Fig. 11.

For $G = \infty$ the locus is formed of the two semi-circles C_1 and C_2; for $G = 0$ it is C_1^1 and C_2^1. For $G = 1$ the locus is the semi-ellipse $E_1\ T\ E_2$; for, in this case $\theta_1 + \theta_2 = 90°$.

$$\therefore \sin 2\,\theta_1 = \sin 2\,\theta_2, \quad \text{and} \cos 2\,\theta_1 = -\cos 2\,\theta_2$$

$$\therefore x = \tfrac{1}{2}\,(a_1 - a_2) \cos 2\,\theta_1, \quad y = \tfrac{1}{2}\,(a_1 + a_2) \sin 2\,\theta_2$$

$$\therefore \frac{x^2}{(a_1 - a_2)^2} + \frac{y^2}{(a_1 + a_2)^2} = \tfrac{1}{4} \qquad (17)$$

For intermediate values of G the loci assume intermediate forms which gradually change from the semi-ellipse to the two semi-circles mentioned above.

Reciprocal values of G are disposed symmetrically about $S\ T$.

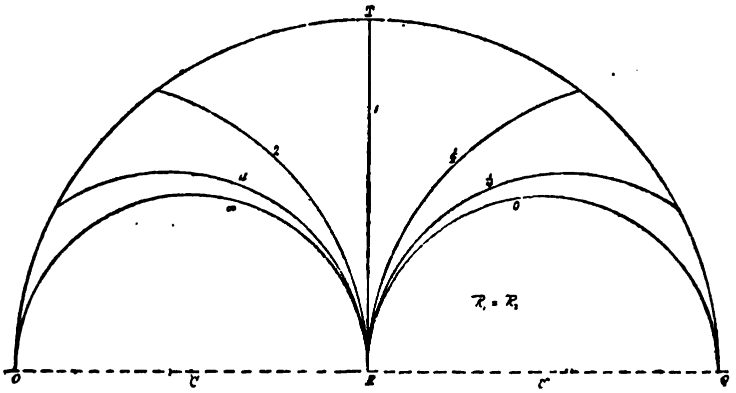


FIG. 12.

For the case of self-induction in both branches the loci lie below $O\ Q$, so as to place the loci upside down with regard to that shown in Fig. 11.

In the special case of $R_1 = R_2$, Fig. 12

$$x = \tfrac{1}{2}\,a\,(\cos 2\,\theta_1 + \cos 2\,\theta_2)$$

$$y = \tfrac{1}{2}\,a\,(\sin 2\,\theta_1 + \sin 2\,\theta_2)$$

$$\therefore x^2 + y^2 = a^2 \cos^2(\theta_1 - \theta_2)$$

$$\frac{y}{x} = \frac{\sin 2\,\theta_1 + \sin 2\,\theta_2}{\cos 2\,\theta_1 + \cos 2\,\theta_2} = \tan\,(\theta_1 + \theta_2).$$

$$\therefore \frac{x^2}{x^2 + y^2} = \cos^2(\theta_1 + \theta_2)$$

$$\therefore \frac{a^2 x^2}{(x^2 + y^2)^2} = \frac{\cos^2(\theta_1 + \theta_2)}{\cos^2(\theta_1 - \theta_2)} = \left(\frac{1 - \tan\theta_1 \tan\theta_2}{1 + \tan\theta_1 \tan\theta_2}\right)^2$$

$$\therefore x^2 + y^2 = \pm \left(\frac{1 + G^2}{1 - G^2}\right) a\, x \qquad (18)$$

This equation represents a set of circles having a common vertical tangent at E, which tangent is itself that one of the set for which $G = 1$ whose radius is infinity. All these circles lie outside the pair whose diameters are $O\,E$ and $Q\,E$, and only so much of each circle forms the locus in question as lies within the semicircle of diameter $O\,Q$. The points where each locus meets the edge of junction is the fixed point of contact mentioned in Fig. 11, where each locus passes from one leaf to the other. That part of each locus which lies in the first leaf falls upon and coincides with the remaining part in the other leaf.

6. Still assuming that both branches contain condensers only, or self-inductions only besides. ohmic resistances, construct loci in case the quotient of the tangents of lead or lag be taken as constant. These loci may also be readily constructed as shown in Fig. 13, which is drawn for the case of a condenser in each branch. Then

$$\tan\theta_1 = \frac{K_1}{R_1\,\omega} \text{ and } \tan\theta_2 = \frac{K_2}{R_2\,\omega}$$

$$\therefore \frac{\tan\theta_1}{\tan\theta_2} = \frac{K_1\,R_2}{K_2\,R_1} = F, \text{ say} \qquad (19)$$

in which θ_1 and θ_2 both lie on the same side of $O\,C$.

In Fig. 13 to construct, for example, the locus for which $F = 4$; at any point B lay off $B\,F\,/\,B\,D = 4$ and complete the parallelogram on $O\,P_1$ and $O\,P_2$. Then P is a point of the locus. By moving this vertical $B\,D\,F$ to different distances to the right of O, other points of $F = 4$ may be constructed. Verticals divided in other ratios give loci for other values of F. Several of these have been constructed by points in Fig. 13 On cross-section paper or profile paper successive points of these loci may be constructed with facility and rapidity. Each of these loci extends from O, where the frequency is infinite, to Q, where it is zero, and $I = O\,P$ may consequently assume any value between zero and $a_1 + a_2$ for each value of F, while I has in general no other maximum or minimum values. It is evident that the locus $F = 1$ is the semi-circle $O\,T\,Q$, which is the edge of

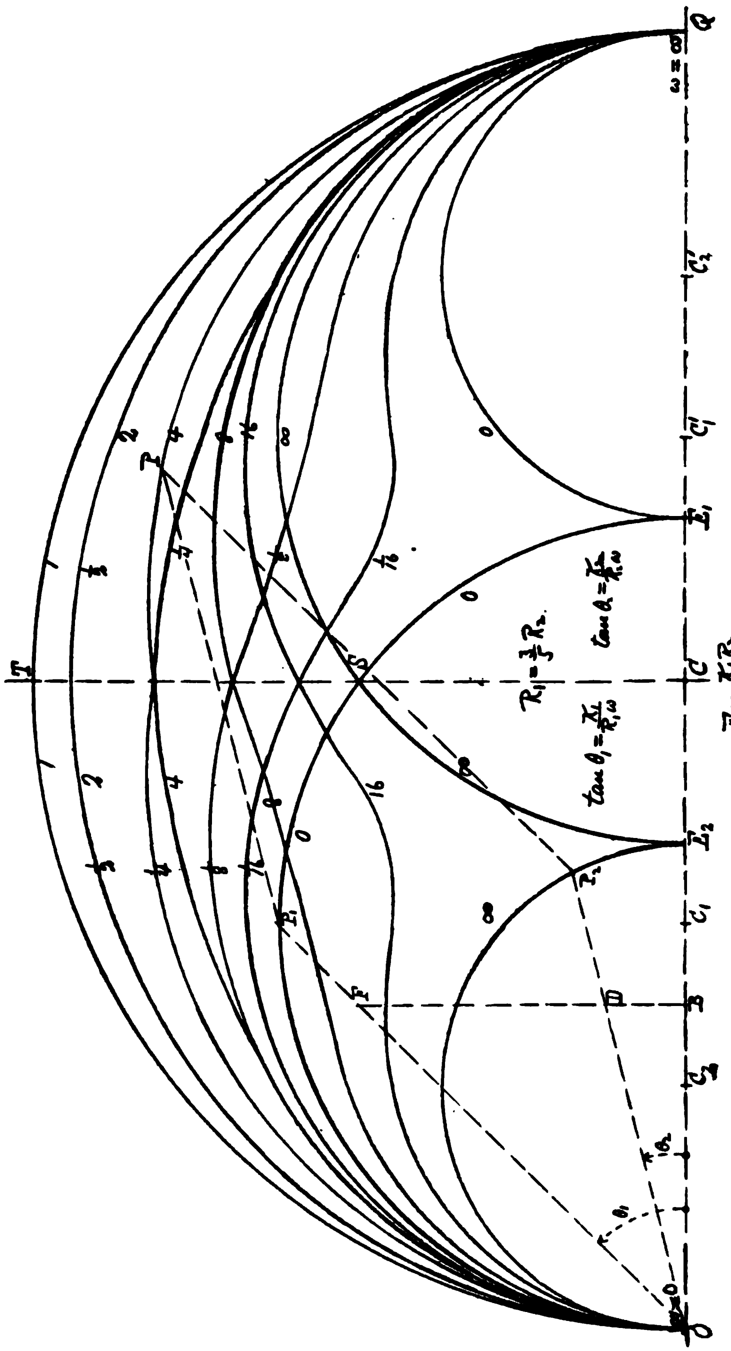


FIG. 13.

junction along which the two leaves join. The system of loci lying in the first leaf are those whose values of F lie between infinity and unity, and they constitute a series of curves which gradually change in shape from the two semi-circles $O\ E_2$ and $E_2\ Q$ in case $F = \infty$, to the single semi-circle $O\ T\ Q$ in case $F = 1$.

To each of these curves in the first leaf there corresponds an equal locus in the second leaf, such that the value of F is the numerical reciprocal of that in the first leaf F, or, if we distinguish magnitudes in the second leaf by primes and let the components I_1^1 and I_2^1 have such directions that

$$\tan \theta_1 \tan \theta_1^1 = 1, \text{ and } \tan \theta_2 \tan \theta_2^1 = 1,$$

then $\dfrac{\tan \theta_1 \tan \theta_1^1}{\tan \theta_2 \tan \theta_2^1} = F_1\, F_1^1 = 1$;

but $\sin \theta_1 = \cos \theta_1^1$, etc.,

and $\cos \theta_1 = \sin \theta_1^1$, etc. (20)

Hence, as shown in eq. (12) P^1 is as far to the right of C as P is to the left of it.

But, $y = y_1 + y_2 = a_1 \sin \theta_1 \cos \theta_1 + a_2 \sin \theta_2 \cos \theta_2$

and $y^1 = y_1^1 + y_2^1 = a_1 \sin \theta_1^1 \cos \theta_1^1 + a_2 \sin \theta_2^1 \cos \theta_2^1$

$\therefore$ by eq. (20), $y = y^1$, or P and P^1 are at the same distance from $O\ Q$. Hence, in case $F\,F^1 = 1$ the loci of P and P^1 are pairs of equal curves symmetrically situated about $C\ T$.

Each locus of the set $F > 1$ apparently intersects each of the set $F < 1$, at some point in the area $O\ S\ Q\ T$, but such is not really the case, since all of the first set lie in the first leaf, while all of the other set lie in the second leaf which overlaps the first in the area just mentioned; so that of two coincident values of $I = O\ P$ which lead to overlapping points, or apparently coincident points, the one can be gradually and continuously changed into the other only by moving P so as to cause F to assume all intermediate values, including $F = 1$.

For very large or very small values of F the locus approximates to the semi-circles with centers $C_2\ C_1^1$ or to $C_1\ C_2^1$. It will be noticed in these cases that since the curve dips toward E_2 or E_1 there may be one value of I for which the lead is a minimum, and another for which it is a maximum, and these are to be located by drawing tangents to the curve through O; but values of F that are neither large nor small afford no maximum or minimum lead except 0° and 90°.

In case both branches contain self-inductive resistances instead of condensers the diagram lies below $O\ Q$ instead of above it.

There is always one value of I for each value of F that affords a maximum wattless current, and for very large and very small values of F there may be two such maxima and one minimum between them. These can be located by drawing horizontal tangents to the locus, or they may be determined analytically by the conditions for a maximum or minimum of y.

Every value of I has a lead, and hence no case of consonance of phase between E and I occurs for any finite frequency, but that state is more nearly possible the more nearly F approaches to zero or infinity. Each locus becomes more and more nearly symmetrical about $S\ T$ the more R_1 and R_2 approach equality, and the special case of $R_1 = R_2$ causes each pair of loci for reciprocal values of F to coincide, *i. e.*, each locus is symmetrical about $S\ T$. The equation of the locus in rectangular co-ordinates may then be obtained in algebraic form. Take the origin at C, then using expressions found previously we have: $a_1 = a_2 = a$, and $x = \frac{1}{2}\, a\, (\cos 2\,\theta_1 + \cos 2\,\theta_2)$, $y = a\ (\sin 2\,\theta_1 + \sin 2\,\theta_2)$

$$\therefore x^2 + y^2 = a^2 \cos^2 (\theta_1 - \theta_2).$$

$$a^2 - x^2 - y^2 = a^2 \sin^2 (\theta_1 - \theta_2)$$

Also,

$$\frac{y}{x} = \frac{\sin 2\,\theta_1 + \sin 2\,\theta_2}{\cos 2\,\theta_1 + \cos 2\,\theta_2} = \tan (\theta_1 + \theta_2)$$

$$\therefore \frac{1}{1 + \dfrac{x^2}{y^2}} = \frac{y^2}{x^2 + y^2} = \sin^2 (\theta_1 + \theta_2)$$

$$\therefore \frac{a^2\, y^2}{(x^2 + y^2)\,(a^2 - x^2 - y^2)} = \frac{\sin^2 (\theta + \theta_2)}{\sin^2 (\theta_1 - \theta_2)} = \left(\frac{\tan \theta_1 + \tan \theta_2}{\tan \theta_1 - \tan \theta_2}\right)^2$$

$$\therefore (x^2 + y^2)\,(a^2 - x^2 - y^2) = \left(\frac{F - 1}{F + 1}\right)^2 a^2\, y^2 \qquad (21)$$

a curve of the fourth degree which is symmetrical about both x and y, of which the upper half is to be used in case of condensers, and the lower half for self-inductance resistances. Equation (21) includes both cases.

The general case in Fig. 13 is specially suited to treat variable frequency, for F remains unchanged by variation of frequency. It will be unnecessary to more than mention in passing the case in which one of the resistances is very small, and the locus is then confined to a narrow band along the semi-circle $O\ T\ Q$.

7. Resuming the case of a condenser in the first branch and self-induction in the second, construct the loci which make the ratio of the curvilinear co-ordinates constant, *i. e.*,

$$\frac{\tan\theta_1}{\tan\theta_2} = \frac{K R_2}{L R_1 \omega^2} = F, \text{ say} \tag{22}$$

In Fig. 14 take $F = 4$. for example, then $B F / B D = 4$ and the construction proceeds as in Fig. 13 except in this that $B F$ and $B D$ being opposite in sign lie on opposite sides of $O Q$. The loci for various values of F appear on Fig. 14, As before stated, the process of constructing by points is much facilitated by using paper ruled in squares. Each of these loci extends from O, where the frequency is infinite, to Q where it is zero, and the current $I = O P$ may consequently have any value between zero and $a_1 + a_2$ for each value of F, while I has in general no other maximum or minimum values. But each locus is tangent at one point to the edge of junction $E_1 T E_2$ and passes at that point from one leaf to the other, so that the envelope of the loci, as F varies from infinity to zero, is the semi-circle of radius $\pm \frac{1}{2}(a_1 - a_2)$ and center C.

It may be proven by steps like those previously given that in case $F F^1 = 1$ (so that F and F^1 are numerically reciprocal), these loci are equal right and left curves symmetrically disposed about $S T$. Thus the loci are separated into two sets according as F is greater or less than unity.

The locus for $F = 1$ is its own reciprocal and consequently its right and left half are alike. It is in fact a semi-ellipse $O T Q$ as may readily be proved. For, in this case $\theta_1 = \theta_2$, and taking the origin at C we have by using the same notation as previously

$$x + \tfrac{1}{2}(a_1 + a_2) = x_1 + x_2 = (a_1 + a_2)\cos^2\theta_1$$

$$y = y_1 - y_2 = (a_1 - a_2)\sin\theta_1\cos\theta_1$$

$$\therefore x = \tfrac{1}{2}(a_1 + a_2)\cos 2\theta_1 \,.\quad y + \tfrac{1}{2}(a_1 - a_2)\sin 2\theta_1$$

$$\therefore \frac{x^2}{(a_1 + a_2)^2} + \frac{y^2}{(a_1 - a_2)^2} = \tfrac{1}{4} \tag{23}$$

This ellipse is tangent at T to the semi-circle of center C and radius $\pm \frac{1}{2}(a_1 - a_2)$, while all those loci for which $F > 1$ are tangent to it between E_2 and T, and all those for which $F < 1$ between E_1 and T. The apparent intersections of the loci of the two sets within the area $S E_1 T E_2$ are double points situated in different leaves.

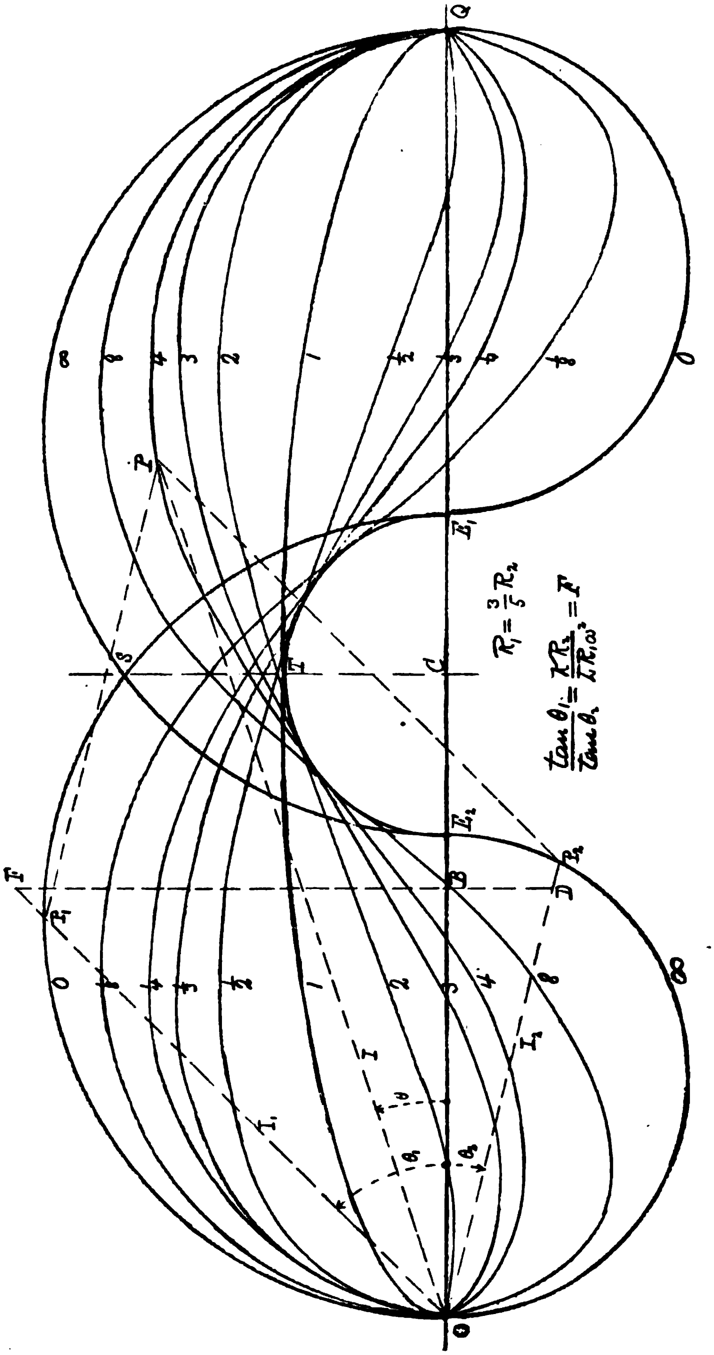

Q
O
E₁
E₂
C
B
D
S
T
F
P₁
P₂
I
I₁
I₂
θ₁
θ₂
0
1/8
1/4
1/3
1/2
1
2
3
4
8
∞
$R_1 = \frac{3}{5} R_2$
$\frac{\tan\theta_1}{\tan\theta_2} = \frac{k R_2}{k R_1 \omega^2} = F$

Fig. 14.

For each value of $F > 1$ there is in general a value of I between $\frac{1}{2}(a_1 - a_2)$ and $(a_1 + a_2)$ at which the lead is a maximum and for each value of $F < 1$, a maximum lag between the same limits, which are to be located by drawing tangents to the loci through O.

There are also maximum wattless currents to be located by drawing horizontal tangents to the loci. There is also for each locus a current I in consonance with E determined by the point where it crosses $O\ Q$, viz: $I < a_2$ in case $F > 1$, and $I > a_1$ in case $F < 1$.

In the special case of $R_1 = R_2$ the circular envelope reduces to the point C through which each locus passes. In this case the loci all fall within two circles whose diameters are $C\ O$ and $C\ Q$, and the locus for any given value of F consists of two parts which are exactly alike (one in each circle, and situated opposite to each other. Thus the pair of loci for any given value of F and its numerical reciprocal form a figure ∞, whose equation is found as follows:—Since in this case $a_1 = a_2 = a$ as before.

$$x = \frac{a}{2}(\cos 2\,\theta_1 + \cos 2\,\theta\,)$$

$$y = \frac{a}{2}(\sin 2\,\theta_1 - \sin 2\,\theta_2)$$

$$\therefore x^2 + y^2 = a^2 \cos^2 (\theta_1 + \theta_2)$$

$$\therefore a^2 - x^2 - y^2 = a^2 \sin^2 (\theta_1 + \theta_2)$$

also

$$\frac{y}{x} = \frac{\sin 2\,\theta_1 - \sin 2\,\theta_2}{\cos 2\,\theta_1 + \cos 2\,\theta_2} = \tan (\theta_1 - \theta_2)$$

$$\therefore \frac{y^2}{x^2 + y^2} = \sin^2 (\theta_1 - \theta_2)$$

$$\therefore \frac{(a^2 - x^2 - y^2)\,(x^2 + y^2)}{a^2\,y^2} = \frac{\sin^2 (\theta_1 + \theta_2)}{\sin^2 (\theta_1 - \theta_2)} = \left(\frac{\tan \theta_1 + \tan \theta_2}{\tan \theta_1 - \tan \theta_2}\right)^2$$

$$\therefore (a^2 - x^2 - y^2)\,(x^2 + y^2) = \left(\frac{F + 1}{F - 1}\right)^2 a^2\,y^2 \qquad (24)$$

which is evidently symmetrical about both the axes of x and y, and is the same for reciprocal values of F. It is not thought necessary to show a figure for this case. It will be noticed that equations (21) and (24) are essentially the same, provided F may have any values from positive to negative infinity. Were θ_1 and

θ_2 to be always reckoned positive for lead and negative for lag or *vice versa*, then F would have this range of values. It has been restricted thus far in this paper to positive values by our conventions of lead and lag. These equations reduce to a circle of radius a in case $F = 1$, and to two circles tangent to $C\,S$ at C in case F is zero or infinity.

8. Consider next the more general case in which each branch contains an ohmic resistance, a self-inductive resistance and a condenser, but no mutual induction. Then using notation like that before employed we have the known equations.:

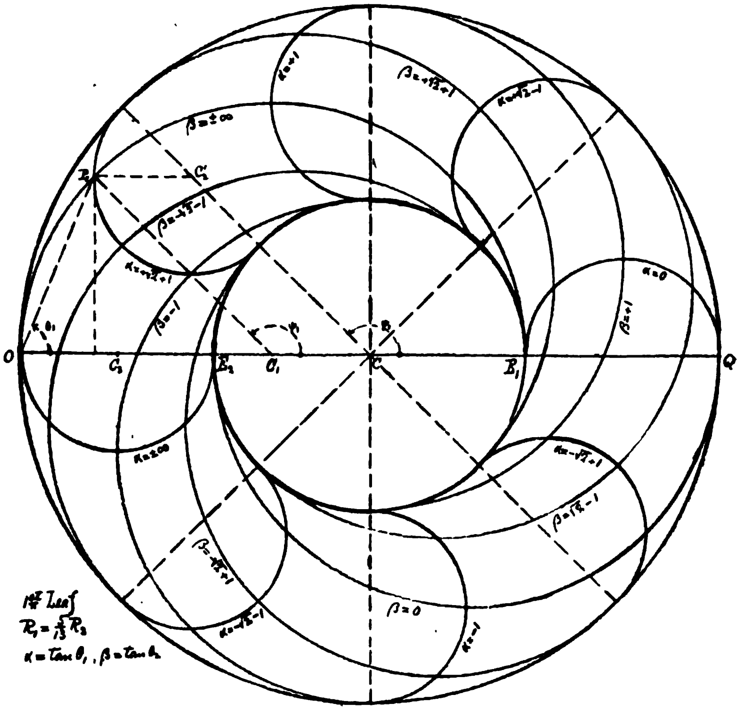


FIG. 15.

$$\tan\theta_1 = \frac{K_1}{R_1\,\omega} - \frac{L_1\,\omega}{R_1}, \qquad I_1 = \frac{E}{R_1}\cos\theta_1 \tag{25}$$

$$\tan\theta_2 = \frac{K_2}{R_2\,\omega} - \frac{L_2\,\omega}{R_2}, \qquad I_2 = \frac{E}{R_2}\cos\theta_2 \tag{26}$$

in which θ_1 and θ_2 are angles of lead or lag according as they are positive or negative; and they may evidently either of them be made to assume any value between + 90° and — 90° (while R_1 and R_2 remain constant), either by suitably varying the frequency or the other constants of the branches.

Since I_1 and I_2 vary in this case as the cosines of θ_1 and θ_2, as also in equations (2) and (4), it is evident that the loci for constant values of tan θ_1 or tan θ_2 are circular arcs as in Figs. 4 and 5; but from the fact that the ranges of θ_1 and θ_2 no longer lie between 0 and 90° but between + 90° and — 90° instead, it appears that the loci are no longer semi-circles merely as in Figs. 4 and 5, but each includes in this case an entire circumference, one-half of which lies in each leaf.

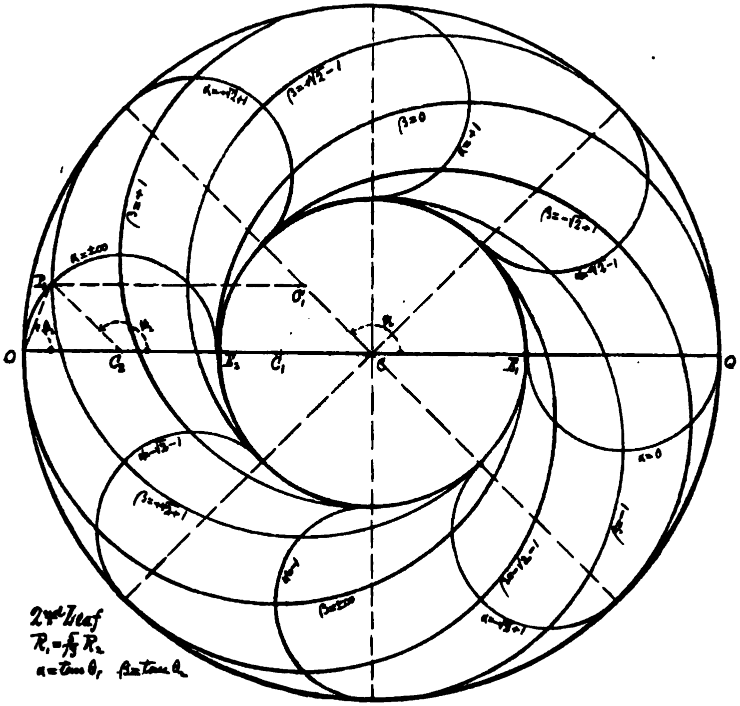


FIG. 16.

In Figs. 15 and 16 these leaves have been for convenience and clearness drawn separately, and it is evident that every point P (the extremity of the vector $I = O\,P$) lies within the area included between the two circumferences whose diameters are $E_1\,E_2$ and $O\,Q$. On this two-leaved surface each circle of one set has one intersection with each circle of the other set on each leaf, and the two leaves are united along the exterior and interior circumferences forming a flat ring with two faces.

The positions of the various loci may be most conveniently designated by the angular positions of their centers with reference to the line $O\ Q$. For example, in Fig. 15, let $Q\ C\ C_2^1 = Q\ C_1\ P_1 = \psi_1$ then we have from the figure

$$\tan \theta_1 = \frac{\sin (180^\circ - \psi_1)}{1 - \cos (180^\circ - \psi_1)} = \frac{\sin \psi_1}{1 + \cos \psi_1} = \tan \tfrac{1}{2} \psi_1 \qquad (27)$$

$$\therefore 2\ \theta_1 = \psi_1$$

Similarly in Fig. 16, $2\ \theta_2 = \psi_2$.

These equations enable us to compute with ease the numerical values of the co-ordinates on the circumference of a circle in any given position ψ_1 or ψ_2.

The peculiarities and properties of these loci for constant values of $\tan \theta_1$ and $\tan \theta_2$ have most of them been detailed at such length in connection with Figs. 4 and 5 as to render repetition unnecessary. Attention should, however, be called to the fact that in case $\psi_1 = \psi_2$, then $\tan \theta_1 = \tan \theta_2$, which shows itself upon the figures in this way: Construct the two circular loci one of each set whose diameters coincide, *i. e.*, $\psi_1 = \psi_2$. They are tangent to the outer edge at the same point and both have the same numerical value.

Again, at every point P of the ring surface except at either of the edges of junction there are two distinct ways of producing the current $I = O\ P$, and one of these cannot be gradually changed into the other except by varying the frequency or other constants of the branches so as to make P travel to the inner or outer edge and back again.

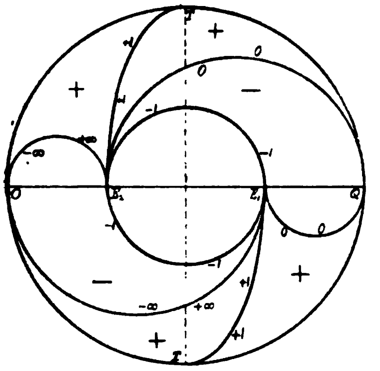
The loci for successive values of ψ_1 and ψ_2 differing by 45° are represented upon Figs. 15 and 16.

9. In continuing the consideration of the general case, expressed by eqs., (25) and (26), let G^2 designate the product of the co-ordinates, as was done previously, *i. e.* $\tan \theta_1 \tan \theta_2 = G^2$. Then the loci for various constant values of G will be those already discussed, but by reason of the doubling of range of θ_1 and θ_2 the loci will combine together the various separate results previously discussed, as shown in Figs. 17 and 18, where the two leaves are shown separately. In these figures, angles of lead are taken as positive, and lag as negative, giving as a result negative

products whenever a lead and a lag are combined. For all negative values of G^2, *i. e.* $-\infty < G^2 < 0$, the loci lie in a single leaf and join the points E_1 and E_2 of the same leaf, as in Fig. 9. But for all positive values of G^2, *i. e.* $0 < G^2 < \infty$ the loci join E_1 of one leaf to E_2 of the other leaf as in Fig. 11.

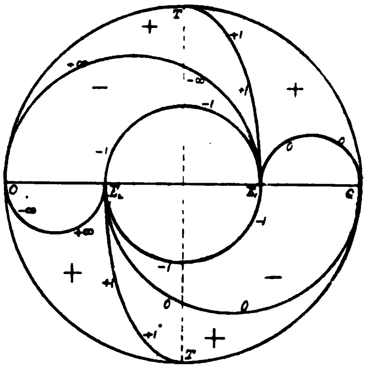
The manner in which these loci succeed one another is clear from Figs. 17 and 18, from which it appears that the values of G^2 along the circumference $O\ T\ Q$ are all positive, being infinity at O, unity at T, and zero at Q, while $G^2 = -1$ along the entire circumference $E_1\ E_2$.

Since lead and lag enter the construction in precisely the same manner, the locus in one leaf for a given value of G is the reflection in $O\ Q$ of the locus for the same value of G in the other leaf. Thus Fig. 17 is a reflection in $O\ Q$ of Fig. 18. It has also been shown before, that the loci for reciprocal values of G are reflections of one another in $T\ T$. These last reflections are in different leaves. By the time a locus has suffered reflections successively in $O\ Q$ and $T\ T$ it has been restored to the leaf from which it started and has been revolved 180° about the center of the leaves. Hence, if from any point P we draw a line $P\ C$ and prolong it to P^1 so that $C\ P = C\ P^1$, then for these two points we have $G\ G^1 = 1$.



1st Leaf. G²

FIG 17.



2nd Leaf. G²

FIG 18.

10. In like manner consider the loci in which the quotient $\tan\theta_1 \tan / \theta_2 = F$ assumes various constant values in the general case of eqs. (25) and (26).

These will consist of combinations of the special cases of Figs. 13 and 14 as shown in separate leaves in Figs. 19 and 20 where the blank spaces may be thought of as filled in with loci for successive values of F from Figs. 13 and 14, due regard being had to their signs. $F = +1$ for the entire circumference $O\ Q$, but F is negative along $E_2\ S\ E_1$; $-\infty$ at E_2, -1 at S, and 0 at E_1.

The same statements respecting reflections etc. are true of the F — loci as of the G — loci, hence if $C\ P = C\ P^1$ and $P\ C\ P^1$ is a straight line, then $F\ F^1 = 1$.

11. In further continuation of the general case in eqs. (25) and (26), it is now proposed to develop the general graphical

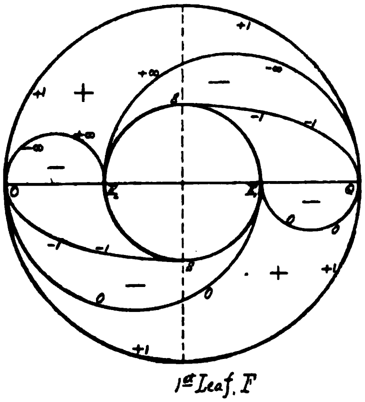


Fig. 19.

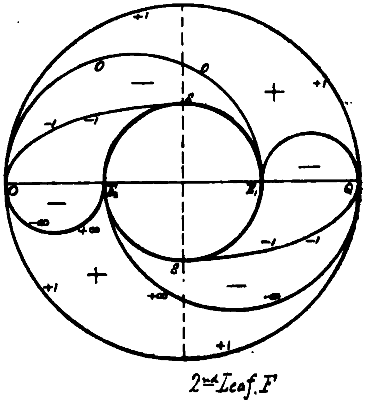


Fig. 20.

process for constructing the locus of the extremity P of the vector $I = O\ P$ representing the total current in case the frequency alone is variable.

In eq. (25) let the subscript 1 designate magnitudes in the first branch: viz, let

$$\tan\ \theta_1' = \frac{K_1}{R_1\ \omega},\ \text{and}\ \tan\ \theta_1'' = \frac{L_1\ \omega}{R_1}$$

$$\therefore\ \tan\ \theta_1 = \tan\ \theta_1' - \tan\ \theta_1''$$

and let,

$$\tan\ \theta_1'\ \tan\ \theta_1'' = \frac{K_1\ L_1}{R_1^2} = G_1^2$$

Also let,

$$\tan \theta_1' = G_1 \tan \varphi_1', \text{ and } \tan \theta_1'' = G_1 \tan \varphi_1''$$

$$\therefore \tan \varphi_1' \tan \varphi_1'' = 1, \; \therefore \varphi_1' + \varphi_1'' = 90^\circ.$$

In like manner let magnitudes in the second branch be designated by the subscript 2

Now in Fig. 21 take any convenient distances $B\,F$ and $B\,O_1$ and let $B\,O_1\,F = \theta_1'$, then,

$$\tan \theta_1' = \frac{K_1}{R_1\,\omega} = \frac{B\,F}{B\,O_1} \tag{28}$$

Whatever may be the values of the constants K_1 and R_1 in this branch, and whatever distances $B\,F$ and $B\,O_1$ may have been assumed, a value of ω which corresponds to them, can be found from eq. (28) if need be.

Next, lay off

$$\overline{B\,A_1} = G_1\,\overline{B\,O_1}$$

$$\therefore \tan \theta_1' = \frac{B\,F}{B\,O_1} = G_1\,\frac{B\,F}{B\,A_1} = G_1 \tan \varphi_1'$$

$$\therefore B\,A_1\,F = \varphi_1'$$

Make $F\,A_1\,D_1 = 90^\circ$, then $B\,A_1\,D_1 = \varphi_1''$

$$\therefore B\,O_1\,D_1 = \theta_1'', \text{and } \tan \theta_1 = \frac{B\,D_1}{B\,O_1}$$

$$\therefore \tan \theta_1 = \tan \theta_1' - \tan \theta_1'' = \frac{B\,F - B\,D_1}{B\,O_1}$$

Lay off

$$B\,H_1 = B\,F - B\,D_1. \quad \therefore \tan \theta_1 = \frac{B\,H_1}{B\,O_1}, \text{and } \theta_1 = B\,O_1\,H_1.$$

Again, lay off $B\,O_2$ such that

$$\frac{R_1}{K_1} : \frac{R_2}{K_2} :: B\,O_1 : B\,O_2,$$

and in this proportion substitute the value of $B\,O_1$ from eq. (28),

$$\therefore \tan \theta_2' = \frac{K_2}{R_2\,\omega} = \frac{B\,F}{B\,O_2} \tag{29}$$

Complete the construction for this branch as in the first branch and we find

$$\theta_2' = B\,O_2\,F, \quad \theta_2'' = B\,O_2\,D_2, \quad \theta_2 = B\,O_2\,H_2$$

In Fig. 21, the constants were so assumed that $G_1 = \frac{1}{2}$ and $G_2 = 2$.

We have thus found θ_1 and θ_2, the angles of lead (or lag) of the components I_1 and I_2 for some unknown value of ω_1 which could be readily computed from eq. (28) or (29), if desired for any purpose. Having thus found the relative positions of O_1, O_2, A_1,

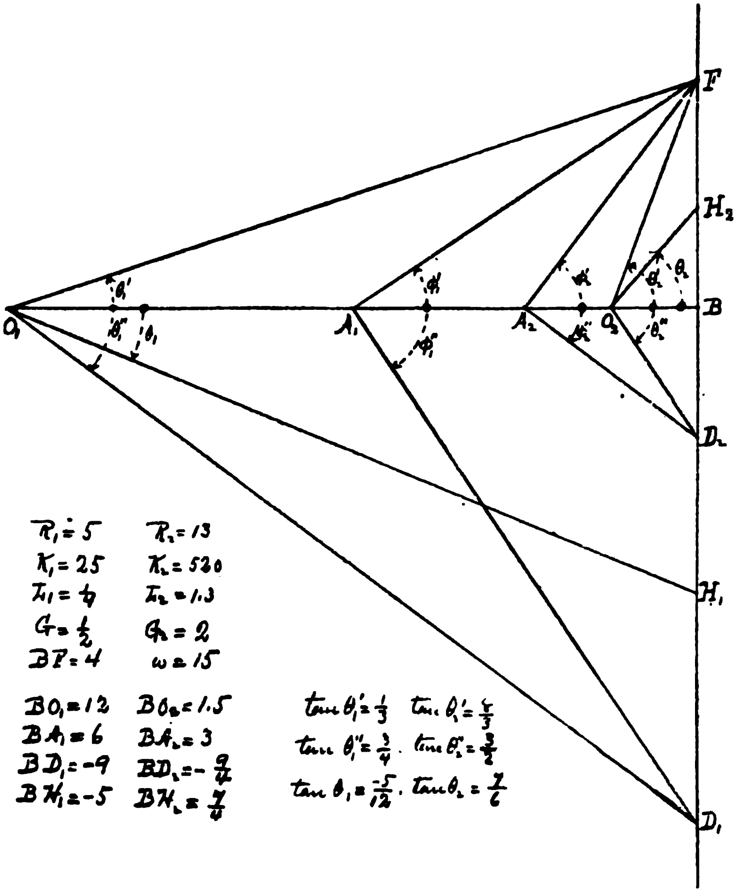


FIG. 21.

A_2, the point F may be moved to successive positions on the vertical through B. Each successive position of F will give values of θ_1 and θ_2 which correspond to some one frequency, and thus completely determine the components I_1 and I_2 of the total current I, for that undetermined frequency.

The construction just given is one of two alternative constructions, for it would have been equally possible to assume at the start any two distances $B\ O_1$ and $B\ D$ on the vertical below B and then let

$$\tan \theta_1'' = \frac{L_1\,\omega}{R_1} = \frac{B\ D}{B\ O_1}$$

and

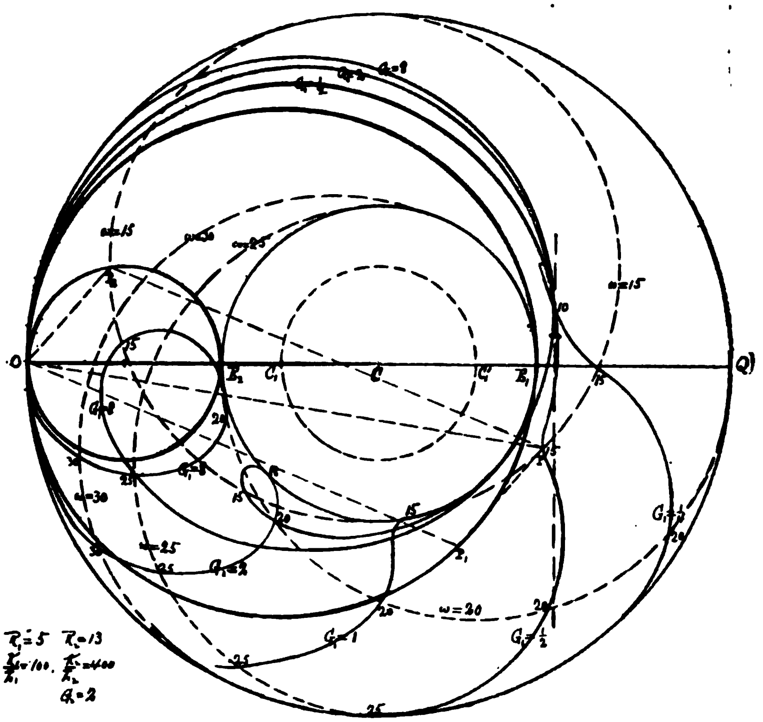


Fig. 22

$$B\ O_1 : B\ O_2 :: \frac{R_1}{L_1} : \frac{R_2}{L_2}$$

$$\therefore \tan \theta_2'' = \frac{L_2\,\omega}{R_2} = \frac{B\ D}{B\ O_2} :$$

Then completing the construction in a manner similar to that just given find two points F_1 and F_2 from which H_1 and H_2

could be found. Successive positions of D would in this case thus serve to determine corresponding values of θ_1 and θ_2 precisely as they were determined in the previous construction by successive positions of F. It may often be more expeditious to compute numerical values of tan θ_1 and tan θ_2 directly from eqs. (25) and (26) by assuming various successive values of ω, and then, if the locus of P be constructed on cross-section paper, θ_1 and θ_2 can be laid off with facility, since tan θ_1 and tan θ_2 are ratios such as can be read off at once on squared paper.

In Fig. 21 the numerical values assumed are:

$K_1 = 25.$ $\qquad K_2 = 520.$
$L_1 = 0.25$ $\qquad L_2 = 1.3$
$R_1 = 5.$ $\qquad R_2 = 13.$

$B\,F = 4$, and $\omega = 15$, consequently we have:

$G_1 = 0.5$ $\qquad G_2 = 2.$
$B\,O_1 = 12.$ $\qquad B\,O_2 = 1.5$
$B\,A_1 = 6.$ $\qquad B\,A_2 = 3.$
$B\,D_1 = -9.$ $\qquad B\,D_2 = -2.25$
$B\,H_1 = -5.$ $\qquad B\,H_2 = 1.75$
$\tan\theta_1' = \frac{1}{3}$ $\qquad \tan\theta_2' = \frac{8}{3}$
$\tan\theta_1'' = \frac{3}{4}$ $\qquad \tan\theta_2'' = \frac{3}{2}$
$\tan\theta_1 = \frac{1}{3} - \frac{3}{4} = -\frac{5}{12}$ $\qquad \tan\theta_2 = \frac{8}{3} - \frac{3}{2} = \frac{7}{6}$

These values are arrived at either by construction as in Fig. 21 or by computation. Probably in most cases computation will be the more convenient; but when the values of the co-ordinates $a = \tan\theta_1$ and $\beta = \tan\theta_2$ of a point P corresponding to some known or unknown value of ω have been thus found they can be at once used as in Fig. 22 for plotting the point P of the locus for $G_1 = \frac{1}{2}$ and $G_2 = 2$.

Numerical values from which the curves in Fig. 22 were plotted, are given in the following tables of values of

$$a = \frac{K_1 - L_1\,\omega^2}{R_1\,\omega}, \qquad \beta = \frac{K_2 - L_2\,\omega^2}{R_2\,\omega},$$

$$G_1 = \frac{\sqrt{K_1\,L_1}}{R_2}, \qquad G_2 = \frac{\sqrt{K_2\,L_2}}{R_2}.$$

VALUES OF G_1 AND α, IN CASE $R_1 = 5$ AND $K_1 / L_1 = 100$.

$K_1 =$	12.5	25.	50.	100.	200.	18.75	37.5	75.	150.	300.
$L_1 =$	0.125	0.25	0.5	1.	2.	.1875	0.375	0.75	1.5	3.
$G_1 =$	0.25	0.5	1.	2.	4.	0.375	0.75	1.5	3.	6.
$\omega = 1$	2.47	4.95	9.9	19.8	39.6	3.78	7.45	14.9	29.7	59.4
4	0.52	1.05	2.1	4.2	8.4	0.79	1.57	3.15	6.3	12.6
5	0.37	0.75	1.5	3.	6.	0.56	1.12	2.25	4.5	9.
6	0.26	0.53	1.06	2.13	4.26	0.4	0.8	1.59	3.18	6.36
7	0.19	0.37	0.75	1.5	3.	0.28	0.56	1.12	2.25	4.5
8	0.11	0.22	0.45	0.9	1.8	0.17	0.34	0.68	1.35	2.7
9	0.05	0.11	0.21	0.42	0.84	0.08	0.16	0.32	0.63	1.26
10	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
11	— 0.05	— 0.09	— 0.18	— 0.36	— 0.72	— 0.07	— 0.14	— 0.27	— 0.54	— 1.08
12	— 0.09	— 0.18	— 0.36	— 0.73	— 1.47	— 0.14	— 0.27	— 0.54	— 1.08	— 2.16
13	— 0.13	— 0.27	— 0.53	— 1.06	— 2.12	— 0.2	— 0.4	— 0.8	— 1.59	— 3.18
14	— 0.17	— 0.34	— 0.69	— 1.37	— 2.74	— 0.26	— 0.52	— 1.04	— 2.07	— 4.14
15	— 0.21	— 0.42	— 0.83	— 1.67	— 3.33	— 0.31	— 0.62	— 1.25	— 2.5	— 5.
16	— 0.24	— 0.48	— 0.97	— 1.95	— 3.9	— 0.37	— 0.73	— 1.46	— 2.91	— 5.82
17	— 0.28	— 0.56	— 1.11	— 2.22	— 4.45	— 0.42	— 0.83	— 1.67	— 3.33	— 6.66
18	— 0.31	— 0.62	— 1.25	— 2.49	— 4.98	— 0.47	— 0.94	— 1.87	— 3.74	— 7.48
19	— 0.34	— 0.68	— 1.37	— 2.75	— 5.5	— 0.52	— 1.03	— 2.06	— 4.12	— 8.24
20	— 0.37	— 0.75	— 1.5	— 3.	— 6.	— 0.56	— 1.12	— 2.25	— 4.5	— 9.
25	— 0.52	— 1.05	— 2.1	— 4.2	— 8.4	— 0.79	— 1.57	— 3.15	— 6.3	—12.6
30	— 0.87	— 1.75	— 2.5	— 5.	—10.	— 0.94	— 1.88	— 3.75	— 7.5	—15.
40	— 0.94	— 1.87	— 3.75	— 7.5	—15.	— 1.41	— 2.81	— 5.62	—11.25	—22.5
60	— 1.45	— 2.9	— 5.8	— 11.6	—23.2	— 2.68	— 4.35	— 8.7	—17.4	—34.8
80	— 2.	— 4.	— 8.	— 16.	—32.	— 3.	— 6.	—12.	—24.	—48.
100	— 2.47	— 4.95	— 9.9	— 19.8	—39.6	— 3.73	— 7.45	—14.9	—29.7	—59.4

VALUES OF G_2 AND β, IN CASE $R_2 = 13$ AND $K_2 / L_2 = 400$.

$K_2 =$	65.	130.	2.60	520.	1040	97.5	195.	390.	780.	1560
$L_2 =$	.1625	0.325	0.65	1.3	2.6	.24375	.4875	0.975	1.95	3.9
$G_2 =$	0.25	0.5	1.	2.	4.	0.375	0.75	1.5	3.	6.
$\omega = 1$	4.99	9.97	19.95	39.9	79.8	7.48	14.96	29.92	59.85	119.7
4	1.2	2.4	4.8	9.6	19.2	1.8	3.6	7.2	14.4	28.8
5	0.94	1.87	3.75	7.5	15.	1.4	2.81	5.62	11.25	22.5
6	0.7	1.39	2.78	5.55	11.1	1.05	2.09	4.17	8.34	16.68
7	0.63	1.25	2.5	5.	10.	0.94	1.87	3.75	7.5	15.
8	0.53	1.05	2.1	4.2	8.4	0.79	1.57	3.15	6.3	12.6
9	0.45	0.9	1.8	3.6	7.1	0.68	1.35	2.7	5.4	10.8
10	0.38	0.75	1.5	3.	6.	0.56	1.12	2.25	4.5	9.
11	0.34	0.68	1.27	2.55	5.11	0.48	0.95	1.9	3.8	7.62
12	0.27	0.53	1.07	2.15	4.3	0.4	0.8	1.6	3.21	6.42
13	0.22	0.44	0.88	1.77	3.55	0.3	0.61	1.21	2.43	4.86
14	0.18	0.36	0.73	1.46	2.92	0.28	0.55	1.09	2.19	4.38
15	0.15	0.29	0.58	1.16	2.33	0.22	0.44	0.87	1.74	3.48
16	0.11	0.22	0.45	0.9	1.8	0.16	0.31	0.62	1.25	1.5
17	0.08	0.16	0.32	0.65	1.3	0.12	0.24	0.48	0.96	1.92
18	0.05	0.1	0.21	0.42	0.84	0.8	0.15	0.31	0.63	1.26
19	0.03	0.05	0.1	0.2	0.41	0.04	0.07	0.15	0.3	0.6
20	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
25	— 0.11	— 0.22	— 0.45	— 0.9	— 1.8	— 0.17	— 0.34	— 0.67	— 1.35	— 2.7
30	— 0.21	— 0.41	— 0.83	— 1.67	— 3.33	— 0.32	— 0.63	— 1.24	— 2.49	— 4.98
40	— 0.38	— 0.75	— 1.5	— 3.	— 6.	— 0.69	— 1.37	— 2.75	— 4.5	— 9.
60	— 0.66	— 1.32	— 2.65	— 5.3	—10.6	— 0.99	— 1.91	— 3.97	— 7.95	—15.9
80	— 0.94	— 1.87	— 3.75	— 7.5	—15.	— 1.4	— 2.81	— 5.62	—11.25	—22.5
100	— 1.2	— 2.4	— 4.8	— 9.6	—19.2	— 1.8	— 3.6	— 7.2	—14.4	— 28.8

It is evident that multiplying both K_1 and L_1 by any given number also multiplies α and G_1 by that number. The two halves of each table have been computed for values of K and L such that in each succeeding column their values are twice those of the preceding column, hence the values of α (and β) follow the same law. So that after one column of either table has been computed the others are simple multiples of it. Additional columns may readily be made. The coordinates given in these tables suffice for plotting many loci. Of these a few have been selected for consideration. $G_2 = 2$ has been assumed for all of the loci in Fig. 22 and more or less complete loci have been plotted for values of $G_1 = \frac{1}{4}, \frac{1}{2}, 1, 2, 4$, and 8.

Numbers placed at various points along these loci designate the values of ω at those points.

Let us continue the consideration of the locus $G_1 = \frac{1}{2}$, $G_2 = 2$. It is very nearly circular until near P, ($\omega = 15$) *i. e.* at frequencies below that the current through the branch 2 is comparatively small, but after that, I_2 rapidly assumes a much greater relative importance and so the locus makes a wide detour from its previous course until at about $\omega = 26$, $\alpha = \beta$, and both components having the same lag the locus reaches the circumference of the circle of junction $O\ Q_1$ becomes tangent to it and passes into the other leaf. It continues near the circumference $O\ Q$ until ω becomes infinite at O.

The frequency at which the locus becomes tangent to $O\ Q$ is to be found from the equation

$$\alpha = \beta,\ i.\ e.,\ \frac{K_1 - L_1\,\omega_0^2}{R_1} = \frac{K_2 - L_2\,\omega^2}{R^2}$$

$$\therefore\ \omega_0^2 = \frac{\dfrac{K_1}{R_1} - \dfrac{K_2}{R_2}}{\dfrac{L_1}{R_1} - \dfrac{L_2}{R_2}} \qquad (30)$$

From (30) we find for this locus $\omega_0^2 = 700$, $\therefore\ \omega_0 = 26.45$. Since frequency must be positive it appears that a given locus never has more than one point of tangency with the circle $O\ Q$ other than O. Following is a table of values of ω_0^2 for various relative values of G_1 and G_2 for the two branches under consideration. It is evident that multiplying K_1, K_2, L_1 and L_2 in (30) by any given number, as m will multiply both G_1 and G_2 by that number but will leave ω_0^2 unchanged. This finds expression in the table in the fact that the values of ω_0^2 are the same in any diagonal sloping downward to the right.

Values of ω_0^2 in equation (30) for $R_1 = 5$ and $R_2 = 13$.

$G_1 =$	m	$2\,m$	$4\,m$	$8\,m$	$16\,m$	$32\,m$	$64\,m$	$128\,m$	$256\,m$	$512\,m$
$G_2 = m$	-200	0	57	80	90.3	95.2	97.6	98.8	99.4	99.7
$2\,m$	$\mp\infty$	-200	0	57	80	90.3	95.2	97.6	98.8	99.4
$4\,m$	700	$\mp\infty$	-200	0	57	80	90.3	95.2	97.6	98.8
$8\,m$	500	700	$\mp\infty$	-200	0	57	80	90.3	95.2	97.6
$16\,m$	443	500	700	$\mp\infty$	-200	0	57	80	90.3	95.2
$32\,m$	420	443	500	700	$\mp\infty$	-200	0	57	80	90.3
$64\,m$	410	420	443	500	700	$\mp\infty$	-200	0	57	80
$128\,m$	405	410	420	443	500	700	$\mp\infty$	-200	0	57
$256\,m$	402	405	410	420	443	500	700	$\mp\infty$	-200	0
$512\,m$	401	402	405	410	420	443	500	700	$\mp\infty$	-200

The value of ω_0^2 for the principal diagonal of the table may be expressed more simply, since then

$$G_1^2 = G_2^2 \text{ or } \frac{K_1 L_1}{R_1^2} = \frac{K_2 L_2}{R_2^2}$$

$\therefore$ by comparison of proportions,

$$\frac{\dfrac{K_1}{R_1}}{\dfrac{L_2}{R_2}} = \frac{\dfrac{K_2}{R_2}}{\dfrac{L_1}{R_1}} = -\frac{\dfrac{K_1}{R_1} - \dfrac{K_2}{R_2}}{\dfrac{L_1}{R_1} - \dfrac{L_2}{R_2}} = -\,\omega_0^2 \tag{31}$$

Let ω_{01}^2 and ω_{02}^2 be values of ω_0^2 on two diagonals at equal distances from the principal diagonal of the table and let K_1, L_1, K_2, L_2, designate the values these quantities have in the first square of the diagonal then their values in the nth square of the top line are $2^n K_1$, $2^n L_1$, K_2, L_2, and in the nth square of the first column K_1, L_1, $2^n K_2$, $2^n L_2$; hence

$$\omega_{01}^2 = \frac{\dfrac{2^n K_1}{R_1} - \dfrac{K_2}{R_2}}{\dfrac{2^n L^1}{R_1} - \dfrac{L_2}{R_2}} \qquad \omega_{02}^2 = \frac{\dfrac{K_1}{R_1} - \dfrac{2^n K_2}{R_2}}{\dfrac{L_1}{R_1} - \dfrac{2^n K_2}{R_2}}$$

$$\therefore \omega_{01}^2\,\omega_{02}^2 = \frac{2^n\left(\dfrac{K_1}{R_1} - \dfrac{K_2}{R_2}\right) + (2^n - 1)\dfrac{K_1 K_2}{R_1 R_2}}{2\left(\dfrac{L_1}{R_1} - \dfrac{L_2}{R_2}\right) + (2^n - 1)\dfrac{L_1 L_2}{R_1 R_2}}$$

Hence by composition of proportions in equation (31) we have

$$\omega_{01}^2\,\omega_{02}^2 = \omega_0^4$$

i. e. the product of two tabular numbers equidistant from the principal diagonal is equal to the square of a number in that diagonal.

Furthermore the tabular numbers increase above that diagonal and decrease below it, to definite limits; for, considering numbers near the right hand end of the upper line in the table as computed by eq. (30), it will be noticed that the first terms of the numerator and denominator are so large compared with the last terms that the value of ω_0^2 approaches the limit K_1 / L_1, obtained by neglecting the last terms. That limit in the present example is 100. But if numbers near the bottom of the first column of the table be considered, the last terms of the numerator and denominator of eq. (30) are large and the limit in this case is K_2 / L_2, or 400 in the present example.

For frequencies between the limiting values $\omega_0^2 = K_1 / L_1$ and $\omega_0^2 = K_2 / L_2$ these loci have no points of tangency on $O\,Q$. In our example no locus is tangent to $O\,Q$ between the frequencies $\omega = 10$ and $\omega = 20$.

It will be noticed also that in this table ω_0^2 is negative and ω_0 is consequently imaginary in case $G_1 = G_2$ and generally in this table unless either $G_1 \gtrless 2\,G_2$ or $G_2 \gtrless 2\,G_1$, *i. e.*, loci lying between these relative values of G_1 and G_2 have no points of tangency with $O\,Q$.

It is then evident that certain of the loci have points of tangency with $O\,Q$ outside definite limits, while others have no such points of tangency anywhere.

Again, let $F = \tan\theta_1 / \tan\theta_2$

$$\therefore F = \frac{(K_1 - L_1\,\omega^2)\,R_2}{(K_2 - L_2\,\omega^2)\,R_1} = \frac{(K_1 / \omega^2 - L_1)\,R_2}{(K_2 / \omega^2 - L_2)\,R_1} \qquad (32)$$

It is evident that for small values of ω the value of F is approximately

$$F' = \frac{K_1}{R_1} \div \frac{K_2}{R_2} \qquad (33)$$

hence any locus in which ω alone is variable approximates near O (where ω is small) to the locus represented by equation (33), a locus which has been fully treated in connection with Fig. 13. That part of any locus in which ω alone varies, which is near O, lies therefore between the upper semi circles on the diameters $O\,Q$ and $O\,E_2'$.

Likewise for large values of ω, in case ω alone varies, the locus approximates to that represented by the equation

$$F'' = \frac{L_1}{R_1} \div \frac{L_2}{R_2} \qquad (34)$$

which near O lies between the lower semi-circles on $O\ Q$ and $O\ E_2$. Whether the locus starts out from O in the first leaf or not, depends upon the value of F''. In case $F' > 1$, *i. e.*,

$$\frac{K_1}{R_1} > \frac{K_2}{R_2}$$

then the first portion of the locus, where ω is small, lies in the first leaf, but in case $F' < 1$ it lies in the second leaf, as was shown in connection with Figs. 19 and 20.

Again, in case $F'' > 1$, *i. e.*,

$$\frac{L_1}{R_1} > \frac{L_2}{R_2}$$

the locus terminates at O (for large values of ω) in such a manner that the last portion of it lies in the second leaf; but in case $F'' < 1$ it lies in the first leaf. In our case of $G_1 = \frac{1}{2}$ and $G_2 = 2$, $F' = \frac{1}{8}$ and $F'' = \frac{1}{2}$. This locus, therefore, starts in the second leaf at $\omega = 0$, and passes from the second to the first leaf at $\omega_0 = 26.45$ and terminates at $\omega = \infty$ in the first leaf.

The most remarkable and important property of the locus $G_1 = \frac{1}{2}$, $G_2 = 2$ for practical applications is this: for frequencies in the wide interval from $\omega = 10$ to $\omega = 20$ the working current varies only a few per cent. with a minimum near $\omega = 15$ and maxima near 11 and 19. The total effect then of this split circuit as compared with the simple circuit $R_1\ K_1\ L_1$ is to permit in the interval $10 < \omega < 20$, a somewhat greater working current to flow than $I = O\ E_1$ which would have flowed in the first branch at $\omega = 10$, but the current is so modified as to have a stable minimum at $\omega = 15$ instead of the unstable maximum at $\omega = 10$ in the single circuit. The possible modifications which can be introduced by simple branching suitably designed to effect automatic regulation of various kinds seems to the author to be a field in alternating current engineering likely to be of great importance to the inventor. Such a device introduced for instance into an alternating circuit would quite do away with the necessity for any very close regulation of speed by the governor.

Next consider the locus in case $G_2 = 2$ and $G_1 = 2$ as shown in Fig. 22. The locus starts in the second leaf, for by equation (33) $F < 1$; but it has no point of tangency with the circle on $O\ Q$ for $\omega_0^2 < 0$ and ω_0 is imaginary.

By equation (34) $F'' > 1$, hence it also terminates at O in the second leaf.

But besides this it has points of contact with the inner edge of the leaf on the circumference $E_1\ E_2$. As shown in connection with Figs. 17 and 18, the numerical value of $\alpha\ \beta = G^2 = 1$, at all points of this circumference an $E_1\ E_2$. Hence to find such points of tangency we have the equations

$$\frac{(K_1 - L_1\,\omega^2)\ (K_2 - L_2\,\omega^2)}{R_1\ R_2\ \omega^2} = -1,$$

or

$$\tan\theta_1\ \tan\theta_2 = -1$$

or

$$\theta_2 - \theta_1 = \pm 90^\circ$$

$$\therefore\ \omega^2 = \tfrac{1}{2}\left[\frac{K_1}{L_1}+\frac{K_2}{L_2}-\frac{R_1\ R_2}{L_1\ L_2} \pm \sqrt{\left(\frac{K_1}{L_1}+\frac{K_2}{L_2}-\frac{R_1\ R_2}{L_1\ L_2}\right)^2-4\frac{K_1\ K_2}{L_1\ L_2}}\right] \tag{35}$$

Designate these roots as ω_1^2 and ω_2^2; their values are given in the accompanping tables in which imaginary values are designated by i.

Values of ω_1^2 and ω_2^2, equation (35).

$G_1 =$	0.25	0.5	1	2	4	8
$G_2 = 0.25$	i	i	i	i	i	200 200
0.5	i	i	i	i	200 200	122 328
1	i	i	i	200 200	122 328	110 364
2	i	i	200 200	122 328	110 364	104.5 383
4	i	200 200	122 328	110 364	104.5 383	102.1 391.6
8	200 200	122 328	110 364	104.5 383	102.1 391.6	101.1 395.8

$G_1 =$	0.375	0.75	1.5	3	6	12
$G_2 = .375$	i	i	i	i	158 253	119 337
0.75	i	i	i	158 253	119 337	108 370
1.5	i	i	158 253	119 337	108 370	104 385
3	i	158 253	119 337	108 370	104 385	102 392
6	158 253	119 337	108 370	104 385	102 392	101 396
12	119 337	108 370	104 385	102 392	101 396	100.5 398.

Since

$$\omega_1^2 \, \omega_2^2 = \frac{K_1 \, K_2}{L_1 \, L_2}$$

we have $\omega_1^2 \, \omega_2^2 = 40{,}000$ throughout this table. All values of ω_1 and ω_2 lie between 10 and 20, and whenever ω_1^2 is real ω_2^2 is also real, or in other words, whenever a locus has one point of tangency with the inner edge, it also has a second such point, though it is possible for the two points to come together, in which case the locus will have a point of double contact with the inner edge.

On the locus $G_1 = G_2 = 2$, $\omega_1 = 11, +$ and $\omega_2 = 18. +$. At the first of these points the locus passes from the second leaf to the first, and at the other point it returns to the second leaf, on which it remains for all values of ω greater than 18. +.

Consider also the locus $G_2 = 2$, $G_1 = 8$. In this case $F' > 1$ and $F'' > 1$. Hence the locus begins in the first leaf and ends in the second. It passes at

$$\omega_0 = \sqrt{57.} + = 7.5$$

from the first leaf to the second. It also intersects both the previous loci and all other loci for which $G_2 = 2$ at $\omega = 10$ and passes again upon the first leaf from

$$\omega_1 = \sqrt{104.5} = 10.2 + \text{ to } \omega_2 = \sqrt{388} = 19.6 +.$$

The striking peculiarity of both these loci is a strongly marked minimum working current, such that a far greater power must be exerted to make the frequency much greater or less than that corresponding to this minimum. Such a split current constitutes an effective automatic speed regulator.

Part of the locus $G_2 = 2$, $G_1 = 1$ has been constructed. It is interesting from the fact that $\omega_0^2 = \pm \infty$ and

$$\omega_1 = \omega_2 = \sqrt{200} = 14. +.$$

It therefore has a double contact with the outer edge at O and with the inner edge $\omega = 14. +$.

Part of the locus $G_2 = 2$, $G_1 = \frac{1}{2}$ is also shown. The portions of these last loci not drawn above the upper semi-circle $O\ E_1$, lie intermediate between those already plotted.

Plotting loci for successive values of G_1 is facilitated by drawing auxiliary loci for successive constant values of ω. These auxiliary loci are circles like those in Figs. 15 and 16, as is evident from equations (25) and (26.) For assuming K_2, L_2, R_2 and ω as given, G_2 and β are known constants, but with K_1 and L_1 variable, G_1 and α are also variable. As shown in connection with Figs. 15 and 16, the auxiliary loci for β constant and α variable are circles whose centers lie on the circle of diameter $C_1'\ C_1'$. Parts of these circles have been drawn on Fig. 22 for values of $\omega = 15, 20, 25, 30$.

DISCUSSION.

DR. A. E. KENNELLY:— This paper is devoted to a subject which at the present time has but little practical interest, since it deals with the effects of alternating currents of different or of variable frequencies; whereas, if we omit telephony, the frequencies which are employed in commercial practice are designed to be uniform and only vary within a small percentage, owing to the variations of the speed of the alternators. Nevertheless, a number of the propositions which are pointed out, are of considerable theoretical interest, and we know how often it happens that a subject which is obscure and of little practical importance at one time may develop into considerable practical importance at a subsequent period.

The paper very amply illustrates the fact that the key to the simplest analysis of alternating currents, lies in the use of graphical methods.

A paper presented at the 15th General Meeting of the American Institute of Electrical Engineers, Omaha, June 30th, 1898. President Kennelly in the Chair.

ALTERNATING CURRENT TRANSFORMERS—FROM THE STATION MANAGER'S VIEWPOINT.

BY W. F. WHITE.

In the early days of alternating central station development, many a sale of alternating central station equipment was lost to direct current competitors by the facts, figures and fancies which the salesman of direct current apparatus was able to advance concerning the wastefulness of energy, the expense of maintenance, and the danger to life which purchasers must accept as inseparably wedded to any transformer system.

Notwithstanding that the danger to life was unfortunately made much of, and the facts grossly misrepresented, still the correctness of many of those arguments, in the light of present knowledge, stand up remarkably well under the scrutiny of qualitative analysis. And it is even more remarkable, in view of the natural tendency to exaggerate induced by zeal to make sales, how little, if any, were the facts of these evils overdrawn or magnified. Quantitative analysis in fact proves that most figures then given to show the amount of transformer "leakages" were understated. On the part of salesmen this was undoubtedly more a mistake of the head than of the heart, for while some few of them knew the results of some isolated tests of some particular size of one type or manufacture of transformer, no one, whether salesman, engineer and designer, or manufacturer, had any knowledge or conception of the cumulative effect of transformer losses on the station output. Such little knowledge as had then been acquired related more to the transformer efficiency under certain percentages of rated load, than to all day efficiency, or the 24-hour ratio of energy output to energy absorbed under average conditions.

Little, if anything, was known of transformer core losses, and the effect of power factor on station and line capacities had not had consideration. As long ago as 1892 the writer, in making a careful examination into the operations of one of the then largest alternating stations in this country, made the discovery that with a net meter rate to consumers of about 20 cents per 1,000 watt hours, the income per K. W. hour output at the switchboard was only about six cents, showing an average loss from station switchboard to consumers' meter of about 70 per cent.

Current was supplied, in accordance with the then existing universal practice, through one or more transformers for each customer. In two or three cases, for large installations, as many as 18 or 20 transformers were erected for a single customer, no transformer of more than 75 lights capacity being used; the transformer primaries connected in multiple, but the secondaries feeding entirely distinct and separate circuits.

Of each 1,000 watt-hours output at the switchboard, it was estimated that approximately 300 watt-hours were delivered through the customers' secondary meter, 600 watt-hours were accounted for by transformer core losses, leaving 100 watt-hours to be accounted for by transmission and other losses.

A statement of these conclusions to a well-known manufacturer, who supplied the wattmeters and many of the transformers, elicited the opinion that either the primary meters registered too fast or the secondary meters too slow.

A meter expert from the factory accordingly spent several weeks in testing all primary and secondary meters, found them correct, and proved that the apparent discrepancy was not due to the meter end of the plant equipment. With the writer's recommendation that a three-wire secondary network be erected, using 100-volt lamps, and fed through large transformers at frequent centers of distribution, the matter was dropped; but there is no doubt that the proportion of the output attributed to transformer losses was approximately correct.

Since that time it has been the writer's good fortune to be in touch with a considerable number of alternating plants, giving him knowledge of their operating results, and he does not hesitate to assert that very few plants exist, giving continuous service, using separate transformers for individual customers, and charging from twelve to twenty cents per 1,000 watt hours, secondary meter measurement, whose income per

K. W. hour output at the switchboard exceeds from four cents to seven cents. In other words, the transmission, transforming and distribution losses are commonly as much as two hundred per cent. of the customers' demand, as shown by the customers' meters. This does not mean operating expenses three times as great as if all these losses were eliminated, but it does mean that large expenditures are made for fuel and feed water for the keeping warm of numerous transformers operating about 20 hours per day with open secondaries. And great numbers of small transformers also mean great variations of secondary voltage, large bills for lamp renewals, unsatisfactory service, and a reduced number of lamps which can be served at any instant from a given generator capacity. To show the benefits to be derived by using a secondary network, fed by large transformers working in multiple, but located one at each feeding point or local center of distribution, as compared with the use of small transformers, one or more to a customer, the writer presents some results accomplished by an existing plant in remodeling its transformer system in accordance with these ideas.

January 1st, 1895, this plant was serving 16,702 incandescent lamps (16 C. P. equivalent) through 547 transformers of 22,190 lamps rated capacity, each transformer averaging 40.6 lamps capacity and serving 30.6 lamps. The transformer load, with open secondaries, was, as near as could be determined, about 80 amperes at 1,000 volts. In view of the fact that the maximum load never exceeded 50 per cent. of the lamp capacity connected, it was evident that a very considerable reduction could be made both in the number of transformers connected, and in their aggregate capacity, by the use of a secondary network. The theoretical limit was to reduce the transformer capacity to equal the maximum load, which would lower the capacity connected from 22,190 lamps to about 7,000 lamps, a reduction of about 64 per cent. This limit was evidently impossible of attainment because of the large number of isolated installations, especially in the residence districts, requiring individual transformers, which of necessity must generally be of capacity equal to several times the average load. A system of 3-wire secondary networks was laid out, and estimates made showing a possible reduction of almost 80 per cent. in the number, and of about 50 per cent. in the lamp capacity, of transformers connected. A large number of tests of core losses of all sizes of transformers in service was then made, for estimating the total core losses for the plant, and for comparisons with the estimated core losses of the large transformers to be erected in replacing the old.

An illustration of one or two of these comparisons may be of interest. One installation of approximately 700 lamps was fed through a large bank of small transformers having an aggregate core loss of 4,440 watts, which could be replaced by two transformers having a combined estimated core loss of 310 watts. On the basis of the number of watt hours per pound of coal then being produced by the plant, not taking into account any line losses, this example shows the following results:--

4.440 watts,	38,894,400 watt-hours per year—requires	190.6 tons coal
310 "	2,715,600 " " " "	8.4 " "
Annual saving,	36,178,800 watt-hours	182.2 tons coal.

The annual income from this installation was about $2,100.00, at twelve cents per 1,000 watt-hours. With a secondary output of about 17,800,000 watt-hours, and transformer core loss of about 38,894,400 watt-hours, the income per K. W. hour output at the switchboard for this installation was evidently less than 4 cents, and the core losses were more than double the total secondary output.

In another case, one section of the city, comprising 10 city blocks, was fed by one dynamo and circuit through 71 transformers, having an aggregate rated capacity of 4,482 lights, and aggregate core losses of 10,402 watts (estimated), or 91,121,520 watt hours per year.

To replace these transformers, a 3-wire secondary network was erected, supplying all customers, and fed by five 400-light transformers, located at as many feeding points or local centers of distribution. Each transformer was provided with primary and secondary switches, by means of which all transformers were thrown into service each night from dusk until midnight, at which latter hour four transformers were cut absolutely out of circuit. On a yearly average, five transformers were in circuit about six hours per day, and one transformer the remaining 18 hours per day. The combined core losses of the five were about 1,250 watts, and for the hours in service aggregated about 4,380,000 watt hours per year. Some results of the above changes on this one circuit therefore were as follows:

Number of Transformers.	Lights Capacity.	Total Core Losses—Watts.	Total Annual Core Losses—Watt Hours.	Equivalent Tons Coal.
71	4,482	10,402	91,121,520	446.7
5	2,000	1,250	4,380,000	21.5
Saving.	2,482	9,152	86,741,520	425.2

A reduction of over 95 per cent. in core losses, and a saving for one year in cost of fuel alone of $815.40 were effected for this one circuit. These examples were extremes, because the lighting covered by them was concentrated; and because in most residence and outlying business districts few changes in the number and capacity of transformers could be made. The results shown by the last example were therefore much above the average for the whole plant, but serve to show the possibilities of such changes and the methods pursued in this case.

Some results for the plant as a whole may therefore be fairly indicative of what other average plants operating under similar conditions may accomplish in the same direction, and were as follows:

Time.	Lamps Connected.	Transformers Connected.	Total Capacity.	Average Lights Capacity.	Average Lights Served.
Jan 1, 1895.	16,702	547	22,190	40.6	30.6
" 1, 1896.	19,282	201	13 865	69.	90.1
" 1, 1897.	20,262	152	13,498	88.8	133.3
" 1, 1898.	23,643	141	14,946	106.	167.7

Year.	Income.	Switchboard Output, K. W. Hours.	Income per K W. Hour Output.	Increase of Income per K. W Hour Output.
1894	$59,012.71	928,400	$.0635	
1895	54,231.67	791,752	.0684	7.7 per cent.
1896	51,415.29	551,064	.0933	46.9 per cent.
1897	56,317.42	508,070	.1108	74.5 per cent.

Year.	Actual K. W. Hours Output.	Estimated K. W. Hours Output—Basis 1894. Conditions.	Estimated K. W. Hours saved by Change.	Estimated Saving in Coal—1894 Basis.	
				Tons.	Cost.
1894	928.400				
1895	791.752	854,042	63 290	310.2	$670.91
1896	551.064	809 689	258.625	1,267 8	2,641.42
1897	508,070	886,888	378.818	1,856.9	4,015 43

It must be borne in mind that the number of 16 C. P. equivalents connected Jan. 1, 1895, was 16,702, and increased by Jan. 1, 1898, to 23,643, or more than 41.5 per cent. The savings estimated in last table are based on the conditions at the beginning of this period, *i e.*, the same number of transformers and the same transformer capacity. But if the same conditions had obtained throughout, an increase of 41.5 per cent., or 226 transformers, of 9,208 lights capacity, would have been added to supply the new lights connected. And while only a part of the core losses of the transformers in service Jan. 1, 1895, was saved by the change, the entire losses of the 227 transformers, which would have been required by increased business, were saved. It is therefore perfectly safe to add 50 per cent. to the savings shown in the last table, in estimating actual benefits. From reduced core losses alone. therefore, there is an annual saving of approximately $6,000.00.

In core losses alone, the savings already effected have more than paid all costs of the entire change of lamps, meters and transformers (for because of a simultaneous change from 52 volts to 106 volts, secondary, all lamps and meters also had to be changed), and of the erection of secondary network; and the annual saving of $6,000.00 is equal to 6 per cent. interest on $100,000.00, secured without one dollar invested.

To be certain that the saving of fuel was in proportion to the reduction in K. W. hours output, as estimated, the plant efficiency under the changed conditions must be known. It is therefore pleasing to note that, using coal from the same mine most of the time, the watt hours output per pound of coal actually increased for 1896 by 3.8 per cent., and for 1897 by 5.9 per cent. over 1895, so that the saving in fuel was at least not less than in proportion to the saving in K. W. hours output.

Some incidental advantages of the change may be mentioned.

First. Under the old plan, the 6,941 lights added would have required about 9,200 lights additional transformer capacity, of 40 lights average size, of $1.00 per light average cost, giving an investment saving of $9,200.00.

Second. The transformer load, with open secondaries, of 80 amperes, was reduced, by the fall of 1897, to about 30 amperes, notwithstanding an increase of about 25 per cent. in the number of lights connected. A saving of 50 amperes at 1,000 volts represents a capacity to serve, without additional station or line equipment, approximately 1,000-16 C. P. equivalents, all burning at one time, or fully 2,000-16 C. P. equivalents connected.

Third. Formerly as many as a dozen transformers were frequently burned out in a single thunderstorm. Ten per cent. of the transformers connected would be a conservative estimate of the number burned out each year from various causes. Of the new transformers connected during the past three years only one has failed from any cause, and that one was defective, and burned out under light load almost immediately upon being put in service. Transformer repair costs are therefore practically eliminated.

Fourth. Incandescent lamp renewals have been greatly reduced. Using lamps from the same factory, of the same efficiency, and bought at the same price per lamp, the cost (estimated) of renewals per K. W. hour consumed by the lamps has been reduced from $.0081 in 1895 to $.0057 in 1897, a reduction of 29.6 per cent. This saving represents the advantage of regulating the secondary voltage by pressure wires connected to the secondary network, as compared with the former method of regulating the primary voltage by station transformers.

Fifth. The principal remaining incidental advantage is the uniformity of voltage, bringing uniformity in quality of service and the consequent satisfaction of customers, the value of which cannot be estimated in dollars or per centages. These are some actual results, and such as any plant operating under similar conditions can achieve at small expense, if the changes are well planned, and the replaced apparatus sold to the best advantage.

In this connection, attention must be called to one other fact, which is, that central stations using separate transformers for individual customers have the great majority of their transformers working on open secondaries probably 80 per cent. of the time. The best transformers have a power factor of about 50 with open secondaries, and of fully 99.9 with almost any load they carry in practice. It is therefore perfectly credible, and the writer has demonstrated it to be so by many actual tests on various plants, that the average power factor of plants operating under above specified conditions is approximately 65.

It scarcely needs demonstration that if, instead, a secondary network is used, and only such transformers allowed to remain in circuit at periods of light load as are required to advantageously carry such load, the average power factor will be approximately 100. The volt-ampere hours therefore, calculated from the station voltmeter and ammeter readings, give approximately the watt-hours output. But almost all existing plants use separate transformers for individual customers, and the great majority of them do not have primary wattmeters on their switchboards, and do calculate their volt-ampere-hours output as equivalent to watt hours, getting results about 50 per cent. in excess of the facts. They therefore are able, apparently, to show 50 per cent. more watt-hours per pound of coal, and 33⅓ per cent. less expense per K. W. hour output than another station operating under the same conditions, and fully equalling theirs in actual performance, but which accepts the primary meter readings as the basis of estimate.

As a matter of fact, the usual disparity is greater than the percentages given, because most station managers in erecting primary switchboard meters, follow their aesthetic inclinations, and use ornamental glass covers which are particularly susceptible to the admission of dust and grit, with the result that the meters rapidly slow down. It is highly probable therefore that in some stations the volt-ampere-hour record would show twice the number of apparent watt-hours per pound of coal, and one-half the expense per apparent K. W. hour output that would be shown by the record of the primary meter already erected on the switchboard, which tends only to show the worthlessness of data from different plants, for purposes of comparison, unless the local conditions are known in each case.

This digression is permissible, we hope, because the average power factor, so far as we know, has never been taken into account, and because for that reason much misleading alternating central station data is in circulation.

Purchasers and users of transformers should insist that transformers meet certain requirements, or be rejected, and some of these requirements will be stated.

Where transformers are used for feeding networks, the secondaries in multiple, small core losses are of much greater importance than close regulation, and should be kept at the lowest practicable point. The regulation will be cared for by treating the transformer and feeder drop together, through the use of secondary pressure wires.

Where the transformers are entirely independent, feeding separate secondaries, close regulation must be had, and the core losses be made as low as the adopted regulation will permit. With constant full load the temperature must not rise to a high point, and should not exceed 50° centigrade above the surrounding air. This is important not only because of the increased life of transformer insulation through low temperatures, but also, and possibly to a greater degree, because magnetic fatigue is a certain follower of high core temperatures. If therefore the core losses might be increased 50 per cent. or possibly 100 per cent. through high temperatures, the cost of these core losses, as shown in case of the plant above, make argument unnecessary as to the desirability of having transformers run cool.

The transformer case should be filled with oil, because of its insulating qualities, its exclusion of air, and because of its assistance in maintaining the low temperature desired.

The insulation resistance between the primary and secondary windings should be able to stand up under not less than 10,000 volts alternating, difference of potential, for transformers having 1,000-volt or 2,000-volt primaries, and the writer would strongly urge a 15,000-volt alternating, test. If both the primary and secondary windings are on the core, the same insulation resistance should be required between either winding and the core, as between the two windings. The use of grounded shields placed between the primary and the secondary windings, the grounding of the shell or core, the grounding of the secondaries, the placing in each customer's service, connections of any device to automatically open the circuit of such customer in case of an unusual difference of potential, are all practices that are opposed as expensive, as liable to cause, more than to prevent trouble, as complicating existing practice, and as wholly unnecessary.

Proper insulation is sufficient protection against the damages sought to be avoided. Station managers as earnestly desire complete safety for life and property as the Underwriters' Association, but vigorously oppose the introduction of any unnecessary devices that are expensive to install and to maintain. That Association, in seeking protection for the secondaries, should do so through sufficient transformer insulation and low temperatures. Both of these requirements mean increased cost of production and higher selling prices, but as the consequent increased economy makes the increased cost a profitable investment, no reasonable manager will object. In this way the ends sought will be best attained, and the interests of all parties duly safeguarded.

Omaha, Neb., May 19, 1898.

A Paper presented at the 15th General Meeting of the American Institute of Electrical Engineers, Omaha, June 30th, 1898. Secretary Pope in the Chair.

AIR-GAP AND CORE DISTRIBUTION.

THE MAGNETIC FLUX AND ITS EFFECT UPON THE REGULATION AND EFFICIENCY OF DYNAMO-ELECTRIC MACHINERY.—I.

BY W. ELWELL GOLDSBOROUGH.

The predetermination of the regulation of any dynamo electric machine involves several important steps, and not the least among these, especially in the case of alternating current apparatus, is the determination of the air-gap distribution of the flux, for upon it depends the inductance of the armature winding, the wave form of the E. M. F. and of the current.

The contours of the pole-pieces and the armature teeth of a machine affect, therefore, to an important degree its commercial usefulness, as the air-gap distribution, and consequently the dynamo regulation, is directly dependent upon the shapes of these iron parts. In designing electrical machinery the mechanical details should always be given careful attention, and frequently a method of successive trial will have to be followed to the end of finding the best pole and tooth shapes to be used to fulfil the requirements of the specifications.

In developing a method for accurately calculating the *armature surface* density, let us consider first the simple conditions illustrated in Fig. 1. Here the armature surface is taken as a plane extending indefinitely to right and left. The pole-piece is a rectangular block extending indefinitely in a vertical direction above the armature, and having perfectly square corners. The length of the air-gap or the vertical distance from the pole-face to the armature surface is the same at all points. Both the armature and the pole-piece extend indefinitely at right angles to

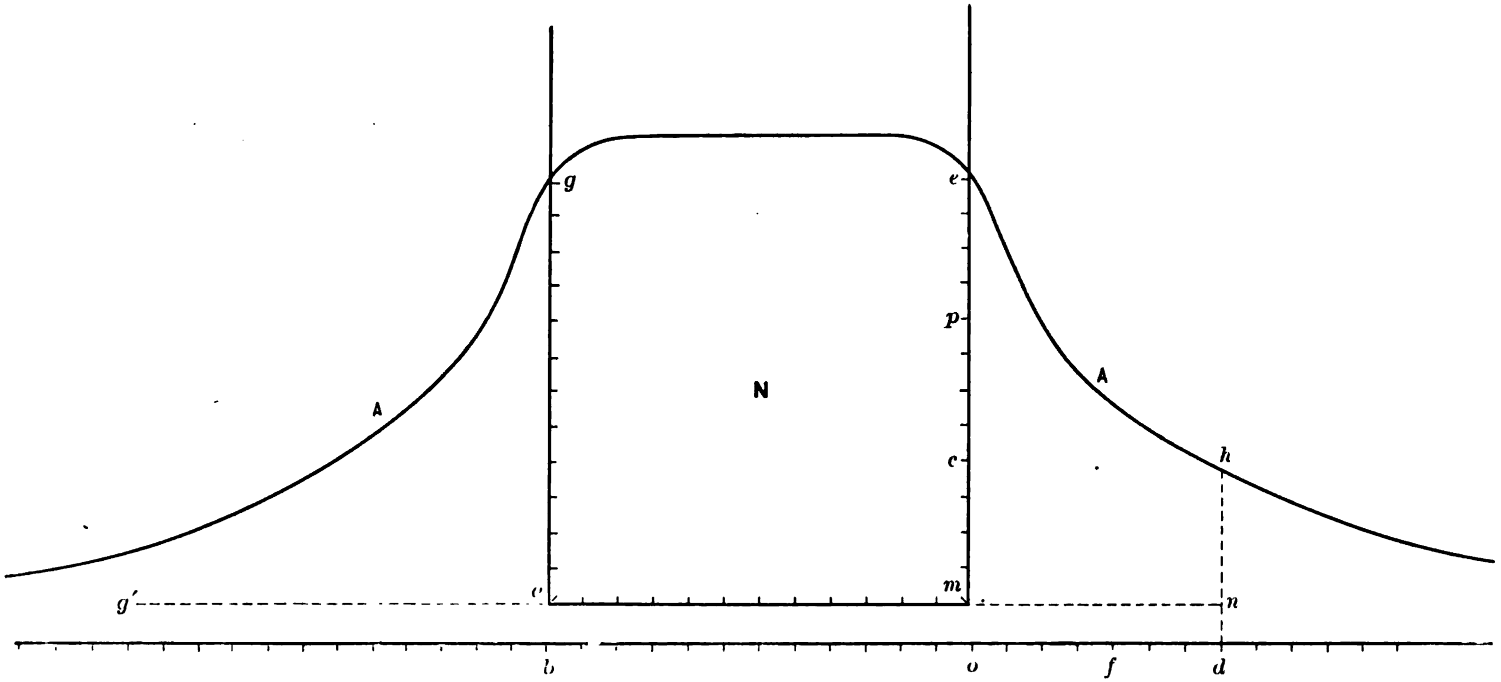


FIG. 1.

the plane of the paper, and Fig. 1 is only a cross-sectional view of the apparatus assumed.

Suppose, now, that a M. M. F. is applied to the pole-piece to set up a magnetic field in the air-gap. Since the permeance of the pole-piece and of the armature is high, we can consider, for all practical purposes, that all points on the sides and face of the pole-piece are at the same potential relatively to the armature surface, and that all points on the armature surface are at the same potential relatively to the pole-piece, and that, therefore, a constant difference of magnetic potential exists between points on the pole-piece and points on the armature. That is, for all practical purposes, there is the same difference of potential between (*a–b*) as there is between (*c–d*) or (*e–f*).

And, *the number of lines of force that pass between any pair of points on the pole-piece and the armature respectively* (as *c–d*, in the plane of the paper) *will be inversely proportional to the distance*[1] *between them. And the strength of the magnetic field at the surface of the armature at any point* (as *d*) *will be proportional to the sum of the reciprocals of the distances of the point* (*d*) *from all the points on the perimeter of the pole-piece made by a section-plane passing through the point* (*d*), as in Fig. 1.

That these assumptions represent a close approximation to the conditions actually existing in dynamo machinery, will be evident when it is remembered that in any dynamo from 60 to 90 per cent. of the M. M. F. impressed upon the magnetic circuit is expended in forcing the flux across the air-gaps, in spite of the fact that these air-gaps are seldom as much as one per cent. of the length of the path traversed by each useful line of force. The drop in M. M. F. is therefore from 600 to 2000 times as great per unit of length in an air-gap proper as it is in an iron portion of the circuit.

The curve A in Fig. 1 represents the distribution of the magnetic flux at the *surface of the armature* as determined by the foregoing method; for the length of any ordinate (*h–d*) at any point (*h*) on this curve is equal to the sum of the reciprocals of the distances of the foot of the ordinate (*d*) from all points (*g* to *e*) indicated on the pole-piece. The curve A extends indefinitely to right and left, and is asymptotic to the surface of the

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[1] In measuring these distances it must be remembered that the most direct path *in air* must be taken, as (*d–a–g*) Fig. 1, *not* (*d–g*) direct.

armature. The curve indicates that the strength of the magnetic field does not diminish as rapidly as is usually supposed after the limits of the working air-gap proper are passed.

Fig. 1 illustrates the field strength at the surface of the armature when but one pole is acting upon it. Suppose we bring up another pole, similar in every respect to the first, except that it is of opposite polarity. It will tend to set up the field density at the surface of the armature that is represented by curve B of Fig. 2; but since this magnetic field is opposed to that of the pole N, a field will result that is equal to the difference of the superimposed fields, or to the field strength represented by the curve C, Fig. 2. As a result of the subtraction, the flux density is shown to be zero at any point on the surface of the armature that is midway between the two poles, and that the sign of the field is reversed at such point. In this case the strength of the field *at the surface of the armature* is greatest at the center of the poles and diminishes to right and left. The reduction in the strength of the field under the pole corners is marked, and the form of the fringing field is clearly outlined. It is to be further remarked that the contour of the curve C of flux distribution changes its form as the distance between the poles N and S is varied.

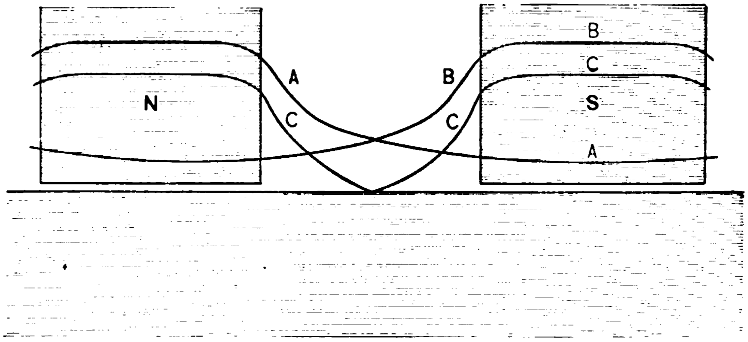

FIG. 2.

The calculation of distribution curves similar to curve A of Fig. 1 is most readily effected by an application of the calculus, although in cases where the contours of either the armature or pole-piece surfaces are very irregular, it may be necessary to space off the pole-piece perimeter and obtain the summation of reciprocals for any given point on the armature by first calculating each one separately.

A simple and most handy formula for use in this connection is that for the determination of the summation of the reciprocals of lines drawn to a series of points on a plane surface. Referring to Fig. 1, let y_e denote the value of the reciprocal (*d-e*) and c_o the value of the distance (*d–o*) and x_e that of the distance (*o–e*),—then,—

$$y_e = \frac{1}{\sqrt{c_o^2 + x_e^2}}$$

Therefore if y denotes the reciprocal of the distance of any point on the surface (*g*, *a*, *m*, *e*) from *d*; *x*, the distance of any point on the line (*o–e*) from *o*; *z*, the distance of any point on the line (*n-g'*) from *n*; and c_n the distance (*d–n*), then,—

$$\sum_{x_m}^{x_e} y = \int_{x_m}^{x_e} \frac{d\,x}{\sqrt{c_o^2 + x^2}} = \log\left(x + \sqrt{c_o^2 + x^2}\right) \Big[_{x_m}^{x_e}$$

and, since, as $(a-g') = (a-g)$, the reciprocal of the distance (*d-g'*) approximates the value of the reciprocal of the distance (*d–a–g*), then,—

$$\sum_{z_m}^{z_g} y = \int_{z_m}^{z_g} \frac{d\,z}{\sqrt{c_n^2 + z}} = \log\left(z + \sqrt{c_m^2 + z^2}\right) \Big[_{z_m}^{z_g}$$

and the value of the ordinate from the point *h*, or

$$(d - h) = \sum_{x_m}^{x_e} y + \sum_{z_m}^{z_g} y.$$

In estimating the value of the theoretical case that has just been discussed as an aid in the practical design of electrical machinery, it may be well to bring out the points of difference between the assumed and the actual conditions. In the first place the dimensions of the pole-pieces are limited vertically and laterally as well as transversely, and therefore although the assumed condition of field strength distribution may exist in a plane passing through the center line of the side faces of the poles, it does not follow that these conditions will in any wise obtain at the outside edges of the poles. Then again the difference of potential maintained between the armature surface and the poles is not constant for all points on the polar surfaces. It is only constant for points below the magnet windings, while the difference of M. M. F.

between points on the yoke (and at the top of the magnet windings) and those on the armature is zero. In passing through the winding spools therefore the M. M. F. diminishes from a maximum to zero.

As will be shown later, the limitation of the dimensions of the poles in practice does not seem to materially affect the results when the outer ends of the armature coils do not cut the lines of force of the outside or end fringe of the field, and where they do, the strength of this fringe can be determined by applying the construction to the end surfaces.

The matter of the variation in the M. M. F. is not in general of great consequence owing to the fact that the distance reciprocals of points on the poles that are near the yokes are very small as compared with those of points on the working air-gap. It is ordinarily sufficient, therefore, to consider the potential constant to points *half way up to the field winding*, and to carry the summation only to these points. With this thought in mind the summation of reciprocals was only carried to *e* and *g* in determining the form of curve A of Fig. 1. In special cases where on account of modifications peculiar to the design it is deemed wise to take account of the variations in the M. M. F., it is only necessary to multiply each reciprocal by a number that is proportional to the M. M. F. acting on the path from which it is determined. In the application of the calculus to this case a special integration is necessary for the polar points lying within the winding spools.

In bringing forward experimental results to show in how far the method that has been discussed can be relied upon, I will first call your attention to the data that is given by Dr. S. P. Thompson in the second lecture of his "Electromagnet," which refer to the determination of "the relation of leakage to pull" in the case of a horse-shoe electromagnet. He says:—

> "The amount of magnetism that gets into the armature does not go by a law of inverse squares, I can assure you, but by quite other laws. It goes by laws which can only be expressed as particular cases of the law of the magnetic circuit. The most important element of the calculations, indeed, in many cases is the amount of percentage of leakage that must be allowed for."

Dr. Thompson then gives the record of the number of lines of force entering the armature when the latter is placed at successive distances from the pole-pieces.

These give ratios of length of air-gap to width of pole-face of

1/13, 2/13, 5/13 and 10/13, and for this series of air-gaps, sets of readings were taken with exciting currents of .7, 1.7, 3.7 and 5.7 amperes. I have taken the data and multiplied each series by a constant which reduces the short air-gap reading of each to the same numerical value, and have plotted these results in Fig. 3; each series is marked and its points connected by a black line. The initial or short air-gap density of the first series is only .2 of the initial density of the last series, and yet the curves practically coincide, showing that for any given position of the armature relative to the poles, the strength of the field is directly

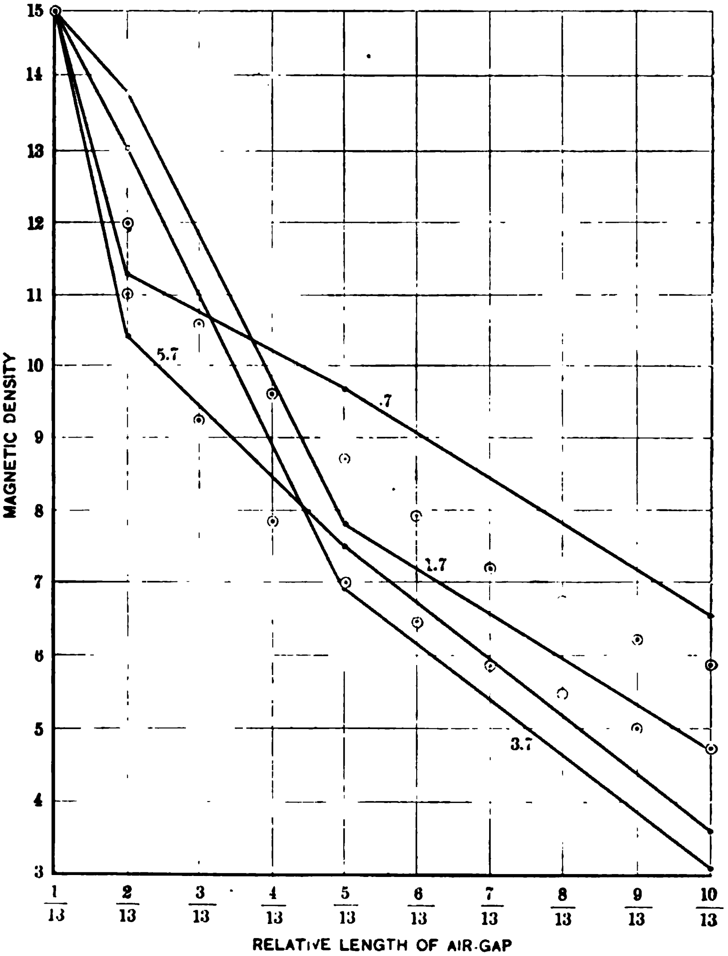

Fig. 3.

proportional to the impressed M. M. F. and that the field distribution of the flux remains constant, as theory requires.

Now supposing the armature of this electromagnet to be a plane surface, and calculating the relative amount of flux that will enter the armature for the several air-gaps, by the method already developed, the data represented by the upper curve of dots were obtained. The ordinates of these points are, therefore, proportional to areas enclosed by curves like curve c of Fig. 2, determined for each position of the armature. Supposing the armature to be of horse-shoe form, the data obtained gave the lower curve of dots. The result for the armature actually used would fall between these two curves of dots. We have here evidence to show that a careful application of this method of *reciprocal summation* will give results within the bounds of experimental accuracy.

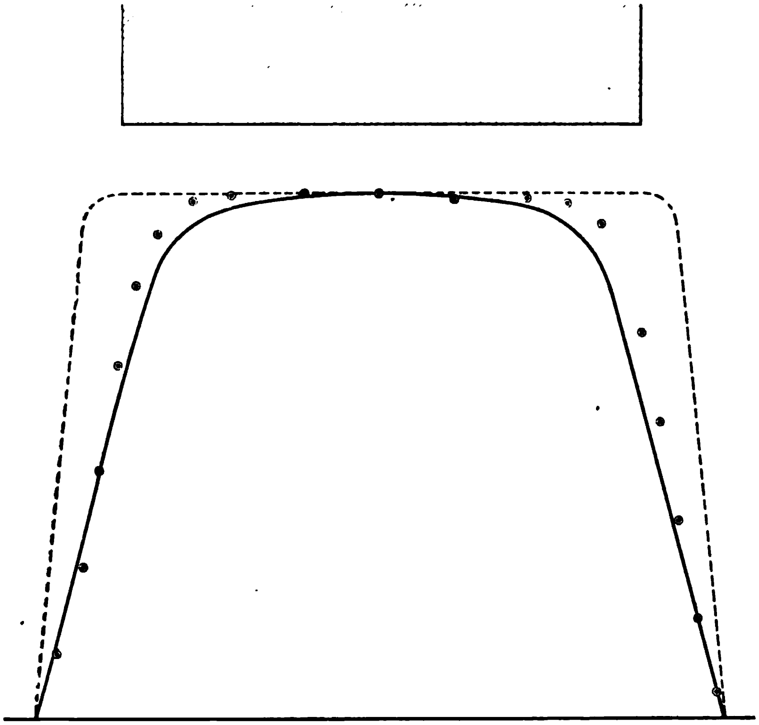

FIG. 4.

An extended series of experiments carried on by Messrs. J. L. Roe and S. R. Fox, under my direction, upon alternating and direct current electromagnets confirm the above.

I am further much pleased that the opportunity is afforded me of calling your attention, at this time, to a set of especially clear and instructive curves recently published[2] from the University of Nebraska. In Fig. 4 I have reproduced in the small circles the graphical presentation of the data from which one of these was plotted. The small circles represent the experimental exploration of the flux distribution in the air-gap of an Edison bipolar dynamo. The curve shown by the black line in Fig. 4 is the calculated curve of flux distribution for this machine obtained by the method of reciprocal summation. It agrees closely with the experimental work.

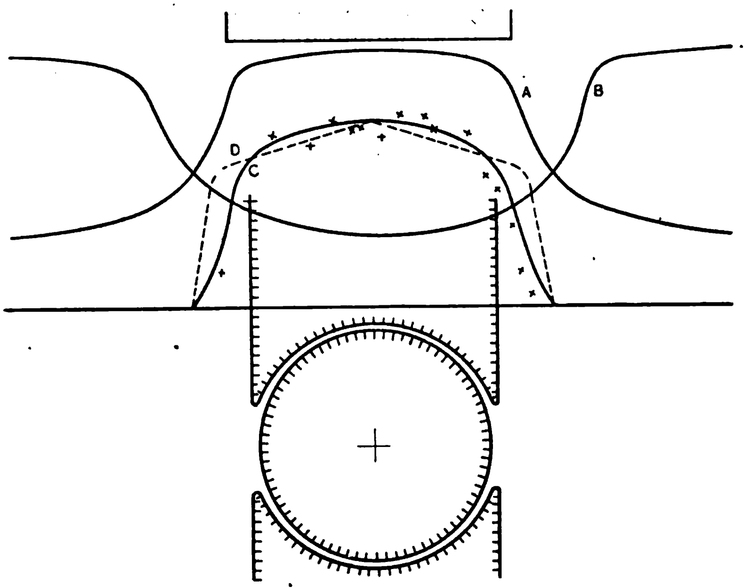

Fig. 5.

The dotted curve of Fig. 4 outlines the flux distribution that is usually *assumed.* Its ordinates are inversely proportional to the length of the air-gap of the dynamo, and it departs noticeably from the real and calculated values through that important space represented by the fringing field.

To give you further evidence of the probable accuracy of results calculated on this basis I have applied the method to the

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[2] "Armature Reactions in a Continuous Current Dynamo," by C. A. Bessey, *The Electrical Engineer*, vol. xxv, p. 511, May 12, 1898.

determination of the flux distribution in the air-gap of a 50-K. W. bipolar Jenney dynamo. The design of this machine is such as to admit of a considerable range of adjustment in the mean length of the air-gap. Under normal working conditions the double air-gap of this machine, which has a smooth core armature, is 1.25″ at the center of the pole-faces, and 1.52″ under the leading and trailing pole-tips. The diagram of Fig. 5 presents the conditions existing with this arrangement. Subtracting curve B from curve A, curve C is obtained, and represents the calculated distribution of the flux in the air-gap. The dotted curve D is plotted by taking the reciprocal of the length of the air-gap at successive points, and plotting the results so obtained above corresponding air-gap positions on the diagram. The ordinates of the curve D are therefore proportional to the armature surface density in the air-gap, if this density is taken as inversely proportional to the length of the air-gap. The star-points on the diagram represent the results obtained by exploring the air-gap field by the "pilot brush" method. As the star-points follow the curve

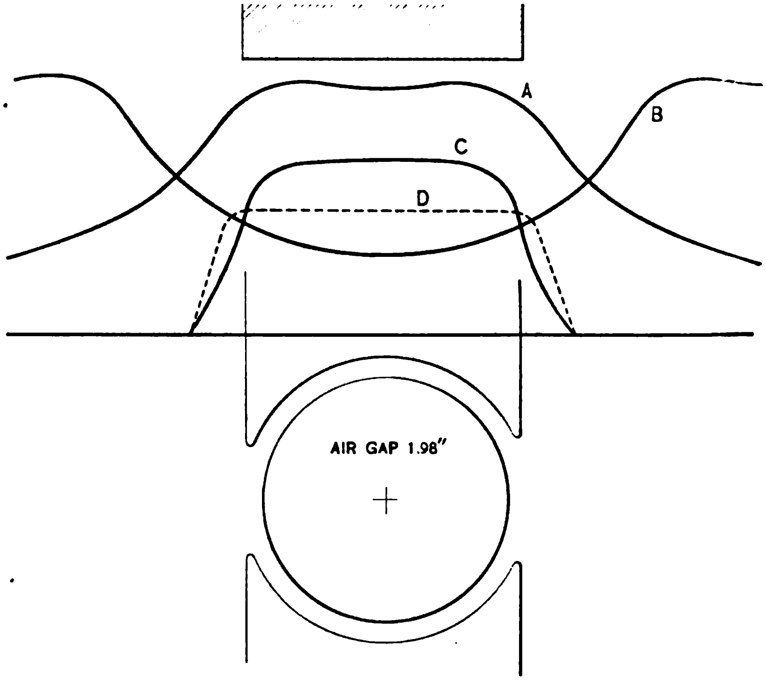

FIG. 6.

C much more nearly than they do the curve D, it seems probable that the calculated values are reasonably accurate.

In Fig. 6 is illustrated the result of imposing another set of conditions upon the same machine. The curve C represents the calculated distribution of the flux in the air-gap when the length of the double air-gap has a constant length equal to 1.98″ at all points. The dotted curve D shows what the relative value of the flux density would be if the strength of the air-gap field were inversely proportional to the length of the air-gap. Since the ordinates of the C curves and the D curves of Figs. 5 and 6 are respectively proportional to the quantities they represent and to one another, they can be compared, and to facilitate this are plotted together in Fig. 7. It is noticeable that the C curve of Fig. 6 represents relatively a very much stronger field than does the D curve. In fact the ratio of the mean ordinates of the C curves of Figs. 5 and 6 is .899, whereas the ratio of the mean ordinates of the D curves is only .699. We see therefore that the rate at which the strength of the air-gap field decreases as the length of the air-gap is increased, falls far short of being inversely proportional to the rate of increase in the mean length of the air-gap, supposing that the C curves represent the true condition.

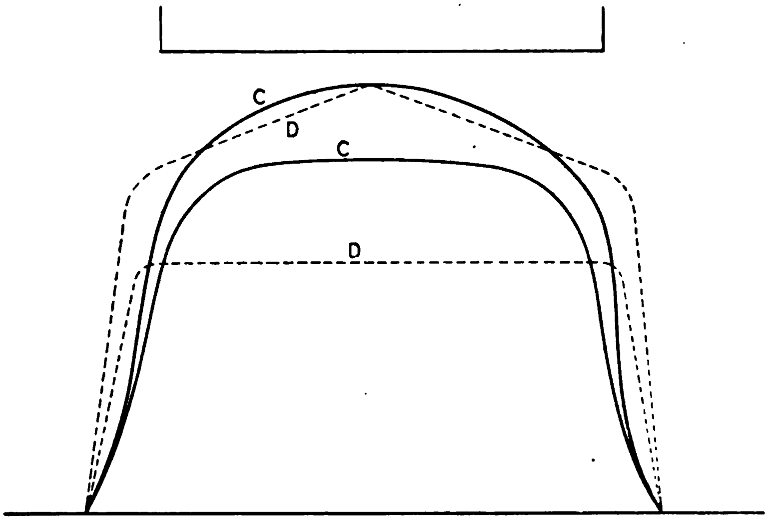

FIG. 7.

This fact is also brought out by the curves of Fig. 3, which indicate that the length of the air-gap had to be increased five-fold before the strength of the field was reduced one-half.

To determine how nearly the calculated results agree with the actual conditions existing in the case of the Jenney dynamo, the magnetic characteristics of the machine were determined both for the short and the long air-gap adjustments; and the ratios of ordinates corresponding to like field currents along the "straight" parts of these curves below the "knee" were found to vary between .824 and .864, the average being about .835. Although not conclusive, these ratios tend to substantiate the calculated results.

Up to the present the application of the method to machines having smooth core armatures has only been considered. But to be of value it should apply with equal force to all types of machines, and in fact the most important field for its application is to modern alternating current machinery in which the shapes given to both the polar and armature projections are very varied in character.

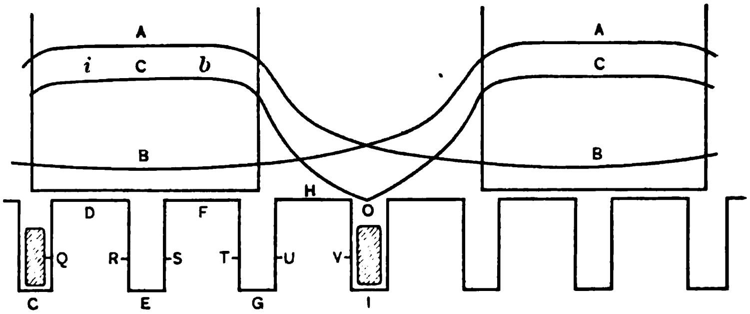

FIG. 8.

The computations required to determine the flux distribution where the armature surface is slotted, are considerably more involved than are those for a smooth core machine. To accomplish a result that will be of value in determining the wave forms of the E. M. F. and of the inductance developed in the armature coils, the armature must be placed in a series of positions, each of which presents a different space position of the teeth to the poles. The complete armature surface distribution of the flux must then be determined for each position of the armature relative to the poles, the exact perimeter of the armature teeth being followed in each case and the measurements being taken from working drawings of the machine. When this has been accomplished a sufficient amount of information will have been obtained to admit of the accurate determination of the rate of change of the flux through any coil on the armature, and consequently of the wave form of the E. M. F. developed in the coil as rotation takes place. In other words, the data will be sufficient to determine the *no load* E. M. F. waves developed in the armature, provided the hysteretic[3] and eddy current disturbances in the armature iron are not sufficiently great to cause a lateral displacement of the wave.

In Fig. 8 is shown diagrammatically a section through the poles and armature of an 8–50–900–1150 two-phase General Electric alternator, the results of calculations in connection with which I wish to report to you at this time. Each of the coils on the armature of this machine embraces three teeth as indicated by the single coil shown in Fig. 8 and in the discussion which follows, I will endeavor to show with what success the wave of E. M. F. developed in these coils has been calculated.

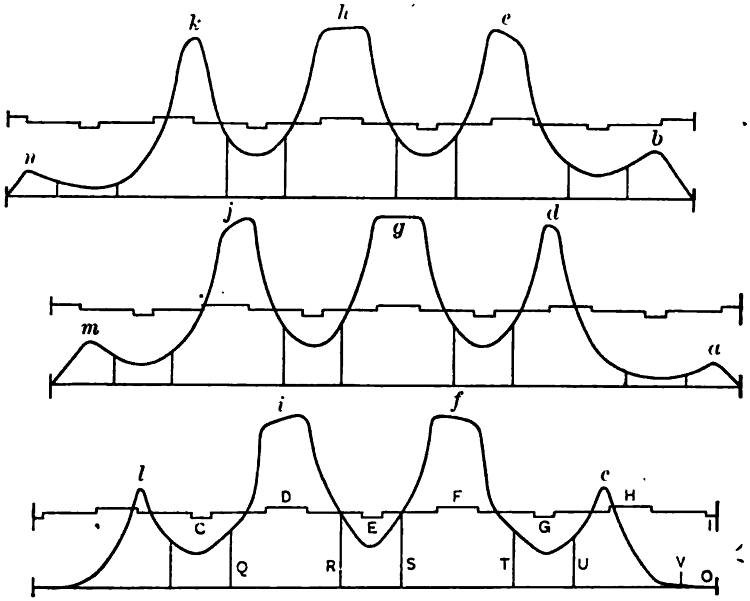

Fig. 9.

The curve c of Fig. 8 represents what the flux distribution in the air-gap would be if the armature core were smooth. Its ordinates are therefore proportional to magnetic density at the upper surface of the teeth. The number of lines of force enter

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[3] Armature Inductance, Transactions, vol. xiv., p. 292.

ing the sides and bottoms of the slots had also to be determined by the method of reciprocal summation. The result of some of this work is shown in Fig. 9, where three of the air-gap distribution curves are plotted relatively to the perimeter of the armature developed into a straight line. The positions of the top of the teeth and the bottoms of the slots are indicated by the breaks in the line through the center of each curve. The curves are determined for positions of the teeth differing by one-third of the pitch of the teeth, and the gradual change in the distribution and amount of the flux that enters a tooth as it passes across the pole-face can be traced by following the small letters *a*, *b*, *c*, *d*, etc.

The areas of the curves of Fig. 9 that are separated off by the ordinates are proportional to the total number of lines of force

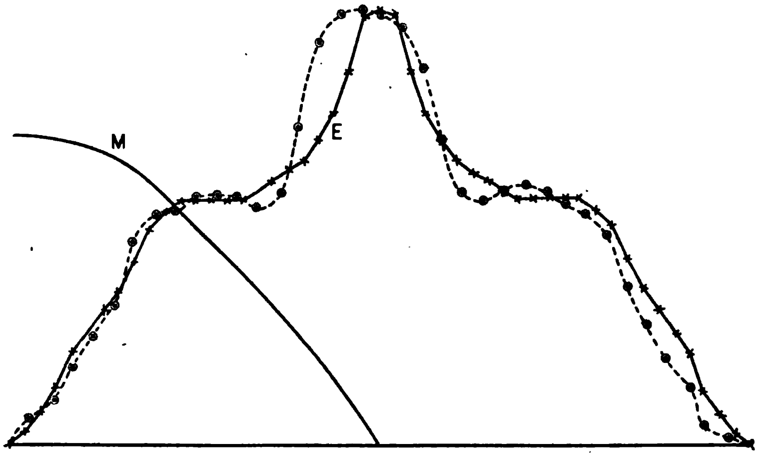

FIG. 10.

entering the upper surfaces of the teeth and the lower surfaces of the slots, respectively. In other words, the area between ordinates Q and R is proportional to the flux entering tooth D of Fig. 8, within the surface between Q and R; and the area between the ordinates R and S is proportional to the flux entering the bottom of the slot E between the limits R and S. The ordinates to the curves are drawn at points that are opposite the center of coils in the slots and represent the limit of the useful flux entering the coil in the slot considered. The coil shown in Fig. 8 rests in slots C and I, and therefore when the coil is in this position the total area between the ordinates Q and V of Fig. 9 must be taken to be proportional to the total flux entering the coil when it is in this position.

In Fig. 10 is shown the curve M, which is the magnetization curve of the armature coils at no load, *i. e.*, its ordinates are proportional to the instantaneous values of the magnetism within the coils as they pass before the poles. The values of the ordinates of this curve were obtained from the distribution curves shown in part in Fig. 9, as already explained.

Now since the rate of change in the amount of flux within the coils is proportional to the E. M. F. developed in the coils, the wave of E. M. F. has been determined directly from the curve M by the method of tangents, and is shown by the broken line and stars of the curve E. The curve E, which is quite an irregular curve, is therefore and finally, the calculated curve of electromotive force developed by this alternator.

The points represented in Fig. 10 by small circles trace the wave of E. M. F. actually developed by this alternator as determined experimentally by the rotary contact method.

The method of calculating field densities which has been outlined can, I believe, be made to play an important part in connection with the design of electrical machinery. It has been used by myself and my students with success within the last two years, in connection with problems involving the calculation of leakage coefficients, the regulation of large direct current units under conditions of load, the determination of the inductance of the coils on the armatures of direct and alternating current machines, and the complete regulation of alternators and motors in so far as it is affected by disturbances in the magnetic field due to rotating masses of iron or reactive currents in the coils. To touch upon these points in detail would make my present paper too lengthy for this occasion, but I hope to be able, at a future meeting, to call your attention to some of the more important problems that have been treated.

Purdue University, Lafayette, Ind., June, 1898.

(COMMUNICATED BY THE AUTHOR AFTER ADJOURNMENT.)

The importance has been emphasized of making due allowance for the fact that the M. M. F. between a point (d, Fig. 1) on the armature surface and a point on the polar surface (between c and e) within the field coil spools rapidly diminishes as the latter point is taken nearer and nearer the yoke, it may be well to add the formula that applies especially to the reciprocal summation of the points within the field coils.

If the M. M. F. impressed upon the magnetic circuit of Fig. 1, were produced by an energized coil occupying the space between the points c and e, the potential between polar surface points below c and points on the armature surface would be uniform and equal to the maximum magnetizing power of the coil. The potential between points above e and points on the armature would be zero, and the potential of points between c and e and the armature would gradually diminish from the maximum value to zero as the points were taken more and more remote from c. Under these conditions, the effect of the reciprocal of $(m - d)$ or $(c - d)$ at d is proportional to its full value; the effect, however, of the reciprocal of $(p - d)$ at d is only proportional to half its full value, while the effect of the reciprocal of $(e - d)$ is zero.

Therefore, the effect of the surface $(c - m)$ at the point d is proportional to

$$\sum_{x_m}^{x_c} y = \int_{x_m}^{x} \frac{d\,x}{\sqrt{c_0^2 + x^2}} = \log\left(x + \sqrt{c_0 + x^2}\right) \Big[_{x_m}^{x_c}$$

while the effect of the surface $(c - e)$ at d is proportional to

$$\sum_{x_c}^{x_e} y = \int_{x_c}^{x_e} \frac{x_e - x}{x_e - x_c} \cdot \frac{d\,x}{\sqrt{c_0 + x^2}}$$

$$= \frac{1}{x_e - x_c}\left[x_e \log\left(x + \sqrt{c_0 + x^2}\right) - \sqrt{c_0 + x^2}\right]\Big[_{x_c}^{x_e}$$

where x_c denotes the distance $(o - c)$ and x_e the distance $(o - e)$. And the total effect of the surface $(m - e)$ at d is proportional to—

$$\sum_{x_m}^{x_c} y + \sum_{x_c}^{x_e} y$$

evaluated as above.

A paper presented at the 15th General Meeting of the American Institute of Electrical Engineers, Omaha, June 30th, 1898. President Kennelly in the Chair.

HIGH-VOLTAGE POWER TRANSMISSION.

BY CHAS. F. SCOTT.

Several years ago an investigation of the conditions and requirements incident to the use of high voltages was undertaken by the Engineering Department of the Westinghouse Electric and Manufacturing Company. In this experimental investigation the size of the apparatus and the conditions of the tests were as far as practicable such as would prevail in actual work.

The transformer, the *sine qua non* of high-voltage working, received first consideration. A design suitable for large sizes was worked out and tested; then high-voltage windings were made. Attention was next directed to the line insulator.

New phenomena were liable to be presented at higher voltages and it was necessary to determine what they were, also how to meet the requirements which they impose. New forms and sizes of insulators were designed, made and tested to determine the losses which would occur and the limit at which they would break down.

The luminosity and the hissing sound emitted by the connecting wires of high voltage, suggested a loss which might be an appreciable addition to that over the surface of the insulators. It was found that a very considerable loss of energy took place between the wires—a loss which at high voltages was much in excess of that across the surface of the insulators.

Mr. L. L. Nunn visited Pittsburg at this time and became much interested in this work. He was a pioneer in power transmission, having put in the first large alternating current transmission plant in this country, namely, that at Telluride, Colorado, which was designed by the writer and described by him[1] at the General Meeting of this INSTITUTE in 1892. It was proposed that this work be taken up conjointly by the Westinghouse company and Mr. Nunn, and prosecuted on a much enlarged scale, by operating the original motor over a high-voltage line. In a report to the Vice President and General Manager of the electric company, dated April 2nd, 1895, the writer said, "The transformers would be arranged to give a line pressure of 10,000, which is to be increased by suitable steps to possibly 50,000 volts.........I regard this as an excellent opportunity to make a thorough and extremely important and valuable test of high-tension working under difficult practical conditions, which our company should take up and carry out as fully as possible." Raising and lowering transformers were made and sent to Telluride, and power for the 100 H. P. synchronous motor was transmitted at voltages far exceeding any which had been previously used anywhere. Exceptional facilities were afforded for observing the practical operation of high-tension working under severe climatic conditions, and for making measurements. The results of the work were so assuring that the Telluride Power Transmission Company has lately installed a plant which is in commercial operation at 40,000 volts and is now making an increase in the plant. This work has been continued on experimental circuits at East Pittsburg, and some measurements have been made at Niagara.

The work which has just been briefly described was an investigation into an unknown field. It has been progressively and systematically carried out and it has determined results which were unforeseen, and which are of both theoretical interest and practical importance.

This present paper describes the more interesting and important parts of this work, and gives the methods by which measurements have been made and the results which have been reached. A number of points of interest and importance are given with regard to long-distance transmission plants now in operation.

HIGH-TENSION TRANSFORMERS.

In 1891 the Westinghouse company furnished transformers for the 10,000-volt transmission to San Bernardino and Pomona. Twenty transformers were used in a set, each giving a pressure

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[1] TRANSACTIONS, vol. ix, p. 425.

of 500 volts and the twenty in series 10,000 volts. This arrangement made the insulation within the individual coils a matter of comparative ease. The insulation between the coils of the high-tension circuit and other parts of the transformer was secured by allowing a space, which was filled with oil.

The first arrangement of transformers for giving from 30,000 to 50,000 volts was made by using a number of transformers, each giving 10,000 or 15,000 volts. The low-tension circuits of the several transformers received current from an insulating transformer in which there were a number of separate coils, each one supplying a separate raising transformer. An arrangement of this kind was used for obtaining the high voltages in the exhibit of the Westinghouse company at the World's Fair. A large transformer was designed in January 1894. The output of 200 K. W., was many times greater than that of any transformers which had been made by the Westinghouse company. The transformer was oil-insulated and was cooled by water flowing through a pipe immersed in the oil. This transformer was pronounced a success, and the type was adopted and has been followed ever since as a standard, except that the water-cooling is employed only on the largest sizes.

The transformer was then rewound for 40,000 volts, and a somewhat reduced output. It was operated at this voltage for a short time, when it was found that through an oversight, the insulation between layers was insufficient. In October the high-tension coils were rewound for 60,000 volts and the transformer is still in use after many months of varied service and a considerable period of inactivity.

The making of a single large transformer for a very high voltage naturally involved new difficulties. Above 10,000 or 20,000 volts there was an unexplored and uncertain field in the matter of insulation. Materials which were commonly used at ordinary voltages might have very different characteristics under the new conditions. Tests were made on materials before the first high-voltage transformers were made, and it has been continued. The large high-tension transformer as made to-day was not designed in a week or a month, but it has been an evolution based upon experimental tests and experience in continued operation.

HIGH-TENSION INSULATORS.

After a high-voltage transformer was constructed, the insulator naturally presented itself as a fundamental factor in transmission. The requisites of an insulator for high-voltage work are, that it shall have a dielectric strength sufficient to prevent the current passing directly through the material, that its dimensions shall be large enough to prevent the passage of current over the outside of the insulator to its support, and that the resistance, both of the material and its surface, shall be sufficiently high to prevent undue loss of energy. In addition to these fundamental electrical requirements are those of a mechanical nature involving strength and convenience. These properties must of course be permanent, and not liable to deterioration while in service.

Up to this time very little attention had been given to the manufacture and design of high-tension insulators. There were available for our laboratory tests the glass insulators which we had designed for the 10,000-volt transmission line at San Bernardino and Pomona, California. (See paper of Mr. G. H. Winslow[2] before the General Meeting of the INSTITUTE in 1895).

A much larger glass insulator was made having the so-called "helmet" form, which was probably the beginning of a type which is now quite common. The large glass insulator presented mechanical difficulties in manufacture, and recourse was had to porcelain. An insulator was designed to be under-hung, the top of the insulator being supported in an inverted cup which was to be bolted to the under side of the cross-arm. From the bottom of the insulator a pin extended which was anchored in a hole in the insulator and held the wire several inches below the porcelain. The object was to place the wire below the cross-arm so that the snow which might pile up on the cross-arm would not come near the insulator. The wire, moreover, instead of being supported upon the top of the insulator, where it is in connection with an extended wet surface, would be supported from the part of the insulator which is most protected and the dryest.

An interesting evolution then began to take place in the manufacture of porcelain. There were eight or ten steps in this history, in which insulators which were presumed by the manufacturer to be satisfactory were broken down on high-voltage test. Porcelain which presented a beautiful smooth glazed surface was

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[2] TRANSACTIONS vol. xii p. 405.

often found to contain internal cracks or cavities which were soon traversed by the current. In other cases bits of pebbles or other impurities were found. In still other cases the porcelain was not homogeneous and was not compact, or the material was porous and absorbed a drop of ink almost as readily as a lump of sugar would do. The effect of this work is seen in the improved quality of material now made by certain porcelain manufacturers who benefited by this experience. It may also be remarked that some of the unpleasant experiences with porcelain insulators might have been prevented if similar preliminary tests had been made instead of employing the more expensive and inconvenient method of testing them in commercial service.

The under-hung form of porcelain insulator, however, did not prove successful nor satisfactory. The insulator was heavy and cumbersome, and no satisfactory method was devised for holding the wire. A wooden pin lacks strength, and a metal pin reduces insulation. Moreover, smaller insulators of the ordinary form were found suitable for higher pressures than was anticipated.

Some measurements were made of the losses on the Pomona insulators. Twenty-four insulators were mounted on wooden pins. A wire was run along the tops of the insulators and a second wire connected the pins. The increase produced in the reading of a wattmeter in the primary of the raising transformer when the wires were connected to the high-voltage terminals, was taken as the loss on the insulators. The loss at 25,000 volts was about two watts per insulator. This voltage between pin and wire corresponds to 50,000 volts between transmission wires.

LOSSES BETWEEN WIRES.

The loss over the surface of insulators was quite small, in fact almost insignificant compared with the amount of power which would ordinarily be transmitted. The various displays of energy about high-tension wires, led us to investigate and determine whether this loss was one of importance. In order to measure the loss between wires, eliminating what occurs on the insulators, it was desirable to have a considerable length of wire, to support it without insulators, and preferably to arrange the wires in such a form as to give a considerable loss. Nine wires each 60 feet long were stretched 4″ apart in a horizontal plane, and were held in place by strings several feet in length at each end. The wires were No. 19 B and S gauge, 0.036″ in diameter. They could be connected in various ways, and any pair or pairs of wires could be omitted as desired.

The power supplied to the raising transformer was measured by a wattmeter placed in the primary low-tension circuit. When the load was placed on the transformer, the wattmeter reading increased, and the amount of increase was taken as the power delivered to the load. This method involves certain errors which will be pointed out further on, but on the whole it gives an approximate and fairly correct indication of the power, and is sufficient to show clearly the general form of the loss curves and a number of interesting characteristics.

The first measurements of this loss are recorded Feb. 26, 1895. The 1st, 3rd, 5th, 7th and 9th wires were connected in multiple to one terminal, and the other wires were connected to the second terminal of the raising transformer; successively increasing voltages were applied.

The wires began to give a hissing or crackling sound and in the dark began to appear luminous at a little below 20,000 volts. As the voltage was increased the sound became more and more intense, the wires vibrated and became more and more luminous, until at the higher voltages they were surrounded by a coating of soft blue light many times the diameter of the wire. Often there were bright points along the wire, probably corresponding to bits of dust or rough places resembling points on the wire. The large room soon became strongly charged with ozone.

Results of measurements on all wires, alternate wires being connected together to one terminal, and the intermediate wires to the other terminal of the raising transformer, are given in the accompanying Fig. 1. Three curves are given for a frequency of 60 periods per second, or 7200 alternations per minute. Two of these curves give the wattmeter readings for the different voltages, one for the transformer alone, and the other for the transformer and high-tension wires; the third curve gives the difference between the two, and therefore represents approximately the loss on the high-tension wires. Corresponding curves are given of tests made at a frequency of 133. The loss in the transformer is less at the higher frequency, but the loss on the high-tension wires is almost the same for both frequencies. These losses are very small below 18,000 volts, but increase

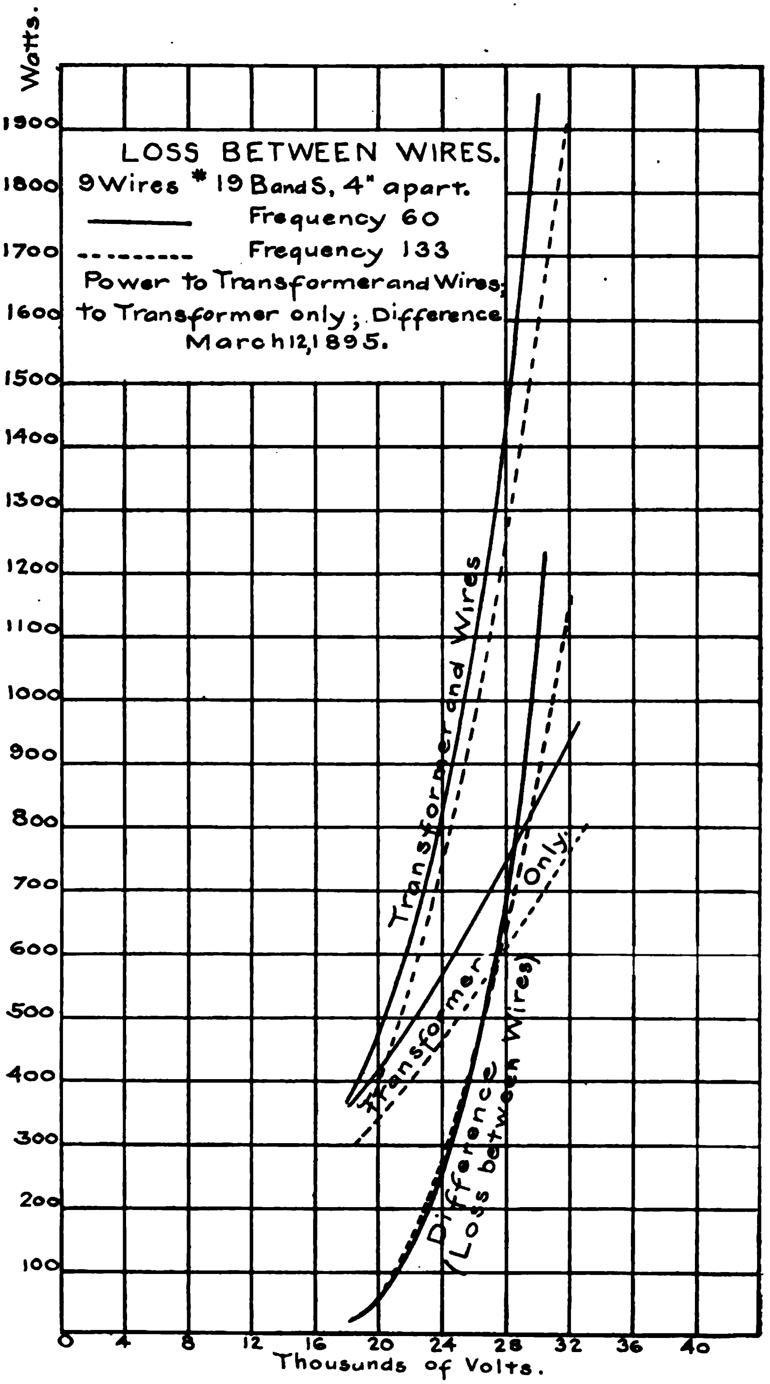
Watts.
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
LOSS BETWEEN WIRES.
9 Wires * 19 B and S, 4" apart.
———— Frequency 60
--------- Frequency 133
Power to Transformer and Wires; to Transformer only; Difference.
March 12, 1895.
Transformer and Wires
Transformer Only
Difference (Loss between Wires)
0
4
8
12
16
20
24
28
32
36
40
Thousunds of Volts.

Fig. 1.

rapidly up to 30,000 volts, which is about the highest pressure used.

As the two sets of tests were made with dynamos having different characteristics, they may not accurately represent the relative effects of the frequencies. The difference due to causes other than the frequency are, however, probably small, so that these tests are correct in showing the general relation between the loss and the pressure, and in indicating that the loss depends little if at all upon the frequency.

Tests were made with different numbers of wires. In one case the measurements were made with the arrangement described above, in which five wires were connected together and the four intermediate wires were connected to the second terminal of the raising transformer. Two wires at one end were then left off. Two of these were next omitted, leaving three connected to one terminal and two to the other. One of these was left off, leaving the 1st and 3rd wires connected together, and the 2nd and 4th also. The 1st and 9th wires were then connected together, also the 2nd and 8th. As the 1st and 2nd wires were well separated from the 8th and 9th, the mutual effect between them is negligible, so that the loss in this case may be considered as double that which would be obtained from the 1st and 2nd wires alone. The results of this measurement are plotted in Fig. 2. The points for both loss and current fall on a straight line and indicate that each additional wire causes a definite increase.

Measurements made upon wires at greater distances show that the action is considerably less as the wires are separated. The loss is approximately the same at 28,000 volts when the wires are 4″ apart that it is at 36,000 volts when they are 16″ apart. The loss for a distance of 8″ is intermediate.

Other measurements were made, but nothing of further importance was developed. It is interesting to note that within a few days of the first measurements the general characteristics of this loss were determined, namely, that the loss between wires increases rapidly after a critical voltage is reached, that the loss is practically independent of the frequency, that it is much less as the distance between wires is increased. When a loss of 1200 watts was obtained on a total length of 540 feet of wire at only 30,000 volts, the important bearing of this phenomenon upon transmission became very evident. The tests were stopped as preparations were begun for the continuation of the work at Telluride.

TRANSFORMERS AT TELLURIDE.

The original Telluride plants operated at 3000 volts. Both the generator and the synchronous motor were wound for this pressure. Two transformers were furnished for the high-voltage tests, one for raising the generator voltage for transmission, and the other for lowering the voltage for the motor. The windings were connected with a number of terminals by which the high-tension voltage could be varied over a wide range up to 60,000 volts.

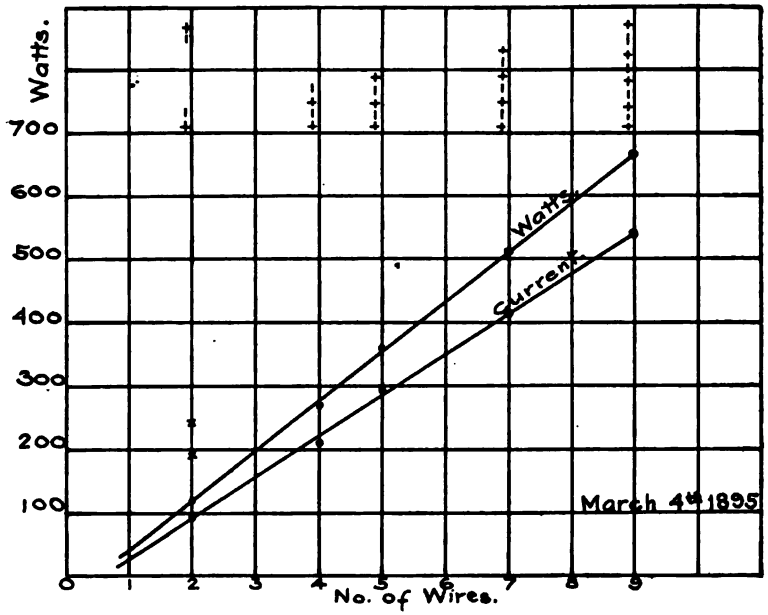

FIG. 2.

Coils of similar shape were placed side by side in what is known as the "parallel" form of construction. Each coil had many layers of wire and but few turns per layer, thus securing a small difference of pressure between consecutive layers. The high-tension winding was divided into four similar coils, each designed to give a maximum of 15,000 volts. The individual coils could be differently connected, either in series or in multiple. The low-tension coils were five in number and were provided with loops, by which the number of effective turns could be varied. Three low-tension coils were placed between two pairs of high-tension coils and the two remaining low-tension coils were placed on the two ends. Between the low-tension and high-tension coils metallic shields were placed, which were connected to the ground for protecting the low-tension circuit from danger in case of accidental contact with the high-tension circuit, and also for screening the low-tension circuit from electrostatic induction from the high-tension windings. The transformer was immersed in a case containing oil. The iron and the case of the transformer as well as the shields between the coils were connected to the ground.

There was also an auxiliary transformer whose primary was connected across the generator terminals while its secondary was placed in series with the circuit to the raising transformer, thus either raising or lowering the generator E. M. F. as desired. The secondary had a number of steps so that the voltage could be varied at will.

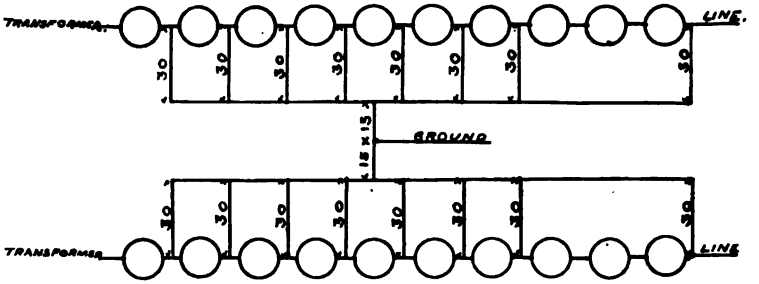

FIG 3.

THE TRANSMISSION LINE.

The line extends from the power station near Ames, which is a few miles from Telluride, Colorado, to the Gold King mill. The line passes over an exceedingly rugged country and has a total length of nearly 2¼ miles (11,720 feet). There are 62 poles, each carrying three cross-arms, the upper being about 26 feet from the ground. Each cross-arm carries two wires supported by insulators which are designated as follows:—Large glass, small glass, porcelain. (See Figs. 4 and 5). The large glass insulator is the same as that used on the circuit in the San Bernardino and Pomona plant. The total height is 5″ and the maximum diameter 5½″. The bottom of the insulator stands 1¼″

Fig. 4.—50,000 Volts on Large Glass Insulators (Upper Cross-arm) and on Porcelain Insulators (Lower Cross-arm.)

Fig. 5.—Insulators used in High-Tension Tests at Telluride.

above the cross-arm. The porcelain insulator is $4\frac{1}{16}''$ high and $5\frac{7}{8}''$ in diameter. The bottom is $3\frac{1}{16}''$ above the cross-arm. The small glass insulator is $3\frac{1}{2}''$ in height, $4\frac{1}{4}''$ in diameter and stands $2\frac{1}{4}''$ above the cross-arm. This insulator is triple petticoat; the other two insulators are double petticoat. The circuits were strung with galvanized iron wire 0.165″ in diameter, which is No. 8 B. W. G., and about No. 6 B and S gauge. Later the circuit on porcelain insulators was changed to No. 6 B and S copper wire 0.162″ in diameter. The measured resistance of one of the iron wire circuits was 66.25 ohms at —7 deg. C.

THE LIGHTNING PROTECTION.

The lightning protection was laid out by Mr. A. J. Wurts, who previous to this time had spent some months at Telluride, determining the requirements for protecting the 3000-volt circuit. The protection consists of choke-coils and spark-gaps of non-arcing metal, as described by Mr. Wurts in his paper[3] before the INSTITUTE, March, 1892.

In each line ten choke-coils were placed. Unit arresters, each consisting of seven non-arcing metal cylinders and having six spark-gaps, were connected as is shown in Fig. 3.

RUNNING TESTS AT TELLURIDE.

The first tests were qualitative rather than quantitative. It was uncertain what phenomena might accompany the operation of a long line at high voltage, and the pressure which could be used on the insulators was a matter to be determined. The first thing was to find what would work; measurements could be made afterwards. A high voltage was placed on the transmission line, sometimes transmitting no power and at other times operating the 100 H. P. synchronous motor. In December 1895, the motor was operated at 25,000 to 33,000 volts for several days. In January 1896, 45,000 volts was used continuously for over a week, and beginning with the latter part of March a continuous run of 37 days was made at 50,000 volts. "Some very severe conditions of weather were encountered during this time, very high gales of wind prevailed, the air was filled with clouds of dust, part of the time the snow which fell was quite damp and during the last few days of the run there was some rain. At this voltage the wires were plainly visible at night and the characteristic hissing of high-tension currents could be heard

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[3] TRANSACTIONS, vol ix, p. 102.

several hundred feet. No lightning arresters had been installed up to this time and the cause of the shut-down was damage to the raising transformer, caused by lightning. Lightning arresters were installed. The lightning season commenced about June 1st. During the latter part of June lightning discharges over the arresters were very frequent. At this time we were limited to a running voltage of about 34,000 volts, as there were not enough arresters to permit of increasing the voltage. No trouble whatever was had with the lightning protection. Discharges were frequently seen crossing the arresters and during two or three days in the early part of the season discharges occurred at intervals of a few seconds for several hours. Enough arresters were afterwards obtained to run at 45,000 volts, but the lightning discharges were much less frequent."

Some measurements upon the line were made by determining the power to the raising transformers when the lines were connected and when they were disconnected. These measurements showed that the loss due to the line is small, below 45,000 volts, but increases rapidly when about 50,000 volts is exceeded, and reached 16.4 K. W. at 59,000 volts. The results up to 52,000 volts are given in curve 2, Fig. 9. Curve 1 in this figure is the loss on the same circuit measured a year later by a different observer using a different method. At the maximum loss shown, there is a difference of only 8 or 9 per cent. in E. M. F. for the same loss on the two curves.

The record of the operation of this line at 50,000 volts for over a month is of very great interest, as it is a practical demonstration of the feasibility of operating a line at 50,000 volts, a pressure four or five times as great as any which had been in general commercial use. Mr. V. G. Converse had been up to this time closely associated with this work. He had much to do with the design and construction of the high-tension transformers and insulators, tests upon losses in lines made at the Pittsburg laboratory and the tests at Telluride.

MEASUREMENTS AT TELLURIDE.

The work at Telluride was then taken up by Mr. R. D. Mershon. The facilities for experimental work were increased and instruments were provided for carrying on the tests. Mr. Mershon found peculiar difficulties in making exact measurements of the power to the circuit. A wattmeter in the low-tension circuit of the raising transformer led to errors under the conditions which prevailed. Some very able and painstaking work was displayed in detecting the error and overcoming it with the facilities at hand—and the facilities were none too plenty in the heart of the Rocky Mountains for making measurements which would tax the resources of almost any laboratory. The apparatus used introduced a disturbing influence in the circuit, which, however, could be measured and eliminated. On the other hand, a wattmeter for measuring power on a high-tension circuit must accommodate a very high voltage and a very small current. As the charging current to an open line is usually very large in proportion to the loss current, the error of the instrument is very sensitive to slight variations of phase in the shunt current. A description of the instruments and the methods used are given in an extract from the report of Mr. Mershon which will be found at the end of this paper in Appendix A. The results of the measurements and the conclusions are given partly by extracts from Mr. Mershon's report, and partly in abstract.

RESULTS OF MEASUREMENTS.

"The results of measurements taken are embodied in curves.

"In every case the measurements were taken upon an open-circuited line—in no case upon a line which was transmitting power. The line losses obtained are therefore a combination of those occurring between the line wires and the very small $I^2 R$ loss in the wire itself due to the charging current of the line.

"Measurements taken with the Weston wattmeter include the loss in the high-tension coil of the power transformer due to the currents applied to the line. This loss is in general small and in the following curves corrections have not been made for it. Curves taken with the Thomson wattmeter require no such correction.

"There is an additional correction which may be made in the case of those curves whose voltages were obtained from the raising transformer. This correction arises from the fact that the action of the capacity current taken by the line, in connection with the series reactance of the transformer supplying it is such as to make the voltage impressed upon the line somewhat greater than that obtained by the ratio of the transformer winding. The measurements taken to determine the amount of the error in voltage show it to be small.

"There were two generators used. One was that regularly running and supplying power to the power circuits of the Telluride Power Transmission Company. It is a 600 K. W., 22-pole, quarter-phase machine, delivering 500 volts at a frequency of 60, or 7200 alternations per minute. Its armature is of the slotted type and is wound with copper bars. In the notes this generator is designated as 'Slotted Armature.'

"The other generator is one whose field is that of the 100 K. W. toothed armature machine, originally sent out as a part of the first Gold King transmission plant. It has twelve poles and as originally run operated at 3000 volts and 10,000 alternations. There are two armatures for this machine; a surface wound armature, designated as 'Smooth Armature,' and a toothed armature, designated as 'Toothed Armature.'"

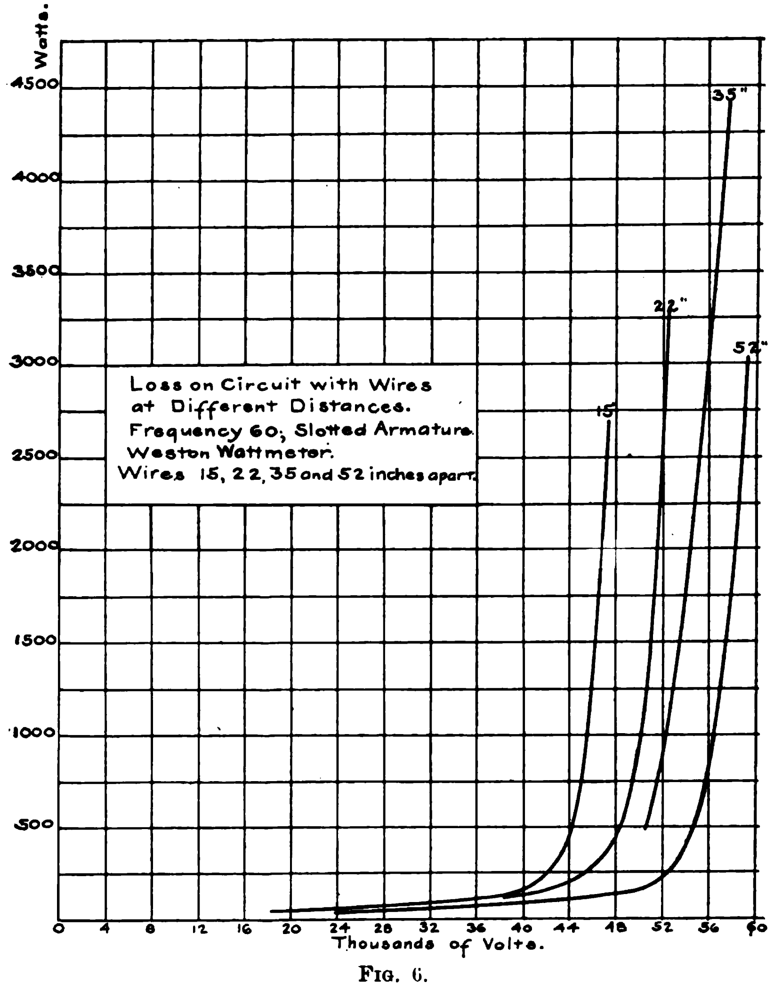

FIG. 6.

Comparison between Insulators.—A set of measurements was made for comparing the loss on the three circuits supplied respectively with large glass, small glass and porcelain insulators. The curves are very nearly identical and correspond very closely with the right hand curve in Fig. 6. "There was a heavy wet snow on the ground and the cross-arms at the generating station, and more or less snow all along the line; that at the further end being drier than at the generating station. There was more or less snow falling during the measurements, and this accounts for a wide variation of the points taken at the high voltages, as falling snow renders the wattmeter reading very unsteady, the unsteadiness being such as one might expect if from time to time there was a discharge between the wires. This unsteadiness does not seem to be as great in the case of falling rain as in the case of falling snow."

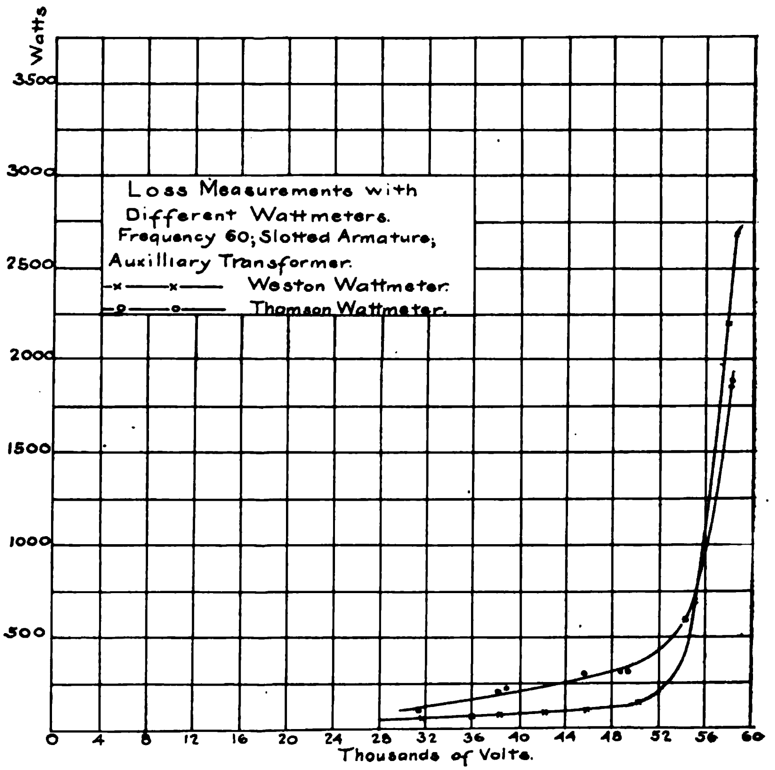

FIG. 7.

Loss and Distance Between Wires.—A series of measurements was made to determine the connection between the loss and the distance between wires. "As at that time it had not been fully demonstrated that the loss was not affected by weather conditions except there was precipitation, changes in distance between wires were made upon one circuit, while the distance between wires on another circuit was maintained always the same, and the latter was used as a reference circuit when a change in loss was obtained."

The several curves have been plotted together, due correction being made for the slight difference in the loss in the reference circuit, which probably resulted from slight differences in the precipitation when the curves were taken. The distance between the wires in the several tests was 15, 22, 35, and 52 inches respectively. The results are shown in Fig. 6. It will be noted that the loss is much greater when the wires are close together and that the curve begins to ascend at a lower voltage.

Comparison of Wattmeters.—The loss curves in Fig. 7 were taken on one of the circuits, first, with the Weston wattmeter and then with the Thomson wattmeter. The Weston wattmeter was not in circuit when the measurements with the Thomson wattmeter were taken. As an additional check, the readings were taken on each of the wattmeters of the loss occurring in the shunt resistance, of the Thomson wattmeter the results were in practical agreement with each other and with those obtained by calculation. The discrepancy in the results obtained on the two instruments when measuring line loss will be referred to later.

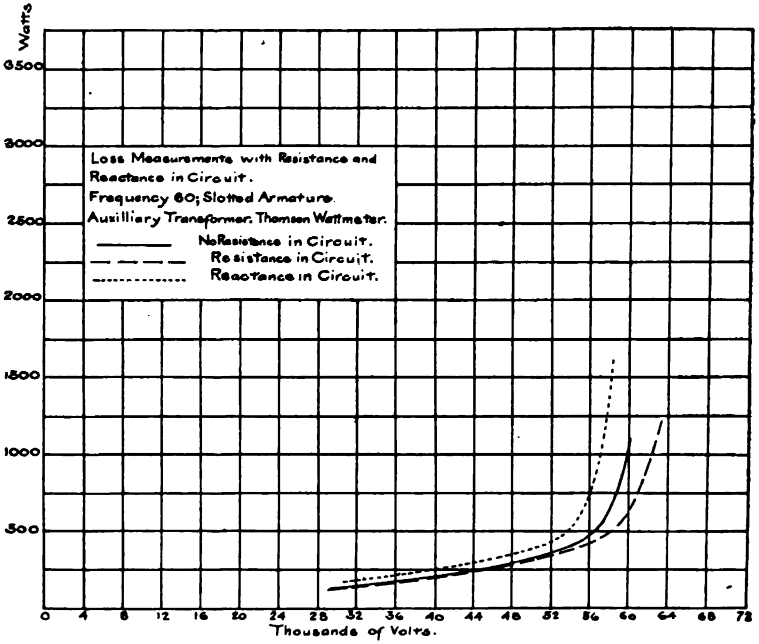

FIG. 8.

Loss on Insulators.—A set of comparative readings was taken on one of the circuits and on a dummy circuit, identical with the main circuit, as regards kind and number of insulators and the size of wire, but only 60 instead of 11,720 feet in length. The results show that the loss on the two circuits is practically identical up to about 50,000 volts, which is the part of the curve below the bend. The losses agree closely with those shown in Fig. 6. At higher voltages the loss on the dummy circuit increased slightly, indicating that the loss was of the same nature as that at a lower voltage. The agreement of the loss on the two lines

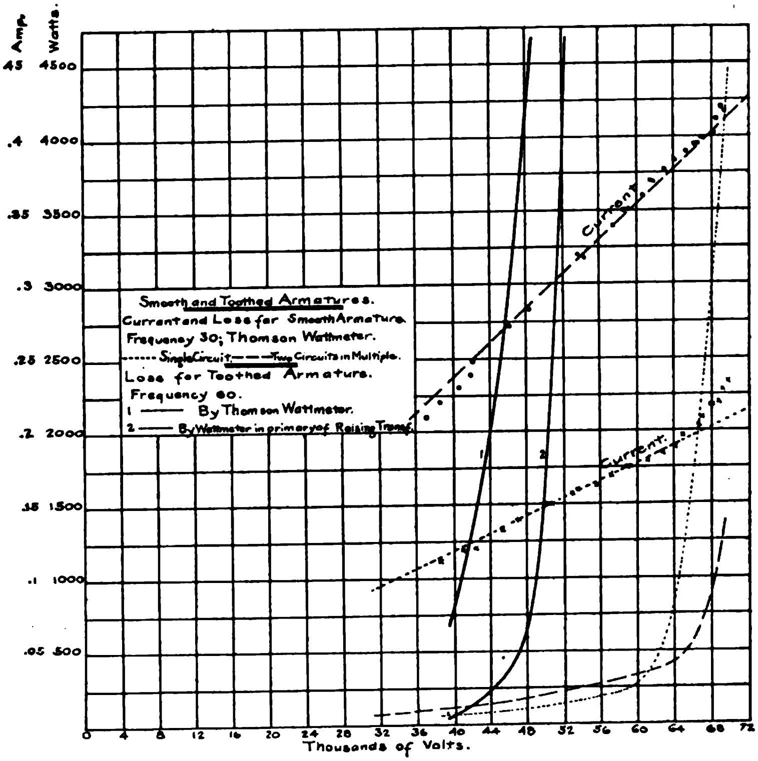

FIG. 9.

at low voltage (*i. e.*, below the bend in the loss curve) indicates that this loss was over the insulators. The great increase in loss on the long line at high voltage indicates that the loss was due, not to the insulator, but to the line.

Resistance and Reactance in the Circuit.—Measurements were made with resistance between the generator and the raising transformer, then with reactance and then with neither resistance nor reactance. The results are shown in Fig. 8, and indicate a different condition, depending upon the character of the circuit supplying the current. It was presumed that this difference arose from a modification of wave form of the E. M. F. applied to the line.

Wave Form and Loss.—Measurements were made upon the wave form and the corresponding losses when different generators

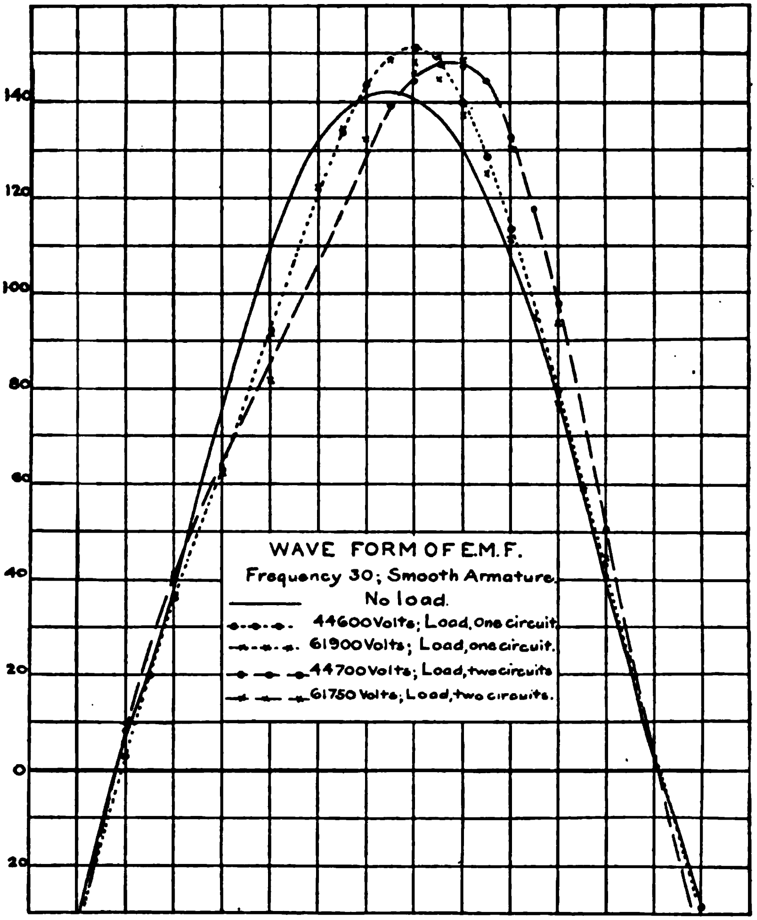

FIG. 10.

were used and different circuits were connected. In one test an armature giving nearly a sine wave was used which delivered current at 30 cycles. Measurements were made upon one circuit only, and then upon two circuits in multiple. The current and the loss are both given in Fig. 9. The wave form for no load and for both conditions of load are given in Fig. 10. The current taken by the two circuits in multiple is twice that to a single circuit. The variation from a straight line in one of the current curves is due to a change in wave form as the voltage is increased.

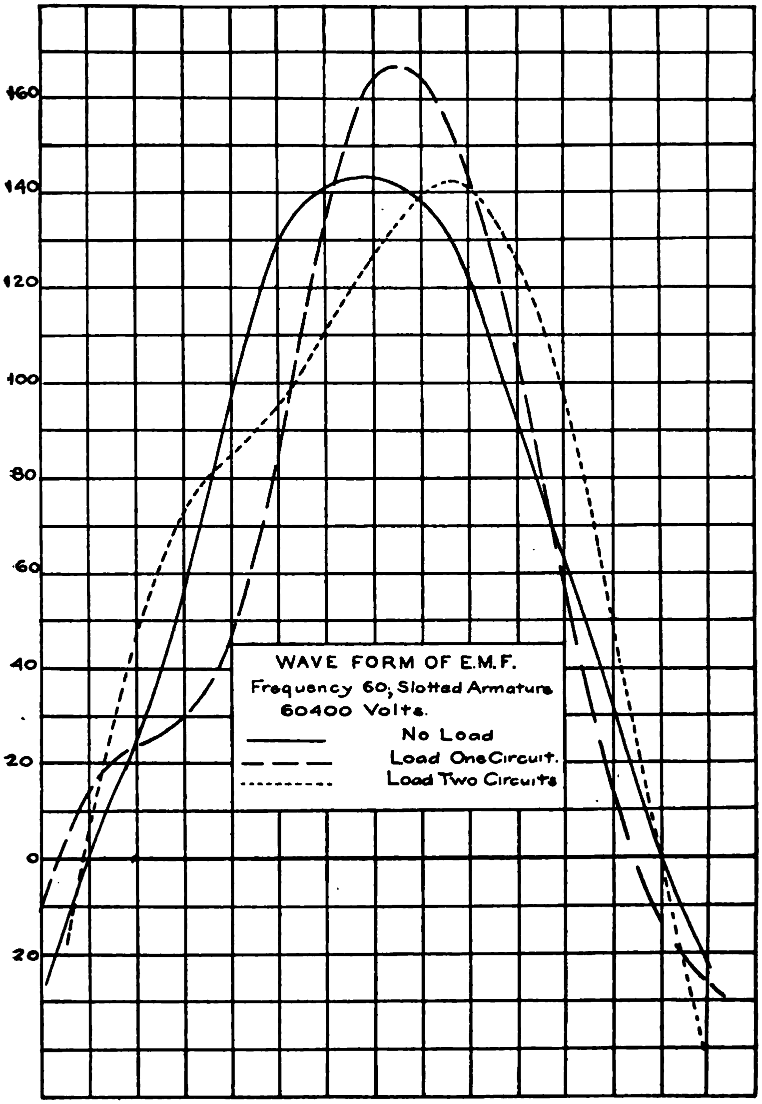

FIG. 11.

The loss for the two circuits in multiple is about twice as great as for one circuit at low voltages, but it is less than that for one circuit at high voltages. Referring now to the wave form taken at high voltage, it is seen that the wave form for the two circuits in multiple has a lower maximum than that for one circuit alone. The reduced loss on the two circuits is undoubtedly due to the different wave form when both circuits were connected. The distortion of the wave form is due to the reaction which the leading current produces in the generator and transforming apparatus.

Wave forms were also taken on the slotted armature giving 60

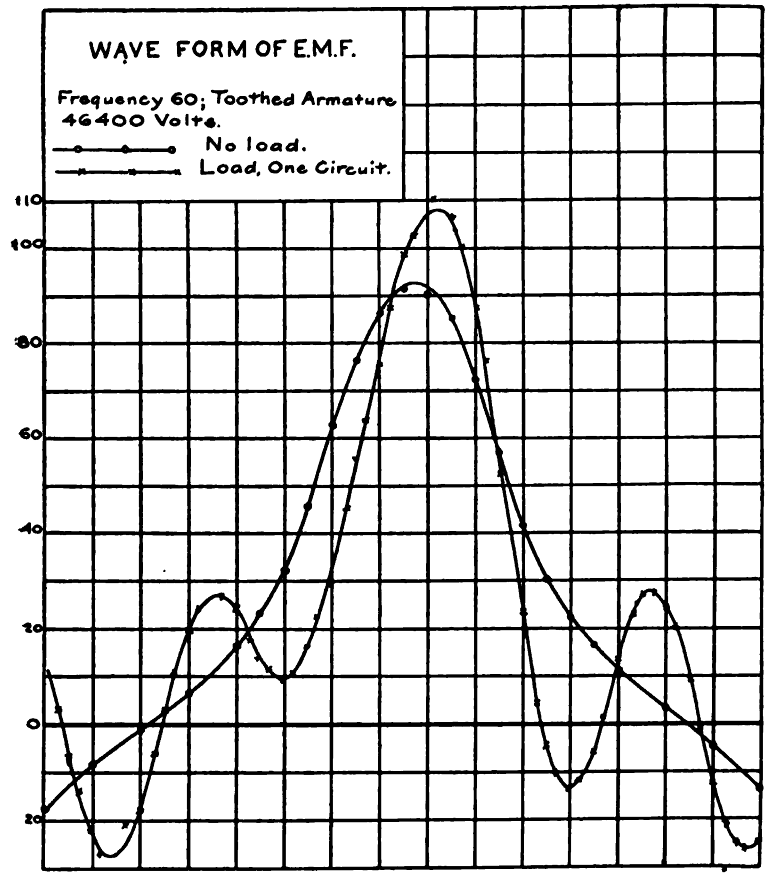

FIG. 12.

cycles. The wave forms are given in Fig. 11. The conditions are similar to those just described, in that a single circuit produces a wave having a much higher maximum than that produced when two circuits are run in multiple. The losses (which are not shown) bear the same general relation as that in the last case, namely, the loss with two circuits is greater at low voltage and at the high voltage is less than that on a single circuit.

A wave form was taken upon the toothed armature both at no load and also when supplying current to one of the circuits. These are shown on Fig. 12. This wave differs radically from a sine wave at no load and is greatly distorted when supplying a leading current. In the no-load wave the value of the fundamental is 72.5 per cent.; the third harmonic 21.6 per cent.; the fifth harmonic 4.8 per cent. The corresponding loss is given in curve 1, Fig. 9. The distorted wave makes the Thomson wattmeter read too high, especially at the lower E. M. F's.

OTHER OBSERVATIONS AND TESTS.

"A series of observations was taken extending over a period of thirty-three days, to determine whether there was any connection between the loss occurring on the lines and the variations in weather conditions. Three readings were taken each day. They were, in addition to the wattmeter readings, readings for barometric pressure, temperature, humidity, wind direction and wind velocity. The weather observations were taken simultaneously at Ames and the King, using sets of weather instruments furnished by the United States Weather Bureau. The range of these observations is shown in a table given below, in which maximum and minimum refer to the maximum and minimum results obtained at any time during the thirty-three days over which the measurements extended:—

Location.		Barometer.	Temperature Deg. F.	Humidity per cent.	Wind velocity miles per hour.
Ames.	Maximum.	22.10"	73.5	43.2	22
	Minimum.	21.68"	56.3	7.1	2
King.	Maximum.	21.82"	62.0	42.5	20
	Minimum.	19.81	47.8	3.0	3

"If there was any variation in the loss on the lines for this range of weather conditions, it was so small as to be inappreciable. The results of all measurements taken during this work seem to confirm the fact that the only weather condition whatsoever which affects the loss to any practical extent is that of precipitation. The loss seems to bear some relation to the size of the particles precipitated, being greater for a fall of snow in which the flakes are large than one in which the flakes are small.

"In the power transformers used, the series reactance was comparatively small because of the subdivision of the coils. A change in the condition on the line as regards loss occurred when the Weston wattmeter was placed in circuit. This was detected by measurement upon the Thomson wattmeter, both when the

Weston wattmeter was in circuit and when it was not. Moreover, the lines hissed when the voltage is 55,500 and the Weston wattmeter is out of circuit, but when the Weston wattmeter is thrown into circuit the hissing ceases, although the voltage rises to 57,700. The hissing sound is a characteristic of high-voltage lines and begins at the bend in the loss curves. It always accompanies luminosity of the lines.

"Along with this change there was another phenomenon not previously mentioned. This was a discharge which took place from time to time between the terminals of individual choke-coils. The discharge would occur sometimes between the terminals of one choke coil and sometimes simultaneously on two or three of the choke coils. These discharges made considerable noise, sounding very much like a pistol shot, and could be heard at a considerable distance from the transformer house. As the choke-coil terminals are distant from each other about 8½", it is not thought that this discharge took place through the air, but over the surface of the wood enclosing the choke-coil. The discharge, however, left no mark on this surface. Simultaneous with these choke-coil discharges one could hear, if standing under the line some little distance from the transformer house, a slight snap which seemed to be a phenomenon rather of the whole line than of any particular spot in it. Sometimes there was a corresponding snap over the lightning arresters. As the lightning arresters make more or less noise at all voltages, this snap over them may have been present at all times, but in some cases not sufficiently well marked to be heard above the continued hissing of the lightning arresters.

"After the preceding results had been obtained, the two power transformers were connected up with their high-tension windings in series, the point of connection between them being grounded, and with their low-tension windings in multiple. With this arrangement voltage was impressed on one of the circuits, power being supplied by the smooth armature at 7200 alternations. The voltage was run by means of the machine field to 90,000.

"As the power taken by the lines at this voltage overloaded the motor used to drive the generator, a span was cut out of the circuits at a little distance from the station, leaving about 500 feet of wire in them. The voltage was run up to 133,000 volts and held there for some minutes; but the current finally jumped from the outside terminal of each transformer to the iron, smashing the heavy glass tube with which these terminals were insulated."

Discussion of Results.

The following is taken from Mr. Mershon's discussion of the results of his tests:

"There is evidently a certain critical voltage at which the loss occurring between wires begins to increase very rapidly; indeed, it seems as though there might be something of the nature of a polarization similar to that which occurs in the case of an electrolyte; that there is something of this nature in the case of air or other gases subjected to an electrostatic stress is well known, and it has been taken as an explanation of the fact, that in the experimental determination of sparking distances in air, a certain minimum potential is necessary to establish an arc, no matter how small be the sparking distance. Also, Varley has done some work on tubes containing gases. This work was done with a series of Daniell's cells yielding 300 to 400 volts. The voltage was impressed upon electrodes sealed into the tubes. He established the following facts:—First, that each tube required a certain potential to leap across; second, that the passage for the current having been once established a lower potential was sufficient to continue the current; third, if the minimum potential which would maintain a current through the tube be P and the voltage varied to P plus 1, P plus 2. etc., to P plus N, the current will vary in strength as 1, 2, 3, etc., N; P always meaning the lowest value at which the current will continue, and is less than that at which the current starts.

"If such a condition of affairs obtains in this case, the loss curves of the preceding sheets must be made up in two parts, one the loss over the insulators and cross-arms, the other the loss occurring through the air. The first part of the loss curve up to or near the point where the abrupt bend begins, must be the loss over the insulators and cross-arms alone; beyond the point where such a bending occurs, the loss curve must be made up of a combination of the two losses referred to.

"If the action which takes place in air is similar to that obtained by Varley, we might expect that both (1) the position of the critical bend on the loss curve and (2) the law which the loss follows above the bend, would be affected by the form of the E. M. F. wave impressed upon the line for the former (1) must depend, not upon the mean square of the voltage impressed upon the line, but upon the mean square of that portion of the E. M. F. wave which is above a certain critical voltage, and the latter (2) must depend upon the form of that portion of the E. M. F. wave above a certain critical voltage because, as Varley shows, the minimum voltage at which this peculiar loss begins, differs slightly from the minimum voltage at which it will continue after the action has been established. If it were not for the latter consideration it would be comparatively easy to determine the equation for such loss at least in the case of a pure sine wave, and it might be that there is a sufficiently small difference between the voltage at which this loss will begin and the voltage at which it will discontinue for such an equation to hold practically. That the loss depends upon the maximum value, if not upon the form of the E. M. F. wave, is shown by several of the loss curves in connection with their corresponding wave forms. This is particularly noticeable in one or two cases where the loss on two lines in multiple is less than that on one line, and although some of these comparisons will have to be made between curves taken on the two different wattmeters and are, therefore, not strictly comparable, they may be compared after such correction as is mentioned below in discussing the wattmeters. In any case the curves are comparable, qualitatively, as regards the position of the critical point.

"It might be objected that the results are rendered questionable by the curves in Fig. 7. The curves were taken under presumably similar conditions, except that one was obtained by means of the Thomson wattmeter and the other by means of the Weston wattmeter. This discrepancy is attributed to a charging current passing through the shunt resistance of the Thomson wattmeter. That the amount of capacity current necessary to produce the discrepancy is small, appears upon the following considerations:—In one case the loss obtained upon a circuit at 38,000 volts when using the Weston wattmeter is 90 watts, and under the same conditions, but using the Thomson wattmeter, the loss is 215 watts. The difference in the loss obtained by the two wattmeters is therefore 125 watts. The current is about 0.25 of an ampere. Now, 0.25 of an ampere if in step with the E. M. F. would give on the Thomson wattmeter at 38,000 volts a reading of 9500 watts; therefore the capacity current through the shunt resistance necessary to produce the discrepancy of 125 watts is 125 divided by 9500, or about 1.3 per cent. of the current in the shunt resistance. The shunt resistance has a value of 1,202,300 ohms; at 38,000 volts the current through it would be about 0.032 amperes; 1.3 per cent of this, or 0.00416 amperes is that required to produce the discrepancy noted. In further support of this method of accounting for the discrepancy, the results obtained at different numbers of alternations using the Thomson wattmeter show a variation for different numbers of alternations of the losses below the bend in the loss curve, and which are thought to occur over insulators and cross-arms. There should be no variation in such loss for a variation in frequency.

"Any discrepancy occurring in the Thomson wattmeter by reason of a capacity current in its shunt resistance will be affected to a greater or less extent by change in the wave form.

"It is believed that all the phenomena connected with this work may be studied in a tube which has been partly exhausted. The work could then be done with comparatively low voltage and using direct current which would much simplify the measurements. The contents of the tube might be partially rarefied air or other gas, as the action would undoubtedly be similar in all gases. With such a tube might be studied the law of variation in distance and form of electrodes, also in material and surface of the same.

Résumé and Conclusions.

"It is undoubtedly true that the loss is made up of a loss over insulators and a loss between wires, and that the latter is the only loss worth considering.

"The loss between wires is not affected by any atmospheric conditions except precipitation. This statement of course must be taken as applying to such a climate as that in which the measurements were taken. The lines were seldom in fogs or clouds, and when they were, or when rain was falling, the moisture was of the purest. Near cities the loss would be undoubtedly much greater than that shown in these curves, because of the impurities both in solution in the moisture of the atmosphere and in suspension.

"There will be for a given transmission a certain economical voltage, because while an increased voltage, with a given line wire, will reduce the loss in this wire by decreasing the transmission current it will also increase the loss between the wires.

"It is believed that attention to wave form is very important. The sine wave is undoubtedly the best as giving a stable form, and because of superior results with all kinds of apparatus. A flat wave would of course give less loss, but would not be stable, and as the nearest practical approach to a sine wave will not be perfectly stable but will still contain some harmonics, it will be of advantage to keep the series reactance of the transformers and generators as low as possible.

"It is believed that 40,000 volts is perfectly conservative and safe as regards loss between wires for any ordinarily good wave form, and in a climate such as that in which the measurements were taken, *i. e.*, where the air and precipitated moisture are practically pure, 40,000 volts comes well below the bend in the loss curve even under the worst weather conditions.

"I can see no advantage of porcelain over glass, unless it be that of superior mechanical strength. The latter is rather a doubtful advantage. The ball from a heavy calibre rifle or revolver such as are used in the western country will smash any insulator whether glass or porcelain. Porcelain offers a more tempting mark, being white. As to hygroscopic properties, no difference could be discovered so far as these measurements were concerned. It will make little difference under running conditions whether the insulator be hygroscopic or not, as the small amount of power necessary to keep the surfaces dry will be insignificant. I say under running conditions, because in starting up a 'cold' line there is danger of break-down if current is put on suddenly at full value, instead of being raised gradually. As far as the resistance to piercing is concerned, glass is just as good practically at least as porcelain. It needs no electrical test to pick out a good glass insulator, which is one advantage of glass over porcelain.

"To sum up, glass insulators are cheaper, lighter, more easily tested and less likely to be shot at than porcelain; on the other hand, they have less mechanical strength.

"In every case, in my experience, where a breakdown has occurred, it has been on a cross-arm which was 'wind shaken' and 'weather cracked,' the current following the cracks. This leads to a curious result. The mark of the current will be on surface of the arm for five or six inches, then disappear from the surface altogether for some inches, then reappear, etc. On cutting open the arm one sees how the current has followed the best path, dodging in and out. Rain and moisture probably settle towards the cracks, carrying salts from the body and surface of the wood. This forms a path of low resistance, especially in wet weather. For this reason I have in the plant of the Colorado Electric Power Company taken particular pains in treating both pins and cross-arms. The cross-arm treatment is such as fills all cracks and fissures as a section of the wood shows.

"This report would be incomplete without an acknowledgment of the assistance rendered in the work by the engineering force of the Telluride Power Transmission Company. headed by Mr. P. N. Nunn. Especial credit should be given Mr. A. L. Woodhouse for his faithful work and constant perseverance in the face of great discouragement."

HIGH-TENSION TESTS AT EAST PITTSBURG.

Laboratory tests and measurements on a small scale cannot take the place of tests under the conditions of practical service, such as those at Telluride. There are, however, many important elements which may be determined by laboratory measurements.

A high-tension line for testing insulators and making measurements upon the losses between wires was erected at the East Pittsburg factory in the fall of 1897. A number of the tests which have been made are here recorded.

(1) A test was made to determine whether the wave form of the charging current to the line was similar to that through a resistance, or whether it was modified by the loss component, the loss occurring only at the higher part of the E. M. F. wave. The current to the high-voltage line, at pressures varying from 30,000 to 60,000 volts, was passed through a coil possessing high self-induction. The E. M. F. upon the coil was measured by a voltmeter. The E. M. F. was also measured when a current of equal strength was passed through the coil, the line being short-circuited and a low E. M. F. applied. It was found that the voltage upon the coil was the same, within a small error of obser-

vation, in both cases, showing practically no difference in the wave form of the current under the two conditions. The current was from an armature giving practically a sine wave.

(2) The charging current to the line was measured under several different conditions when the current was obtained from a generator giving practically a sine wave. The results of measurements were compared with the currents as calculated by the theoretical formula. The last measurement in the table was made upon the Niagara-Buffalo line, with current from a Niagara generator, which differs slightly from a sine wave.

COMPARISON OF MEASURED AND CALCULATED CHARGING CURRENT TO PARALLEL WIRES. LENGTH, ONE MILE—10,000 VOLTS.

Size of Wire.	Distance between Wires.	Frequency.	Measured Current.	Calculated Current.
No. 8 B and S	21.7″	60	.0307 Amperes	.028 Amperes
8 B and S	48.0′	60	.0245 "	.0252 "
8 B and S	79.5″	60	.0234 "	.0238 "
8 B and S	127 5″	60	.0225 "	.0222 "
No. 8 and ground	120.0″	60	.0427 "	.0412 "
0.71″ diameter	18″ for 2/3 of distance 36″ " 1/3 " "	25	.0176 "	.0170 "

A table giving the calculated charging current for a number of conditions will be found in Appendix B.

(3) The fall of potential around the wires was noted by tests made with spark-gaps. The wires 48″ apart were connected to the high-voltage terminals and a spark-gap was placed between two idle wires also 48″ apart, placed about 21″ below the first wires. A spark-gap consisting of brass terminals with a $\frac{1}{4}$″ radius was placed between the two idle wires. When the gap was $\frac{1}{32}$″ the sparking began when the E. M. F. from the raising transformer was 26,000 volts. A gap of $\frac{1}{32}$″ requires an E. M F. of 2,200 volts to produce sparking. When the spark-gap was made $\frac{8}{32}$″ (equivalent to 12,000 volts) the sparking began at 103,000 volts from the raising transformer. At intermediate points there is a fair proportionality between the spark-gap and the E. M. F.

In another test a spark-gap was placed between one of the idle wires and the adjacent wire of the live circuit. When the spark-gap was ⅛″ (equivalent to 6,000 volts) the spark passed when the E. M. F. was 17,500 volts, and when the spark was made ¼″ (equivalent to 12,000 volts) the sparking began at 33,000 volts. When the gap was ⅜″ (equivalent to 16,000 volts) sparking began at 41,000 volts. When the gap was ½″ (equivalent to 20,000 volts) sparking occurred at 49,000 volts. The E. M. F. did not differ greatly from a sine wave. These tests have an important bearing in connection with the running of telephone and

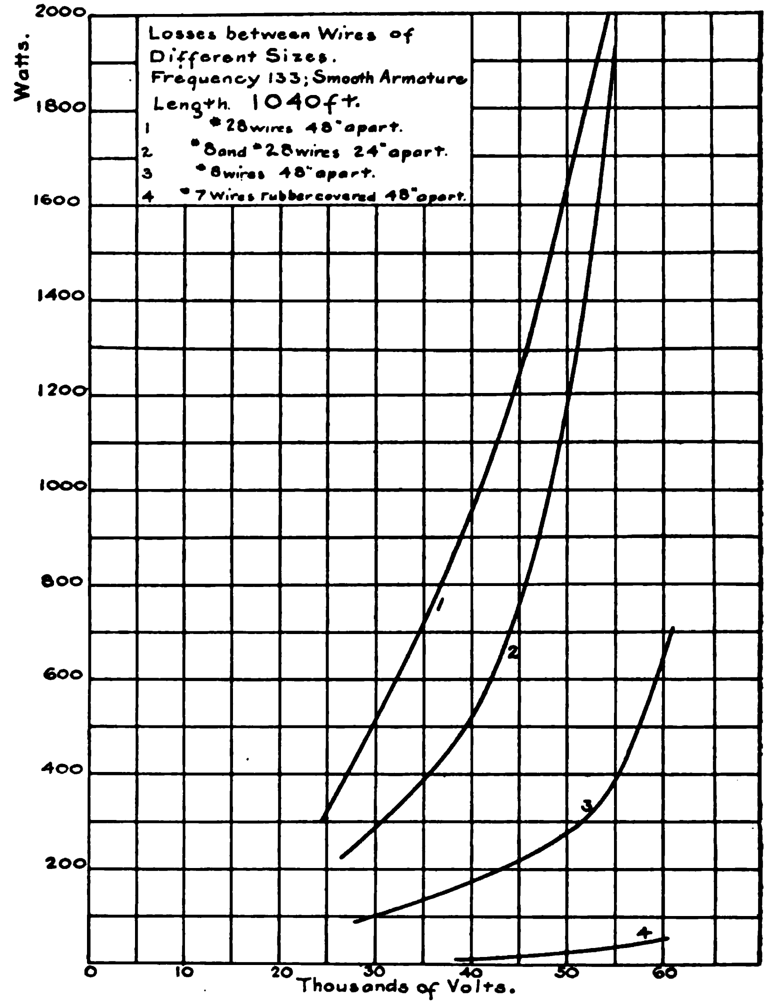

FIG. 13.

other circuits adjacent to high-potential wires. It is essential that the wires of a high-potential circuit be spiraled so that each wire sustains the same relation as every other wire to the second circuit, in order that the effects of static induction may be neutralized.

(4) The effect of the size of wire upon the loss was investigated by running a pair of No. 28 brass wires 0.0126″ in diameter and then replacing it by large rubber-covered wires. The rubber-covered wire was No. 7 B and S. gauge 0.144″ in diameter; the outside diameter of the rubber covering was 0.3″ and the diameter over the braid was 0.35″. In each case measurements were made upon another circuit which was unchanged during the different tests, and thus served for comparison. The results of these tests are shown in Fig. 13, which also gives the conditions when one fine wire and one wire of larger size, No. 8 B and S, constituted the circuit. This comparison shows the very marked increase in loss when the fine wire is used. The loss is greatly decreased when the rubber-covered wire is used. The loss on the rubber-covered wire, however, increased considerably after the voltage had been raised and the rubber had broken down, thus permitting the current to pass freely to the outer surface of the insulation. It is quite probable that the loss would increase as the insulation became defective, until it was nearly equal to that of a wire having the same total diameter.

The measurements on wires of different sizes given in Fig. 13. are qualitatively correct, although some of the readings on which the curves are based were quite small, so that the absolute values may not be exact.

(5) The effect of the current in drying the surface of the insulators was illustrated in a test made during a rain. Upon applying 45,000 volts to a circuit the wattmeter indicated 116. After four minutes the deflection had decreased to 72, the current remaining the same. The E. M. F. was then increased to 60,000 volts, the wattmeter deflection increased to 155, and at the end of three minutes it had fallen to 138. The current was one-third greater than at the lower voltage, but remained constant while the wattmeter changed. The rain continued during the test, which shows, therefore, that the condition of the insulator is materially improved by the presence of the current.

(6) It was noticed that when there was a break-down upon the line and the current passed suddenly between wires over the

surface of the cross-arm that there was a sparking between the terminals of the ammeters in the high-tension circuit across the surface of the instrument. This was further investigated by placing in circuit a coil of low resistance through which one ampere would be sent by about 1½ volts at a frequency of 125. A spark-gap was placed in shunt to this coil. A 2″ spark-gap was also placed between the line wires. The voltage of the primary was gradually raised until at 35,000 volts the current passed across the spark-gap between the line wires. A spark also passed across a gap of ⅜″, shunting the small choke-coil. This test shows the remarkable suddenness of the rush of current when the short-circuit occurs due to the breaking down of the spark-gap on a high-voltage circuit. This phenomenon was observed by Mr. Mershon in choke-coils used in connection with lightning arresters at Telluride.

Running tests were made on four lines in multiple at high voltages. Each line consisted of two wires 1,040 feet in length held by 26 insulators. The insulators were of various types of glass and porcelain, some of the ordinary form and some underhung. For hours at a time 100,000 volts or slightly more were kept upon the line. For about six weeks voltages ranging from 70.000 or 80,000 to 100,000 volts were kept on the lines for about eight hours a day. When there was rain the line would short-circuit and the voltage had to be reduced. During a driving rain storm 48,000 volts was kept on the lines, and it may have required a considerably higher voltage to have caused short-circuiting.

(7) A high-tension wattmeter similar to the Thomson wattmeter at Telluride was used. To correct the wattmeter for the errors caused by charging current in the shunt resistance, a condenser was placed in parallel to the shunt circuit of the wattmeter. This condenser should be so adjusted that the current through the shunt circuit of the wattmeter is the same that it would be if there were no condenser and the shunt resistance had no capacity. This permits the capacity current in the circuit to be shunted round the wattmeter by the condenser. The condenser in shunt to the wattmeter was capable of adjustment, and by varying its capacity the deflection could be made positive or zero or negative when current was delivered to a constant load. The proper adjustment was made by taking a comparatively low voltage, at which the charging

current was very high in comparison with the loss, so that the loss was nearly negligible, and adjusting the wattmeter to indicate zero. At higher voltages, when there was a considerable loss, the error with this adjustment would be inappreciable. Certain variations with temperature and humidity were noted which would be explained by a variation in the capacity of the resistance, causing a variation in the charging current to the shunt circuit of the wattmeter. The high resistance for the shunt circuit was wound upon fuller-board plates containing brass stiffening-pieces. Tests were made upon individual plates by measuring the capacity between the wire and the supporting strip of brass, and it was found that the capacity and the insulation resistance both varied with the amount of moisture in the fuller-board insulation. In order to prevent variations of this kind, subsequent resistances were wound upon glass plates, which seems to be a very satisfactory form of construction.

TESTS AT NIAGARA.

Some measurements have been made upon the Niagara-Buffalo transmission line. There are two circuits of three wires each, one of which was in service and the other was available for tests. Each circuit consists of three cables each of 350,000 C. M., approximately 0.7″ in diameter. The cables are run on porcelain insulators, and are on the same cross-arm. Adjacent insulators are 18 inches apart and the circuit is spiraled, so that each of the three wires occupies the middle position for a third of the distance. Current from one of the 5000 H. P. generators was applied to the line through a raising transformer, by which the voltage can be increased by small steps to 100,000 volts. This transformer is part of a high-tension testing outfit which is described by Mr. C. E. Skinner in the *Electrical World*, March 5, 1898. The wattmeter is a Thomson inclined coil instrument with a high resistance shunt of german silver wire wound on glass plates. The ammeter is a Thomson inclined coil instrument, connected directly in the high-voltage circuit.

Measurements were made between the various pairs of wires, *i.e.*, 1 and 2, 2 and 3 and 1 and 3; the current was found to be practically the same in each case; the loss on one of the circuits was slightly greater than that on either of the other two, on which the losses were about equal. The accompanying curve shows the measurements of current when two wires were connected and the measurement of loss; the latter measurements were made upon one pair of wires up to about 26,000 volts and then upon a second pair. The results are given in Fig. 14.

On another day measurements were made of the resistance between each wire and the ground, and corresponding measurements of loss were made by placing the high potentials between each wire and the ground. The measured loss was somewhat greater than the loss calculated by using the E. M. F. and the measured resistance. In these measurements, at voltages from 13,000 to 23,000 volts, the power factor calculated from the current and

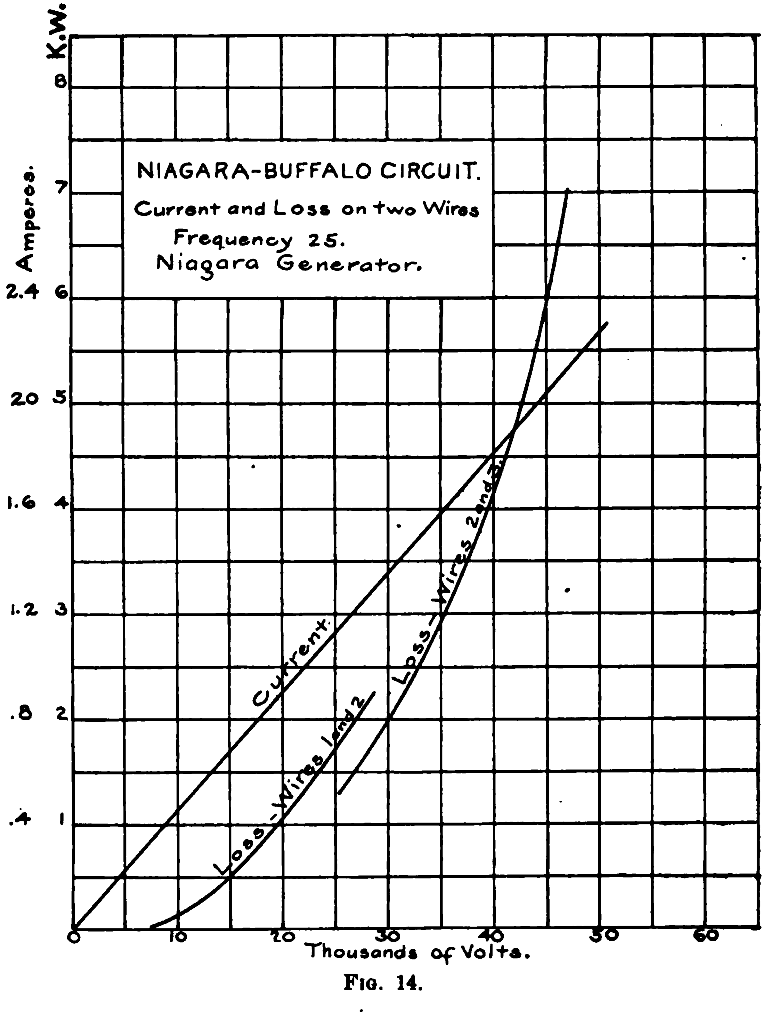

FIG. 14.

wattmeter measurements, varied from about 4% to 6%, so that a very small charging current in the wattmeter would produce a considerable error in the reading.

Some measurements were made upon a pair of fine wires, in which the wires were placed at different distances apart. No. 31 B and S gauge spring brass wire 0.0089″ in diameter was

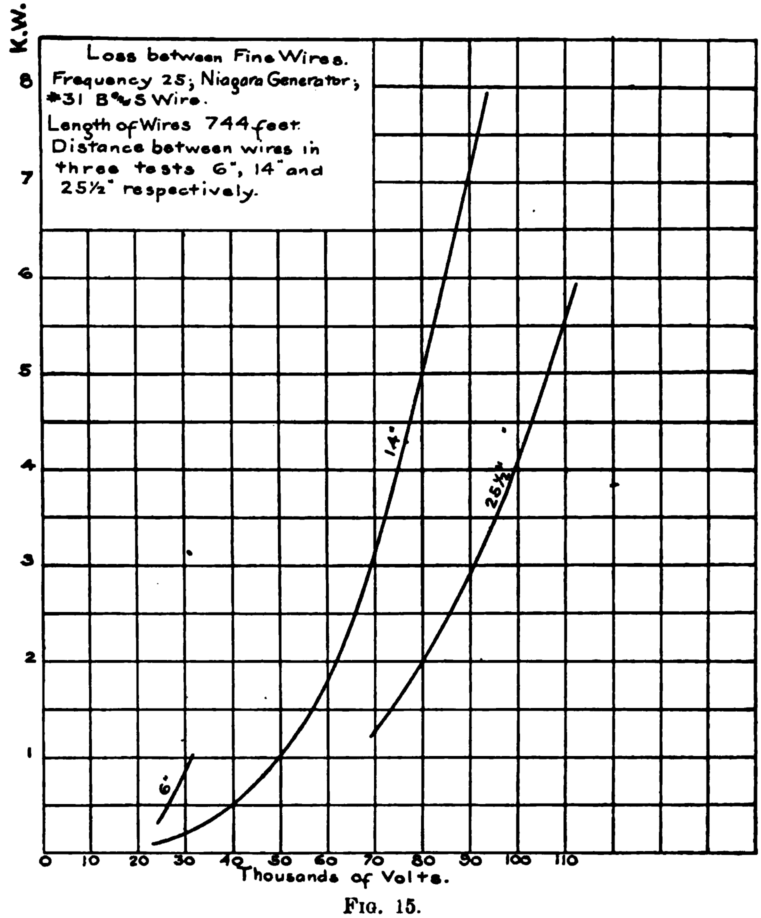

FIG. 15.

used. The length of the parallel wires was 744 feet. They were suspended by light strings successively at 6″ apart, 14″ apart, and about 25″ apart, the distance varying from 24″ to 27″. The wattmeter readings are given in the curves in Fig. 15. The power factor of the measurements made above 100,000 volts is about 95%, and is over 80% above 70,000 volts. There can be but little error in the wattmeter due to charging current in the resistance at these power factors

The measurements on the Buffalo line were made by the writer. Those on the fine wires were made by Mr. E. M. Tingley, who conducted the tests at East Pittsburg, and rendered valuable assistance in the preparation of this paper.

POWER TRANSMISSION PLANTS IN OPERATION.

Beginning with the plant at San Bernardino and Pomona, which began operation in 1892, using 10,000 volts and transmitting 30 miles, a constantly increasing number of plants have been installed operating at 10,000 or 15,000 volts. In some cases there has been little or no trouble experienced with the transmission lines, while in other cases the experiences have been less satisfactory. The principal trouble seems to have been a poor grade or an insufficient size of porcelain insulator. In other cases the insulators, sometimes porcelain and sometimes glass, have given almost perfect satisfaction.

The superintendent of a power company which has been running fifteen months with about 15,000 volts, reports that they "have had absolutely no trouble whatever of an electrical nature." Some insulators were broken because they had been used as targets by small boys or hunters, but only the outer petticoats were broken, and no short-circuits occurred, although in some cases insulators were in use for months with most of the outer petticoats chipped off. The distance of transmission is twelve miles. Porcelain insulators are used.

In another plant which has been in operation about a year and a half employing 15,000 volts for a distance of nearly thirty miles, there have been but three shut-downs on account of line difficulties. These were due to the breaking of insulators at a point where the line was spiraled. In one case the repair was made in half an hour, and in the other case a few minutes interruption to the service was sufficient for repairs.

The line is regularly patroled, and if a defective insulator or pin is found, the generating station is notified by telephone and the line is shut down for a few moments at noon. In one case two poles were burned by a defect in the insulators on the top of each. The poles burned to the ground, leaving the line hanging clear without any one at either the generating station or substation being aware of the fact.

Troubles have arisen on some lines by the burning off of pins by the passage of sparks from the outer edge of the insulator to the pin. These sparks make small holes in the pin no larger than a needle point, but after continuous sparking for some time the pin becomes entirely charred. An iron pin suggested itself as a remedy, but additional strains and tendency to breakdown are liable when a conductor is placed within the insulator. The burning off of pins has occurred where small porcelain insulators are porous and the outside glaze is imperfect, while the glaze on the inside is good. When the porcelain is filled with water the current readily passes through it to the lower rim of the insulator and then sparks across to the pin. In one place which has been running for about three years some 250 pins burned off. The early insulators have been replaced by larger and better ones, and this defect has disappeared.

A 10,000 volt-line which runs for a dozen miles or more within a few hundred yards of the Pacific coast has burned cross-arms on nearly every pole. The cross-arms near the ends of the line, which are away from the coast, are not burned. Usually the burning appears as a mere blackening of the cross-arm for a short space between the insulators, on one side of the arm. In some cases the charring is deeper, and appears on both sides. The side on which almost all of the burning occurs is the one toward which the winds come from the ocean, bearing the mist of salt water. The wire shows discoloration, and the iron braces for holding the cross-arms are in a few cases eaten through. Moreover, the cross-arms were green and full of sap when erected. The early porcelain insulators were porous, and have now been replaced, and the pins are of iron. The charring has ceased almost entirely since the new porcelains were put up.

It may be observed that in the plants which are herein referred to and in the experimental tests, no mention has been made of insulators with cups containing oil for reducing the surface leakage. Insulators of this kind were used in the Frankfort-Lauffen experimental transmission line at 30,000 volts. Practically, however, the surface insulation is adequate without oil cups and the principal duty of the insulator is to prevent the current passing over the surface and jumping to the pin or cross-arm, a matter with which the oil would have nothing to do.

Telephone lines are in use in a number of plants placed on the poles which carry the transmission wires. The telephone lines are usually placed some distance below the transmission wires and are crossed at frequent intervals. The telephones in general work very satisfactorily.

There appears to be practically nothing in power transmission in Europe using high potentials outside of Switzerland. The installation in Paderno in Switzerland is operating at 15,000 volts, the highest voltage which has been used in that country. The damp weather is one of the limiting factors. The insulators used are porcelain with a triple petticoat.

40,000 Volts in Commercial Service.

Fig. 16.—Insulator used at Provo for 40,000 volts.

The highest voltage which is used for transmission is in the Provo plant of the Telluride Power Transmission Company in Utah, which transmits power 35 miles to the Mercur mills at 40,000 volts. Raising transformers are three in number and are connected in the star form. Each transformer has a capacity of 250 k. w. The middle points of both the high-tension and low-tension circuits are grounded. In general design these transformers resemble the transformers used in the high-tension tests at Telluride; the design and construction having been under the direction of the same man in both cases. The line extends from Provo at an elevation of 4,500 feet to Mercur, at 2,000 feet above Provo, and the line reaches an extreme height of about 10,000 feet above the sea level. Three miles of the line are strictly mountain construction. The lightning protection is afforded by choke-coils and Wurts non-arcing metal arresters. The insulators are of glass. The design was based on the tests at Telluride and they were made especially for this plant. The form is shown in Fig. 16. The insulators are held on special pins of oak which are thoroughly paraffined. The lower part of the insulator is 5″ above the cross-arm.

In dry weather there has been no difficulty whatever in operating. The insulators do their work as effectively as could be expected if the voltage were only a few thousand volts. When everything is dry, the line will operate without difficulty, even if some of the insulators are off and the wire rests upon the cross-arm. When it rains there is sometimes trouble. It is indicated in the station by the ammeters giving quick swings, showing momentarily strong currents. Sometimes this is apparently a short-circuit and blows a fuse. In every case when there has been trouble on the line it has been in rainy weather, and broken insulators have been found which located the trouble. It is certain that in most cases these have been previously broken by bullets, and in other cases it is probable that the insulators were likewise broken. It is believed therefore that had there been no intentional break-

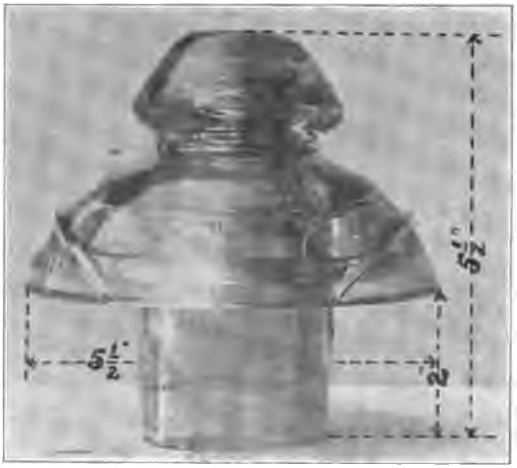

FIG. 17.—Insulator used by Colorado Electric Power Company for 20,000 volts.

age of insulators there would have been no trouble upon the line since the plant began operating in February last. A few of the insulators near the station are not far from the overflow and are in a moisture equivalent to a rain all the time without doing any damage. Snow has often backed from the cross-arm up against the bottom of the insulator and around the first petticoat. It is usually found that the part of the insulator around and near the wire does not receive deposits of moisture or frost but remains dry, the particles being repelled. At this plant, current for about 700 H. P. is carried through three fuses of copper wire 0.01″ in diameter. Iron wire is used on a branch line for transmitting about 100 H. P. for about 3 miles.

This plant has been in operation in winter and in summer, "in thunder, lightning or in rain," the sole supply of power for the enormous De Lamar mines and mills, at Mercur, and is a happy and fitting consummation of the high-tension tests described in the beginning of this paper.

LIMITATIONS OF HIGH-VOLTAGE TRANSMISSION.

The important commercial question is: To what distance can power be transmitted? The relation between distance and voltage is well known. The same weight of copper can transmit with equal efficiency the same power to any distance, provided the voltage is increased directly as the distance is increased. The limiting commercial ratio between voltage and distance is easily found. If the distance be three miles per 1000 volts and the loss 16%, the cost of copper is about $20.00 per H. P. The interest on the latter investment is about $1.00 per year. A distance in miles equal to three times the number of thousand volts may therefore be covered without an excessive annual charge per H. P. for copper. The limits to the voltage which are practicable depend principally upon the insulator and upon the loss between wires.

The Insulator—The two fundamental requirements are dielectric strength sufficient to prevent puncture, and a size and form which will prevent the passage of the current around the insulator. A given insulator will be adequate for a higher voltage where the atmosphere is comparatively pure and dry, than it will be under other conditions. The rapid progress which has been made in the design and construction of insulators during the last few years, will doubtless provide an insulator which will accommodate the highest voltages that can be used due to other limitations. The insulator therefore while remaining the critical point in a transmission system will probably not determine the limit of practicable voltages.

Loss Between Wires—The loss between bare wires at high voltages seems to determine a positive limit, beyond which the voltage cannot be increased. This loss is subject to variation due to diameter of wire, distance between wires, and wave form of the E. M. F., but the variations which may occur under favorable commercial conditions locate the point of increase of loss about 50,000 or 60,000 volts. Under favorable conditions this may be raised somewhat, but it is not probable that any material increase can be made.

Amount of Power—The amount of power to be transmitted involves some interesting commercial limits. There are certain elements in a transmission which do not vary greatly with the amount of power transmitted. Thus, the charging current to the line will be practically the same whether the wire will transmit 1000 H. P. or 100 H. P. If the charging current happens to represent 300 H. P. it would be insignificant in one case, but for the smaller output it would require generating apparatus several times that necessary for the actual power.

It is not mechanically practicable to use wires as small as would be sufficient, in so far as conductivity is concerned, for transmitting a small power. For example, a No. 7 copper wire, which is as small as is ordinarily used, if employed in a 3-phase circuit fifty miles in length, will transmit over 1000 K. W. at 40,000 volts with 10% loss. If only a few hundred kilowatts were to be transmitted, the cost per K. W. would be excessively high, and on the other hand a lower voltage could be used without undue loss. In some cases, indeed, where a high voltage is used for small power, as for example on a branch circuit, an iron telegraph wire would have ample conductivity. In other cases an aluminium wire could be used to advantage, as an aluminium wire of the same conductivity as a copper wire has only about half the weight, and possesses greater mechanical strength in comparison to its weight.

It may also be noted that high-voltage transformers cannot be economically built for small output, as the insulation spaces required are so large. The cross-section of the copper is often not more than 10 or 20 per cent. of the area of the opening in the iron. The cost per K. W. increases very rapidly when the size of transformer falls under a few hundred K. W.

Cables and Conduits.—The overhead transmission line has been considered, and its limitations are the insulating strength of the insulator and the losses through the intervening medium. In a cable or a conduit the insulation must be provided continuously instead of at points a hundred feet apart. Rubber covered cables are made for 10,000 and 20,000 volts but it is quite possible that it will not be commercially practicable to make cables for much higher voltages. The effect of continued electric stresses on the insulation of the cable, which is an unknown factor, may prove to be a very important one. A conduit composed of a pipe containing oil, in which the wires are separated by glass tubes has been proposed. Many mechanical difficulties arise in constructions of this kind; the cost is high and the action of continued high voltages on solids and liquids opens a field which is little known. A suitable insulation on the wires on high-voltage lines may enable higher voltages to be used than can be used with a bare wire.

Liquid air with its high insulating properties and the low temperature and consequent high conductivity which it would give to a conducting wire may enable us to use air insulation in a new way.

Difficulties and Precautions.—High voltages have been referred to in this paper with perhaps undue familiarity. Familiarity with high voltages is not one which breeds contempt. A voltage which can produce sparks several inches in length, which can be felt through several feet of air, which causes hissing sounds, which produces luminosity and which in a confined room generates strong odors of ozone, is one which creates profound respect. Dangers and difficulties accompany it and the highest intelligence, vigilance and excellence must be employed to avoid accident and ensure success. While ordinary types of construction do not seem to reach their limitations until some 50,000 volts is reached and pressures of this order have been and are in regular use, nevertheless they are not to be used indiscriminately or where they can be avoided. There are difficulties enough in handling 15,000 and 20,000 volts. As the pressure is raised the liabilities to trouble increase at an alarming rate. It is, however, a fact that these voltages have been and can be used, and also that no new or modified methods of transmission will be required before 50,000 or 60,000 volts can be employed for distances up to 150 or 200 miles.

APPENDIX A.

INSTRUMENTS AND METHODS USED IN TELLURIDE MEASUREMENTS.

[Extract from report of Mr. Mershon.]

" *The Wattmeters*—At first, all the measurements of power were made in the low-tension circuit. The attempts to measure the power delivered to the line by taking the difference in the readings of the wattmeter in the low-tension circuit of the transformers when the lines were on and when they were off, proved worse than useless. This was due to the fact that throwing on the lines distorted the E. M. F. wave impressed on the transformer. As a result, at low voltages, readings obtained in this way indicated a negative line loss, and it was only when the voltage was raised to such a point that the line loss was greater than the reduction in iron loss, due to the E. M. F. distortion, that positive results could be obtained; such results were of course incorrect. In order to overcome this, it was determined to balance on the wattmeter the effects of the iron loss in one of the power transformers against that of the other in such a manner that both transformers would be subject to the same E. M. F. distortion, and the iron loss would therefore at no time register anything on the wattmeter. The line loss could then be measured directly. This was accomplished as is shown in Fig. 18.

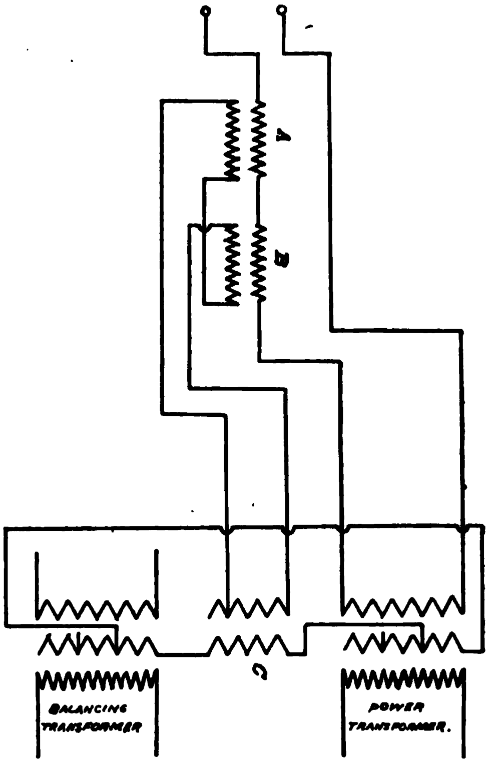

FIG. 18.

"Here the transformer which supplies the line is designated as the 'power transformer', while that which is used in balancing the iron loss of the power transformer is called the 'balancing transformer'. As was stated in the description of the transformers, the power transformer has four of its low-tension coils in multiple for receiving power, while the fifth or middle low-tension coil is independently used in connection with the measuring instruments. This middle coil of each transformer is shown in the sketch, and it is through these coils that the balancing transformer receives its voltage. That is, one-third of the middle coil of the power transformer feeds one-third of the middle coil of the balancing transformer. With such an arrangement, the balancing transformer receives practically the same wave form as that impressed upon the balancing transformer, no matter what the amount of wave form distortion may be. A is the field coil of the wattmeter. It has two windings. Through one of them, the primary winding, passes the current to the power transformer; through the other, the secondary winding, passes the balancing current—the current to the balancing transformer. As these currents are in opposite directions in their respective windings, when adjusted to the proper values, their effects on the shunt coil of the wattmeter annul each other. It is evident that if A only were used, a balance for iron loss when the lines were off would not necessarily mean a balance when the lines were on, because the change in current due to putting the lines on would cause a change in the reactance E. M. F. of the secondary of the wattmeter field coil, and consequently a change in the balancing current through this secondary. The air transformer B is therefore used: B is preferably, but not necessarily, exactly similar to the field coil A, and supplies an E. M. F. in its secondary exactly equal to and in step with that of the secondary of A. These two secondaries are connected in series, so that their E. M F.'s oppose, and through them both, is sent the balancing current. The secondaries of A and B are not connected directly in series with the circuit connecting the middle coils of the power transformer and balancing transformer, but are included in this circuit through the medium of a series transformer, C. C makes possible the adjustment of the balancing current to the value necessary for zero wattmeter reading when the lines are off, and it, or some equivalent device, is necessary because of the impossibility of securing two transformers with exactly the same iron loss. Indeed, in this particular case the ratio of the hysteresis to the Foucault current loss differed sufficiently in the two transformers to necessitate adding in shunt to one of them an ohmic resistance which made up for the lack of Foucault current loss in it. This method of reading power is, if properly carried out, a most admirable one, and has the advantage that the instruments to be handled are all in the low-tension circuit. The balance may be obtained without difficulty, and when once properly obtained holds through all ranges of voltages and distortions of wave form. Tests of this balance were made repeatedly with the lines off, by varying the impressed E. M. F. through wide ranges and distorting the E. M. F. wave, the distortion being produced by introducing in series with the power transformer large amounts of both resistance and reactance. In every case the balance was perfectly preserved. There is one drawback, though not a serious one, to the method as here employed. The power transformer, because of the load upon it, heats up faster than the balancing transformer, and the balance is in consequence impaired. The amount of unbalancing is, however, small, even for wide difference of temperature, and it can be easily corrected for by means of zero readings taken before and after a set of observations. This unbalancing, due to unequal heating, could be rendered negligible by placing the power transformer and the balancing transformer in the same tank of oil.

"Although in this case the balancing transformer was of the same size as the power transformer, it may be much smaller, though both transformers should be worked at the same induction. Of course it is not necessary that the balancing transformer have a full set of windings. It need only have a coil suitable for receiving E. M. F. impressed upon it.

"The wattmeter actually used in this work (shown in Figure 19) consists of a field coil so mounted that a Weston wattmeter can be slid in and out of it, and different ranges thus obtained. The scale originally on the wattmeter was replaced by one of equal parts. The wattmeter's own field coil is not used at all, the field being supplied wholly by the large external field bobbin. The voltage impressed upon the wattmeter shunt coil was at first obtained from the auto-transformer above mentioned, but later it was obtained directly from one-third of the middle coil of the power transformer by the use of an additional resistance or multiplier. The winding of the field bobbin consists of 72 turns of a cable composed of seven No. 8 double cotton-covered magnet wires which were twisted together after having been separately treated with 'P & B' insulating compound.

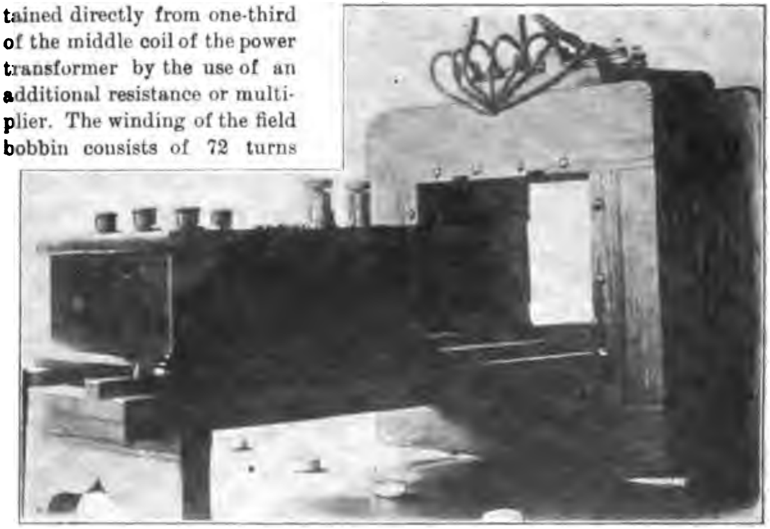

FIG. 19.—Wattmeter with External coil, used in Tests at Telluride.

"The wires are brought out separately to terminals on the top of the bobbin, and can be used singly or in any desired series or multiple combination. They were, for this work, connected up into two sets, forming the primary and secondary of the wattmeter coil. The size of this field coil, necessitated by the size of the wattmeter box, gives it a large reactance, and as this has added to it the equal reactance of the air transformer, the reactance of the combination is considerable. This is objectionable because of the consequent distortion of the generator E. M. F. wave, for though the results obtained under these conditions are accurate, they are in some cases the results of conditions differing widely from those which will ordinarily be met with in practice. The combined reactance of the field coil and the air transformer at a frequency of 60, when passing a current taken by a power transformer supplying the line, is 2.83. The current used in obtaining this figure probably differed somewhat from a sine wave. If the wattmeter were specially constructed with a view to this work, the movement being surrounded as closely as possible by the protecting case, the external field coil into which the movement projected could be made small enough to reduce the reactance to a negligible quality. In designing a wattmeter for this work, it should be borne in mind that it must measure under the condition of a very small power-factor.

"In these notes the term 'Weston wattmeter' is meant to include the field bobbin of the wattmeter and the air transformer used in connection with it.

"After the above wattmeter had been in use for some time, another was obtained for use in the high-tension circuit. It is a Thomson inclined-coil instrument, whose field coil was rewound for this work. In connection with this wattmeter are two external resistances—the one with a resistance of 1,202,-300 ohms, for use in series with the shunt circuit of the wattmeter; the other with a resistance of 3,495 ohms, being equal to that of the wattmeter shunt circuit and intended for use in shunt to the latter, in which case the wattmeter shunt coil receives only one-half of the current in the shunt circuit. When in use, the case of the wattmeter was connected to one of the wattmeter shunt terminals, so that the inside and case of the wattmeter were always at the same potential and the case formed a screen against any external electro-static effects. This wattmeter was of considerable value as furnishing a means of studying the effect of the distortions due to the Weston wattmeter, and also to the readings at low frequency, since in the latter case, it was necessary to use both transformers as power transformers, which left nothing for use as a balancing transformer. In the notes this wattmeter is designated as Thomson wattmeter.

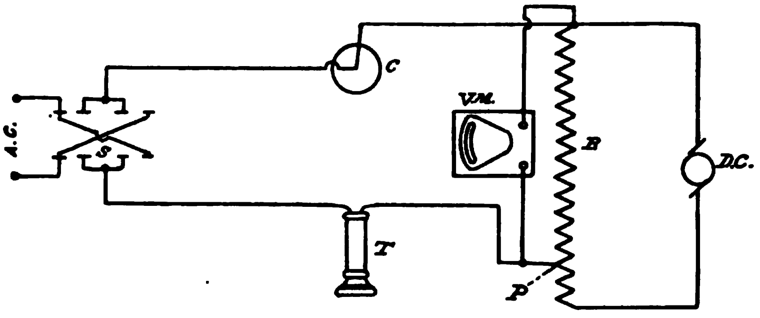

FIG. 20.

"*The Ammeters*—The ammeters used were two Thomson inclined-coil instruments. They had a capacity of one-half and two and one-half amperes respectively. They were put directly into the high-tension circuit, the cases being connected to one terminal of the instrument.

"*The Wave Form Apparatus*—The method of taking wave forms was that devised and published by the writer, [Mr. Mershon], in 1891. It is an instantaneous potentiometer method, employing a telephone receiver to indicate a balance. The connections are those shown in Fig. 20.

"A C is the source of the alternating E. M. F., whose wave form is to be plotted, S is a double-pole switch for reversing the alternating current terminals, C is the usual instantaneous contact device, T is a telephone receiver. V M is a D. C. voltmeter—in this case the Weston laboratory standard, R is a resistance along which the contact P can be moved. D C is a source of direct current—in this case a direct current dynamo feeding the resistance R. The contact C being set at any desired point, the value of the E. M. F. at the instant of contact is determined by moving P backward or forward until there is no sound in the telephone T. The reading of the direct-current voltmeter V M gives the desired value. The E M. F. A. C was obtained from the same source as the E. M. F. for the A. C. voltmeter, *i.e.*, from an auto-converter connected across one-third of the middle coil of the power transformer.

"*The Speed Indication*—The indication of proper speed, or rather frequency, was obtained from the vibration of a weighted steel wire hung in front of the poles of an alternating electro-magnet energized by the machine supplying power. The wire always vibrated at the frequency for which the suspended weight was adjusted, and ceased to vibrate when there was any appreciable deviation from this frequency."

APPENDIX B.

CALCULATED CHARGING CURRENT TO TWO PARALLEL WIRES.

LENGTH, ONE MILE; 10,000 VOLTS; SINE WAVE.

The charging current to a single-phase line one mile long has been calculated from the formula for capacity between wires and on the assumption that the E. M. F. is a sine wave. The results are given for several cases and as the variations between the quantities given are not very great, intermediate values can be readily interpolated. The current varies directly as the length of line, the voltage and the frequency.

Size of Wire—B & S.	No. 8	No. 4	No. 1	No. 0000	1" diam.
Distance between centers of Wires.	Amperes at 60 cycles.				
12 inches.	.032	.035	.038	.0414	.053
24 "	.0284	.0309	.0328	.0362	.043
48 "	.0252	.0274	.029	.0313	.0369
	Amperes at 25 cycles.				
12 inches	.0133	0146	.0158	.0172	.0221
24 "	.0118	.0129	.0137	.0151	.0179
48 "	.0105	.0118	.0121	.0130	.0154

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

New York, September 28th 1898.

The 127th meeting of the American Institute of Electrical Engineers was held this date at 12 West 31st Street, and was called to order by President Kennelly at 8:20 P. M.

The Secretary read the following names of associate members elected at the meeting of Council in the afternoon.

Name.	Address.	Endorsed by
Carter, Frederick William	Lecturer in Electrical Technology, City and Guilds of London Institute, Exhibition Road, London, S. W.	Edwin J. Houston. A. E. Kennelly. A. J. Rowland.
Coleman, Walter H.	Supt. and Treasurer, Andover Electric Co., Andover, Mass.	Chas. B. Burleigh. Sidney B. Paine. C. D. Haskins.
Doherty, Henry L.	General Manager and Engineer, Madison Gas and Electric Co., Madison. Wis.	M. C. Beebe. D. C. Jackson. C. F. Burgess.
Frank, Geo. W., Jr.	Secretary, Treasurer and General Manager, The Kearney Electric Co., Kearney, Neb.	J. G. White. W. F. White. D. C. Jackson.
Mansfield, R. H., Jr.	Electrical Engineer and General Manager, Ward Leonard Electric Co., Bronxville, N. Y.	H. Ward Leonard. F. S. Holmes. F. A. Pickernell.
Miller, Kempster B.	Chief Electrician, Western Telephone Construction Co., 38 Elaine Place, Chicago, Ill.	S. G. McMeen. Fred'k Bedell. Harris J. Ryan.
Rosenbusch, Gilbert	Engineer, Sprague Electric Co., South Orange, N. J.	Frank J. Sprague. Philip Torchio. R. W. Pope.
Thompson, John West	Supt. Cia. de Luz'y Fuerza Motriz Electrica, Guadalajara, Mexico.	F. A. C. Perrine. F. V. T. Lee. F. E. Theberath.
Tripier, Henri	Counsel and Technical Engineer, of the Campagnie des Transports Electriques del Exposition, Paris, France; residence, 16 rue Ganneron, Paris, France.	Chas LeBlanc. Ralph W. Pope. W. J. Hammer.

Wagner, Herbert A.	Gen. Supt., Missouri Edison Electric Co., and also with Wagner Electric Mfg. Co., 415 Locust St., St. Louis, Mo.	T. C. Martin. Joseph Wetzler. Wm. E. Geyer.
Williams, William Henry	Professor of Mechanical and Electrical Engineering, Montana State College, Bozeman, Mont.	D. C. Jackson. S. B. Fortenbaugh F. R. Jones.

Total 11.

THE PRESIDENT:—The paper for the evening is on the "Photometry of the Enclosed Alternating Arc," and copies of the paper are already in your hands. We are not fortunate enough to have Prof. Matthews with us, but the Secretary will kindly read the paper on his behalf.

A paper presented at the 127th Meeting of the American Institute of Electrical Engineers, New York, September 28th, 1898, President Kennelly in the Chair.

THE PHOTOMETRY OF THE ENCLOSED ALTERNATING ARC.

BY CHARLES P. MATTHEWS, W. H. THOMPSON AND J. E. HILBISH.

INTRODUCTORY.

The enclosed arc of the direct current type has received a noteworthy development at the hands of Marks[1] and subsequent workers. It has been the subject of more or less experimental study by Houston and Kennelly, Freedman,[2] Hesketh,[3] Nichols[4] and a number of others on both sides of the Atlantic. The enclosed arc of the alternating current type is of somewhat more recent development and has received less attention experimentally. It was with the thought of observing something of the behavior of this latter type of illuminant that the data of the following pages were taken.

THE PHOTOMETRY OF THE ARC.

Arc light photometry, in so far as it involves the mere determination of luminous intensity[5] yields unsatisfactory results for three chief reasons: The first of these is the marked difference

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[1] London *Electrician*, xxxviii, 615; March 5, 1897. See also "Proc. Electrical Congress," Chicago, 1893.

[2] TRANSACTIONS, xiv, 361; August, 1897.

[3] London *Electrician*, xxxviii, 793

[4] Sibley *Journal of Engineering*, xi, 368; June, 1897.

[5] That our photometric nomenclature needs standardizing can not be doubted. The quantity that has been called *candle-power* is hardly appropriate if the Hefner unit be used. If we have arrived at the passing of the candle, should not *candle-power* go? This same quantity is variously styled *intensity*, *total intensity* (Palaz.,) *luminous intensity* and *brightness* (Nichols). The unit of *illumination* also goes by several names.

in quality between the light of the arc and that of any of the ordinary standards. The photometrist realizes the generally unsatisfactory character of the existing standards[6] for the study of sources of a quality similar to that of gas light. Nevertheless, he is vastly better off, in this respect, than he is in the matter of a standard of suitable quality and intensity for arc light measurement. The eye estimates accurately an equality of brightness in two surfaces, only when those surfaces are of the same tint. Moreover, with a color difference, the judgment of an equality differs with different observers. It should be said, however, that the difficulty arising from difference of color is less troublesome in the case of the enclosed arc than in the case of its progenitor, the open arc. The inner, opalescent globe absorbs the rays of short wave-length in greatest proportion, a fact which brings the color of the arc nearer that of the standard. When an outer globe of milky glass is used—the standard being a glow lamp maintained at, or above, its normal voltage—there is no annoyance from color difference.

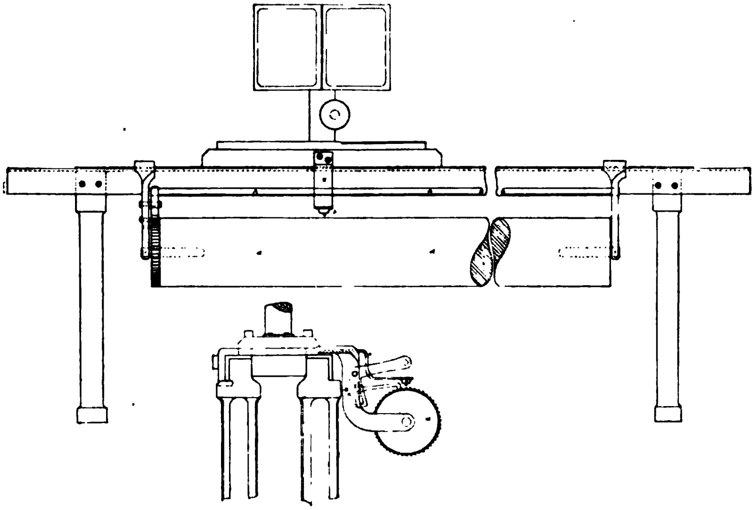

FIG. 1.

The second obstacle to careful measurement, is to be found in the variability of the quantity to be measured. These variations are largely due to the wandering condition of the arc—a peculiarity that is especially noticeable in the open alternating arc,

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[6] See report of Nichols, Sharp and Matthews, TRANSACTIONS, xiii, p. 133, May, 1896.

and in both types of the enclosed arc. Indeed, it is to this feature of the enclosed arc that the flat-ended carbons are due. The change in luminous intensity corresponding to a shifting in the position of the arc from one side of the carbons to the other side is enormous. Curves of horizontal intensity showing the magnitude of these changes have already been published[7]. An attempt to get at the intensity of such a source by a few readings might easily lead to results discordant by 100 per cent. or more. The only hope of securing a result that will show the mean intensity of the arc is in taking a large number of settings, distributed, as to time, with some degree of uniformity. To accomplish this it would seem desirable to do away with the considerable and variable interval of time used, in the ordinary process, in reading the bar. This end was reached by the use of a mechanical device for recording a setting as soon as it is made. The essentials of this device will be readily understood from an inspection of Fig. 1. Its collateral advantages, for the study of personal error and for other photometric uses, have been dwelt upon in a note published elsewhere[8]. For our present purpose, it is sufficient to point out that it permits the observer to keep his eye continually trained on the photometer disk, so that all the major fluctuations may be readily followed and recorded, and this, too, without the visual fatigue resulting from introducing light into the photometer room. The act of depressing the rod r makes a permanent record on the paper surrounding the drum, and at the same time advances the drum so that the record may be subsequently identified.

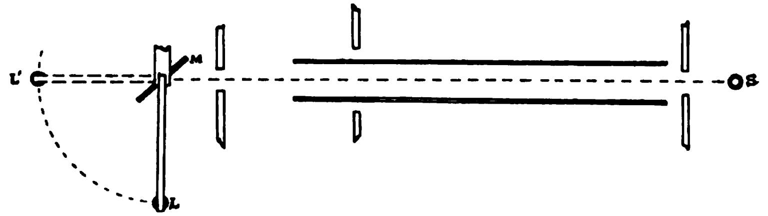

FIG. 2.

The inaccuracy of photometric settings, due to the causes just mentioned, is perhaps more a question of process than of prin-

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[7] Nichols, *loc. cit.*

[8] Matthews. Current number of the *Physical Review.*

ciple. There is a third and more fundamental source of trouble —one, indeed, which brings into question the validity of the term "candle-power" as a measure of worth in illuminants. For the sake of clearness, let us first consider what the term means. A 16 C. P. lamp, for example, is one that produces at a distance of four units the same illumination that one candle produces at one unit. That is, if two similar surfaces be illuminated separately by these two sources at these distances, and if they be viewed in juxtaposition from the same direction, they appear equally bright. This is, in fact, what the photometer shows, and is really all that can be affirmed as a result of the comparison. Having established a distance ratio of 4 : 1, the observer applies the law of inverse square to calculate an intensity ratio of 16 : 1. This intensity ratio is *numerically* equal to the illumination ratio on two surfaces at unit distance, but it is important to note that an observer would be quite unable to assign a numerical value to the relative illumination of these surfaces. In other words, the optical stimulus varies as the inverse square, but by Fechner's law, the sensation varies as the logarithm of the stimulus—a fact of which we can not take direct cognizance. Thus the intensity or "candle-power" ratio of two sources is a *derived* quantity, of indirect significance, whose chief value is to be found in the fact that it enables one to calculate an indefinite number of pairs of distances, at each of which will be found an *equality of illumination.* If two sources be compared by some method which takes account of their quality and which gives as a result the ratio of their total luminosities—determined, say by the relative value of their component rays in distinguishing characters—something quite different from their "candle-power" ratio may be obtained. These matters have already been brought to the attention of the members of the INSTITUTE by Nichols[9]. Fortunately the luminosity ratio of sources of nearly the same color, is not widely different from their intensity ratio. Hence it is to be hoped that, in the acetylene flame or some similar source, we shall soon have a suitable standard for the photometry of the arc

ADJUSTMENT AND STANDARDIZATION OF APPARATUS.

For the photometric measurements, a Krüss-Bunsen photometer was used. The method adopted was the usual one of a swinging crane in connection with a 45° mirror. The total dis-

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[9] TRANSACTIONS, vi : 158, May, 1889.

tance between sources was 829 cm. The coefficient of reflection of the mirror was determined by the use of two glow lamps connected in multiple. The lamp nearest the mirror was mounted at the end of an arm capable of being swung through an angle of 90°, as indicated in Fig. 2. This arrangement maintains the same length of bar with and without the mirror—a fact which makes for simplicity in the calculations. For the coefficient of reflection the first values obtained by three different observers were:

H, .828 T, .826 M, .82

An inspection of the image of the arc in the mirror gave rise to the belief that the absorption of the luminous rays was in some degree selective—an undue proportion of the violet rays being taken up. Were this the case, the value of the coefficient determined by glow lamps would be incorrect for use with the arc itself. To test this matter, the electromotive force on the lamps was varied through a wide range and a determination made for each change. The values found were:

TABLE I.

Volts on Lamps.	Reflecting Power.
95	.824
105	.805
112	.785
117	.800
122	.783
127	.836
132	.808
137	.825

Although the change in the quality of the light was very marked in this experiment, the results do not indicate any regular change in the coefficient of reflection such as was looked for. Hence, in all subsequent measurements, the mean of these various determinations, namely .814, was used.

The standard source was a glow lamp; it was referred after each test to the Hefner lamp. Electrical measurements were made by various portable voltmeters, ammeters and wattmeters, all of which were repeatedly referred to Kelvin balances.

RESULTS ON THE ALTERNATING ARC.

A number of enclosed arc lamps, in their commercial form, were kindly placed at the disposal of the writers by their respective manufacturers. As this paper has no other object than to exhibit such features of the performance of these lamps as are largely typical, the trade names of the lamps are withheld.

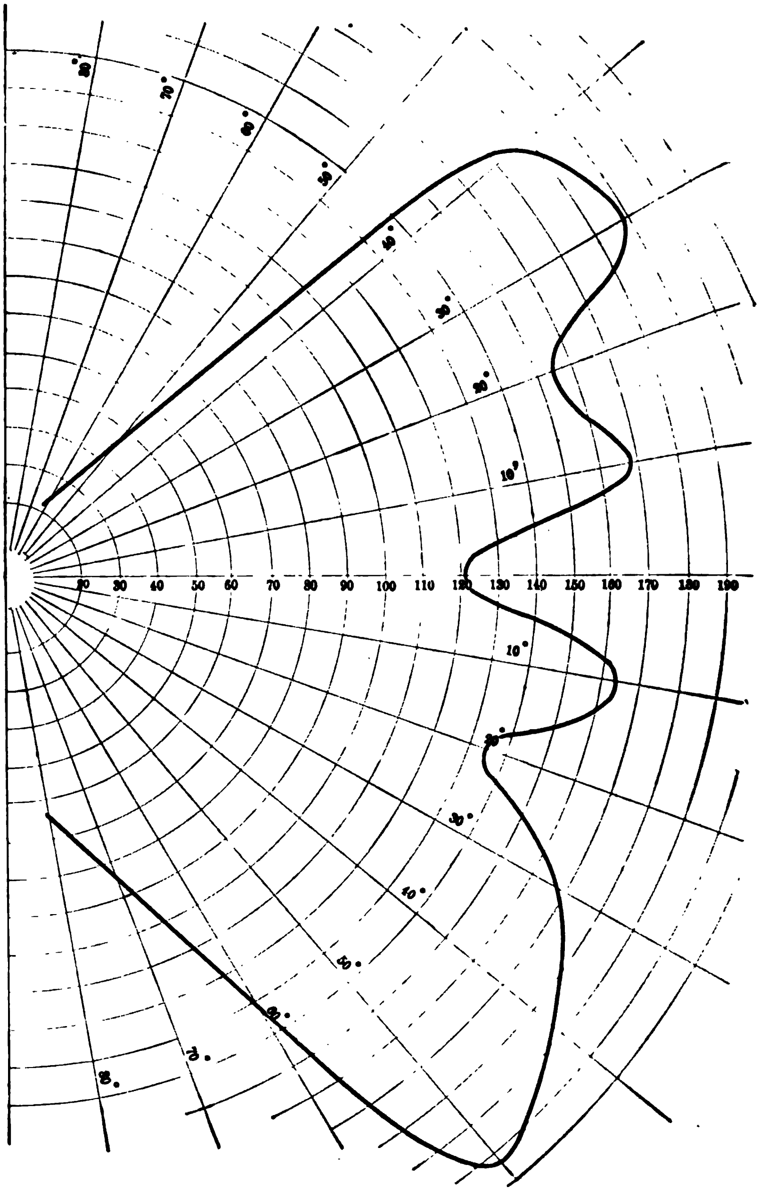

Fig. 3.—Distribution of Intensity. Lamp A.

For each position of the arc, no fewer than 44 photometric settings were recorded. It was found that this number was sufficient to include the maximum and minimum values, and a sufficient number of intermediate values to give a mean that could be reproduced quite closely at different times, thus showing the reliability of the method.

Lamp A.—The distribution of intensity from this lamp is shown in the polar diagram of Fig. 3; the figures for the curve are as follows:

TABLE II.

Angle.	Intensity.
0° horizontal	121.4 H. U.
10° above	169.0
20° "	155.0
30° "	189.0
40° "	176.0
50° "	46.5
60° "	22.4
10° below	164.5
20° "	184.7
30° "	167.4
40° "	187.5
50° "	203.0
60° "	130.5
70° "	82.6
80° "	64.0

The following is a summary of the results of the test of this lamp:

TABLE III.

Volts	103.2
Amperes	5.84
Apparent watts	602.
True watts	407.
Watts in mechanism	80.
Power factor	0.67
Maximum intensity	203.
Direction of maximum intensity	below 50°
" " " "	above 30°
Mean hemispherical intensity:	
Upper hemisphere	91.8
Lower hemisphere	129.1
Mean spherical intensity	110.5
Watts per mean spherical Hefner unit	3.68
Watts in arc per mean spherical H. U	2.96
Watts in arc	327.
Globes, character of	opalescent inner.
Carbons	½ inch "Electra."

The lamp was intended for an electromotive force of 104 volts, and the attempt was made to keep it at this pressure, but at the close of the test, the average electromotive force proved to be 103.2. The power factor is due to the inductance of the mechanism, as it has been clearly established by Blondel[10] that, in the arc itself, the electromotive force and current are strictly in phase. It is easy to confirm this fact by current, pressure and power readings taken with reference to the arc alone.

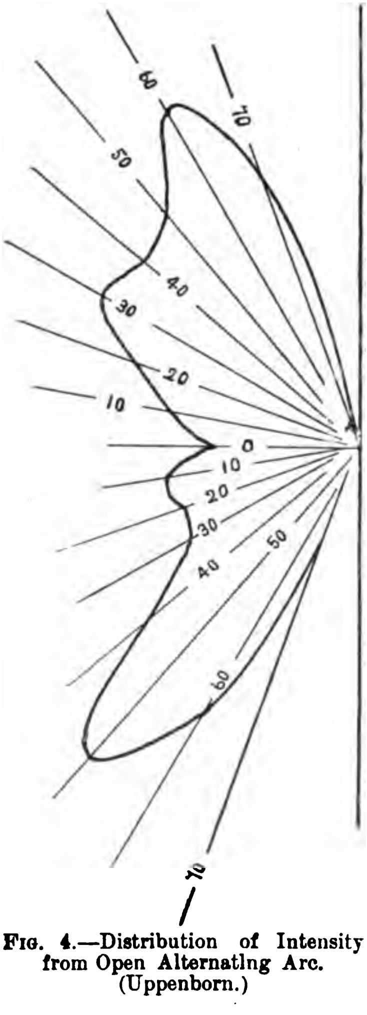

Fig. 4.—Distribution of Intensity from Open Alternating Arc. (Uppenborn.)

The upper and lower lobes of the distribution curve do not yield the same mean values. The discrepancy is due, no doubt, partly to the fact that the bulb about the arc is not of symmetrical curvature, and partly to the greater reflection from the parts of the lamp situated just above the arc. The shape of the distribution curve alters somewhat as the burning of the carbons progresses. The general shape of the curve is not far from that which has been obtained for the open arc. For comparison, one of the several curves taken by Uppenborn[11] for the open arc is here shown. (Fig. 4.) In the enclosed arc the lobes of the distribution curve are shorter, blunter, and extend outward at smaller angles with the horizontal. These changes are due to the shape of the carbon points. It may be pointed out that the distribution curve as plotted above, is a half-section

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[10] Blondel, *La Lumiere Electrique*, vol. 41, 1892.

[11] See Palaz, " Photométrie Industrielle " or translation by Patterson.

of the mean photometric surface, which is a surface of revolution. The actual photometric surface- so far from being a

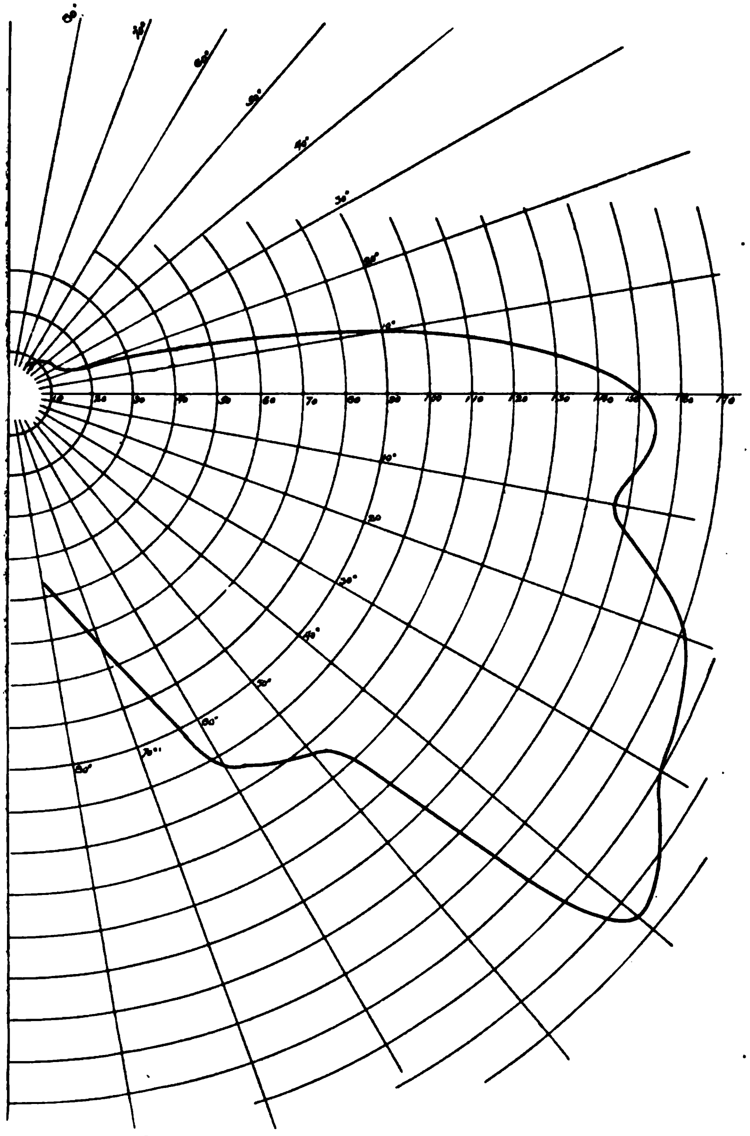

Fig. 5.—Distribution of Intensity. Lamp B.

surface of revolution—is continually swelling, contracting and twisting in a marvellous fashion. As to whether the light thown upward is of value, will depend on whether the lamp is suspended in the open air or under a reflecting ceiling. In most cases considerable benefit will be obtained by the use of a reflector, as is illustrated in the following figure.

Lamp B.—This lamp was provided with a bell-shaped reflector of milky glass. The effect of the reflector on the distribution curve is very noticeable, the upper lobe being largely removed. (Fig. 5.) The minimum corresponding to the horizontal is displaced downward by about 10 degrees. This peculiarity cannot be ascribed to the presence of the shade, as it was found in one or two cases where the lamps were fitted with inner globes only. It is quite surely due to the fact that the carbons so burn, that the planes of their ends, although parallel, are rarely normal to their axes. Thus in the case illustrated in Fig. 6, the minimum intensity might be found displaced either above or below the horizontal, according to the point of view.

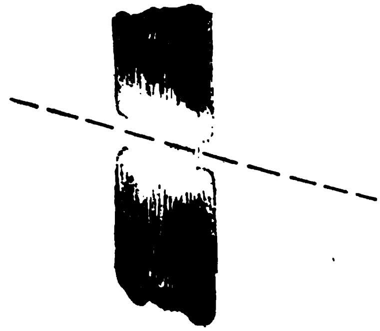

FIG 6.

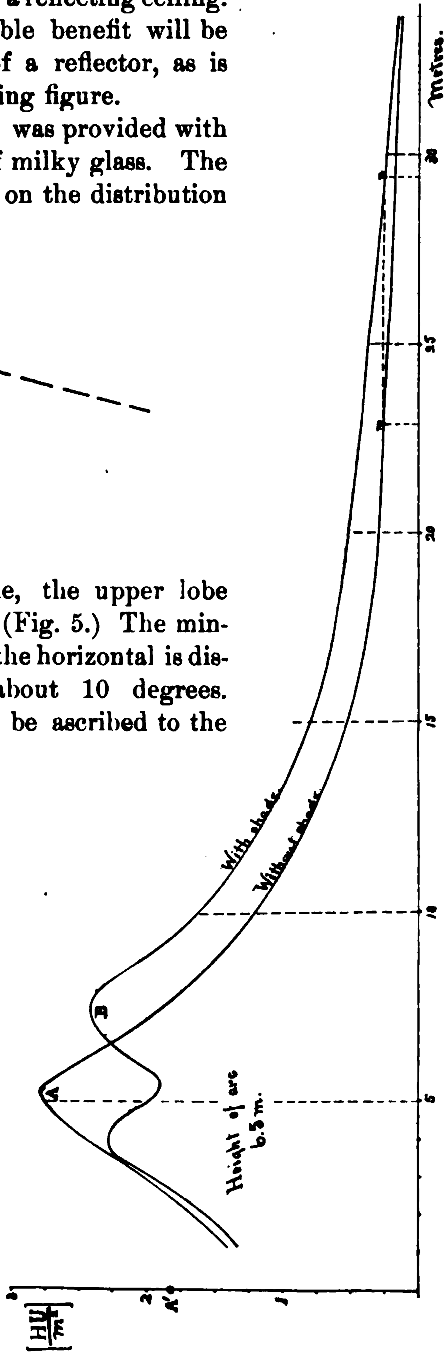

FIG. 7.—Comparison of Illumination on Normal Plane, With and Without Shade, Due to Lamps A and B.

TABLE IV.

Angle. Deg.		Intensity. H. U.
0	horizontal	150.0
10	above	90.8
20	"	18.4
30	"	12.8
40	"	11.5
50	"	9.8
60	"	8.4
10	below	146.5
20	"	171.5
30	"	180.0
40	"	196.0
50	"	112.0
60	"	102.7
70	"	65.4
80	"	46.5

That the effect of the shade is distinctly advantageous will be further evident if curves of illumination be considered. And here unfortunately we must resort to an approximation. Data was taken for an exact determination of the effect of the shade on lamp B, but owing to an accident the figures are not now available. However, certain assumptions permit us to draw a comparison in the following way: Let

I_a = mean intensity of B above the horizontal and without shade,
I_b = " " B below " " "
I_a' and I_b' be similar quantities as found for B with shade,
I'' = mean intensity of A below horizontal.

Let it be further assumed that 30 per cent. of I_a is absorbed by the shade. Now since the altered distribution from B is due wholly to the shade—the light incident upon the shade being partially reflected, partially transmitted and partially absorbed—we have, if $I_a = I_b$,

$$I_b = \frac{I_a' + I_b' + .3\,I_b}{2}.$$

$$= \frac{I_a' + I_b'}{1.7} = 112.2,$$

which is the mean hemispherical intensity of lamp B without shade. If now the radii of the curve B are multiplied by the ratio $I'' : I_b$, we shall have the effect of putting the shade on lamp A.

In plotting the illumination curves shown in Fig. 7, this last was done. Some difference of opinion exists as to whether the ordinates of a curve[12] like this should be the illumination on a surface normal to the ray or on a horizontal plane. In Fig. 7, the illumination on the normal plane has been used, as this quantity serves very well for the purpose of a comparison. It will be noted that the benefit resulting from the use of the shade is most marked at distances remote from the lamp, which is as it should be, since there is no lack of light in the vicinity of the lamp. The following table gives distances at which an equality of illumination will be found:

Unit of normal illumination.	Without shade. Metres.	With shade. Metres.
2.25	6.5	8.2
2.00	7.1	8.8
1.75	7.8	9.5
1.50	8.7	10.4
1.25	9.7	11.7
1.00	11.0	13.2
.75	12.7	15.5
·50	15.2	21.0
.25	22.9	29.4

Lamp C.—This lamp was provided with an outer spherical globe of milky glass. The data obtained for the distribution of intensity were as follows:

TABLE VI.

Angle. deg.	Without globe. H U.	With globe. H. U.
0 horizontal	132.0	37.2
10 above	137.0	42.8
20 "	158.0	42.7
30 "	122.0	38.4
40 "	85.0	28.7
50 "	30.4	17.4
60 "	18.0	7.7
10 below	126.0	36.1
20 "	133.8	32.6
30 "	140.7	31.4
40 "	117.0	30.0
50 "	120.0	28.2
60 "	90.0	30.7
70 "	68.0	29.8
80 "	47.5	24.7

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[12] It is probable that the unit of illumination most consistent with the C. G. S. system is $H.\ U.\ /\ cm.^2$. This unit is many times too large, however, and throws the numerical expression for an illumination far into the decimal places. The unit $H.\ U.\ /\ m.^2$, obtained by multiplying the first named unit by 10^{-4}, is preferable in this respect.

The foregoing values are plotted in Fig. 8. This distribution is in some respects anomalous. The larger area below the horizontal is due to the presence of a narrow reflector placed inside the outer globe. No reliable reason can be given for the presence of the maximum at 20 degrees above. It may be due to

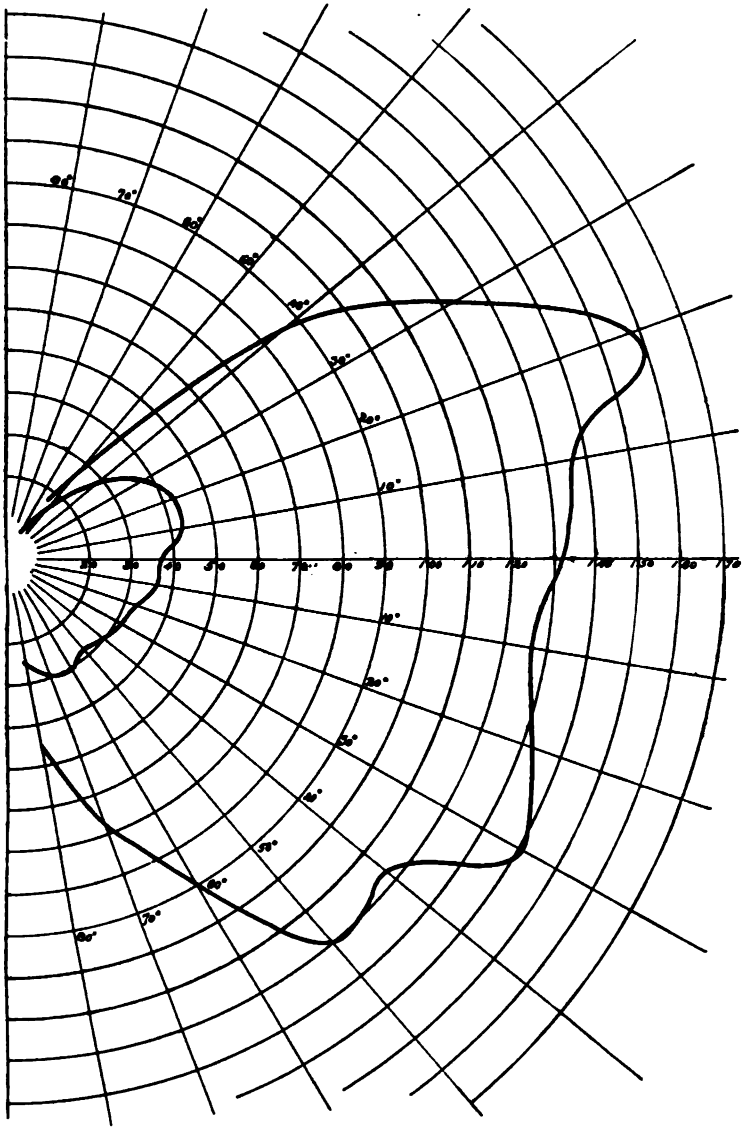


FIG. 8.—Distribution of Intensity. Lamp C.

some lack of accurate centering of the carbons. The peculiar shortening of the radii of the inner curve in the lower angles, baffled the observers for some time. It was finally found that the milky glass of the outer globe was much more dense in the lower hemisphere than in the upper, and the absorption was correspondingly greater.

It should be said in connection with the inner curve that the amount of light cut off was in reality not so great as the figure indicates. The dispersion is so great, with a globe of milky glass, that the globe plays a strong part as a radiant. Now, the mirror used was not sufficiently large to furnish rays on the photometer disk from all parts of the globe, and hence the lamp was not given quite full credit for what it was doing.

The results of the test of this lamp may be summarized as follows:

TABLE VII.

Volts	110.0
Amperes	7.0
Apparent watts	770.0
True watts	484.0
Watts in mechanism	116.0
Power factor	0.63
Maximum intensity	158.0
Mean hemispherical intensity :	
Upper hemisphere	68.5
Lower "	99.0
Mean spherical intensity	83.8
Watts per mean spherical H. U.	5.76
Watts in arc	364.0
Watts in arc per mean spherical H. U.	4.34
Globes, character of	opalescent inner.
Carbons	"Electra."

In the course of the measurements on this lamp, the terminal electromotive force was varied between the limits of 87 and 118 volts, and readings of intensity, power and current taken for each step. The results are plotted in Fig. 9. It will be noted that the power increases directly as the voltage; while the intensity is a rapidly increasing function of the voltage. The change in the current is slight. The high intensity at high voltage is partly due to the longer arc, but more especially to the higher temperature of the carbon points and consequent increased surface in the craters.

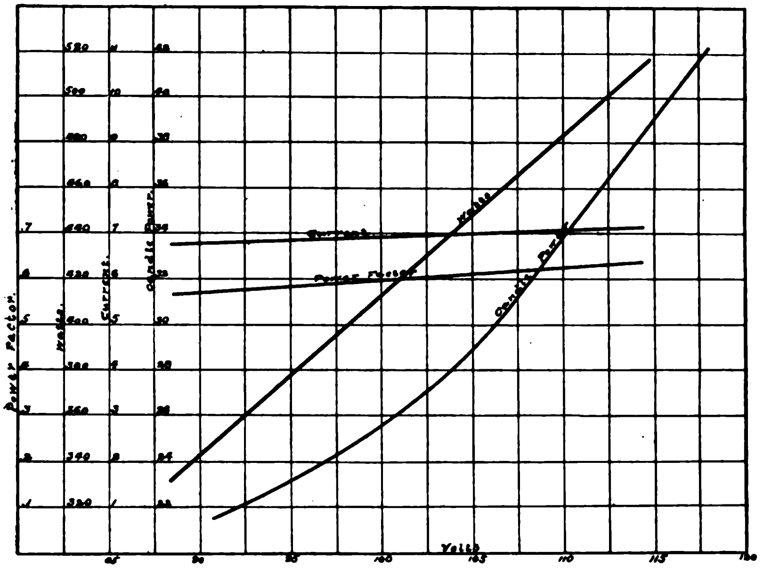


FIG. 9.—Effect of Varying Impressed Electromotive Force. Lamp C.

FLUCTUATIONS IN THE INTENSITY.

In Fig. 10 are shown the fluctuations in intensity which occur in the enclosed alternating arc. With the recording device already described, it is possible to get settings of fair accuracy

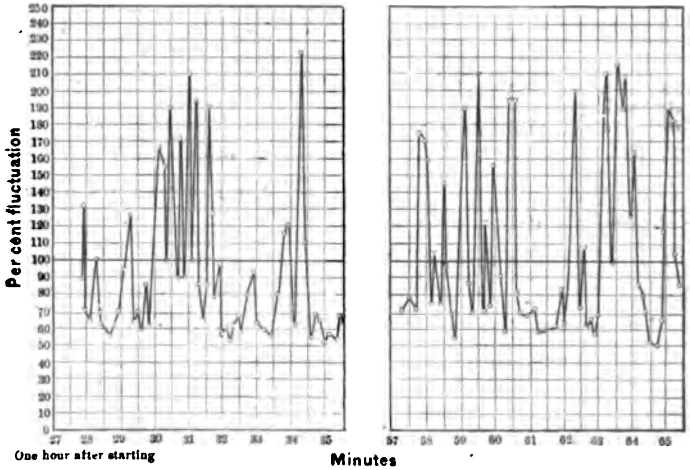


FIG. 10.

with a considerable degree of rapidity, as is here shown. The large changes in intensity are plainly noticeable in watching the arc, but the eye does not furnish an estimation of them comparable with that to be gained from the curves, for the psychophysical reason already referred to. It will be noted that the higher values shown in Fig. 10 are of more infrequent occurrence than the lower values. Indeed, it is only when the arc is towards the photometer and flaring out in the manner shown in Fig. 11, so that both craters are inclined towards the disk, that these extreme values are obtained, and then they last but an instant. For all other positions of the arc, whether on the sides or on the back, only the lower values are obtained.

Two causes, it was thought, might contribute to these fluctuations, namely, the changing length of the arc and the "wandering" character of it. To test this, the curve in Fig. 12 was taken with a fixed length of arc, the clutch being entirely out of action. The result plainly shows that the chief cause of the fluctuations is the hunting of the arc. While the intensity varies with the length of the arc, the motion of the carbons is so slight, in a well-regulated lamp, that it plays little if any part in causing the variations shown.

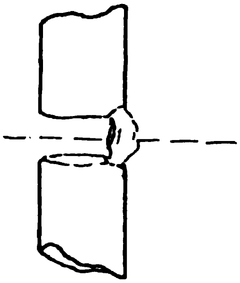


FIG. 11.

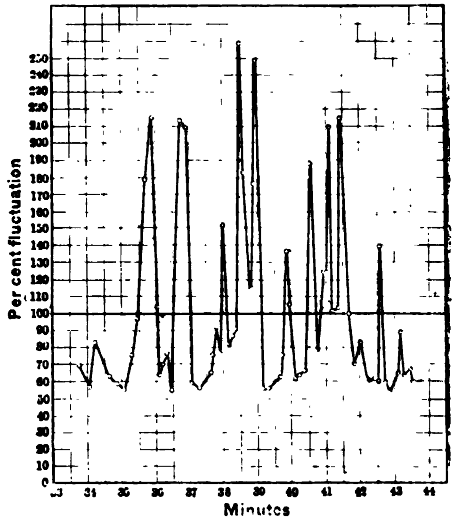


FIG. 12.

COMPARISON WITH THE ENCLOSED DIRECT-CURRENT ARC.

Lamp D.—Measurements were made on a direct-current lamp of the same manufacture as lamp A, with a view of bringing this type of lamp under conditions identical with those of the tests of the alternating arc. The lamp was fitted with an inner opalescent globe only. The distribution of intensity is as follows:

TABLE VIII.

Angle. Deg.	Intensity. H. U.
0 horizontal	218
10 above	165
20 "	237
30 "	159
40 "	144
50 "	121
60 "	60
10 below	410
20 "	391
30 "	341
40 "	377
50 "	369
60 "	416
70 "	172
80 "	106

In Fig. 13, these values will be found plotted in the usual manner. This curve was taken with great care and may be taken as typical of the distribution due to the enclosed arc fed by a direct current. The peak at 20 degrees above is due to the small crater of the negative carbon. Here also the depression in the curve due to the low luminosity of the arc is found displaced by 10 degrees above the horizontal. This lamp will give an excellent illumination at points somewhat remote, because the curve is so full in the region just below the horizontal. A shade would still further improve the lamp in this respect. Detailed results are given in the following table:

TABLE IX.

Volts	108.
Amperes	4.96
Watts	536.
Watts in mechanism	152.
Maximum intensity	416.
Mean hemispherical intensity:	
Upper hemisphere	106.5
Lower hemisphere	288.
Mean spherical intensity	197.3
Watts per mean spherical H. U	2.72
Watts in arc	384.
Watts in arc per mean spherical H. U	1.95
Globes	Opalescent inner
Carbons	"Electra."

As regards efficiency, or better *economy*, say in watts per Hefner unit, the direct current lamp is superior to its alternating current competitor. The performance of lamp A was the best found in these tests, that of lamp C the worst. The other lamps

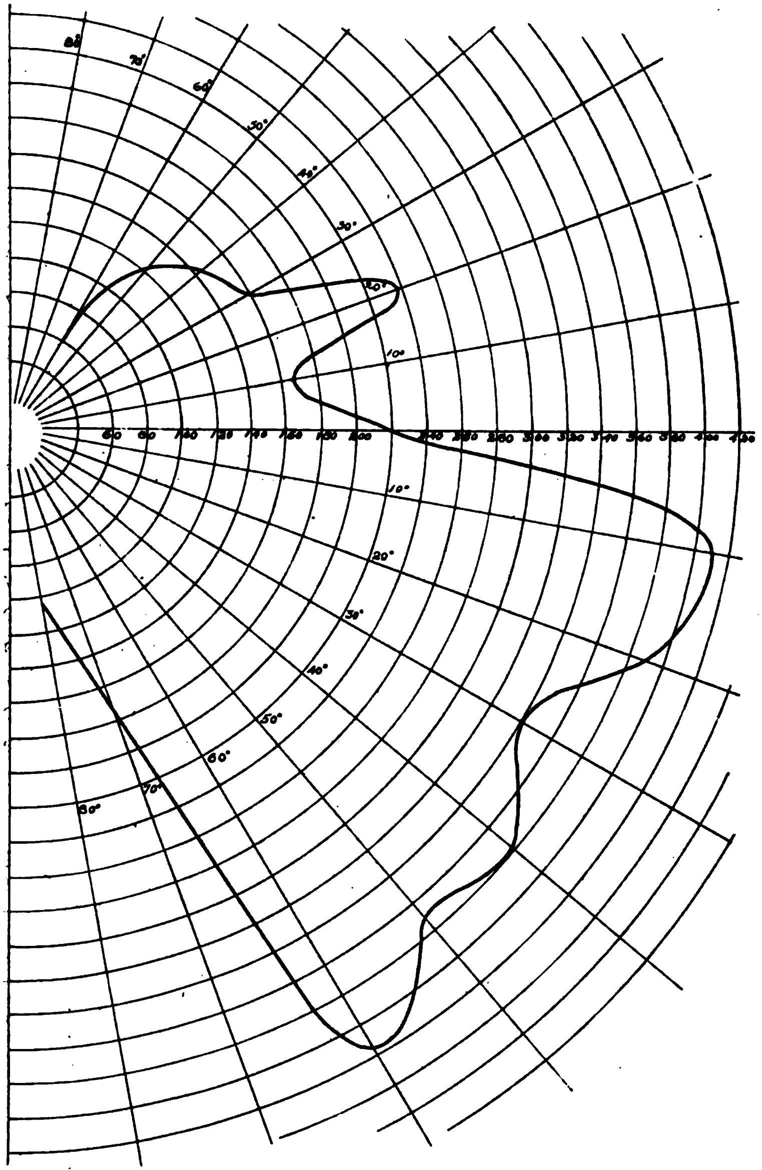


FIG. 18.—Distribution of Intensity. Lamp D. (Direct Current.)

tested showed different degrees of economy lying between the limits set by these two.

The writers feel justified in saying that the lamps of low economy could, by improvement in mechanism, be brought to a performance equal to that of lamp A. All the lamps tested, with one exception, were furnished with the same brand of carbons. With similar carbons and similar globes, a difference in economy must be attributed largely to the mechanism.

If the alternating arc be regarded apart from any regulating device, the physical reasons for its poorer qualities as a light source are to be found in the lower temperature of the glowing points and in the diminished area of crater surface. In the direct current arc, we find two bright surfaces of unequal area and of widely different temperature. In the alternating current arc we find two bright surfaces of the same area and of the same temperature. According to Rossetti, the temperatures in the first case are 3900 C. and 2700 C. Now the points in the alternating arc are as much positive as negative, and hence, whatever the unknown law connecting the temperature of glowing carbon with the intensity of the light due to it, we should expect the mean spherical intensity of the alternating arc to have a value intermediate between the values of mean hemispherical intensity for the upper and lower lobes of the distribution due to the direct current arc. A comparison of lamps A and D shows this point, although the total power is not the same. If the power consumption of the alternating arc were raised from 327 to 384, it is very probable that the mean intensity would be found raised from 110.5 to a considerably higher intermediate value.

The values of the intensity of the direct-current lamp are lower than those found by some earlier observers. In fact, the enclosed arc has been reported in some instances as quite equal to the average open arc. It is difficult to see how these results can be accurate for a lamp fitted with an opalescent globe. The results of a test recently reported by Nichols agree closely with those given for the direct current lamp in this paper.

Electrical Laboratory, Purdue University,
Lafayette, Ind., September, 1898.

DISCUSSION.

MR. LOUIS B. MARKS :—It is very seldom that one is treated to so concise and lucid a description of the limitations of arc-light photometry as is contained in this able paper by Messrs. Matthews, Thompson and Hilbish. For my part, I think that the first part of the paper, which goes into detail regarding photometry, is perhaps more important than the latter portion, which gives some measurements of the candle-power of the alternating current arc. So that I trust you will bear with me for a few moments while I consider what is said in the paper with relation to the photometry of the arc.

Prof. Matthews says that the first reason for the difficulty in determining the luminous yield of an arc, is the marked difference in quality between the light of the arc and that of the standard. This is perhaps one of the most important difficulties in arc-light photometry. We are apt to be confronted, as Prof. Matthews points out, with a difference of color between the arc-light and the standard. This makes it very difficult to set a photometer carriage properly so as to obtain the true relative candle-power of two sources of illumination which differ in color. You will notice that in this paper the Hefner amyl-acetate lamp is taken as the standard. The tinge of the flame of this lamp is quite reddish, whereas the tinge of the alternating current arc, as you all know, is decidedly violet; so that, strictly speaking, we are comparing a violet light with a light that is red in color. Comparative candle-power measurements of this kind are limited in value and are often misleading.

I find on page 580 the statement that "the inner, opalescent globe absorbs the rays of short wave-length in greatest proportion, a fact which brings the color of the arc nearer that of the standard."

Now, the question occurs to me, if we use such an opalescent globe, thereby altering the quality of the issuing light, are we obtaining a fair comparison between the candle-powers of the two lamps? The nature of the light is undoubtedly changed in passing through this tinted glass, so that the results will depend upon the composition of the glass of the enclosing bulb. There is also another question, namely, the amount of light cut off by this opalescent globe. I am not alluding to this now, but simply to the effect of the difference in quality of the light caused by the interposition of a glass globe absorbing a large percentage of the violet or shorter wave-lengths of light. Unless a clear glass globe be used, this modification in the character of the rays may considerably impair the value of the comparative measurements.

It is well known that light of one color impresses the eye with quite a different force than light of another color, and the intensity of the sensation—the physiological sensation—determines to a considerable extent the power of the light. I think that Helmholtz stated that the sensation was a function of the luminous intensity and varied with different kinds of light. Of two lights, one of which is rich in blue and the other rich in red, the sensation increases more rapidly for the red and decreases more rapidly for the blue for the same range of luminous intensity. In order to make this a little clearer, suppose we have two lights, one of which is rich in the shorter wave lengths of the spectrum, and the other of which is rich in the longer wave lengths. Now, suppose these lights have the same candle-power exactly. If we then simultaneously double the quantity of light thrown by each on the photometer screen, we will find that the yellow light or the red light, as the case may be—the light of longer wave-length—will appear brighter than the light of the shorter wave-length. Whereas, if you then suddenly decrease the quantity of light in each case, you will find that the light of the shorter wave-length, that is the blue light, will appear brighter than the yellow light. Now, here is a condition of affairs that depends, it appears, on physiological causes, and is not taken into consideration by the photometer in the measurement of the power of a source of illumination. I lay stress on these points because in interpreting the figures given by the authors of this paper, we must bear in mind that, although the readings have been undoubtedly most carefully taken, the candle.power measurements, which at best can have but a relative value, are subject to numerous limitations.

On page 580, near the bottom, the authors refer to the second obstacle to careful measurement, namely, the variability of the quantity to be measured. "These variations," they say, "are largely due to the wandering condition of the arc—a peculiarity that is especially noticeable in the open alternating arc, and in both types of the enclosed arc." And then they add, "Indeed, it is to this feature of the enclosed arc that the flat-ended carbons are due." Now, is it not just the other way? Is not this feature of the enclosed arc due, if anything, to the flat-ended carbons? The flattening of the carbon ends is due, not to the wandering of the arc, but to the absence or partial absence of oxygen in the enclosing bulb. When the carbons are enclosed, the oxygen is excluded, or has very limited access, and the tips of the carbons are no longer subject to the same conditions of oxidation as exist in the ordinary arc which burns in free air. Hence, the carbon ends become blunt or flattened. The arc being quite small in cross-section and tending to lengthen as the carbons burn away, seeks the path of least resistance, and so gradually travels over the surface of the carbon ends. This wandering, or "hunting" as it is sometimes termed, continues as long as the lamp is in action, and appears to be primarily brought about by the flattening of the carbon ends.

On page 581 is mentioned a new instrument which I think will be a boon to all those who have use for a photometer. The mechanical device designed by Prof. Matthews for recording a setting as soon as it is made, will enable us to take quick and accurate readings. Many of us who have experienced the visual fatigue incident to the use of a light in the photometer room, will give a hearty welcome to this new device. Prof. Matthews is to be congratulated on the invention of this simple and ingenious arrangement, which I trust will quickly find its way into photometer rooms throughout the country.

The third point mentioned is the question of the validity of the term "candle-power." Although I do not intend to take up your time now with a discussion on this particular point, I trust that others who have gone into it more fully than myself will expand on what is said here especially in relation to the term *luminosity* as compared with candle-power. This question is of great importance. It is safe to say that no measurement of candle-power *per se* can give us a complete expression of the true illuminating power. One light may have as much candle-power so-called as as another, and have a much smaller illuminating power. I think the question referred to here, on page 582, is one which should command our serious attention.

In making their measurements the authors used a Kruss-Bunsen photometer and a swinging crane in connection with a 45 degree mirror. I have made use of this particular arrangement quite often, and it has occurred to me that possibly there is such a thing as selective absorption in the mirror. The authors employ glow lamps in determining the reflecting power of the mirror. In order to get a correct value of the coefficient of reflection they operate the incandescent lamps at 95 volts, at 105 volts, and so on up to 137 volts. They state that "although the change in the quality of the light was very marked in this experiment, the results do not indicate any regular change in the coefficient of reflection." Their maximum value for this coefficient is .836; their minimum, .782, making a difference of about 5% in the reflecting power of the mirror. Although they do not find the value of the coefficient to follow any regular law with the increase in temperature in the filaments, the authors may not be justified in taking the mean of these various determinations as a fair value of the coefficient of reflection for the arc. Have you ever noticed an enclosed arc lamp, especially an enclosed alternating arc with clear outer globe, on the street in front of a show-window? At night when the current is on, if you look at the lamp the small opalescent globe appears to be filled with a soft white light; but if you observe the reflection in the window-glass, the small globe seems to emit a strong violet light. Now the authors noted the same phenomenon when they lit their arc and looked into the mirror mounted on their photometer. But they probably erred in assuming that measurements of selective absorption based on the reflection of an incandescent filament at high temperature, will hold for the arc.

As to the candle-power measurements given for the alternating current arc I shall have very little to say just now. I note that the curves of distribution are carefully worked out; that they have all the kinks with which we are more or less familiar, due to reflection of the light, to the shape of bulbs, to the inequalities in the glass, to the distortion of the plane of the carbon ends, etc., etc.

I also note, and I call your attention to this point, that the authors have, I believe, taken all their candle-power measurements for small opalescent globes. They have not given us any measurements with small clear globes in their lamps. So in comparing the results of the authors and those of other experimenters, it is well to bear in mind that there may be a difference of perhaps 30 per cent or even more between these candle-power values and those given in tests of lamps in which the small globes are clear.

I notice that the authors refer to some tests by Dr. Nichols. As far as I can remember, Dr. Nichols used clear globes in all of the tests that he has published on standard lamps,—at least all that I have seen. The difference in density in the case of opal or opalescent glass globes is very marked, and those who have used enclosed alternating arc lamps much will know that some of the small globes are very dense indeed and cut off as much as 50 per cent of the light. I do not know just what percentage of light is cut off by the globes that the authors used. They do not mention this in their paper, and consequently we are left in the dark as to quite a vital point.

As far as the ultimate results are concerned, that is, the actual efficiency of an enclosed alternating arc as compared with a direct, I find that they give for lamp A, alternating current type, the curve of which is on page 584, and the data on page 585, 2.96 watts at the arc per mean spherical Hefner unit; and for lamp D, which is the direct current lamp, supposed to be a typical lamp, data on page 595 and curve on page 596, 1.95 watts at the arc per mean spherical Hefner unit. Thus there appears to be a difference in candle-power output of over 50 per cent. in favor of the direct current lamp. But unfortunately the authors took two lamps whose power at the arc was different. The alternating lamp consumed less power at the arc than the direct. If both lamps consumed the same power at the arc, it is probable that the difference in favor of the direct current lamp would fall to 35 per cent. or less.

I intended to make a few remarks regarding some other parts of the paper. But I am aware that there are others who have something to say and shall therefore close my discussion at least for the present. I thank you very much for your kind attention.

Mr. W. H. Freedman:—Mr. Marks, in his very able discussion of this paper, has left very little to be said. I will, however, add a few remarks, and try not to repeat anything that he has alluded to, except the one point in regard to the hunting of the arc. Now, it seems to me that if the oxygen were excluded from an arc so that the carbon could not go off in carbon mon-oxide and di-oxide vapors, the ends would be flat, and in the open arc they assume that more conical shape on account of this oxidation of the carbon. Accordingly, it seems to me that on account of their being flat, as the carbon is vaporized, a little pocket tends to form, and so increases the distance; therefore, it will require more energy to keep up the arc between those two points, and consequently, due to the resulting stresses, the arc wanders to a place where less energy will maintain it. Nature is rather lazy, and all operations go on with the least expenditure of energy. Therefore, this arc wanders so as to always keep up its luminosity and burning, if I may use the word, with the least expenditure of energy. So, in my opinion, that criticism is rather correct, and instead of the flat carbons being due to the wandering, it is exactly the opposite—that on account of the carbons being flat the arc wanders around and so adds to the troubles of the photometrist who is trying to determine its candle-power.

On page 586 the authors make the statement that "the power factor is due to the inductance of the mechanism, as it has been clearly established by Blondel that in the arc itself the electromotive force and current are strictly in phase." Without laying any stress on the use of the word electromotive force, it is perfectly true that the difference of potential between the carbons of the arc is zero when the current through the arc is zero in the case of an alternating arc which is used for illumination, or I should more properly say a self-regulating arc. But I think that statement ought to be somewhat qualified, because if you take an alternating current arc and clamp it rigidly and work it by a hand feed, if there is no self-induction in the current, then that statement is not true, and the current has rather gaps of zero value. It does not pass through zero at a point; it has a zero value for quite an appreciable period of time, so that there is a zero line in the current. That being the case, there is a power factor in the arc which is slightly different from the power factor in a simple alternating power circuit, in that we cannot strictly say there is a phase between the electromotive force and the current, but on account of the current not following the sine law, we will find that taking voltmeter and ammeter readings and multiplying the two together, the apparent watts are a great deal larger than the readings of the wattmeter, and we have a power factor in this kind of an arc. So unless that statement is qualified it seems to me it is erroneous to state that the power factor is entirely due to the mechanism of the lamp. There is no doubt that the self-induction in the lamp causes the phase of the current, but unless that happens to be exactly balanced with respect to the distance, etc., the arc might not go through the zero values at a point, and if that is the case, then the total power factor is due partly to the mechanism and partly to the shape of the current wave in the arc.

Now, coming to the measurements of the candle-power, personally, not being an enthusiast on photometry, I think that it adds slightly to the complication of photometric measurements for everybody to use their own units, and it seems to me, as far as engineers are concerned, it is usual to speak of candle-power. I am willing to confess that I had to look up what the value of the Hefner unit was before I could compare this paper with any other published results which heretofore have always appeared in candle-power. If I remember correctly, Dr. Nichols, of Cornell University, said that the best way to measure candle-power, the most certain way, is to use the Hefner unit, which is 88 per cent. of the British candle. If we forget that number, however, we are somewhat at sea in comparing different papers.

Then when it comes to the measurement itself, Mr. Marks has already pointed out that although carefully made, the results are not absolute, as one curve presented by the authors themselves shows—the curve on page 591. They present a lamp. c, with and without a milky globe. When they put the milky globe on, they of course get the smaller distribution of luminous intensity, but, strange to say, the upper portion seems to be of the greater candle-power or Hefner unit, and they advance the explanation, which is undoubtedly correct, that the lower half is of less intensity on account of the absorption of the globe. That in itself must bring to mind the fact that if we change the globe we are going to get an entirely different distribution. The distribution which they present on page 596 for a normal direct current lamp is one which is entirely different from any that were obtained at Columbia University—that being another argument or another evidence to show that the globes which were used in each case were different, and the difference in the form of the curve being, no doubt, largely due to that fact. I also think that the curve on page 586, perhaps by some inadvertence of the printer, has become reversed. The curve given by Uppenborn shows the greater area on the top. I think that the greater luminous intensity must be at the bottom and not at the top. So those butterfly wings ought to be inverted.

I will close by merely stating that, so far as I know, these are the first results and figures that have been published on the alternating current arc with respect to its distribution of luminous intensity, and from that standpoint, bearing in mind the photometric limitations, I consider the paper rather valuable as being an addition to the data available to an engineer.

The President:—I understand that we have Captain John Millis, of the Lighthouse Board, with us this evening. If so, I should be pleased to hear from him upon his aspect of this subject.

Captain Millis:—Mr. President, I am somewhat disappointed at being discovered, since I would have preferred to be only an interested listener in an obscure corner. There is very little that I can add to what has already been said on this subject, but possibly I may submit one or two remarks presently. I should like very much to ask the gentleman who first addressed us to give us a somewhat more explicit idea as to what he means when he says that one light may have a greater candle-power than another, but a less luminous intensity. I do not understand exactly what he means, and I should be very glad if he could make this a little clearer.

MR. MARKS:—I think that possibly in a few words I may be able to give my view of the matter. The candle-power of an arc, as I understand it, simply represents its power as compared with a standard source of light known as the candle. For instance, we have an ordinary standard candle. It burns 120 grains in an hour, or given standard time. We compare an incandescent lamp with that candle, and by the aid of the photometer obtain a ratio representing the illuminating power of the incandescent lamp in terms of the candle. From that we get the power of the arc lamp. Supposing the power of the arc lamp thus photometrically measured is 400, this would indicate that it has 400 times the illuminating power of the candle which was used as the source of the comparison. Now let us take the arc light and put it in a reading-room, and read by it. Then let us take it and put it in the fields and distinguish the color of the trees and natural objects by it. I ask you, will the true illuminating power of that arc lamp be 400 in both cases? I also ask you, will the illuminating power of an arc lamp not depend upon the use to which the light is put? Will it not depend upon its power of bringing out the true colors of objects, as well as of aiding the eye in seeing and distinguishing objects? I say that the illuminating power of a lamp depends largely upon the quality of the light. And the quality will depend upon the proportion of rays of short wave-length and of long-wave length in the light. In some cases, as in bringing out the colors of natural objects, and so on, the proportion of shorter wave-lengths in the light is all-important; while as far as the power of illumination as applied simply to black and white is concerned, the importance of the longer wave-lengths is paramount.

Now in the production of *candle-power*, the various rays of the spectrum do not count in proportion to their energy; the influence of the shorter or more refrangible rays is much less than that of the longer wave-lengths Indeed some of the rays of short wave-length, at the extreme violet end of the spectrum, do not enter to any appreciable extent into the production of candle-power; yet these very rays often constitute a most important factor in the illuminating power of an arc light. This is what I mean when I say that the candle-power of an arc is not a measure of its illuminating power and that one lamp may have as much candle power as another and yet have a much smaller illuminating power. As Dr. Nichols pointed out in a paper before this INSTITUTE in 1889, candle-power is a well-nigh meaningless term and may give us a very misleading value of the power of illumination of a light. He records a number of tests which prove quite conclusively that even though two lights have the same candle power, the illuminating power of one may be widely different from that of the other. The reasons for this difference have already been given. I do not know whether I have gone into the matter too much at length or not, or whether I have made myself clear; but I shall ask the President, Dr. Kennelly, whether I have explained to his satisfaction why it is that one lamp may have more illuminating power than another without having more candle-power.

THE PRESIDENT:—I think we all understand Mr. Marks as to his meaning of the terms. These terms are unfortunately given so many different meanings by different men that it is quite easy to misinterpret them until they are explained.

CAPTAIN MILLIS:—The gentleman has referred to exactly the point that I was going to speak about. I think, however, that he gives us a somewhat incorrect impression in passing from something which we regard as the measurement of the power or intensity of a light, in a physical sense, to something which is rather a question of judgment, of individual preference, or of adaptability to the conditions, and I must still differ with him in his view that we can properly say that a light which has a greater candle-power than another may have a less luminous power. Both terms imply a measurement which requires a unit in determining the candle power, but for luminous power, as the gentleman has just explained the term, I do not understand that any fixed unit or standard is possible. These considerations suggest the fundamental question of the real basis of all so-called photometry. Is it strictly correct to say that photometry as generally practiced is a physical measurement at all, or does it consist merely in approximate comparisons and attempts to express in figures something which cannot be properly so expressed in a mathematical sense? I think we all remember having learned, in the days of our elementary education, that the measurement or the expression of the value of any quantity was the numerical equivalent of that quantity as compared to a fixed quantity of the same kind which was taken as the unit. That may not be exactly the correct wording, but you get the idea. Now, when we attempt to express the intensity of a light and say that it is so much candle-power, it is not a physical expression of its value in all cases, because the standard is not a quantity of the same kind or quality. Anybody who has had experience in a photometer room knows that it is possible to arrive at an approximate idea of the relative luminous intensities of two lights, whether these lights are of the same color or not. In fact, many of you, perhaps, have attempted, as I have, to compare a white light with a red one. It is entirely possible to put the movable box containing the translucent screen near enough to the red light so that you can say that the side of the screen illuminated by that light is brighter than the other side illuminated by the white light. Similarly, the box could be placed so that the side of the screen towards the white light is unmistakably the brighter, but when an attempt is made to place the box at a point where the two sides of the screen are equally illuminated, difficulties arise, and only an approximate result can be expected at best. It is very largely so in all photometric comparisons that I have had experience with, except, of course, in comparing two lights that were absolutely of the same quality.

The method of measurement to be used, and the conclusions reached, may be materially affected by the particular use that the light is to be applied to. To illustrate by an extreme case, in the Lighthouse Service the vital question is: How far can a light be seen if you are looking at it directly? While in ordinary cases of artificial illumination the question almost invariably is: To what extent will the light enable you to see other objects? If we wish to determine the power or intensity of a light in the sense of how far it can be seen, a practical way to make a comparison with a standard is to put the standard and the light to be measured where they can both be seen from a distance, and go off until first one and then the other have disappeared. It is perfectly easy to understand that the distance at which the lights disappear respectively enable us to determine their relative intensities. Now, if we have two sources of light, for instance, two candles placed a few feet apart so they will not blend, you cannot see the two candles any farther than you can see one; but if you are near the candles and hold a sheet of paper so that both will illuminate the paper, you have got twice the illumination with the two candles that you would have with one candle. For one purpose two candles are twice as good as one, and for the other purpose one is just as good as two.

I wish to endorse what the gentleman said with reference to the recording apparatus. I think that is something we all wish we had thought of ourselves. I know I have felt the need of it a great many times, and I should think it would be very useful, and would expedite photometric work to a notable degree. I notice the author does not say what sort of scale he uses in deducing the results from the recorded observations. Ordinarily, if used with a photometric bar of a fixed length I should think it would be of great convenience to use a scale graduated as photometric bars frequently are, for a fixed distance between two sources, so that the record would give directly the relative intensity of the two lights. I have found, however, in experimenting with lights of a variety of intensities, that bars of various lengths are required, and that it is more generally convenient to use an ordinary scale of equal parts, as inches and tenths, and make calculations from the readings, although it is somewhat more tedious.

With reference to photometer rooms in general, there is a suggestion which I desire to make as the result of my experience. I think it is a mistake to paint the inside of the photometer room entirely black. It is a very great convenience, in the handling and adjustment of apparatus, etc., to have as much of the interior of the room white, or at least light in color, as you possibly can. If the end walls and the ceiling and floor are black, and adjustable screens are used to cut off the light from sources which are liable to cause interference with your measurements, it will be possible to have the side walls, or a considerable portion of them, light in color.

With the alternating enclosed lamp described in the paper I have had no experience, but I have had considerable experience with the alternating lamp which is not enclosed. With cored carbons, using proper material for the core, I have failed to find the wandering of the arc that the author refers to. I have found the lamp to burn very steadily and very satisfactorily if the proper quality of carbon, of uniform density, and having a core of proper material, is used.

There was one more point that occurred to me. It seems that the lamp described, giving such extremely variable results with a wandering arc, is a very unsatisfactory light machine, and before I should go into very great refinements of measurement to determine what the candle power of the lamp is, I think I should try to devise something to make it give some approach to a fixed candle power, even if the average were somewhat less than the results it gives now. This lamp certainly appears to be open to considerable improvement.

The President (Dr. Kennelly):—I think we are indebted to the authors for giving us some measurements upon the alternating current arc lamp which have been badly needed, since the only measurements which have been available hitherto have been for the direct-current arc lamp. I think we are also indebted to them for giving us their measurements in units that we can understand. When we speak about British candles we are often in doubt as to how the candles were obtained, how the measurement was made, and whether the British candles were evaluated from Hefner units by process of calculation. Whereas, by giving the results in Hefner units directly, we know that a definite instrument was employed, which is the most satisfactory that has been obtained up to this time. The results show, as pointed out by preceding speakers, how very indefinite and unreliable the photometry of an enclosed arc is from the engineering point of view. You have a source of light varying with the distance between the carbons and with the current strength supplied to them, with the nature and quality of the carbons, and their distance apart, with the angle of depression or elevation, and also with the particular quality, shape and dimensions of the enclosing globe. So that you have at least two more variables in this kind of lamp than you have in the ordinary alternating arc lamp, non-enclosed. We know how difficult it is with the ordinary alternating arc or continuous arc, to get steady readings or reliable measurements, and the difficulties are therefore augmented in this case. The fact is that until the absorption of the interior globe is taken into account, it is almost impossible to get a fair criterion of the luminous power of the arc within, so much is apt to be absorbed by the opalescent or semi-transparent globe.

I think that we are apt, as engineers, to forget that arc lamps are not employed, as a rule, by engineers, and that their quality and capability are not always to be determined by the methods which we are wont to employ. We set up an arc lamp in a photometer, measure its candle-power in various directions, compute, it may be, its spherical candle-power, compute its economy or efficiency, or inefficiency, as shown in these tables, and then we decide that one lamp is better than another because it is more efficient, or because it gives more candle-power than another; whereas the ordinary individual who uses an arc lamp and who purchases it is not guided very much by such measurements. At a given cost price he is guided by the appearance of the lamp and by its steadiness, by its freedom from noise, and the length of time it will go without re-carboning. His eye gives him very little intimation as to the real candle-power. If he sees a nice opalescent globe around it and it gives a nice, diffused light, he is very apt to consider that that lamp is much superior to one which an engineer may tell him is much more economical as a luminous source.

As regards measurement of candle-power of arc lamps, I think that from the engineering point of view, the only fair criterion is the mean spherical candle-power, if only for the reason that the individual candle-power in any particular direction of luminous intensity, at any particular angle or azimuth, is so variable with time; and these wide variations which are shown in Figures 10 and 12, as are pointed out in the paper, are not so much variation of the lamp as a whole, as merely variations in one particular direction, namely that, of the photometer screen.

We have been able to measure the spherical candle-power of an arc lamp by placing a mirror outside the arc and nearly over it, and spinning that mirror at about 400 revolutions a minute in a circle about four feet in diameter around the arc, throwing the light into a second mirror at the axis, and through a tube to the photometer screen. It is not sufficient to merely employ a revolving mirror, because you must cut off the light at different azimuths according to a sine law, and you must have, therefore, a sinusoidal shutter to open the light to full candle-power at horizontal and gradually cut off the light as you bring the mirror either below or above. By that means you can get a closely reliable reading of the spherical candle-power in any particular vertical plane, and by slowly spinning the arc lamp upon its own centre, so as to turn successively in all directions, the effect of the combination of revolving the mirror in the vertical plane and revolving the lamp in the horizontal plane, gives you a very close approximation, indeed, at any particular moment to the spherical candle-power in all directions.

[Adjourned.]

DIED.

DAVENPORT:—At Ponce, Puerto Rico, October 26th, 1898, Clarence G. Davenport, formerly Expert and Agent, for the General Electric Co., at the New York offices of the company, No. 44 Broad Street. He was a son of Rev. John G. Davenport, of Waterbury, Conn., and had been in the employ of the General Electric Company for eight years. He enlisted in the 1st Regiment U. S. V. Engineers, and accompanied that regiment to Puerto Rico where he contracted typhoid fever which was the cause of his death. He was elected an Associate Member of the INSTITUTE Nov. 21, 1894.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

New York, October 26th, 1898.

The 128th meeting of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS was held at 12 West 31st Street this date and was called to order by President Kennelly, at 8.10 P. M.

THE SECRETARY:—At the meeting of the Executive Committee this afternoon, the following associate members were elected:

Name.	Address.	Endorsed by
MURPHY, JOHN MCL.	Electrical Engineer, Safety Third Rail Electric Co., 5 Beekman St., Room 233 N. Y.	G. T. Hanchett. E. V. Baillard. Ralph W. Pope.
VREELAND, F. K.	2nd Ass't. Engineer, Crocker-Wheeler Electric Co., residence, 228 Orange Road, Montclair, N. J.	Henry Morton. F. B. Crocker. Gano S. Dunn.
WOODBRIDGE, J. E.	Editor *Electrical World* 9 Murray Street, N. Y.	T. R. Taltavall. A. E. Kennelly. Townsend Wolcott

Total 3

The following associate members were transferred to full membership:

Approved by Board of Examiners, Sept. 22d, 1898.

C. H. WORDINGHAM	City Electrical Engineer, Manchester, England.
WILLIAM STANLEY,	Electrical Engineer and Inventor, Pittsfield, Mass.

In the President's Inaugural Address at Omaha, a recommendation was made by him that the INSTITUTE undertake to bring about a plan of cooperation with the various colleges in regard to experimental research work. In accordance with that recommendation, the Council passed a resolution that a committee of seven should be appointed, and the President will inform you as to the action that was taken by that Committee to-day, and the progress of the work.

THE PRESIDENT:—I may say that the Committee has held its first meeting and a circular letter is being prepared to send to the various technical colleges and laboratories throughout the country, inviting their cooperation with the INSTITUTE, and submitting to them a list of problems in connection with practical subjects upon which measurements, observations and data are required. Sufficient encouragement has already been received from a number of college laboratories, to ensure the initiation of this movement, and it is hoped that all the principal technical institutions will take the matter up. The plan presents advantages to all parties concerned. The instructors receive information as to the practical work calling for observation and measurement from those engaged in electrical engineering. The students are stimulated to their best efforts by feeling that the work upon which they are engaged is of direct practical application. The INSTITUTE gains by the publication of the results obtained, as well as by the reception of material for good papers. It is not expected that the results of such investigations should be published exclusively or voluminously in the TRANSACTIONS. The main results of each investigation with the names of those engaged upon it, would be, as a general rule, all that the members of the INSTITUTE desire to obtain. In this way no extra expense is attached either to the INSTITUTE or to the technical colleges engaged in the experimental work.

It is desirable that the members of the INSTITUTE should communicate to the Secretary such problems as may arise in their practical work and which call for experimental investigation. The Committee would receive these suggested problems and add them to the list of material for investigation.

The paper before the meeting this evening is "An Electrical Survey in the Borough of Manhattan, New York City," and Mr. Knudson will now read it to us.

A Paper presented at the 128th Meeting of the American Institute of Electrical Engineers, New York, October 26th, 1898, President Kennelly in the Chair.

AN ELECTRICAL SURVEY IN THE BOROUGH OF MANHATTAN, NEW YORK CITY,

SHOWING RESULTS OF STRAY CURRENT MEASUREMENTS BETWEEN ELECTRIC RAILWAYS, UNDERGROUND PIPES, ETC., ALSO RESULTS OF TESTS ON THE BROOKLYN BRIDGE.

BY A. A. KNUDSON.

The corrosive effect of straying currents upon underground metallic structures is now so well known and understood that obviously there is no need to dwell upon this fact as a reality, but rather it is the purpose of the author to show from actual tests, some of the locations and characteristics of the stray currents in New York city.

About eighteen months ago the question was raised by some of the municipal officers of this city as to the possibility of electric currents leaking or straying to underground pipes from the conductors of the "open conduit" electric railway on Lenox avenue, and adjoining streets at that time, as applications had been made to extend this system.

This matter was investigated at that time by the author, and some of the results becoming known to one of the officers of this INSTITUTE, he suggested that with some additional tests and the whole presented in a paper, it would prove of interest to the members and perhaps throw further light on this interesting subject.

I have since made a number of additional tests throughout the city, from Harlem river to the Battery, between various metallic structures such as "L" (Elevated railway) pillars, surface railways, water pipes, etc., and give the results here, trusting that they may prove acceptable, and possibly of some value.

Previous to making any tests on the Lenox avenue line, we had a well settled theory that in a double conductor system as this is, very little, if any of the current could be found diverted from the conductors to water or other pipes underground in its vicinity.

The tests were begun on Lenox avenue near the Metropolitan company's 146th street power-station, and continued south. From the first, unmistakable signs were encountered of railway current leakage from the rails of this road to both water and gas pipes, the sudden fluctuation of the voltmeter needle proving this beyond a doubt. It was noticed, however, that when a Lenox avenue car passed, there was no advance of the needle as should be expected, and when two cars passed, going in opposite directions, there was no advance of the needle at the moment; continuing down the street and testing at each fire hydrant and gas post the voltage tended to increase upon nearing 135th street. The readings during these tests were as follows, the rails being positive to the water and gas pipes.

Location.	Water.	Gas.	Remarks.
145th Street	⅛ volt	⅛ volt	
138th "	⅔ "	⅙ "	
136th "	⅔ "	⅔ "	
135th "	1/5 "	1/5 "	During this test no trolley car in sight on 135th street
135th "	⅔ "		Test repeated when the 135th street overhead trolley car crossed Lenox avenue tracks.
125th "	½ "		
116th "	⅓ "		
109th " and Columbus Ave	⅓ "		

It was apparent from these tests, that the most, if not all of this leakage, came from the Union railway company's line, operating the overhead trolley system, a branch of this road running through 135th street, and thereby crossing the rails of the Metropolitan company's tracks at Lenox avenue. This seemed the more certain from the fact that the maximum reading (⅔ volt) was obtained when a Union railway car was crossing the rails at Lenox avenue, or was quite near. Further proof, however, was necessary to determine if that company was responsible for all or only a portion of this current escape; advantage was therefore taken of the period when the Union railway cars stopped running for the night at 1:30 A. M., to make some further tests.

At this time there were no fluctuations of the needle whatever, and consequently no sign of a trolley current escape from the rails to underground pipes. Tests were made over the same route as during the day, as well as at other places, but although the Lenox avenue line was running (they have an all night service) no evidence could be obtained of current straying from those conductors to either water or gas pipes. What we did find, however, worthy of mention, was another current, emanating from an entirely different source, passing from the water pipes to the rails, the pipes this time being *positive*, which, as will be perceived, was the reverse of the polarity found during the day. This current was as perfectly steady as if from a galvanic battery. The difference of potential, however, was low, in some places $\frac{1}{30}$th of a volt only was found, while in others the reading was $\frac{2}{30}$ths. In my efforts to identify this current I consulted the Manager of the power station which supplied current to the Lenox avenue road, and he obligingly offered to shut down the plant for half an hour during that portion of the night when traffic is the lightest and give me a chance to re-test. This was done between the hours of 2:30 and 3 A. M., when both of these electric roads were then shut down so that no possible current could come from either one. The same steady current was found, however, as before, passing from the water pipes into the rails. The voltmeter proving insufficient as a means of completely identifying this current, telephone receivers were used, and with one at each ear there was no difficulty in recognizing the familiar sing of the incandescent dynamo. This test with the telephone was repeated several times by my assistant and myself so that there could be no possibility of error.

It appears from the tests made, that an open conduit system, or one in which an insulated metallic return is used, effectually confines the current to the conductors provided for it. For this reason it is preferable to the ordinary ground return, especially in large cities, where the space below the streets is so largely occupied with various lines of iron pipes, more or less subject to electrolytic action.

The distances the overhead trolley current would sometimes reach, were shown by a rise in voltage when a Union railway car crossed the tracks of the Lenox avenue road at 135th street. This was found as far down as 116th street, where the latter road branches east and west; in fact, there was no portion of this road where these trolley current fluctuations could not be obtained when cars were passing through 135th street.

Desiring to learn the difference of potential between the elevated railway pillars, and water pipes, with the Union railway, if any, in this part of the city, tests were begun at 157th street (Harlem River) on the Eighth avenue line and continued down as far as 109th street, which is the western terminus of the Metropolitan company's open conduit system. Rather than make this paper monotonous with long tables of tests, some plans have been prepared of different locations in the city,

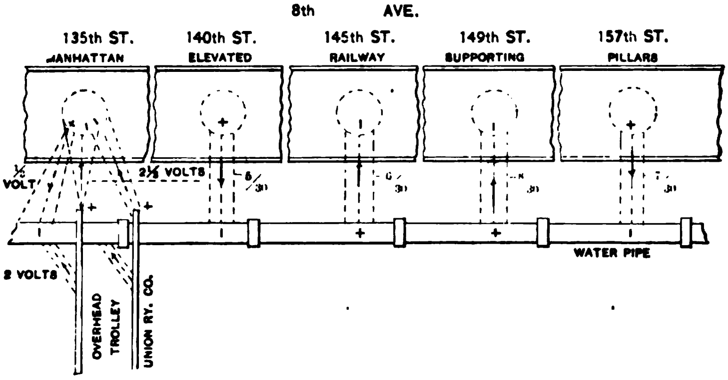


FIG. 1.

showing where these tests were made, and giving the difference of potential at the points indicated. It may be well to state here that the voltmeter used was a Weston two scale; the lower scale reading to 5 volts with 30th divisions; this scale was used in most of the tests, and accounts for the record being given in a number of cases in thirtieths of a volt. The upper scale read to 150 volts in 1 volt divisions.

The following is a general description of the method of procedure touching in detail at such points as may be of interest.

The starting point as already stated was at 157th street; from this point down to 135th street the tests are given in a table, as well as in plan, Fig. 1. The table gives both day and night tests for comparison, while the plan gives the day tests only.

The Union railway (overhead trolley) heretofore spoken of as passing through 135th street, terminates at Eighth avenue; in fact, the ends of the two trolley wires of that road are supported by being attached to the "L" structure which as is well known passes through that avenue.

Location.	Day test 9 to 10 A. M.	Night test 1:30 to 2:30 A. M.
157th Street	"L" + to Hydrant 7/30 Volt.	7/30 Volt "L" + to Hydrant
149th "	"L" – " " 8/30 "	3/30 " "L" + " "
145th "	"L" – " " 6/30 "	1/30 " "L" + " "
140th "	"L" + " " 5/30 "	2/30 " "L" + " "
135th "	Rails U. E. Ry. + to "L" 2¼ volts	2/30 " Rails + " "L" Ry.
135th "	" U. E. Ry. + " Hydt. 2 "	
135th "	"L" + to Hydrant ⅓ volt	1/30 " "L" + " Hydrant
		Night readings steady throughout.

Referring to the table, it will be noticed that the reading at 157th street shows that the night test was the same as during the day. It was afterwards discovered that the last car of the Union railway had not then left the track, which accounts for this reading being higher than the other, as well as a trolley variation being shown. All of the other night tests, however, showed the same indications of an incandescent current as were found on Lenox avenue, as well as at several other places. One feature worthy of notice in the day test, shown in the plan, as well as the table, is the change of polarity found at different points on this section of the road.

The current passes into the water pipes and "L" structure from the rails of the trolley road at 135th street (they being positive) from 2 to 2¼ volts maximum, then along the pipes for five blocks to 140th street, then reverses and passes along the "L" structure for another five blocks to 145th street, where it again reverses and takes the water pipes to another reversal at 157th street.

The cause of this erratic jumping of the railway current up some pillars and down others may be explained in two or three ways, two of which I will mention:

1st. Proximity of water pipes to the "L" structure, they being at some points closer than at others, offering a more favorable path for this portion of the current.

2d. The current passing into the water pipes at 135th street as well as the "L" structure at the same polarity, and possibly at a higher voltage at times to water may cause this change in polarity at different points along the line.

A few days ago tests were made over this same section of road with almost identically the same readings in each case as prevailed over a year ago. It was noticed, however, that the terminal rails of the Union railway company at 135th street and 8th avenue had recently been replaced by new ones which appears to be a good illustration of "cause and effect."

Similar conditions also prevail on the section of road below 135th street down to 109th street. At this point the "open conduit" road has its western terminus. Day tests have shown a maximum reading of $\frac{1}{3}$ of a volt, the rails being positive to "L" pillar, and to water, the night test when Union railway was not running, $\frac{2}{30}$ steady, showing plainly that the current was from that road.

Attention is now directed to the east side of this part of the city where another branch of the Union railway is located. Tests made here show even more pronounced results than at the branch running through 135th street to the west side. It may be stated that the power-station of this road is located on the Bronx river in Westchester county.

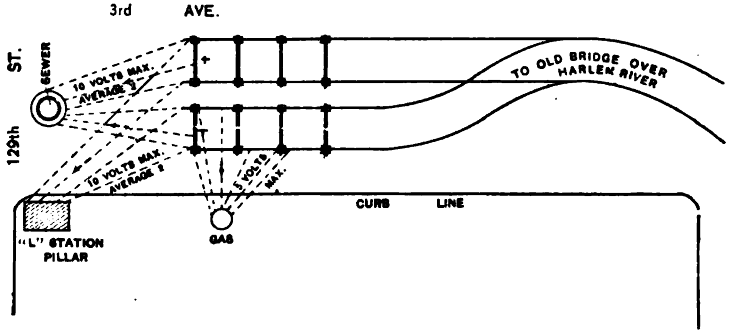


FIG. 2.

Something more than a year ago when these tests were made, this branch had a terminus at Third avenue and 129th street, immediately in front of the "L" station, the cars then passing over the Harlem river at the old wooden bridge, which is now being removed. The cars now pass over the new public bridge recently opened, to the new terminal at Lexington avenue. Fig. 2 shows the location of the old terminal when these tests were made, as well as the difference of potential.

It will be noticed that the maximum reading here was 10 volts, rails positive to "L" pillar, sewer, and gas. A test was also made on the old Harlem bridge at the same time, which showed the same reading, except it was made to gas only, no other pipes being at hand. A few days ago this locality was visited with a view of obtaining

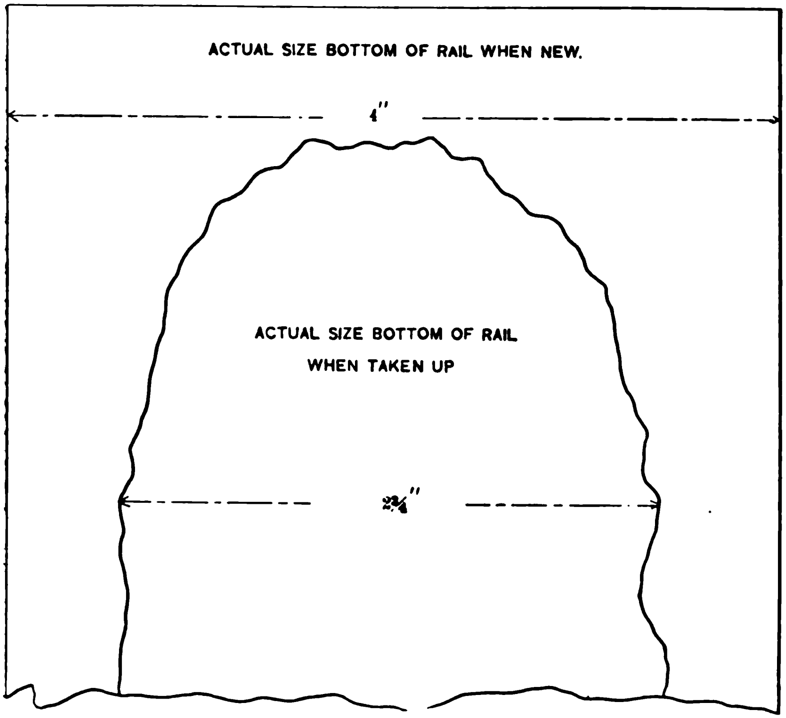


Fig. 3. Plan.

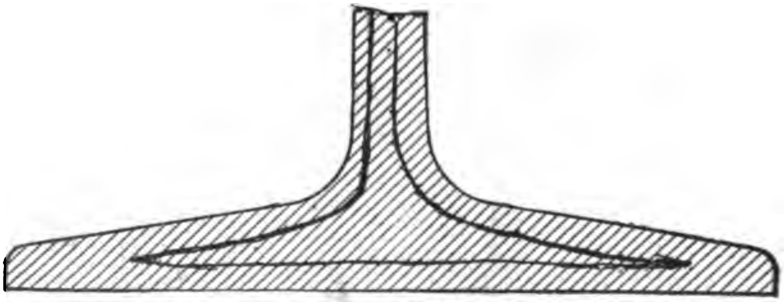


Fig. 3. Section

Fig. 4.

any further items which might be of interest for this paper, and workmen were found engaged in removing the rails of this very terminal.

Information was therefore obtained as to the results of electrolytic action on these rails (they having been positive). An impression was taken on paper of the exact size and shape of the

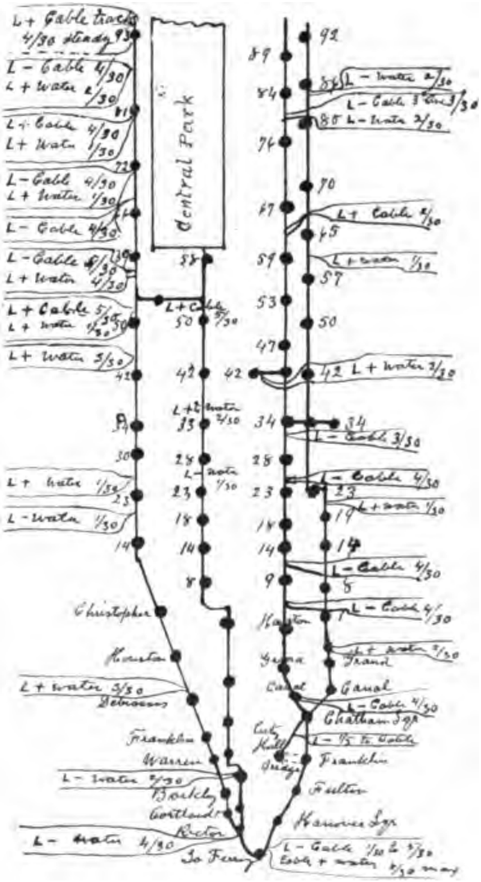


FIG. 5.

end of one of the four rails which composed that terminal switch, the ends of the other rails all being in just about the same condition. Fig. 3 shows a comparison of the size and shape of the rail when new and its present condition; the position of the outlines as to each other being about as shown. From the condition of these rails now, it is quite plain that a large amount of metal has been removed from them by electrolysis. The original size of the rails was furnished by the company supplying the rails, they being 70 lbs. to the yard; furthermore, the bottom sides of all these rails were cut by the current down to knife edges for several feet back from the ends. These edges were irregular in shape and somewhat jagged in appearance.

Another feature of interest is the condition of the cross-bars or tie-rods which keep the rails in position. These bars, which were originally $1\frac{1}{2}''$ wide by $\frac{3}{8}''$ thick, were nearly all so eaten away that the middle portion was missing, the ends protruding from the rails at from 6″ to 12″. Fig. 4 gives a view of one of these bars which was conveniently left behind when the other materials were removed. It is the only one I saw which was intact, and is in a much better state of preservation than the others, consequently not an average sample.

This specimen is on the table for inspection by those who care to examine it, as well as some small pieces, broken off by hand which were protruding from the rails. Your attention is called to a feature not shown in the cut and that is the sharp knife-edge of the side that was deepest in the ground from where the current passed out, somewhat similar in appearance to the sides of the rails above referred to; the ridges and pitting characteristics of electrolysis are also plainly visible in this, and in a lesser degree in the smaller specimens.

Further tests were made in this part of the city, but being not specially important, are omitted until 93d street is reached, from which point to the Battery a plan is given, showing the locations where tests have been made, their voltage and polarity. These tests refer mostly, as you will notice, to the incandescent current, passing at low voltage, ranging from $\frac{1}{30}$ to $\frac{1}{5}$ of a volt. One feature worthy of attention is the lowest reading being generally found at the "L" stations, between pillars under the stations and water pipes. This is accounted for by the fact that as there are water pipes supplied to most if not all the "L" stations they would make a fairly good electrical connection with the structure itself, and, therefore, not much difference of potential could be expected. This point also suggests a method for remedying this condition of affairs. Coming down the west side of the city, I was surprised to encounter a full fledged trolley current in the extreme lower part of the city. The first intimation was found at Rector and Greenwich streets, it became more pronounced in the vicinity of South ferry where in testing between the rails of the Metropolitan cable road and an "L" pillar, a variation of from $\frac{1}{30}$ to $\frac{8}{30}$ volt was found, the rails positive, and the same reading between the rails and water pipes.

Just why there should be indications of a trolley current in this part of Manhattan Island was difficult to understand, but after making further tests coming up on the east side, this current was found to come from the Brooklyn bridge. Having pointed out how an overhead trolley, using the water pipes and incidentally the rails as a return, such as is operated on 135th street, can spread its influence, so to speak, for a distance of over 20 blocks in either direction north and south, through various pipes, railway structures, etc., the existence of this current from the bridge permeating underground metals through a large portion of the lower part of the city, is accounted for.

The tests were continued at the New York entrance of the bridge, and at the pillars which stand in the street just west of the Third avenue cable railway, I found the readings as follows: At one pillar a maximum of three volts, average $1\frac{1}{2}$ volts, pillar positive to Third avenue cable rails. At another practically the same reading. Further up Park Row at the corner of Chambers street, pillar positive to cable rails, 1 volt maximum; water positive to cable rails $\frac{1}{2}$ volt; pillar positive to water $\frac{1}{5}$ of a volt.

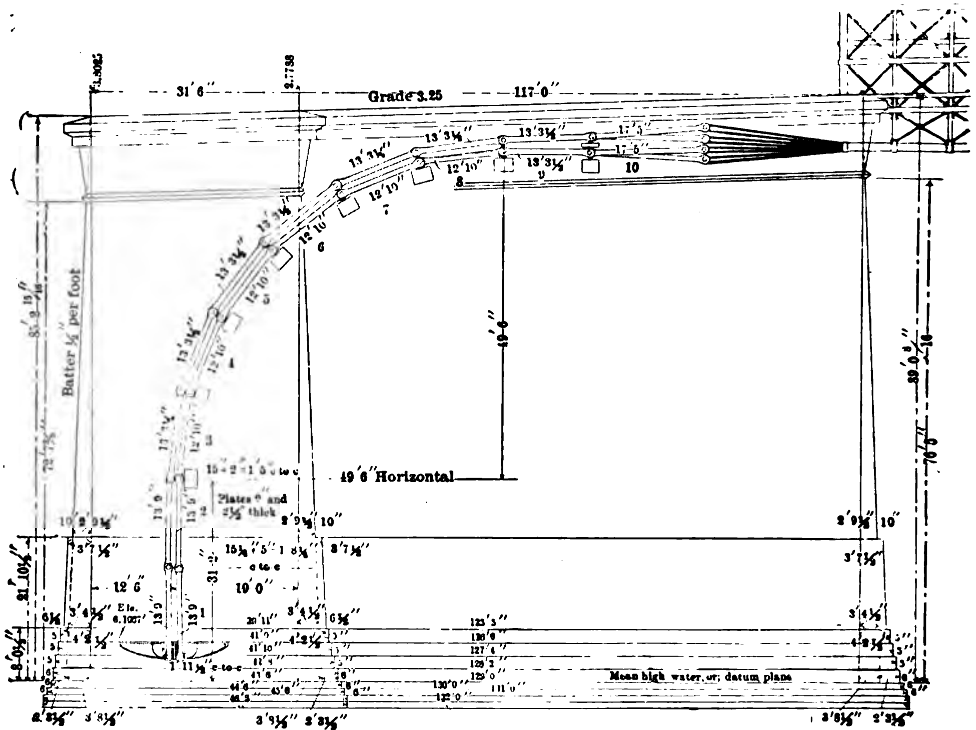
All of these tests were made nearly a year and a half ago. A few days ago, tests were made over this same ground, and at places where a difference of potential of three volts maximum existed at that time, it is now found to be $3\frac{1}{5}$ volts, pillars positive as before to rails of Third avenue cable and also to water pipes, showing in all probability that this current has been during all this time actively and unceasingly passing down the pillars which support the "L" station at this place, as well as the bridge crossing the street, and out from their foundations to other metals as stated, with now a fifth of a volt more for good measure.

In the light of present knowledge on this subject the very serious question presents itself to any practical mind here present, in what condition would we expect to find the anchor bolts and iron foundations of these pillars, if excavations were made at their bases?

In Mr. Farnham's excellent paper read before this INSTITUTE four years ago, he showed that but a small fraction of a volt was necessary to establish electrolytic action between metals.

What then can be expected from an incessant action of from 1½ to 3½ volts jumping out of these foundations during the past year and a half or perhaps two years.

Further tests at the New York entrance of the bridge at pillars nearest the four loop tracks, show that they are negative to rails of these tracks with maximum voltage of 3½ an estimated average of 2½. These tests were made on three different days at different times of the day, the highest maximum reading as above being taken at 4.45 P. M.



ELEVATION
FIG. 6.

The other tests, one made during the so-called rush hour between 5.30 and 6 P. M., where a maximum reading of 2½ volts noted at track 1, did not vary much from the tests made in the afternoon of another day at from 2 to 2:30 P. M. at track 4, where the voltage was found to be 2⅓ maximum. Previous to any use of electricity for operating cars on the bridge it had been known that currents were escaping to that structure from trolley lines in Brooklyn, and passing over would find their way through the city by underground pipes, etc., and thence crossing the river arrive back to the power-station in Kent avenue.

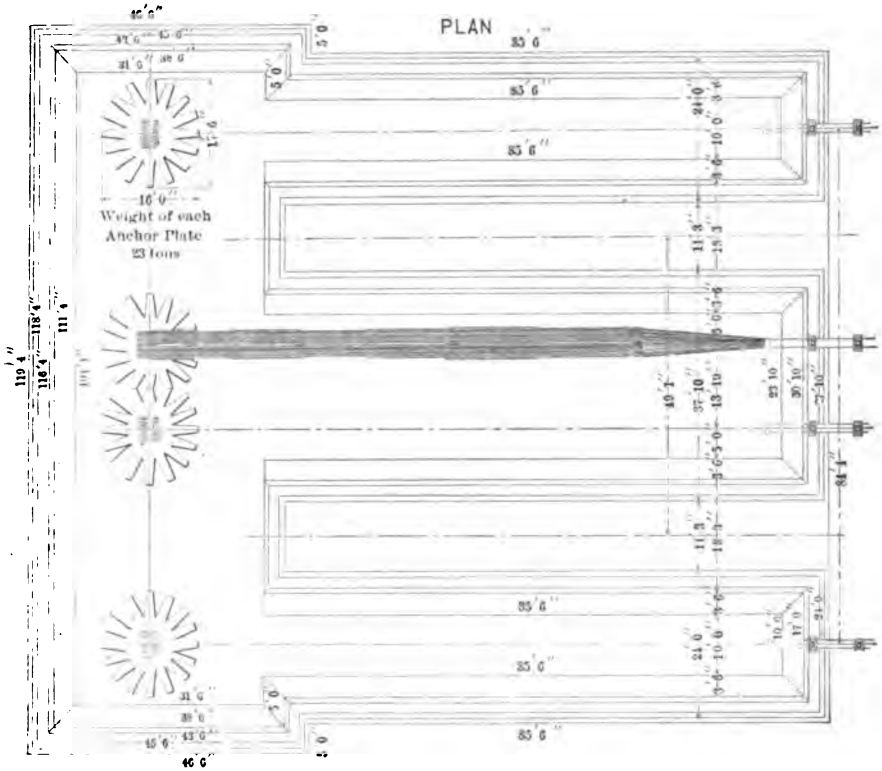


Fig. 7.

The polarity of both of these railway systems now operated on the bridge, indicates that these currents escape from their lines, but it is also quite likely that currents are even now coming over the bridge as they were a year ago. Only an extended investigation would determine these points, even if it were desirable that they should be known.

Let us now take up the investigation made on the bridge to determine if possible the movements of straying trolley currents and their possible effect on the cable terminals. In view of the importance of this matter I regret not being able to make it more thorough than here stated, as it would involve not only a fortnight's work at least, but the shutting down of the bridge plant for a time, which could hardly be expected under the circumstances. Such facts are represented however as it was practicable to obtain. Recognizing the necessity of having every detail as to the construction, location, etc., of these terminals before being able to intelligently consider the matter, plans prepared by the bridge engineers were obtained which are given in Figs. 6 and 7. These show the exact construction of the cable terminals and anchor plates, besides other information regarding construction, all of which is from an official source.

In regard to the construction of the cable terminals; as most of us know, the main cables are made up of eighteen strands, or smaller cables, which are practically continuous, the wire running back and forth from New York to Brooklyn, passing through the holes at the ends of heavy steel bars or links at each place, and the ends of the single wire being finally fastened by a rigid screw coupling. These two rows of steel bars of nine each, which are attached to the cable strands, one row placed over the other, as shown in Fig. 6, pass down with a graceful curve into solid stone masonry to the anchor-plates, and are secured to them by heavy steel bolts passing through the eyes at the ends, as shown in the figure. The anchor-plates are in shape somewhat longer one way than the other (see plan), each being a single piece of cast-iron, weighing twenty-three tons.

Coming now to the tests, it will be noticed that there is no possibility of reaching the anchor-plates other than by connection through the cables themselves, and they being firmly attached to the structure, cables and all are practically one conductor; and a connection on the structure would mean connection with the cables, and consequently with the anchor-plates.

This point therefore being settled, the next thing was to obtain a suitable ground, and on the suggestion of Mr. C. B. Martin, the electrician of the bridge, one of the railway cables was used during that portion of the day when it was not in operation for hauling a bridge train. This was a convenient as well as a good ground, the cable surface being polished bright through friction in passing over the pulleys, it was possible to obtain a good contact, and as it passed over the large drums in the engine room which were on foundations connecting with engines, water-pipes, etc., it was probably the best ground independent of the structure obtainable. The connection to the structure was made by the use of a two-inch screw-clamp, the wire to the voltmeter being attached to it by the simple means of a screw and washer. Two of these clamps were generally used in nearly all of the previous tests, as they were found very convenient for attaching and detaching quickly to and from hydrants, pillars, etc. The first test under these conditions was made just over the Brooklyn anchorage, where the structure was found to be positive to the ground, with a difference of potential of 2¾ volts maximum, estimated average 1¾ volts.

At the Brooklyn tower another ground connection was made to a water-pipe, which ran down the side of the tower, and is intended for use in case of fire on the bridge. At this point the reading was 3¾ volts maximum, average 2¾, bridge structure was as before positive. At center of span, structure positive at first, with 2¼ volts maximum, but during the readings there were two reversals, one of them only remaining long enough to obtain a reading, which was 1¼ volts maximum, structure negative. At the New York tower: structure positive to cable ground, with trolley variations ranging from ¾ths to 3 volts, average 2 volts. At New York anchorage: maximum 2¾ volts, average 2 volts, structure positive, to ground.

Other tests were made to determine the polarity of the rails of the bridge trains, and they were found positive to the structure, the same as the rails of the trolley road heretofore tested. Let us now consider the question of the electrolytical conditions of the cable anchorages, as this point appears to be of high importance in this matter, if not the key to the whole situation in determining whether or not electrolytic action is going on. First: These anchorages are composed of solid stone masonry and are put together with the highest quality of cement; there is no brickwork or mortar in their construction.

2d. The 23 tons of iron composing the plates are set about 80 feet below the top of the anchorage. The distance from the bottom of the plates to mean high water is 3 feet 8 inches at the New York end, 5 feet at the Brooklyn end; there is no earthy matter, salts or alkalies, such as is found prevalent in the streets which go to make up an electrolyte, so I am informed, in any part of this structure.

I was at first apprehensive that on account of the comparatively short distance between mean high water and the plates at both anchorages there might be opportunity for salt water to reach the plates through seepage or capillary attraction and thereby produce such an electrolyte as to cause corrosion, but have been informed that it is not possible for salt water to reach these terminal plates on account of the distance from the river, the anchorages being over 900 feet from the towers which stand at each side of the river. Even allowing 100 feet for the salt water to work back, there is still ample margin as to distance before salt water can reach these plates; besides this, one of the bridge engineers showed me a plan of the construction of the foundation under each anchorage, which consists of heavy timbers 10″ x 10″ and some 12″ x 12″ arranged in 4 to 7 layers, placed a short distance apart, and the intervening spaces filled in with concrete cement.

In view of the tests therefore that have been made showing the structure and cables to be positive at both ends, it is quite possible that a portion of the currents straying from the trolley lines, and possibly from the bridge service, find their way out of the anchor plates through the dampness of the stone-work of these anchorages. The construction of these anchorages however is such, as I have endeavored to set forth, that it seems reasonable from the general construction of these piers that the mass of stone and concrete surrounding these plates will not constitute an electrolyte such as would favor electrolysis, and thereby cause corrosive action on them.

One of the bridge officials informed me that a certain authority had reported that electrolysis would not attack cast-iron, consequently their cast-iron anchor-plates were exempt from such danger. In the light of recent experience in other cities, that theory is now untenable; for instance, I will quote a few extracts from a pamphlet, giving the reports of four experts, besides that of the Secretary of the Water Board of the City of Dayton, Ohio, embodying an estimate of cost for repairing the damage.

Mr. E. E. Brownell, E. E., states: "To my surprise I have found in this city a six-inch water main that was corroded to the depth of one-quarter of an inch where the voltage did not average over 1.5 to 2 volts positive to the rails, therefore it is impossible to establish a certain voltage that will cover all cases for low readings."

The following extracts are quoted from the report of Mr. J. H. Shaffer, metallurgist:

He says: "In accordence with instructions from the Board, I have made a careful inspection of the cast-iron water mains at fifteen different locations in the city," and then gives the results of excavations, etc., two of which I will quote.

1st. "This excavation was made at the corner of Washington and Mound streets. It exposed a six-inch main and a ten-inch tee; the pipe was laid in 1874, and the tee in 1888, both were subjected to electrolytic action for about ten years. Both pipe and tee showed great evidence of electrolytic corrosion, the pipe being damaged to an alarming degree, with holes pitted from one-eighth to five-sixteenths of an inch in depth, and covering a large portion of the same............The lead caulking was found to be in bad condition, and showed perceptible evidence of leaking. The pipes at this point were nine volts positive to the rails.

"2d. This excavation was made on Germantown street, near Krug. It uncovered a six-inch pipe. This pipe was electrolytically corroded in about the same proportion, with other conditions identical. A lead service pipe was also exposed at this point, and was found to be entirely destroyed."

A quotation from the report of the secretary on an approximate estimate of the cost of replacing water-pipes damaged by electrolysis caused by electric railway currents may also be interesting.

He says: "In calculating the cost of replacing the pipes in the whole affected territory, it is estimated at $77,208.80.

"There is 17,513 feet of pipe that shows a voltage of from two to nine volts positive, and from pieces of pipe removed where electrically charged to this extent, it is found that they have deteriorated fifty per cent. in four years.

"Where they were required, when laid, to withstand a hydrostatic pressure of over 300 pounds per square inch, when tested by J. H. Shaffer, iron expert, after being subjected to 4.5 volts for four years, leaked at 150 pounds pressure."

He also states the following: "At 4.5 volts it has been shown that a six inch pipe can certainly become useless in 5 years."

I have quoted thus freely from this pamphlet for two reasons, one to show that it is a mistake to suppose that cast-iron is not subject to corrosion by electrolysis produced by railway currents, and also to show the penalty to which a city is subjected through permitting such conditions to exist so long that they cause such heavy damages to its property. In the light, therefore, of what has been shown to be the state of affairs in the upper part of this city due to escaping railway currents, as well as the experience at Dayton, O., it appears to be the duty of engineers to exercise every possible precaution against the effects of this invisible element of destruction, which if left to itself will certainly shorten the life of valuable city property.

In the cases found to exist up town, it is true that the rails of the road referred to are apparently the principal metals damaged, for the reason that they happen to be positive to the water pipes, but as the escaping current goes into the pipes at one place it must come out at others, and at these places damage may be looked for.

The damages already done and threatened to public works in England by electrolysis has led to the establishment of regulations to prevent such action in the future, and similar legislation may be expected in this country should these conditions be allowed to continue. One of the provisions in the regulations prescribed by the British Board of Trade may be of interest just here. It is to the effect that if the pipe is negative to the rails the potential difference shall not exceed 4.5 volts, and if the pipe is positive to the rails the potential difference shall not exceed 1.5 volts. This appears to be very liberal for the railways, in view of the experience in cities on this side of the water; it is probable however they will be made more stringent as future experience in this direction dictates.

I have purposely avoided elaborating in this paper, any particular scheme for preventing damage by stray railway currents for the reason that methods are perfectly well known to railway companies for confining currents to their proper conductors, such as efficient bonding, and providing a return that will leave no inducement for the current to seek underground pipes, in preference to a legitimate conductor. It is simply a question of additional expense. Referring to the incandescent light current which was found prevailing everywhere in this part of the city from the Harlem river to the Battery, passing between all kinds of underground metals, and some on the surface, I do not consider these currents as particularly dangerous at the moment on account of their low voltage, but as before stated, it having been established that a fraction of a volt difference of potential will cause electrolytic action, it then comes down simply to a question of time, when those straying incandescent currents will have to be seriously considered.

In conclusion, I wish to say that these remarks regarding possible damage to public structures through the action of electrolysis, have been made with no desire on my part to appear as an alarmist, but to present simple facts as found in these investigations. I believe that too little attention has heretofore been paid to this matter by any of us; perhaps for the reason that electrolytic action being invisible, as well as noiseless, it has thus escaped attention, and its baneful effects not fully appreciated. It is my opinion, however, that ordinary caution would suggest, that periodical tests should be made in every city by competent parties where a trolley road using a ground return is in operation, and the reports placed before those having authority to deal with the matter. In this way threatened damage by electrolysis to water and other pipes, as well as bridges, might be arrested and finally controlled.

Discussion.

Mr. William Maver, Jr.:—I feel that the Institute is under great obligations to Mr. Knudson for presenting to us to-night in such an admirably succinct and clear manner the more important results of his electrical survey of the city; a survey which the text shows has extended over several years, and which has entailed a large number of tests, many of which were made at all hours of the night and day. And necessarily so, for it is obvious that to arrive at a definite conclusion as to the source of the fluctuating currents in the vicinity of 135th street, the effects must be observed when the known and possible sources were temporarily absent. In this case Mr. Knudson was rewarded by discovering a normally suppressed source, namely, the comparatively steady current from the incandescent light circuits.

The exhibits which Mr. Knudson has been at the trouble to procure for us are excellent instances of the biter bitten. If the state of affairs which these exhibits illustrate may be taken as at all comparable with what is taking place at the rails and tie-rods of similar roads all over the country, it should teach the managers of such roads that it may be a matter of economy to provide efficient conductors for the return current apart from gas and water pipes, etc.

The tie-rod which Mr. Knudson exhibits appears to have corroded to a greater extent in the middle, and towards the middle than at the ends. Inasmuch as it may be assumed that all parts of the rod were at equal potentials, and that the soil between the rails was of a uniform character, I am somewhat at a loss to account for this action. Perhaps Mr. Knudson or some other member may be able to offer an explanation, which doubtless will be interesting.

Since learning of Mr. Knudson's intention of presenting this paper, I have taken occasion to make inquiry of some of the gas companies as to whether any electrolytic effect had been thus far observed in the vicinity of 135th street, and was informed that a recent careful examination of the pipes had not disclosed any such action; which is so far reassuring, and also is confirmatory of Mr. Knudson's tests. It does not, however, prove that some such action may not be taking place at a remoter point where the current leaves the pipes.

In connection with my duties as supervising electrician of the high-tension subways in this city, I have naturally been on the alert for any evidences of electrolysis that might arise. I may repeat what I have on other occasions stated in this regard, namely, that no clear evidence of electrolysis has thus far been discovered on the cables or iron ducts of the subways of this city. I should perhaps make the further statement which, however, is known to most of you, that until comparatively recently there may have been no electric traction companies, either overhead trolley or open conduit in New York city, proper. There have been one or two instances where corrosion of cables has been observed, but investigation indicated that it was due to chemical action pure and simple.

What was said to be a case of electrolysis in a "solid" iron tube which passed through one of the hand boxes of the subways on Park Row, this city, was reported to me four or five years ago. On investigation I found a small hole about three-fourths of an inch in diameter in the said tube. As, however, I was aware that there had been a "burn out" in a joint of one of the "high-tension" cables in close proximity to this pipe I concluded that this was the result of a different kind of electrolysis to that which we are discussing. Furthermore, a test of the conductors in the tube in question showed them to be up to the usual standard; proving that the defect in the tube was of very recent origin; the insulating material of the conductors being of a fibrous nature.

I mention this unusual incident, however, because of the fact that at the time of its occurrence I made an electrical survey of this entire neighborhood, over a distance of about half a mile from the Post Office east, testing from the subways to gas and water mains, and elevated road structures, and obtained readings of from two-tenths to five-tenths of a volt at every point tested. The deflections were steady, indicating the source to be at some electric light station. These tests were made, it will be understood, long before the trolley roads crossed the Brooklyn bridge. As a result I concluded that readings of this nature would probably be found in any city where electric light and power, or even telegraph terminal stations were in operation.

Mr. Knudson's query at the bottom of page 623 regarding the possible condition of the anchor bolts and iron foundations of the pillars of the L structure where his tests showed them to be positive to the surface rails and water pipes, recalls to my mind a case in which I was interested some time ago. It does not answer his inquiry, but it may be interesting in connection with it. At the time when the surface roads of Brooklyn had decided to change from horse power to the overhead trolley system, application was made by one of the surface roads to one of the elevated roads in that city for permission to use their structure for the support of their trolley wires and feeders, wherever they ran under them, which, as is well known, is the case for considerable distances. The chief concern of the elevated road authorities was as to what effect a possible contact of the trolley wire with their structure would have upon a passenger on their lines, or upon a passer-by in the street, who might, at that time, touch the structure. Being consulted on that and other points, I expressed the opinion that no apprehension need be felt on the score of injury to any one coming in contact with the structure under the conditions stated, excepting under almost impossible circumstances, but I strongly recommended for other reasons that in the event of the desired permission being given, it be provided that no intentional electrical contact should ever be made with the elevated structure. The desired permission was given, but I presume the recommendation was overlooked, for in the course of a year or two it was discovered that the surface road had at various places connected their rails by large copper wires to the iron pillars of the structure, under the surface. On being required to vacate the premises, so to speak, I believe it was naively claimed that this use of the structure went with the right to suspend their wires from the structure. If I am not mistaken, I think the further contention was made that the passage of the electric current through the structure would be a positive benefit to it; possibly on the principle that "electricity is life." Of course the structure was an excellent return wire.

The information which Mr. Knudson has been at the trouble to obtain for us regarding the Brooklyn bridge anchorages, etc., is certainly interesting and valuable, and while he is in no sense an alarmist, rather the contrary, with regard to the ultimate effect upon the bridge terminals of possible electrolytic action, the results which he has obtained should be an incentive to the proper authorities to take every possible precaution to avoid any possible detrimental effects.

The fact that the anchorages are securely and deeply embedded in cement should perhaps not be accepted too surely as a positive obstacle to electrolytic action, especially as high voltages may be placed upon the structure.

I have more than once pointed out that although the iron pipes of the New York subways are embedded in cement, and might therefore be considered as partially insulated, there has never been a time when the lead coverings of the cables therein have not furnished excellent "grounds." Dr. J. A. Fleming, also, in a paper recently delivered before the British Association, on "The Electrolytic Corrosion of Water and Gas Pipes by the Return Currents of Electric Tramways," has expressed the opinion that the conduction through such materials as moist clay, cement, etc., must in great part at least be of an electrolytic character.

Prof. A. C. Peckham:—May I ask Mr. Knudson a question—if he knows whether this tie-rod was horizontal in the ground, or whether it stood edgewise. The question is based upon the idea that it may be difficult to account for one edge growing thin if it lay flatwise in the ground. But if it lay edgewise it might be natural to suppose that the lower edge would be the one that would grow thin.

Mr. Knudson:—It lay edgewise in the ground, being an inch and a half wide. The lower part was the side that was cut the most. That is the part that was deepest in the ground.

PROF. PECKHAM:—It might be supposed that one part of the ground would be damper than another.

MR. KNUDSON:—They were all in just about the same condition.

MR. THATCHER T. P. LUQUER:—I would like to ask Mr. Knudson if he knows whether there is a return feeder for the Union railway on 135th street, or whether there is any method used for bonding the rails efficiently.

MR. KNUDSON:—I have seen no indication of any overhead return feeder at all. I presume, however, that the rails are bonded, but just how well they are bonded, of course I do not know, as they are covered up with earth.

[Information on this point raised by Mr. Maver and Prof. Peckham, received since reading the paper, shows that the presence of the ground wire is probably the cause of the tie-rods being eaten away at the middle.

The wire is usually placed on the ties midway between the rails, and consequently but a few inches below the rods. The escaping current in such case would pass from about the middle of the rods to the ground wire (the rods and rails being positive to earth and pipes,) and the excessive cutting at this portion of the rods would, without doubt, be accounted for. A. A. K.]

MR. JESSE M. SMITH:—I would like to ask Mr. Knudson for my own information, being a stranger in the city, how they propose to overcome the difficulty in the new lines on Sixth avenue and Broadway.

MR. KNUDSON:—Metallic circuits will be used. There are two conductors with the open conduit system, lying side by side. Of course there is little inducement for a current to be diverted from those conductors, and straying off on iron pipes, and taking some other course back to the station. It is confined to those conductors.

MR. SMITH:—Both insulated of course from the conduit?

MR. KNUDSON:—Both insulated.

MR. TOWNSEND WOLCOTT:—I would like to ask Mr. Knudson if he observed any great difference in the quality of the soil—if the chemical nature of the soil has anything much to do with electrolysis.

MR. KNUDSON:—No. I have not made any examination of the soils in the different parts of the city.

MR. WOLCOTT:—It is a little hard to understand just what becomes of metal chemically unless there is an acid of some kind present. I know it as a fact, (I have tried it myself), if you take two copper wires from a dynamo—(I think the dynamo I tried was about 300 volts) and stick them in a pail of ordinary well water, pretty nearly pure, the positive wire will be corroded away in a very short time. I believe it was a No. 4 wire I used. It was pointed as sharp as a needle in a few minutes by the electrolysis. But I do not know in what form the copper went into in solution. I did not make any chemical analysis or anything of that kind. But there was the fact that nearly pure water will dissolve copper under the influence of current. Of course if there had been any acid in the water, it would have gone very much faster.

THE PRESIDENT:—Has the author any further remarks to make?

MR. KNUDSON:—I think not, with the exception perhaps regarding the last remark made by Mr. Wolcott, I would say that so far as my knowledge goes, the character of the soil is about the same in all of the cities; for instance that up town from where we got this sample, is shown to be sufficiently electrolytic to cause that much corrosion. I have no doubt that the same character of the soil exists in every part of New York city as well as in other cities. Some of the reports from Dayton, Ohio, which I did not quote, that are published in the pamphlet, show analysis of the character of the soil there, and it is evidently about the same as it is here. In some cases the action on pipes has shown a covering something similar to graphite where electrolysis has acted upon it, and I have no doubt that the soil in most of the large cities of the country is of just about the same nature.

MR. WOLCOTT:—There are some parts of Manhattan Island where the soil is almost clean sand, if you go down a little depth, hardly any organic matter. I have no doubt that a soil, for example, that contained iron pyrites would corrode the wire very much faster on account of sulphuric acid being formed.

MR. JESSE M. SMITH:—I think that the soil of all cities certainly contains a great deal of animal matter, animal acids, due to the droppings of the horses and from nuisances of that kind in the street, making a soil which is admirably adapted for electrolytic action, particularly where there is water present, as there is nearly always especially in streets paved with stone.

I want to state a fact which is probably known to a great many of you, that in the city of Cincinnati they started out at the beginning with an overhead double trolley system of electrical transmission for railroads. They have persistently stood by that system, and I think it is probably the only city in the country where the double trolley is used to any great extent. My information is that they never have had any trouble whatever from electrolytic action in that city, although the electric lighting is largely done by underground conductors. But all of the trolley system, and it is a very large one, has overhead double conductors, and in that way there is no loss of current from the mains to the water pipes or gas pipes, and I understand that they find it a great economy to put the two conductors above ground where there is no leakage from one to the other.

[ADJOURNED.]

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

New York, Nov. 23rd, 1898.

The 129th meeting of the AMERICAN INTSITUTE OF ELECTRICAL ENGINEERS was held at 12 West 31st Street, this date, and was called to order by President Kennelly at 8:10 P. M.

THE SECRETARY: At the meeting of the Executive Committee this afternoon the following associate members were elected:

ABBE, CLEVELAND	Professor of Meteorology, The Weather Bureau, Washington, D. C. residence 2017 I St., N. W. Washington, D. C.	Jos. Wetzler. T. C. Martin. C. F. Chandler.
CASSIDY, JOHN	Superintendent Mutual Telephone Co., Honolulu, Hawaiian Islands, U. S A.	T. C. Martin. Geo. H. Guy. Jos. Wetzler.
COSGROVE, JAMES FRANCIS	Head of Locomotive Engineering Dept. International Correspondence School, 631 Madison Ave., Scranton, Pa.	D. C. Jackson. J. Glen Wray. W. H. Donner.
FRY, DONALD HUME	Assistant to Robt. McF. Doble, 202 Sansome St., San Francisco, residence, Blue Lakes City, Cal.	Geo. P. Low. T. E. Theberath. F. P. Medina.
HAMILTON, JAMES	Patent Attorney and Expert in Patent Causes, 54 State St., Boston, Mass.	E. L. Nichols. H. J. Ryan. Fred'k. Bedell.
HOFFMANN, BERNHARD	New York Telephone Co., 15 Dey St., New York City.	Stephen D Field. U. N. Bethell. Herbert Laws Webb
JAMES, HARRY D.	Expert Draughtsman, Otis Bros. & Co., residence, 100 Buena Vista Av,, Yonkers, N Y.	W. M. Scott. C. W. Pike. Edwin R. Keller.
KNOX, S. L. G.	First Asst. Engineer, Crocker-Wheeler Electric Co., Ampere, residence, Montclair, N. J.	Gano S. Dunn. F. V. Henshaw. F. M. Pedersen.
LEITCH, HOWARD WALLACE	Switchboard Regulator, The Edison Elect. Illuminating Co., residence, 878 Madison St., Brooklyn, N. Y.	Sam'l. Sheldon. Ralph W. Pope. J. W. Lieb, Jr.

Lohmann, R. W.	Electrical Engineer, 1387 Madison Street, Oakland, Cal.	Geo. P. Low. Sidney Sprout. F. F. Barbour.
Reno, C. Stowe	Electrical Engineer, Triumph Electric Co., 620 Baymillen Street, Cincinnati, Ohio.	T. J. Creaghead. Thos. French, Jr. A. L. Searles.
Sperling, R. H.	Assistant Engineer, British Columbia Electric Railway Co., Ltd. Victoria, B. C.	W. F. C. Hasson. F. F. Barbour. Wynn Meredith.
Wilkinson, James	Station Manager, Chief Engineer, Consolidated Electric Light Co., 812 South 19th Street, Birmingham, Ala.	Geo. H. Harris. S. R. Gross. R. W. Pope.
Zahn, A. Wilford	Electrical Engineer and Supt., Manhattan Light, Heat and Power Co., Manhattan Building, St. Paul, Minn.	G. D. Shepardson. C. L. Pillsbury. A. A. Nimis.

Total 14.

The following associate members were transferred to full membership:

Approved by Board of Examiners, March 18th, 1898.

Brooke-Ridley, A. E.	Agent, Electrical Engineer, Siemens & Halske Electric Co., San Francisco, Cal.

Approved by Board of Examiners, October 20th, 1898.

Franklin Robert Anson,	Secretary and Manager, Salem Light and Traction Co., Salem, Oregon.
Sidney Hand Browne,	Consulting Electrical Engineer, Baltimore, Md.

The President: The paper for the evening, advance copies of which are in your hands, is on the Design of Alternating Current Transformers. It is somewhat lengthy, and it contains, as you will notice, a number of mathematical expressions. Such a paper is very difficult to have read aloud, but Prof. Franklin has kindly promised to present the salient features of this paper in such a manner that we will be able to follow it.

A paper presented at the 129th Meeting of the American Institute of Electrical Engineers, New York, November 23rd, 1898. President Kennelly in the Chair.

THE DESIGN OF TRANSFORMERS.

ON THE BEST PROPORTIONS TO GIVE TO TRANSFORMER CORES, AND THE MOST ADVANTAGEOUS DISTRIBUTION OF THE WASTED ENERGY, TOGETHER WITH A DIRECT METHOD FOR THE DESIGN OF TRANSFORMERS, IN ORDER TO OBTAIN MAXIMUM ALL-DAY EFFICIENCY.

BY FREDERICK W. CARTER.

I. *Introductory.*—In designing transformers it is usual to assume values for certain of the quantities which occur, and to determine the details of the transformer to suit the prescribed values of these quantities. Thus, the maximum induction to which the iron is subject, the proportions, or even the size of the cross-section of the magnetic circuit, the resistance of the coils and the maximum current density in them are often assumed. It is not, however, necessary in general that these quantities should have these prescribed values, and, in fact, in practice the effect of changes in the assumed quantities is tried, and the best transformer is really arrived at by a method of trial and error. Any such method is, however, tedious and imperfect in the case of a machine in which there are so many quantities that may be varied, and the present paper is intended principally to determine once for all the conditions of proportion and distribution of wasted power which lead to as little loss of energy as possible. The transformer may be made to satisfy these conditions by the method of trial and error, by successive approximation, or by any other method that may be thought suitable by the designer, but as the analysis used indicates a perfectly direct method of obtaining particulars of the transformer to satisfy the outside conditions and to give minimum waste of energy with materials of given quality, the author has included a description of the method in the paper.

The assumptions on which the work is based are:

1. That the hysteresis loss is given by Steinmetz formula, that is, it varies as the volume of iron, as the frequency, and as some power of the maximum induction. (The 1.6th power is generally taken, but the results are worked out for a general index in Appendices B and C.)

2. That the eddy current loss varies as the volume of iron, as the square of the frequency, as the square of the thickness of the core plates, and as the square of the maximum induction.

3. That the ohmic loss varies as the resistance of the coils and as the square of the current in them.

These assumptions are probably sufficiently nearly correct for the work, especially over the range of induction which occurs.

All that we shall assume known at the outset concerning the transformer itself are:

1. The magnetic quality of the iron of the core.
2. The electric quality of the copper of the circuits.
3. The thickness of core plates and the amount of insulation between them: and often —
4. The maximum current density allowable in the coils.

The second of these is practically invariable, or so far as it varies, it chiefly depends on the temperature of working. The third is discussed in Appendix A. The fourth is usually assumed, because, as shown in section VII., some condition is necessary to fix the absolute size of the transformer.

The outside conditions supposed given are:

1. The primary and secondary voltages.
2. The frequency of alternation.
3. The normal full load.
4. The load time curve, as nearly as it can be predetermined.
5. The wave form, or the form factor, of the primary P. D. wave wherever possible.

The fourth of these is required because it is the "all-day" efficiency that is made a maximum, and the conditions of load should be known as nearly as they can be predetermined. When the fifth condition is known, the transformer can be designed to suit the wave form, which, although it has no effect on the proportions of the transformer, affects to some extent the absolute size and the number of convolutions of the wire.

The satisfaction of the condition of maximum efficiency, besides making the energy wasted as small as possible, will also give minimum heating for the amount of radiating surface, since the heat developed is a direct measure of the energy wasted. Again, the drop of secondary voltage as the load is increased depends principally on the ohmic resistance; a type, then, which has small ohmic losses should have this drop of voltage correspondingly small, so that making the waste of energy a minimum conduces to good regulation. The result will show that the shape of the core is not favorable to large magnetic leakage, so that the regulation on this account, too, should be good.

The transformers contemplated are of the closed-iron-circuit type and the load is supposed non-inductive.

II. *Sources of Waste Considered.*—The chief sources of loss of energy in a transformer are:

1. The ohmic loss in the primary and secondary coils.
2. The hysteresis loss in the core.
3. The eddy-current loss in the core.

Of these, the last is usually small compared with the two preceding it, and the calculations of the size of the various parts are best performed by neglecting it in the first instance, and then, if required, applying corrections to the results in order to take account of it. (See Appendix A).

III. *A Theorem on the Distribution of the Losses Between the Magnetic and Electric Circuits.*—The first proposition we shall prove is concerned with the distribution of loss of energy between the iron and copper circuits and may be stated thus:

"Given the iron circuit of a transformer of prescribed output, then, in order to make the wasted energy a minimum, the number of turns of wire in the coils must be such as to make the ohmic loss equal to 0.8 times the hysteresis loss, plus the eddy current loss."

This statement assumes that the index occurring in the Steinmetz formula is 1.6. Be it otherwise, a small obvious change must be made in the statement of the proposition; in fact, if it be ϵ then instead of 0.8 we must write $\epsilon/2$ in our enunciation. The copper circuit, including its insulation, is supposed to take up all the space allotted to it, so that any increase in the number of turns in the coils necessitates a corresponding decrease in the cross-section of the wire. In other words, the *total* cross-section of each coil is known.

Let A be the total cross-section of copper in the primary.
l the mean length of a turn of the primary.
n the number of turns in the primary.
and I the primary current.

Then $\frac{A}{n}$ is the cross-section of the primary wire and

$$\rho \frac{l\,n}{\frac{A}{n}} \text{ or } \rho \frac{l}{A} n^2$$

is the resistance of the primary, where ρ is the specific resistance of copper. Thus the power wasted in the primary =

$$\rho \frac{l}{A} n^2 \; I^2 \propto n^2$$

Similarly the power wasted in the secondary varies as the square of the number of secondary turns, or as n^2, since the ratio of transformation is supposed given.

Thus the ohmic loss varies as n^2, and if we call it Ω, we may write $\Omega = \omega n^2$, where ω is independent of n.

The maximum number of lines of force through the magnetic circuit is

$$\frac{V_m \, 10^8}{2 \pi f n}$$

at no load, where V_m is the maximum value of the potential difference between the primary terminals, and f is the frequency. The number is very slightly less at full load, but we are only concerned with the fact that it varies inversely as n at all safe loads. Hence the induction, which is this divided by the area of cross-section of the magnetic circuit, varies inversely as n. Hence the hysteresis loss, which varies as the induction to the power of 1.6, varies as $n^{-1.6}$.

Thus if H be the hysteresis loss, we may write $H = h\,n^{-1.6}$, where h is independent of n.

Again, the eddy current loss varies as the square of the induction, and therefore as n^{-2}.

Thus if E be the eddy current loss, we may write $E = e\,n^{-2}$, where e is independent of n. Hence if W be the total loss,

$$\begin{aligned} W &= \Omega + H + E \\ &= \omega n^2 + h\,n^{-1.6} + e\,n^{-2} \end{aligned}$$

thus

$$\frac{\delta W}{\delta n} = 2\,\omega\,n - 1.6\,h\,n^{-2.6} - 2\,e\,n^{-3}.$$

This is zero when W is a minimum,

$$\therefore\ \frac{2}{n}\left(\omega\,n^2 - 0.8\,h\,n^{-1.6} - e\,n^{-2}\right) = 0$$

or $\Omega = 0.8\,H + E$, which proves the proposition.

The fact that this solution corresponds to a minimum value of W, and not to a maximum, can be seen from the nature of the case, or from the fact that

$$\frac{\delta^2 W}{\delta n^2} = 2\,\omega + 1.6 \times 2.6\,h\,n^{-3.6} + 2 \times 3\,h\,n^{-4}$$

which is necessarily positive.

IV. *Extension of the theorem to the case of a variable load.*—The above conclusion is true whether the load is constant or variable, provided that, in the latter case, by the various losses we understand the time average of those losses. For if W be the time average of the total loss, using the same notation as in the last section, we shall have

$$W = \frac{1}{T}\int_0^T \omega\,n^2\,d\,t + \frac{1}{T}\int_0^T h\,n^{-1.6}\,d\,t + \frac{1}{T}\int_0^T e\,n^{-2}\,d\,t$$

where ω, h, and e, are now functions of t.

Thus

$$\frac{\delta W}{\delta n} = \frac{2}{T}\int_0^T \omega\,n\,d\,t - \frac{1.6}{T}\int_0^T h\,n^{-1.6}\,d\,t - \frac{2}{T}\int_0^T e\,n^{-3}\,d\,t$$

Hence, if

$$\frac{\delta\,\omega}{\delta\,n} = 0$$

$$\frac{1}{T}\int_0^T \omega\,n^2\,d\,t = \frac{0.8}{T}\int_0^T h\,n^{-1.6}\,d\,t + \frac{1}{T}\int_0^T e\,n^{-2}\,d\,t$$

or

$$\Omega = 0.8\,H + E$$

where Ω, H, and E, are now the time averages of the ohmic loss, the hysteresis loss, and the eddy-current loss, respectively.

V. *Limits of the theorem.*—It is to be understood that the theorems of the last two sections refer to a transformer whose core is given. In a transformer where some other condition is prescribed, we might find the relation between ohmic and iron loss, required to give minimum total loss, to be quite other than that found above; but having so determined the transformer, we can, with the same core, always find a copper circuit of the same weight, which will give less total loss, but it will only be by violating the prescribed condition. For instance, if the ohmic loss is prescribed, we shall have the total loss a minimum when the iron loss is as small as possible. Thus, a large core, and a large number of turns of thick wire, will give less loss than a core designed to make the ohmic loss equal to 0.8 times the hysteresis loss together with the eddy-current loss; but, given that larger core, we can, with the same weight of copper make a more efficient transformer by satisfying this relation, though it will, by diminishing the ohmic loss, violate the prescribed condition.

In fact, if the relation proved above is not satisfied, we can, without altering the core, and without altering the weight of the copper, (and so, practically, without altering the cost,) improve the transformer, as regards efficiency, by satisfying this relation. So that, hereafter, in designing transformers, we shall usually assume that the above relation is to be satisfied as well as the prescribed conditions.

VI. *Direct application of the theorem.*—The results of sections 3 and 4 enable us immediately to find the number of turns of wire in the primary and secondary coils, which will make the efficiency a maximum, when the core is given. For if, as before Ω, H, and E, be the average values of the ohmic loss, the hysteresis loss, and the eddy-current loss respectively, and we write

$$\Omega = \omega\, n^2, \qquad H = h\, n^{-1.6}, \qquad E = e\, n^{-2},$$

where ω, h, e, are independent of n, then, to a first approximation

$$\Omega = 0.8\, H,$$

or

$$\omega\, n^2 = 0.8\, h\, n^{-1.6},$$

or

$$n^{3.6} = 0.8\, \frac{h}{\omega},$$

and h, ω, are known in terms of the size of the core, and the quality of the materials.

The correction to be applied to this to take account of eddy-current loss is easily made.

For suppose n given by the equation above, and $n + \delta n$ to satisfy

$$\Omega = 0.8\, H + E, \text{ or that}$$

$$\omega\, (n + \delta\, n)^2 = 0.8\, h\, (n + \delta\, n)^{-1.6} + e\, n^{-2}.$$

Thus

$$2\, n^2\, \omega\, \frac{\delta\, n}{n} = -\, 0.8 \times 1.6\ \ h\, n^{-1.6}\, \frac{\delta\, n}{n} + \ e\, n^{-2},$$

neglecting squares of small quantities.

This may be written

$$2\, n^2\, \omega\, \frac{\delta\, n}{n} + 1.6\, n^2\, \omega\, \frac{\delta\, n}{n} = e\, n^{-2},$$

or

$$3.6\, n^2\, \omega\, \frac{\delta\, n}{n} = e\, n^{-2},$$

or

$$\delta\, n = \frac{e\, n^{-2}}{3.6\, \omega\, n^2}\, n.$$

The calculations required to find ω, h, and e, will be given hereafter. (§ § XVII. and XVIII.)

VII. *Necessity of a condition to determine the size of the transformer.*—If the *proportions only* of the core are given, and not the actual size, then, as stated in the first section, some condition will be necessary to limit the actual size, as there is no transformer whose waste of energy is an absolute minimum, when only the quality of the materials and the external conditions are given. This can be seen as follows:—

Suppose the linear dimensions of the transformer are increased x times in all parts, except the *thickness* of the core plates, which is to remain constant.

Since the output and voltage are given, the currents are practically given, hence the ohmic loss varies as the resistances that is as $\dfrac{\text{length of wire}}{\text{area of cross-section}}$ or as $\dfrac{1}{\text{linear dimensions}}$ or as $\dfrac{1}{x}$.

Again, since the voltage and frequency are given, and the number of turns of wire remains constant, the total flux of magnetic lines remains constant, hence the induction, or flux per unit area varies as $\frac{1}{x^2}$.

Now the hysteresis loss varies as the volume of iron and the 1.6th power of the induction, that is as $x^3\ (x^{-2})^{1.6}$, or as

$$x^3 \times x^{-3.2}, \text{ or as } \frac{1}{x^{0.2}}.$$

And the eddy current loss varies as the volume of iron and the square of the induction, that is as $x^3\ (x^{-2})^2$, or as

$$x^3 \times x^{-4}, \text{ or as } \frac{1}{x}.$$

Thus this increase of the transformer diminishes the ohmic and eddy current losses x times, and the hysteresis loss $x^{0.2}$ times; so that all the losses are decreased by the increase of the size.

Of course, if the index of the power of the induction in Steinmetz's formula were less than 1.5, the hysteresis loss would increase slightly with increase of size, but as exact proportionality need not be aimed at in the increase, there is little doubt that, by slightly increasing the number of turns of wire on the coils, we could always make all the losses decrease, by increasing the size of the transformer.

Thus, we see that some condition is necessary to determine the absolute size of the transformer. Practically this is limited, on the one hand by cost, and on the other, by considerations of safety, performance, and economy. The ideal way of proceeding with the design would be to allow these limits to determine the size. They, however, are not definite, and are incapable of being accurately expressed, in any simple manner, in terms of the linear dimensions. In the last section the size was determined by the size of the core. In order to investigate what core will best satisfy our conditions, we shall assume that the maximum current density in the copper is given. This is a usual assumption to make in designing transformers, and the current densities practically used are well known. The ohmic loss per unit volume of copper is determined by the current density, which is, accordingly, intimately connected with the heating, and which will not vary very much between different transformers of the same standard of excellence.

VIII. *Principles of the design of a transformer whose proportions are given.*—We will now discuss the question of the actual size of a transformer whose proportions are given, which will satisfy the relation proved in sections 3 and 4, and be such that the maximum current density in the copper is given.

Since the power and voltage are given, the maximum current in each coil is practically known; so that, to be given the maximum current density, is virtually to be given the size of the wire used for the coils.

Let a, b, c,—be proportional to linear dimensions of the transformer.

Let $x\,a$, $x\,b$, $x\,c$,—be the corresponding actual linear dimensions. Since the cross-section of the wire is given, the number of turns, (n), varies as the area of the winding space, or $n \propto x^2$.

Now the induction varies inversely as n and inversely as the area of cross-section of the magnetic circuit, and therefore, inversely as x^4.

Hence the hysteresis loss, which varies as the volume of iron, and as the 1.6th power of the induction, varies as $x^3\,(x^{-4})^{1.6}$, or as $x^{-3.4}$.

Thus if we call it H, we may write,

$$H = h_1\,x^{-3.4}, \text{ where } h_1 \text{ is independent of } x.$$

Similarly, the eddy-current loss varies as the volume of iron, and the square of the induction, or as $x^3\,(x^{-4})^2$, or as x^{-5}.

Thus if we call it E, we may write

$$E = e_1\,x^{-5}, \text{ where } e_1 \text{ is independent of } x.$$

The ohmic loss, since the maximum current density is given, varies as the volume of copper, or as x^3.

Thus if we call it Ω, we may write

$$\Omega = \omega_1\,x^3 \text{ where } \omega_1 \text{ is independent of } x.$$

Thus x is given by the equation

$$\omega_1\,x^3 = 0.8\,h_1\,x^{-3.4} + e_1\,x^{-5}.$$

To solve this, we may first neglect E, and so get

$$x^{6.4} = 0.8\,\frac{h_1}{\omega_1}$$

which gives a first approximation to x.

The correction to be applied to this to take account of the eddy-current loss may be found thus:

Calling the correction to be applied to x, $\delta\,x$, we shall have $\delta\,x$ given by

$$\omega_1\,(x + \delta\,x)^3 = 0.8\,h_1\,(x + \delta\,x)^{-3.4} + e_1\,(x + \delta\,x)^{-5},$$

where x is given by

$$\omega_1\,x^3 = 0.8\,h_1\,x^{-3.4}\,;$$

thus

$$3\ \omega_1\ x^3\ \frac{\delta x}{x} = -\ 3.4 \times 0.8\ h_1\ x^{-3.4}\ \frac{\delta x}{x} + e_1\ x^{-5},$$

or

$$6.4\ \omega_1\ x^3\ \frac{\delta x}{x} = e_1\ x^{-5},$$

or

$$\delta x = \frac{e_1\ x^{-5}}{6.4\ \omega_1\ x^3}\ .\ x$$

The calculations required to find ω_1 h_1 and e_1 will be given hereafter. (§§ XVII and XVIII.)

IX. *Discussion of the same design, when the conditions of* §§ III *and* IV *are not assumed.*—It must be observed that the problem of the last section is quite different from that of finding a core which will give the greatest efficiency with the given cross-section of wire, and, just as in § V we found that, for a minimum loss of energy, the core would have to be infinite, when the ohmic loss is prescribed, so here we may show that the core which gives least wasted energy when the cross-section of the wire is prescribed, is larger than is required to give the best distribution of losses between iron and copper.

For, using the same notation as in the last section, if W be the total loss,

$$W = \Omega + H + E,$$

$$= \omega_1\ x^3 + h_1\ x^{-3.4} + e_1\ x^{-5}$$

$$\frac{\delta W}{\delta x} = 3\ \omega_1\ x^2 - 3.4\ h_1\ x^{-4.4} - 5\ e_1\ x^{-6}$$

Hence if W is a minimum

$$\omega_1\ x^3 = \frac{3.4}{3}\ h_1\ x^{-3.4} + \frac{5}{3}\ e_1\ x^{-5},$$

or

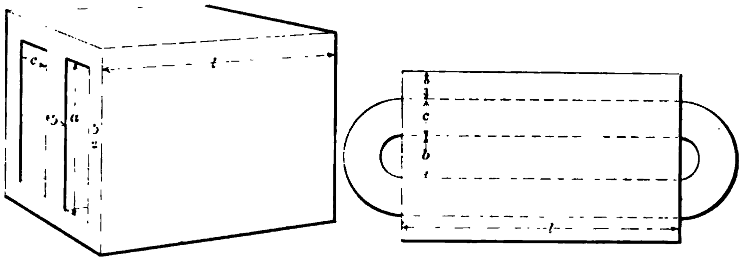
$$\Omega = 1.13\ H + 1.67\ E.$$

Thus $$\Omega > 0.8\ H + E.$$

Hence, if we increased the cross-section of the wire and diminished the number of turns, we should diminish the ohmic loss, and increase the iron loss, but we should diminish the total loss. The increase of the cross-section of the wire is not a detrimental variation, so that, as a rule, it will be advantageous to assume that the given cross-section of the wire is that which makes the energy wasted as small as possible *with the core found;* in other words, the method of design given in the last section is the appropriate one to apply to the problem.

X. *The shell transformer, which gives least waste of energy, considered.*—Thus we see how, when we are given the proportions of the core, we can find the size which will give least wasted energy, subject to the condition that the maximum current density is prescribed. We will now investigate the subject of the best proportions to give to the core, in order that the efficiency may be a maximum when the maximum current density is prescribed as before. We shall also assume that the copper circuit is that which gives greatest efficiency with the core found, in other words, we shall assume the condition of sections 3 and 4.

It will be necessary to fix upon the general type of the transformer, and I shall deal first with one of the ordinary shell type, in which the dimensions a, b, c, l, are as indicated in the accompanying diagram. (Fig. 1.)



ELEVATION PLAN

Fig 1

Since the maximum current in the coils is known, as also the maximum current density, the cross-section of the wires is known. Hence the number of turns in a coil varies as its cross-sectional area, that is as the winding space. Hence, if n be the number of primary turns.—

n varies as $a\,c$.

Again, the magnetic induction varies inversely as the cross-section of the magnetic circuit, and inversely as n, that is, inversely $ac.\ bl$.

The volume of iron varies as the measured volume of the core, that is as $2\,b\,l\,(a+b+c)$, or as $b\,l\,(a+b+c)$.

The hysteresis loss varies as the volume of iron and as the 1.6th power of the induction, that is, as $b\,l\,(a+b+c)\,(a\,c\,b\,l)^{-1.6}$.

Thus if H be the hysteresis loss, we may write

$$H = H_1\,(a+b+c)\,(b\,l)^{-0.6}\,(a\,c)^{-1.6},$$

where H_1 is independent of the dimensions.

The eddy-current loss varies as the volume of iron and as the square of the induction, that is as $b\,l\,(a+b+c)\,(a\,c\,b\,l)^{-2}$.

Thus if E be the eddy-current loss, we may write:—

$$E = E_1\,(a+b+c)\,(b\,l)^{-1}\,(a\,c)^{-2}$$

where E_1 is independent of the dimensions.

Since the current density is given, the ohmic loss varies as the volume of copper, that is as the volume of the coils, that is as $a\,c\,(2\,l + \pi\,\overline{b+c})$, (assuming the ends of the coils to be semicircular.)

Thus if Ω be the ohmic loss, we may write:—

$$\Omega = \Omega_1\,a\,c\,(2\,l + \pi\,\overline{b+c}),$$

where Ω_1 is independent of the dimensions.

The problem we have to solve, is to find the values of a, b, c and l, which make $\Omega + H + E$ a minimum, subject to the condition, $\Omega = 0.8\,H + E$, or as we may state it, we have to make the total loss,—which we will call W, and write $W = \Omega + H + E + K\,(\Omega - 0.8\,H - E)$, a minimum where K is a constant so chosen that $\frac{\partial W}{\partial l} = 0$ identically for the values of a, b, c, l, which give maximum efficiency, and a, b, c, are now independent variables.

Hence

$$\left.\begin{aligned}
\frac{\delta W}{\delta l} &= (1+K)\,\mathcal{Q}\,\frac{2}{2l+\pi\overline{b+c}} - (1-0.8\,K)\,H\,\frac{0.6}{l} \\
&\qquad - (1-K)\,E\frac{1}{l} = 0 \\
\frac{\delta W}{\delta a} &= (1+K)\,\mathcal{Q}\,\frac{1}{a} + (1-0.8\,K)\,H\left[\frac{1}{a+b+c}-\frac{1.6}{a}\right] \\
&\qquad + (1-K)\,E\left[\frac{1}{a+b+c}-\frac{2}{a}\right] = 0 \\
\frac{\delta W}{\delta b} &= (1+K)\,\mathcal{Q}\,\frac{\pi}{2l+\pi b+c} + (1-0.8\,K)\,H \\
&\quad \left[\frac{1}{a+b+c}-\frac{0.6}{b}\right] + (1-K)\,E\left[\frac{1}{a+b+c}-\frac{1}{b}\right] = 0 \\
\frac{\delta W}{\delta c} &= (1+K)\,\mathcal{Q}\left[\frac{\pi}{2l+\pi\overline{b+c}}+\frac{1}{c}\right] + (1-0.8\,K)\,H \\
&\quad \left[\frac{1}{a+b+c}-\frac{1.6}{c}\right] + (1-K)\,E\left[\frac{1}{a+b+c}-\frac{2}{c}\right] = 0
\end{aligned}\right\}\text{I}$$

In order to solve these, we will, as usual, first find an approximation to the solution by neglecting the eddy currents.

Thus we get

$$\frac{(1+K)\,\mathcal{Q}}{(1-0.8\,K)\,H} = \frac{0.3\,[2l+\pi\,\overline{b+c}]}{l} = \frac{1.6\,\overline{b+c}+0.6\,a}{a+b+c}$$

$$= \frac{[2l+\pi\overline{b+c}]\,[0.6\,\overline{a+c}-0.4\,b]}{\pi\,b\,(a+b+c)} = \frac{[1.6\,a+b+0.6\,c]\,[2l+\pi\overline{b+c}]}{[a+b+c]\,[2\,l+\pi\,\overline{b+2\,c}]}$$

and $\mathcal{Q} = 0.8\ H$.

These have the unique solution

$$\frac{l}{9\pi} = \frac{a}{14} = \frac{b}{9} = \frac{c}{7}$$

and $$K = \frac{1}{5.12}$$ (See Appendix B).

Thus the proportions of l, a, b, and c, are found, and their absolute values are given by the equation

$$\mathcal{Q} = 0.8\ H.$$

Had the solution not been restricted by the condition $\mathfrak{Q} = 0.8\,H$, we should have found the same proportions for l, a, b, and c, but their absolute values would have been given by $\mathfrak{Q} = 1.13\,H$, which latter fact also follows from § IX since the proportions are the same as when the equation $\mathfrak{Q} = 0.8\,H$ is satisfied.

These results follow immediately by putting $K = 0$ in the equation above.

As is shown in § IX, however, we shall do right to assume that the conditions expressed by the equation $\mathfrak{Q} = 0.8\,H$, are satisfied.

Thus the absolute value of the dimensions is given by this relation, and, expressing them all in terms of c, we get

$$c^{6.4} = 0.0138\,\frac{H_1}{\mathfrak{Q}_1}$$

So that we have found the first approximation to the required values of l, a, b, and c. We can now find the corrections to be applied to the values so found. To do this, suppose the corrections to be applied to l, a, b, and c, to be $\lambda\,l$, $\alpha\,a$, $\beta\,b$, and $\gamma\,c$, respectively, so that the correct values of the magnitudes in question are $l\,(1+\lambda)$, $a\,(1+\alpha)$, $b\,(1+\beta)$, and $c\,(1+\gamma)$, respectively; then, if $\mathfrak{Q}'$, H', and E', are the first approximations to the ohmic, the hysteretic and the eddy losses respectively, the true value of these losses to the second approximation will be

$$\mathfrak{Q}'\left(1+\frac{34\,\alpha+9\,\beta+41\,\gamma+18\,\lambda}{34}\right),$$

$$H'\left(1-\frac{34\,\alpha+9\,\beta+41\,\gamma+18\,\lambda}{30}\right),$$

and E respectively, and equations I. of this section reduce to

$$6.12\,\alpha+0.86\,\beta+6.79\,\gamma+4.59\,\lambda = 3.65\,\frac{E'}{\mathfrak{Q}'}-\delta\,K,$$

$$6.75\,\alpha+1.27\,\beta+7.10\,\gamma+3.24\,\lambda = 2.96\,\frac{E'}{\mathfrak{Q}'}-\delta\,K,$$

$$4.78\,\alpha+5.74\,\beta+6.12\,\gamma+1.72\,\lambda = 5.11\,\frac{E'}{\mathfrak{Q}'}-\delta\,K,$$

$$5.89\,\alpha+1.34\,\beta+8.14\,\gamma+2.98\,\lambda = 2.83\,\frac{E'}{\mathfrak{Q}'}-\delta\,K.$$

Whilst the equation

$$\mathfrak{Q} = 0.8\ H + E'$$

reduces to

$$34\ \alpha + 9\ \beta + 41\ \gamma + 18\ \lambda = 15.9\ \frac{E'}{\mathfrak{Q}'}.$$

The solution of these equations is

$$\alpha = \gamma = -\ 0.036\ \frac{E'}{\mathfrak{Q}'},$$

$$\beta = \lambda = 0.69\ \frac{E'}{\mathfrak{Q}'},$$

$$\delta K = 0.36\ \frac{E'}{\mathfrak{Q}'}.$$

(See Appendix C).

To sum up then, the first approximation to the values of l, a, b, c, is given by

$$\frac{l}{9\ \pi} = \frac{a}{14} = \frac{b}{9} = \frac{c}{7}$$

and

$$c^{6.4} = 0.0138\ \frac{H_1}{\mathfrak{Q}_1}$$

whilst the corrected values of these magnitudes are got by increasing l and b each by $0.69\ \frac{E'}{\mathfrak{Q}'}$ of itself, and diminishing a and c each by $0.036\ \frac{E'}{\mathfrak{Q}'}$ of itself.

The calculations proposed to find H_1, $\mathfrak{Q}_1$, E' and $\mathfrak{Q}'$ will be given hereafter. (§ XVII.)

XI. *The core transformer, which wastes least energy, considered.*—We will next consider the size and proportions to give to a transformer of the ordinary core type, in order that the total energy wasted may be a minimum, the maximum current density being, as before, prescribed. We shall again suppose the conditions of § § III and IV to be satisfied.

We will suppose that the shape of the core is as in Fig. 2, that the coils are wrapped on both vertical limbs, and that the wires are straight where they pass the edges of the plates, and semicircular across the faces. Let the dimensions a, b, c, and l, be as shown in Fig. 2.

Exactly as in the last section we shall have

1. Number of turns of wire varies as $a\,c$.
2. The induction varies as $(a\,c.\;b\,l)^{-1}$.

But the volume of iron is now proportional to

$$b\,l(a + c + 2\,b),$$

and the volume of copper is proportional to

$$a\,c\left(2\,l + \pi\,b + \frac{c}{2}\right)$$

Thus the hysteresis loss, which we will call H, is

$$H = H_1\,b\,l\,(a + c + 2\,b)\,(a\,c\,b\,l)^{-16},$$

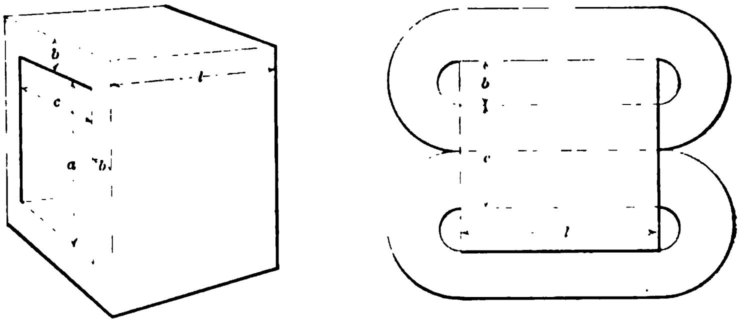


Fig. 2

where H_1 is independent of the dimensions.

The eddy-current loss, which we will call E, is

$$E = E_1\,b\,l\,(a + c + 2\,b)\;(a\,c\,b\,l)^{-2},$$

where E_1 is independent of the dimensions.

The ohmic loss, which we will call Ω, is

$$\Omega = \Omega_1\,a\,c\left(2\,l + \pi\,b + \frac{c}{2}\right),$$

where Ω_1 is independent of the dimensions.

If we write $a = 2\,a'$, $c = 2\,c'$ we shall get,

$$H = H_1\,.2 \times 4^{-1.6}\,b\,l\,(a' + b + c')\;(a'\,c'\,b\,l)^{-1.6},$$

$$E = E_1 .2 \times 4^{-2} b l (a' + b + c') (a' c' b l)^{-2},$$

$$\mathfrak{Q} = \mathfrak{Q}_1 .4 a' c' [2 l + \pi b + c'].$$

Thus we have to choose a' b c' l so that

$\mathfrak{Q} + H + E$ may be a minimum, when $\mathfrak{Q} = 0.8 H + E$.

This is exactly the same problem as that of the last section, and the first approximation to the solution will be

$$\frac{l}{9\pi} = \frac{a'}{14} = \frac{b}{9} = \frac{c'}{7},$$

where

$$c'^{6.4} = 0.0138 \times \frac{2 \times 4^{-1.6}}{4} \frac{H_1}{\mathfrak{Q}_1},$$

or

$$c'^{6.4} = 0.0633 \frac{H_1}{\mathfrak{Q}_1}.$$

Thus we obtain the first approximation to the dimensions required. The correction for the eddy currents is the same as for the shell transformer.

Thus, summing up the results for a core transformer, the first approximation to the values of l, a, b, and c, is given by

$$\frac{l}{9\pi} = \frac{a}{28} = \frac{b}{9} = \frac{c}{14}, \qquad \text{and } c^{6.4} = 0.0633 \frac{H_1}{\mathfrak{Q}_1},$$

whilst the corrected values of these magnitudes are obtained by increasing l and b each by $0.69 \frac{E'}{\mathfrak{Q}'}$, of itself, and decreasing a and c each by $0.036 \frac{E'}{\mathfrak{Q}'}$, of itself.

The calculations for finding H_1, $\mathfrak{Q}_1$, E', $\mathfrak{Q}'$, will be given hereafter. (§ XVIII.)

XII. *Remarks on the two preceding sections.*—Thus we have found the actual dimensions of the cores of transformers, both of the shell and core type, which will make the loss of energy a minimum, when the maximum current density is prescribed and the coils are such that no change in them would make the transformer more efficient. These dimensions are given in terms of quantities which are known when we know the quality of the materials, and the external and prescribed conditions.

We shall next proceed to show in detail how to express the quantities involved, in order to directly calculate the particulars of the transformer. In any particular case, the calculations can be made, by means of a slide rule, with very little trouble.

If several not very different transformers have to be designed, an approximate value of the eddy current correction might be found which would be sufficiently near to apply to all—this especially when the particulars of the iron are not accurately known. The increase of b and l due to the eddy current losses will rarely be greater than 0.2, and the decrease of a and c is of the order 0.01, which might in many cases be neglected. It may be mentioned that, since the quality of transformer iron deteriorates a little at first, the constants should be taken for aged iron.

The solution given corresponds to an absolutely minimum waste of energy, as will be shown in Appendix D.

XIII. *Determination of the average losses in terms of the maximum.*—We will first show how we may find, approximately, the average values of the various losses when we are given the pre-estimated relation between load and time. We may regard the load as measured by the inverse of the resistance in the secondary circuit. If we call this resistance r, the primary voltage V, the resistances of the primary and secondary transformer coils R and R' respectively, and their number of turns n and n', we may take it as sufficiently near for our purpose to write for the primary current (I)

$$I = \frac{n'^2}{n^2}\,\frac{V}{r}$$

and for the secondary current (I')

$$I' = \frac{n'}{n}\,\frac{V}{r}$$

Hence the ohmic loss (Ω) at this load is

$$\begin{aligned}\Omega &= R\,I^2 + R'\,I'^2,\\ &= R\,\frac{n'^4}{n^4}\,\frac{V^2}{r^2} + R'\,\frac{n'^2}{n^2}\,\frac{V^2}{r^2},\\ &= \left[R\left(\frac{n'}{n}\right)^2 + R'\right]\left(\frac{n'}{n}\right)^2\frac{V^2}{r^2}.\end{aligned}$$

If $\mathfrak{Q}_0$ be the ohmic loss at full load, and r_0 the corresponding resistance

$$\mathfrak{Q}_0 = \left[R\left(\frac{n'}{n}\right)^2 + R'\right]\left(\frac{n'}{n}\right)^2 \frac{V^2}{r_0^2}.$$

$$\therefore\ \mathfrak{Q} = \mathfrak{Q}_0 \frac{r_0^2}{r^2}.$$

The average ohmic loss $\overline{\mathfrak{Q}}$ is given by

$$\overline{\mathfrak{Q}} = \mathfrak{Q}_0\, r_0^2 \frac{1}{T}\int_0^T \frac{d\,t}{r^2} = \mathfrak{Q}_0 \frac{r_0^2}{\overline{r^2}}$$

where $\frac{1}{\overline{r^2}}$ is the mean value of $\frac{1}{r^2}$

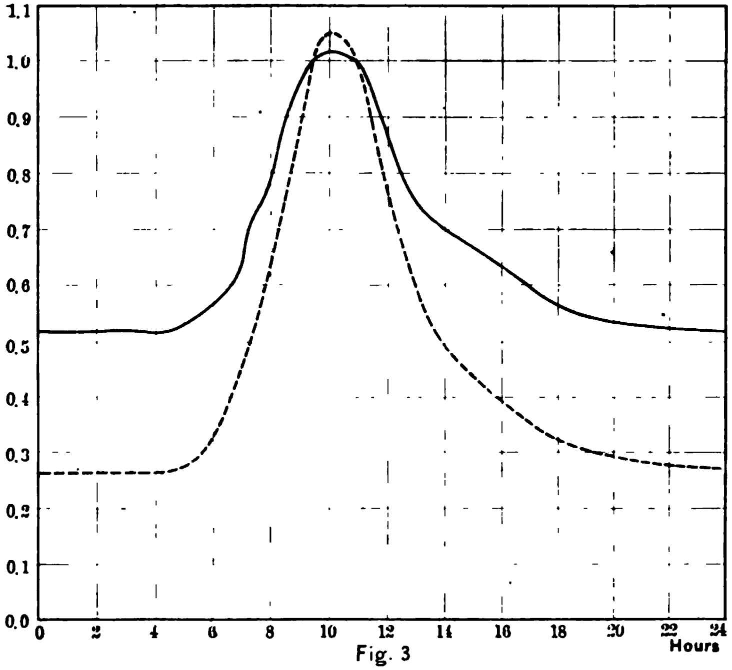


Fig. 3

[The full line curve is between load and time, the ordinate being the fraction of full load. The dotted curve is between square of load and time, the ordinate being the square of that of full line curve.

For this curve

$$k = 0.45\ ]$$

Hence, if we are given the curve Fig. 3, between the load, $\left(\frac{1}{r}\right)$ and the time, and from it deduce the curve between the square of the load and the time, the ratio of the mean to the maximum ordinate of this latter curve, is the ratio of the mean to the maximum ohmic loss.

The ratio so found, we shall call k, and write

$$\Omega = k\,\Omega_0.$$

This approximation will probably be as near as can be relied on, as the load curve can in general hardly be pre-estimated with very great accuracy.

The average value of the hysteresis loss will perhaps be very near to the maximum value, that is, within perhaps two per cent. We can, however, find this average as follows :—

The induction, as far as it depends on the load, varies inversely as $1 + \frac{n'^2}{n^2}\,\frac{R}{r}$ nearly; hence the hysteresis loss varies as

$$\left(1 + \frac{n'^2}{n^2}\,\frac{R}{r}\right)^{-1.6}.$$

Thus if H be the hysteresis loss with the load $\frac{1}{r}$, and H_0 that at no load

$$H = H_0\left(1 + \frac{n'^2}{n^2}\,\frac{R}{r}\right)^{-1.6},$$

$$= H_0\left(1 - 1.6\,\frac{n'^2}{n^2}\,\frac{R}{r}\right).$$

approximately.

Thus, if $\overline{H}$ be the mean value of the hysteresis loss

$$\overline{H} = H_0 - 1.6\,\frac{n'^2}{n^2}\,R\,H_0\,\frac{1}{T}\int_0^T \frac{d\,t}{r},$$

$$= H_0\left[1 - 1.6\,\frac{n'^2}{n^2}\,\frac{R}{\overline{r}}\right],$$

where $\frac{1}{\overline{r}}$ is the mean ordinate of the load-time curve.

Thus the maximum hysteresis loss H_0 must be diminished by

$$1.6 \frac{n'^2}{n^2} R H_0$$

times the mean load, $\frac{1}{\bar{r}}$, to obtain the mean hysteresis loss.

Thus if we write

$$1 - 1.6 \frac{n'^2}{n^2} \frac{R}{\bar{r}} = j, -$$

$$\bar{H} = j H_0.$$

We may notice that

$$\frac{n'^2}{n^2} R = R',$$

nearly, if the maximum current density is to the same in primary and secondary. It is also to be observed that R and R' are not known at the outset, but as R' will hardly be more than $\frac{1}{100}$ of $\bar{r}$, the effect of a considerable error in R' will have very little effect on j; so that we may either estimate R' from former experience, or, design the transformer roughly, with $j = 1$, and then correct it for the small change in j, if such a degree of accuracy as the correction implies is really obtainable in the quantities.

In a similar manner, if $\bar{E}$ be the mean value of the eddy-current loss and E_0 the maximum value.

$$\bar{E} = E_0 \left[1 - 2 \frac{n'^2}{n^2} \frac{R}{\bar{r}}\right].$$

So that the change in the eddy-current loss is small, and since the eddy-current loss is itself small, we may take the maximum value for the mean.

Thus we have introduced two constants j and k, such that

The mean hysteresis loss $= j$ times the maximum hysteresis loss.

The mean ohmic loss $= k$ times the maximum ohmic loss.

and have shown how to obtain them from the load curve. We may note that k may be anything less than unity, whilst j is very nearly unity but somewhat less.

We shall preserve this notation for these constants throughout.

XIV. *Introduction of a constant determined by the insulation of the coils.*—We will next define a constant which will be required in writing down the general expression for the ohmic loss, and which depends upon the proportion of insulation between the coils. This is the ratio of the total cross-section of copper in the primary or secondary circuit, to the cross-section of both coils, that is, of the winding pocket. When the maximum current density is given, the size of wire for the primary and secondary circuits is known, so that the proportion of the coils taken up by insulation can be predetermined with considerable accuracy.

Let σ, σ,' be the cross-sections of the wires of the primary and secondary respectively. $s\,\sigma$, $s'\sigma'$, the average cross-section of wire and insulation corresponding (wherein s, s', not only include the immediate covering of the wire, but the insulation and ventilation spaces between layers and coils as well; in fact $s\,\sigma$ is the quotient of the total cross-section of the primary coil, by the number of primary turns).

Let n, n', be the number of primary and secondary turns respectively.

Then

$n\,s\,\sigma + n'\,s'\,\sigma'$ = the total area of the winding pocket. $= A$ let us say. (A is the "*a.c*" of §§ x and xi.)

Now if the maximum current density is to be the same in both primary and secondary $n\,\sigma = n'\,\sigma'$, and if we write each of the quantities equal to $p\,A$, we shall have

$$p\,A\,(s + s') = A.$$

$$\therefore p = \frac{1}{s + s'}.$$

s and s' are both greater than 1, so that p is less than a half.

This, (p), is the constant we shall require.

XV. *Constants depending on the insulation of the core plates.*—Two constants will also be required depending on the insulation of the core plates; these can be determined immediately when we know the thickness of the plates, and that of the insulation.

We will call them q and q', and they are defined thus:

q is the ratio of the *volume of iron* in the core, to the *measured volume* of the core.

q' is the ratio of the area occupied by iron in the cross-section of the magnetic circuit, to the total cross-section.

As a rule $q = q'$.

The five constants p, q, q', j, k, are all, then, pre-determinable with considerable accuracy, and these are all that we shall require, besides those depending on the quality of the materials, viz ρ—the specific resistance of copper, η—the hysteretic constant in Steinmetz's formula, and $\mathfrak{S}$—a corresponding constant in the eddy-current formula.

XVI. *Detailed expressions for the losses in a shell transformer.*—We will now obtain general expressions for the various losses, in terms of the dimensions of the core of the transformer and the number of turns of wire on the coils, which number we shall express in terms of the dimensions when the maximum current density is given.

We will first consider a transformer of the shell type; and will suppose the dimensions a, b, c, l, to be given by Fig. 1.

If the maximum currents in the coils are I and I' respectively their number of turns n and n' and their resistances R and R', then the maximum ohmic loss of power is

$$\mathfrak{Q}_0 = R\,I^2 + R'\,I'^2.$$

Now, the mean length of a turn of wire is $2\,l + \pi\,(b + c)$, and the cross-section of the primary wire is $\frac{p\,a\,c}{n}$, and of the secondary wire $\frac{p\,a\,c}{n'}$.

Thus

$$R = \rho\,\frac{(2\,l + \pi\,\overline{b + c}).n}{\frac{p\,a\,c}{n}} = \rho\,\frac{2\,l + \pi\,\overline{b + c}}{p\,a\,c}\,n^2,$$

and

$$R' = \rho\,\frac{2\,l + \pi\,\overline{b + c}}{p\,a\,c}\,n'^2.$$

Thus

$$\mathfrak{Q}_0 = \rho\,\frac{2\,l + \pi\,\overline{b + c}}{p\,a\,c}\,(n^2\,I^2 + n'^2\,I'^2);$$

$$= 2\,\rho\,\frac{2\,l + \pi\,\overline{b + c}}{p\,a\,c}\,n^2\,I^2,$$

approximately.

The mean ohmic loss is $\overline{\mathfrak{Q}} = k\, \mathfrak{Q}_0$, or

$$\overline{\mathfrak{Q}} = 2\, k\, \rho\, \frac{2\, l + \pi\, \overline{b + c}}{p\, a\, c}\, n^2\, I^2 . \tag{1}$$

If the maximum current density is given,

$$\frac{n\, I}{p\, a\, c}$$

is known.

Thus if we write

$$\frac{n\, I}{p\, a\, c} = \delta ,—$$

the current density, in amperes per sq. cm., and

$$\frac{p\, a\, c}{n} = \sigma ,—$$

the cross-section of the primary wire,

$$\overline{\mathfrak{Q}} = 2\, k\, \rho\, p\, a\, c\, (2\, l + \pi\, \overline{b + c})\, \delta^2 \tag{2}$$

Again if V and V', be the primary and secondary voltages (V' is supposed on open circuit), f the frequency and φ the form factor of the primary or secondary potential difference waves, (being the same for both)—the form factor being defined as such that the mean value, of the volts taken positively, is φ times the root mean square of the volts,—then the greatest number (N) of lines of force passing through the core is

$$N = \frac{\varphi\, V}{4 f\, n} \times 10^8 .$$

Of course, if φ is not known we must assume the wave to be a sine wave and

$$\varphi = \frac{2\sqrt{2}}{\pi} .$$

Thus the induction, B, which is N divided by the area of iron in the cross-section of the magnetic circuit, is

$$B = \frac{\varphi\, V\, 10^8}{4 f\, n\, q'\, b\, l} .$$

And the hysteresis loss is $\eta\, B^{1.6}$ ergs per c. c. per cycle.

Thus the total maximum hysteresis loss of power is

$$H_0 = \text{volume of iron} \times \text{frequency} \times \eta\, B^{1.6} \text{ ergs per second.}$$

$$= 2\,q\,b\,l\,(a + b + c)\,f\,\eta\left(\frac{\varphi\ V\,10^8}{4\,f\,n\,q'\,b\,l}\right)^{1.6} \times 10^{-7} \text{ watts.}$$

The mean value ($\overline{H}$) of H is $j H_0$

$$\therefore \overline{H} = 2\,q\,\eta\,j\,f\,b\,l\,(a + b + c)\left(\frac{\varphi\ V\,10^8}{4\,f\,n\,q'\,b\,l}\right)^{1.6} \times 10^{-7} \text{ watts} \quad (3)$$

And if the maximum current density is prescribed, so that σ is known, and

$$n = \frac{p\ a\ c}{\sigma}$$

we shall have

$$\overline{H} = 2\,q\,\eta\,j\,f\,b\,l\,(a + b + c)\left(\frac{\varphi\,.\,V.\,10^8\,.\,\sigma}{4 f p\,q'\,a\,c\,b\,l}\right)^{1.6} \times 10^{-7} \text{ watts.} \quad (4)$$

The eddy-current loss varies as the square of the induction, as the square of the frequency, as the square of the thickness of the plates, and as the volume of iron. So that if t be the thickness of the plates, we may write the eddy-current loss (E)

$$E = \mathfrak{S}.\,2\,q\,b\,l\,(a + b + c)\,t^2 f^2\left(\frac{\varphi\,.\,V.\,10^8}{4 f\,n\,q'\,b\,l}\right)^2 \text{ watts.} \quad (5)$$

Where $\mathfrak{S}$ is a constant.

Dr. Fleming gives the constant $\mathfrak{S} = 10^{-16}$ when t is in mils, the volume in cu. cms. and E in watts.

If the maximum current density is given, so that

$$n = \frac{p\,a\,c}{\sigma},$$

we may write

$$E = \mathfrak{S}.\,2\,q\,b\,l\,(a + b + c)\,t^2 f^2\left(\frac{\varphi\,.\,V\,.10^8\,.\sigma}{4 f p\,q'\,a\,c\,b\,l}\right)^2 \text{ watts.} \quad (6)$$

XVII. *Applications of the expressions of the last section.*—

We will now apply the results of the last section in the finding of some of the constants used in the former part of the paper.

In § VI, quantities ω, h, and e, are introduced, and equations 1, 3, and 5, of the last section give us

$$\omega = 2\,k\,\rho\,\frac{2\,l + \pi\,\overline{b + c}}{p\,a\,c}\,I^2,$$

$$h = 2\,q\,\eta\,j\,f\,b.\,l.\,(a + b + c)\left(\frac{\varphi.\,V.10^8}{4\,f\,q'\,b\,l}\right)^{1.6} \times 10^{-7},$$

$$e = 2\,\mathfrak{E}\,q\,b\,l\,(a + b + c)\,t^2 f^2\left(\frac{\varphi.\,V.10^8}{4\,f\,q'\,b\,l}\right)^2$$

In § VIII, we are given the proportions of the core. Let a, b, c, and l, be proportional to the dimensions instead of the actual dimensions, then ω_1 h_1 and e_1 are given by the equations 2, 4, and 6, of the last article as follows:

$$\omega_1 = 2\,k\,\rho\,p\,a\,c\,[2\,l + \pi\,\overline{b + c}]\,\delta^2,$$

$$h_1 = 2\,q\,\eta\,j\,f\,b\,l\,(a + b + c)\left[\frac{\varphi.\,V.\,10^8\,.\sigma}{4\,f\,p\,q'\,a\,c\,b\,l}\right]^{1.6} \times 10^{-7},$$

$$e_1 = 2\,\mathfrak{E}\,q\,b\,l\,(a + b + c)\,t.^2 f.^2\left[\frac{\varphi.\,V.10^8\,.\sigma}{4\,f\,p\,q'\,a\,c\,b\,l}\right]^2.$$

And the number of turns of wire on the primary coil is given by

$$n = \frac{p\,a\,c}{\sigma}\,x^2,$$

where

$$x^{6.4} = 0.8\,\frac{h_1}{\omega_1}$$

In § X, the size of the core is given in terms of quantities H_1, Ω_1, E', and Ω', which can be found from equations 2, 4, and 6, of the last section as follows:

$$\Omega_1 = 2\,k\,\rho\,p\,\delta^2,$$

$$H_1 = 2\,q\,\eta\,j\,f\left\{\frac{\varphi\;V\,10^8\,\sigma}{4\,f\,p\,q'}\right\}^{1.6} \cdot 10$$

$$\mathfrak{Q}' = 2\,k\,\rho\,p\,\delta^2\,\frac{68}{7}\,\pi\,c^3 = 30.5\ \mathfrak{Q}_1\,c^3,$$

$$E' = 2\,\&\,q\,t^2 f^2 \left\{\frac{\varphi.\,V.\,10^8\,\sigma.}{4\,f\,p\,q'}\right\}^2 .\ \frac{30}{7}.\ \frac{9}{7}.\ \frac{9\,\pi}{7}.\ \left[2.\,\frac{9}{7}.\ \frac{9\,\pi}{7}\right]^{-2} c^{-5},$$

$$= 0.413\ \&\ q\ t^2 f^2 \left\{\frac{\varphi\,V\,10^8\,\sigma}{4\,f\,p\,q'}\right\}^2 c^{-5},$$

where c is given by

$$c^{6.4} = 0.0138\ \frac{H_1}{\mathfrak{Q}_1}.$$

The number of primary turns of wire is given by

$$n = \frac{p\,a\,c}{\sigma},$$

and the number of secondary terms is, of course,

$$n' = n.\ \frac{V'}{V}.$$

Thus we are able to find all the particulars of the transformer in the terms of known quantities.

XVIII. *Similar expressions for the core type of transformer.*—Some small alterations will be required in these results, when the transformer considered is of the core type. Let a, b, c, and l now refer to the dimensions of the transformer shown in Fig. 2.

The volume of iron is now $2\,q\,b\,l\,(a + c + 2\,b)$.

And the mean length of a turn of copper wire is now,

$$2\,l + \pi\left(b + \frac{c}{2}\right).$$

Thus, corresponding to the six equations of § XVI, we get:

$$\overline{\mathfrak{Q}} = 2\,k\,\rho\,\frac{2\,l + \pi\,\overline{b + \frac{c}{2}}}{p\ a\ c}\ n^2\,I^2 \qquad \ldots.1$$

$$\overline{\mathfrak{Q}} = 2\,k\,\rho\,p\,a\ c\left[\,2\,l + \pi\,\overline{b + \frac{c}{2}}\,\right]\delta^2, \qquad \ldots.2$$

$$\overline{H} = 2\,q\,\eta\,j\,f\,b\,l\,(a + c + 2\,b) \left\{ \frac{\varphi.\,V.\,10^8}{4\,f.q'.n.b.l} \right\}^{1.6} \times 10^{-7} \ldots.3$$

$$\overline{H} = 2\,q\,\eta\,j\,f\,b\,l\,(a + c + 2\,b) \left\{ \frac{\varphi.\,V.10^8.\sigma}{4\,f.q'.p.a.c.b.l} \right\}^{1.6} \times 10^{-7}, \ldots.4$$

$$E = 2\,\mathfrak{E}\,q\,b\,l\,(a + c + 2\,b)\,t^2.f^2 \left\{ \frac{\varphi.\,V.\,10^8.}{4.f.q'.n.b.l} \right\}^2, \ldots.5$$

$$E = 2\,\mathfrak{E}\,q\,b\,l\,(a + c + 2\,b)\,t^2 f^2 \left\{ \frac{\varphi.\,V.10^8\sigma}{4.f.q'.p.a.c\,b.l} \right\}^2 \ldots.6$$

Thus the quantities ω, h, and e, used in § VI, become, for a core transformer:

$$\omega = 2\,k\,\rho\,\frac{2\,l + \pi\,\overline{b + \frac{c}{2}}}{p\,a\,c}\,I^2$$

$$h = 2\,q\,\eta\,j\,f\,b\,l\,(a + c + 2\,b) \left(\frac{\varphi.\,V.10^8.}{4\,f\,q'\,b\,l} \right)^{1.6} \times 10^{-7},$$

$$e = 2\,\mathfrak{E}\,q\,b\,l\,(a + c + 2\,b) \left(\frac{\varphi\,V\,10^8}{4\,f\,q'\,b\,l} \right)^2 t^2 f^2.$$

The quantities ω_1, h_1, e_1, of § VIII now become

$$\omega_1 = 2\,k\,\rho\,p\,a\,c \left[2\,l + \pi\,\overline{b + \frac{c}{2}} \right] \delta^2,$$

$$h_1 = 2\,q\,\eta\,j\,f\,b\,l\,(a + c + 2\,b) \left\{ \frac{\varphi.\,V.10^8\,\sigma}{4\,f\,q'\,p\,a\,c\,b\,l} \right\}^{1.6} \times 10^{-7},$$

$$e_1 = 2\,\mathfrak{E}\,q\,b\,l\,(a + c + 2\,b) \left\{ \frac{\varphi\,V\,10^8\,\sigma}{4\,f\,q'\,p\,a\,c\,b\,l} \right\}^2 t^2 f^2,$$

and the number of turns of wire on the primary coil is given by

$$n = \frac{p\,a\,c}{\sigma}\,x^2, \qquad \text{where } x^{6.4} = 0.8\,\frac{h_1}{\omega_1}.$$

In this, it must be remembered that a, b, c, l, are proportional to the dimensions, instead of being the actual dimensions.

We next come to the core transformer of maximum efficiency discussed in § XI.

Here

$$H_1 = 2\,q\,\eta\,j\,f\,\left\{\frac{\varphi.\,V.\,10^8.\,\sigma}{4\,f\,q'\,p\cdot}\right\}^{1.6} \times 10^{-7},$$

$$\mathfrak{Q}_1 = 2\,k\,\rho\,p\,\delta^2,$$

$$\mathfrak{Q}' = 2\,k\,\rho\,p\,\delta^2 \times \frac{34}{7}\,\pi\,c^3 = 15.25\,\mathfrak{Q}_1\,c^3,$$

$$E^1 = 2\,\mathfrak{S}\,q\,t^2\,f^2\left\{\frac{\varphi.\,V.10^8.\sigma}{4.\,f\,q'\,p}\right\}^2 \times \frac{9}{14}\cdot\frac{9\pi}{14}\cdot\frac{60}{14}\left\{\frac{9}{14}\cdot\frac{9\pi}{14}\cdot 2\right\}^{-2} c^{-6},$$

$$= 1.65\,\mathfrak{S}\,q\,t^2\,f^2\left\{\frac{\varphi\,V\,10^8\,\sigma}{4\,f\,q'\,p}\right\}^2 c^{-6}.$$

Where c is given by

$$c^{6.4} = 0.0683\,\frac{H_1}{\mathfrak{Q}_1}$$

he number of turns of wire in the primary coil is given by

$$n = \frac{p\,a\,c}{\sigma},$$

and the number of turns in the secondary is of course

$$n' = n\,\frac{V'}{V}.$$

Thus the transformer of maximum efficiency is completely determined. (See also Appendix B).

XIX. *Remarks on some of the constants.*—Since the dimensions and particulars of the transformer designed as above are given by an equation of the form,—

$$c^{6.4} = \text{a known constant},$$

it follows that a small error in this constant will produce an error of only about a sixth of the amount in the linear dimensions; and, since the energy wasted is a minimum, a small error in any dimension will produce but a very small increase in this waste of energy.

In the expression for $c^{6.4}$, the constant involved to the highest power is that which we have called p, and this is raised to the

2.6th power. There should, however, be no difficulty in determining p, and, if care be taken to so choose it that there is plenty of room for insulation, it can hardly be said to be subject to error, as there is never any harm in putting a little more insulation in.

Some of the constants, such as k and φ, may not be determinable with any degree of accuracy, but they are worth determining as nearly as possible when the highest efficiency is sought. The difference in the power factor φ for a peaked wave, and for a square wave, for instance, may make as much as 20 per cent. difference in the iron losses.

The constant η, in the above formulæ, should be such that η times the 1.6th power of the maximum induction represent the hysteresis loss, in ergs per cu. cm. per cycle, at something like the right induction. I have preserved 1.6 as the index throughout as giving results sufficiently near for most practical purposes, and in order to obtain the definiteness given by numerical results as far as possible. Nevertheless, the index usually seems somewhat less than 1.6. Thus Ewing and Klassen[1] came across a specimen of transformer iron in which the index was about 1.475 over the range of induction usual in this work. Accordingly the results of this paper are worked out for a general value of the index in Appendices B. and C., and tables are given to facilitate the calculations for different values of the index.

XX. *Comparison with actual transformers.*—We will now show how transformers, designed according to the foregoing methods, compare with those at present in use. With this view, we will obtain the dimensions and particulars of transformers, having the same output, and working under the same conditions of voltage and frequency, as two of the transformers at the Central Technical College. Moreover, such constants as we want at starting, we will take precisely the same as obtain in these transformers, and, since the conditions of variations of load, under which the transformers were intended to work are not known, we will assume, if possible, that the transformers in question, are designed to best suit their all day load, that is, as shown in § IV, that the conditions of load are such that the average value of the ohmic loss, is equal to 0.8 times the average value of the hysteresis loss, together with the average value of the

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[1] Phil. Trans. Vol. 184, p. 1019.

eddy-current loss; and we will satisfy the same conditions of load in the transformers designed.

We will consider first, a five kilowatt Westinghouse transformer of recent type, and of the shell pattern. The particulars of the transformer are as follows:

Primary Voltage = 2,000.
Secondary Voltage = 100.
Frequency = 100.

Core

Thickness of plates (t) = 13.3 mils.
Thickness of insulation = 1.7 mils.
Hence $q = q' = 0.89$. (§ xv).
Number of plates 400.
Length of core (l Fig. 1) = 6 inches.
Breadth of core (b Fig. 1) = $3\frac{1}{4}$ inches.
Winding space ($a \times c$ Fig. 1) = $5\frac{3}{4} \times 3\frac{1}{4}$ square inches.
Volume of iron = 467 cubic inches, approximately.
Weight of iron = 130 lbs., approximately.

Coils

Primary. resistance 7.32 ohms.
Secondary, resistance 0.02 ohms.
Number of secondary turns = 48.
Mean length of a turn = 34 inches.
Area of cross-section of wire = 0.0595 sq. ins. = 0.383 sq. cm. Hence maximum current density = 840 amps. per sq. inch.
= 130.5 amps. per sq. cm.
Hence p,—the ratio of the total cross-section of copper in a coil, to the area of the winding pocket, is

$$\frac{48 \times 0.0595}{5.75 \times 3.25} = 0.153 \qquad (\S\ \text{xiv.})$$

The maximum induction is 3900 lines per sq. cm.
The losses appear to be proportioned as follows:

Maximum ohmic loss, 100 watts.
Maximum hysteresis loss, 79.5 watts.
Maximum eddy-current loss, 20.5 watts.

Hence the hysteretic constant

$$\eta = 0.00187.$$

and the eddy loss constant

$$\mathfrak{E} = 10^{-16}.$$

We are assuming that the mean ohmic loss is equal to 0.8 times the mean hysteresis loss, together with the eddy-current loss, and, assuming the mean hysteresis loss is 0.99 of the maximum, and the mean ohmic loss is k times the maximum, we have

$$k \times 100 = 0.8 \times 0.99 \times 79.5 + 20.5.$$

Whence $k = 0.835$, and $j = 0.99$. (§ XIII.)
Hence, using the same notation as in §§ X and XVII we have (See § XVII).

$$\mathfrak{Q}_1 = 2 \times 0.835 \times 1.85 \times 10^{-6} \times 0.153 \times 130.5^2,$$

$$= 8.04 \times 10^{-3},$$

$$H_1 = 2 \times 0.89 \times 0.00187 \times 0.99 \times 100$$

$$\left\{ \frac{100 \sqrt{2} \times 10^8 \times 0.383}{2\pi \times 100 \times 0.153 \times 0.89} \right\}^{1.6} \times 10^{-7},$$

$$= 9.98 \times 10^4.$$

$$\therefore c^{6.4} = 0.0138 \frac{9.98}{8.04} \times 10^7 = 1.714 \times 10^5,$$

$$c = 6.57 \textit{ cms.}$$

Again

$$E' = 0.413 \times 10^{-16} \times 0.89 \times 13.3^2 \times 10^4$$

$$\left\{ \frac{100 \sqrt{2} \times 10^8 \times 0.383}{2\pi \times 100 \times 0.153 \times 0.89} \right\}^2 c^{-5},$$

$$\mathfrak{Q}' = 30.5 \, \mathfrak{Q}_1 \, c^3,$$

$$\therefore \frac{E'}{\mathfrak{Q}'} = 0.31.$$

Hence

$$1 + 0.69 \frac{E'}{\mathfrak{Q}'} = 1.21,$$

$$1 - 0.036 \frac{E'}{\mathfrak{Q}'} = 0.989,$$

and the corrected values of l, a, b, and c, are:—

$$l = \frac{9}{7}\pi \times 6.57 \times 1.21 = 32.1 \text{ cms.}, = 12.6 \text{ inches.}$$

$$b = \frac{9}{7} \times 6.57 \times 1.21 = 10.21 \text{ cms.}, = 4.02 \text{ inches.}$$

$$a = 2 \times 6.57 \times 0.989 = 13.00 \text{ cms.} = 5.12 \text{ inches.}$$

$$c = 6.57 \times 0.989 = 6.5 \text{ cms.}, = 2.56 \text{ inches.}$$

Hence the number of turns in the low pressure coil is

$$n = \frac{0.153 \times 2 \times 6.50^2}{0.383},$$

$$= 34$$

The volume of iron is

$$2 \times 0.89 \times 4.02 \times 12.6 \times 11.7 \text{ cu. inches,}$$
$$= 1054 \text{ cu. inches.}$$

The weight of iron is

294 lbs.

The maximum ohmic loss is

$$2 \times 1.85 \times 10^{-6} \times 0.153 \times 13.0 \times 6.5 \times 116.7 \times 130.5^2,$$

$$= 94.8 \text{ watts.}$$

The mean ohmic loss is $94.8 \times 0.835 = 79.1$ watts.

The maximum induction in the iron is

$$\frac{10^8 \sqrt{2} \times 0.383}{2\pi \times 0.89 \times 0.153 \times 13 \times 6.5 \times 32.1 \times 10.21},$$

$$= 2290 \text{ lines per sq. cm.}$$

The eddy-current loss is

$$E = 10^{-16} \times \text{volume of iron} \times t^2 \times f^2 \times B^2,$$

$$= 10^{-16} \times 1054 \times 16.39 \times 13.3^2 \times 10^4 \times 2290^2,$$

$$= 16.0 \text{ watts.}$$

The maximum hysteresis loss is

$$H = 0.00187 \times 1054 \times 16.39 \times 100 \times [2290]^{1.6} \times 10^{-7},$$

$$= 76.8 \text{ watts.}$$

Hence the total loss at full load is,—

$$94.8 + 76.0 + 16.0 \text{ watts},$$

$$= 187 \text{ watts}.$$

against 199 watts in the Westinghouse transformer:—a saving of 12 watts, or about 6 per cent. of the total loss.

The mean loss is.

$$(79.1 + 0.99 \times 76.8 + 16) \text{ watts},$$

$$= 171.1 \text{ watts}.$$

Against $0.835 \times 100 + 0.99 \times 79.5 + 20.5$ watts

$$= 182.5 \text{ watts in the Westinghouse},$$

a saving of 11.4 watts or 6½ per cent of the total loss.

Thus, a transformer designed according to the principles here advocated wastes 11 or 12 watts less power than the Westinghouse transformer in question. It, however, requires more than twice the weight of iron, and about 5 per cent. less copper than the latter. (The amount of copper varies as the ohmic loss when the current density is given).

It must be said, however, that by adopting constants which hold in a transformer of very different proportions, we rather handicap ourselves. Thus, whilst we have less heat to dissipate, we have a greater radiating surface, and so might do with less ventilation space among the coils, and so with a larger value for p. This would reduce both the size of the transformer and its losses.

As shown in Appendix A, the losses could be reduced, without altering the size, by making the core plates thinner.

The thickness, for the maximum efficiency is, in this case, about 7 mils, (assuming the same thickness of core insulation, 1.7 mils). With this thickness, using the same constants as above, except that

$$q = \frac{7}{8.7} = 0.805$$

we shall have, just as before

$$c^{6.4} = 1.82 \times 10^5,$$

$$c = 6.64 \text{ cms.}$$

Again

$$\frac{E'}{\Omega'} = 0.087,$$

$$\therefore 1 + 0.69 \frac{E'}{\Omega'} = 1.060, \qquad 1 - 0.036 \frac{E'}{\Omega'} = 0.997,$$

$l = 28.4$ cms., $=$ 11.18 inches.
$a = 13.24$ cms., $=$ 5.20 inches.
$b = 9.05$ cms., $=$ 3.56 inches.
$c = 6.62$ cms., $=$ 2.60 inches.

The volume of iron is 726 cu. inches; and its weight is 202 lbs.

The induction is 3130 lines per sq. cm.

The number of turns of wire on the low pressure coil is 35.

The maximum ohmic loss is 89.5 watts.

The eddy-current loss is 5.7 watts.

The maximum hysteresis loss is 87.4 watts.

The maximum total loss is

$$89.5 + 86.5 + 5.6 \text{ watts.}$$
$$= 181.6 \text{ watts.}$$

thus wasting 17½ watts, (8¾%) less than the Westinghouse transformer.

The mean loss is 167 watts,—15.5 watts less than the Westinghouse apparatus.

Thus we see that we save about 8¾ per cent. of the energy but our transformer has 202 lbs. of iron instead of 130 lbs. and 55 lbs. of copper instead of 61 lbs. We should however expect the transformer so designed to keep cooler than the Westinghouse as it has less heat to dissipate and a greater radiating surface. Thus it will better stand an overload. Its regulation, moreover, should be better, for the same subdivision of the coils, both because the copper losses are less, and that the magnetic leakage is very much smaller.

We shall next find the particulars of a transformer, designed as above, and having, as far as possible, the same constants as a certain "Mordey Victoria" transformer at the Central Technical College.

The transformer in question is of the shell pattern and intended to convert three kilowatts from a pressure of 2,000 volts, to a pressure of 100 volts. The particulars of it are as following:—

Core

Thickness of core plates = 15 mils.
Ratio of volume of iron to total volume of core = 0.89 (= q).
Thickness of insulation between plates = 1.85 mils.
Length of core (l Fig. 1) = 52 cms. = 20½ inches.
Breadth of magnetic circuit (b Fig. 1) = 7.62 cms. = 3 inches.
Winding space ($a \times c$ Fig. 1) = 7.62 × 3.81 sq. cms. = 3 × 1½ sq. ins.
Volume of iron = 820 cubic inches, } approximately.
Weight of iron = 230 lbs . }
Hysteresis constant, (η), (with index 1.6) = 0.0020.
Eddy-current constant ($\mathcal{E}$) = 0.95×10^{-16}.

Coils.

Primary, 456 convolutions, 8.8 ohms resistance.
Secondary, 24 convolutions, 0.033 ohms resistance.
Cross-section of strips of secondary coils = 0.0316 sq. ins. = 0.204 sq. cms.
Hence maximum current density = 950 amps. per sq. inch,
= 147 amps. per sq. cms.,
and ratio of cross-section of copper in the secondary coil to the total area of winding pocket (p) = 0.169.
The total weight of copper is about 29 lbs.
The normal frequency is 100, and we shall assume the applied P. D. to follow a sine law. Thus $\phi = 2\sqrt{2} \div \pi$.

In the Mordey transformer the induction, when working normally, is 2670 lines per sq. cm.

The maximum ohmic loss is 60 watts.
The maximum hysteresis loss is 81.5 watts.
The maximum eddy-current loss is 20.5 watts.

Thus we see that it is impossible to make the mean ohmic loss equal to 0.8 times the hysteresis loss, together with the eddy-current loss, as the maximum ohmic loss is already less than the mean should be. I shall assume, therefore, that the transformer has been designed to work always at full load, this being as favorable as possible to the Mordey transformer.

Hence $k = 1$,

and we will assume $j = 0.985$. (§ XIII).

Thus we have (§ XVII).

$$\mathcal{Q}_1 = 2 \times 1.85 \times 10^{-6} \times 0.169 \times 147^2,$$

$$= 1.35 \times 10^{-2}.$$

$$H_1 = 2 \times 0.89 \times 0.002 \times 0.985 \times 100 \left\{ \frac{\sqrt{2} \times 10^8 \times 0.204}{2\,\pi \times 0.169 \times 0.89} \right\}^{1.6} \times 10^{-7},$$

$$= 3.31 \times 10^4.$$

$$c^{6.4} = 0.0138 \frac{H_1}{Q_1'},$$

$$= 3.381 \times 10^4,$$

$$\therefore c = 5.10 \textit{ cms.}$$

$$E' = 7.31 \times 10^4 c^{-5},$$

$$Q' = 4.12 \times 10^{-1} c^3,$$

$$\frac{E'}{Q'} = 0.394,$$

$$1 + 0.69 \frac{E'}{Q'} = 1.271,$$

$$1 - 0.036 \frac{E'}{Q'} = 0.986.$$

Hence the corrected values of the linear dimensions are:

l = 26.1 cms., = 10.25 inches.
b = 8.31 cms., = 3.27 inches.
a = 10.02 cms., = 3.95 inches.
c = 5.01 cms., = 1.97 inches.

Volume of iron

$$= 2\,q.\,b.\,l.\,(a + b + c),$$

$$= 550 \text{ cu. inches.}$$

Weight of iron = 153 lbs.

Volume of copper.

$$= 2\,p\,a\,c\,(2\,.\,l + \pi\,\overline{b + c}),$$

$$= 97.1 \text{ cubic inches.}$$

Weight of copper = 30.9 lbs.
The number of turns of wire in the secondary coil is

$$n = \frac{p\,a\,c}{\sigma} = \frac{0.169 \times 10.02 \times 5.01}{0.204} = 42.$$

Maximum ohmic loss (§ xvi).

$$1.85 \times 10^{-6} \times 97.1 \times 16.39 \times 147^2,$$
$$= 63.6 \text{ watts.}$$

The maximum induction = 2810 lines per sq. cm.
Hence

$$\text{Maximum hysteresis loss} = 59.3 \text{ watts.}$$
$$\text{Eddy-current loss} = 15.2 \text{ watts.}$$

Hence the mean total loss

$$= 63.6 + 58.4 + 15,$$
$$= 137 \text{ watts.}$$

against 160.5 watts in the Mordey transformer.

Thus there is a saving of 23½ watts by designing the transformer so as to have a maximum efficiency. This is accompanied by an increase of weight of copper of nearly 2 lbs. and a decrease of weight of iron of about 77 lbs.

We will next find what the particulars of the transformer would have been, if the plates had been 7½ mils thick,—which thickness about gives minimum iron loss, with the given thickness, (1.85 mils), of core insulation. (Appendix A). This thickness of core plate gives $q = 0.803$.

We will also assume, (which is true for the iron of the Mordey transformer over a considerable range of induction), that the hysteresis loss per cubic cm. per cycle is equal to 0.00251 times the 1.57th power of the induction. (Appendix B).
Thus

$$\frac{H_1}{\Omega_1} = 2.94 \times 10^{-6}\,(3.39 \times 10^7)^{1.57}, \qquad (\S\,\text{xvii})$$

$$c^{6.28} = 0.0165\,\frac{H_1}{\Omega_1},$$

$$= 4.85 \times 10^{-8}\,(3.39 \times 10^7)^{1.57},$$

$$c = (4.85 \times 10^{-8})^{\frac{1}{6.28}} \times (3.39 \times 10^7)^{\frac{1}{4}},$$

$$= 5.22 \text{ cms.}$$

$$\therefore b = 6.24 \text{ cms.,—[Table I, Appendix B.]}$$
$$a = 10.45 \text{ cms.,}$$
$$l = 19.60 \text{ cms.}$$

These are the first approximations to a, b, c, and l, uncorrected for the effects of eddy-currents.

Again

$$E' = 5.9 \text{ watts,}$$

and

$$Q' = 55.4 \text{ watts.}$$

$$\therefore \frac{E'}{Q'} = 0.107,$$

and

$$1 + 0.75 \frac{E'}{Q'} = 1.08, \quad 1 - 0.047 \frac{E'}{Q'} = 0.995, \quad \text{[Appendix C].}$$

Hence the corrected values of the dimensions are:

$$a = 10.45 \times 0.995 = 10.40 \text{ cms.,} = 4.09 \text{ inches,}$$
$$c = 5.22 \times 0.995 = 5.20 \text{ cms.,} = 2.04 \text{ inches.}$$
$$b = 6.24 \times 1.08 = 6.73 \text{ cms.,} = 2.65 \text{ inches.}$$
$$l = 19.60 \times 1.08 = 21.20 \text{ cms.,} = 8.35 \text{ inches.}$$

Hence the volume of iron

$$= 0.803 \times 2 \times 2.65 \times 8.35 \times 8.78 \text{ cu. ins.,}$$
$$= 312 \text{ cubic inches.}$$

Weight of iron = 87 lbs.

Induction of iron

$$= \frac{3.39 \times 10^7}{10.4 \times 5.2 \times 6.73 \times 21.2} = 4400 \text{ lines per sq. cm.}$$

Maximum hysteresis loss

$$= 0.00251 \times 312 \times 16.39 \times 100 \times (4400)^{1.57} \times 10^7,$$
$$= 67.2 \text{ watts.}$$

Eddy-current loss.

$$= 0.95 \times 10^{-16} \times 312 \times 16.39 \times 10^4 \times 7.5^2 \times 4400^2,$$
$$= 5.3 \text{ watts.}$$

Maximum ohmic loss

$$= 2 \times 1.85 \times 10^{-6} \times 0.169 \times 10.40 \times 5.20 \times 79.9 \times 147^2,$$
$$= 58.3 \text{ watts.}$$

Hence the full load total loss is

$58.3 + 66.2 + 5.2 = 129.7$ watts, against 160.5 watts in the Mordey transformer.

Volume of copper 89.1 cubic inches.
Weight of copper 28.4 lbs.

Number of turns of wire in secondary coil is

$$n = \frac{0.169 \times 5.2 \times 10.4}{0.204} = 45.$$

Thus this transformer, running always at full load, wastes 31 watts, (nearly 20 per cent.) less power than the Mordey, whilst there is almost 1 lb. less copper, and about 143 lbs. less iron used in its construction. The Mordey transformer in fact, can claim an advantage in only one important particular, viz.:—that its radiating surface is proportionately larger, so that it should keep cooler. Had we taken a lower maximum current density, however, we should have increased the surface, and diminished the wasted energy, and so we could have designed a transformer better than the Mordey in every particular of moment.

It may be mentioned that the Mordey transformer is an older apparatus than the Westinghouse, and the type has doubtless been improved since the time of its manufacture.

The following table exhibits the particulars of the transformers considered in convenient form, and enables a comparison to be made between them without difficulty. They are numbered 1, 2, 3, 4, 5, 6, in the order in which they are discussed above.

TRANSFORMER.	1.	2.	3.	4.	5.	6.
Output in kilowatts	5	5	5	3	3	3
Primary P. D., (V) in volts	2000	2000	2000	2000	2000	2000
Secondary P. D., (V') in volts	100	100	100	100	100	100
Frequency of alternations, (f) in periods per second	100	100	100	100	100	100
Power factor of primary P. D wave (φ)	$\sqrt{2} + \pi$	$2\sqrt{2} + \pi$	$2\sqrt{2} + \pi$	$2\sqrt{2} + \pi$	$2\sqrt{2} + \pi$	$2\sqrt{2} + \pi$
Maximum secondary current, (I') in amperes	50	50	50	30	30	30
Cross-section of secondary wire, (σ) in sq. cms	0.383	0.383	0.383	0.204	0.204	0.204
Maximum current density, (δ) in amperes per sq. cm.	130.5	130.5	130.5	147	147	147
Number of convolutions (n') in the secondary	48	34	35	24	42	45
Value adopted for specific resistance of copper, (ρ) microhms per cm. cube	1.85	1.85	1.85	1.85	1.85	1.85
Ratio of volume of *wire* in secondary to total winding space (p)	0.153	0.153	0.153	0.169	0.169	0.169
Ratio of mean to maximum ohmic loss, (k)	0.835	0.835	0.835	1	1	1
Ratio of mean to maximum hysteresis loss, (j)	0.99	0.99	0.99	0.985	0.985	0.985
Hysteretic constant, (η)	0.00187	0.00187	0.00187	0.0020	0.0020	0.00251
Index occurring in Steinmetz formula for hysteresis loss, (ϵ)	1.6	1.6	1.6	1.6	1.6	1.57
Eddy-current constant, ($\ddot{\epsilon}$)	10^{-16}	10^{-16}	10^{-16}	0.95×10^{-16}	0.95×10^{-16}	0.95×10^{-16}
Thickness of core plates, (t) in mils	13.3	13.3	7	15	15	7.5
Thickness of insulation between core plates, (t') in mils	1.7	1.7	1.7	1.85	1.85	1.85
Ratio of volume of iron to that of core, ($q = t + t + t'$)	0.89	0.89	0.805	0.89	0.89	0.803
l, (Fig. 1) in inches	6	12.6	11.18	20.5	10.25	8.35
a, (Fig. 1) in inches	5.75	5.12	5.20	3	3.95	4.09
b, (Fig. 1) in inches	3.5	4.02	3.56	3	3.27	2.65
c, (Fig. 1) in inches	3.25	2.56	2.60	1.5	1.97	2.04
Maximum ohmic loss, (Q) in watts	100	94.8	89.5	60	63.6	58.3
Maximum hysteresis loss, (H), in watts	79.5	76.8	87.4	81.5	59.3	67.2
Maximum eddy-current loss, (E), in watts	20.5	16.0	5.7	20.5	15.2	5.3
Maximum total loss, in watts	199	187	181.6	160.5	137	129.7
Mean total loss, in watts	182.5	171.1	167	160.5	137	129.7
Magnetic induction in iron, in lines per sq. cm	3900	2290	3130	2670	2810	4400
Weight of copper, in lbs	61.5	58.5	55	29.2	30.9	28.4
Weight of iron, in lbs	130	294	202	230	153	87
Drop of secondary voltage at full load, due to copper losses only, in volts	2	1.9	1.79	2	2.12	1.95
Radiating surface per watt wasted, at full load, in sq inches	3.75	5.3	4.9	5.0	4.6	3.85

APPENDIX A.

The Best Thickness of Core Plates

Wherever we have had occasion to discuss the effects of eddy-currents on our design, we have assumed the energy wasted by them to be small compared with the other losses. But as, in many cases, the eddy-current loss of energy is a considerable fraction of the total iron loss it will not perhaps be thought out of place to discuss whether it is better so than small.

Professors J. J. Thomson and Ewing[1] have discussed the subject of the energy wasted by the eddy-currents in transformer plates, and included the effect on the hysteresis loss of the screening action of the eddy-currents.

They conclude that this latter action is practically negligible when the plates are no more than 20 mils thick, and as transformer plates are usually thinner than this, we shall neglect it in our investigations. The professors show the value of effective lamination, and Professor Ewing points out that the limit of thinness is determined by the consideration that, if the plates are too thin, the core will either have to be larger or to be worked at a higher induction than is consistent with small hysteresis loss.

The following investigation is made with a view to determine the thickness of plate which will make the total iron loss a minimum. We shall assume that the core has a definite size and shape, and that the thickness (t') of insulation between core plates is given, as also the total number of lines of force (N) in the magnetic circuit.

Let v be the volume of the core, including insulation, A the area of cross-section of the magnetic circuit, also including insulation, f the frequency, and t the thickness of the core plates.

Then the volume of iron is $\frac{t}{t+t'}\, v$,

The area of the iron portion of the cross-section of the magnetic circuit is $\frac{t}{t+t'}\, A$.

The induction in the iron is $\dfrac{N}{\dfrac{t}{t+t'}\, A}$

Hence the hysteresis loss is

$$\eta\, \frac{t}{t+t'}\, v . f . \left[\frac{N}{\dfrac{t}{t+t'}\, A} \right]^{1.6} \times 10^{-7} \text{ watts,}$$

---

[1] See *London Electrician*, volume xxviii.

and the eddy-current loss is

$$\mathfrak{E}\,\frac{t}{t+t'}\,v f^2 t^2 \left[\frac{N}{\frac{t}{t+t'}\,A}\right]^2 \text{ watts.}$$

Putting $\frac{t}{t+t'} = q$, as in § xv

$$t = \frac{q}{1-q}\,t',$$

the total iron loss is

$$f v \left\{ \eta\, q \left(\frac{N}{qA}\right)^{1.6} \times 10^{-7} + \mathfrak{E}\, q f \frac{q^2\, t'^2}{(1-q)^2} \left(\frac{N}{qA}\right)^2 \right\} \text{ watts.}$$

Thus, if q is such as to make the iron loss a minimum.

$$-\,0.6\,\eta\, q^{-1.6}\, 10^{-7} + \mathfrak{E}\, f \frac{q}{(1-q)^2}\, t'^2\, B^{0.4} \left[\frac{1}{q} + \frac{2}{1-q}\right] = 0,$$

$$\text{where } B = \frac{N}{A},\text{—}$$

the average induction through the area A.

Thus

$$0.6\,\eta\, q^{-1.6}\, 10^{-7} = \mathfrak{E}\, f\, t'^2\, B^{0.4}\, \frac{1+q}{(1-q)^3},$$

or

$$\frac{(1-q)^3}{q^{1.6}(1+q)} = \frac{\mathfrak{E}}{0.6.\eta}\, f\, t'^2\, B^{0.4}\, 10^7.$$

This gives q

We shall best find q by plotting a curve having q as ordinate, and

$$\frac{(1-q)^3}{q^{1.6}(1+q)}$$

as abscissa, (Fig. 4) and obtaining q from the curve.

With ordinary values for the constants we shall find that q is less than the value which usually obtains, and except for low frequencies, t is usually less than the 10 mils which appears to be about the inferior limit of thickness at present used.

Thus if

$$\mathfrak{S} = 10^{-16}, \quad f = 100, \quad \eta = 0.002,$$

$$B = 2500, \quad t' = 3 \text{ mils},$$

$$\frac{(1-q)^3}{q^{1.6}(1+q)} = \frac{10^{-16} \times 100 \times 3^2 \times (2500)^{0.4} \times 10^7}{0.6 \times 0.002},$$

$$= 0.01706.$$

Hence from the curve

$$q = 0.737,$$

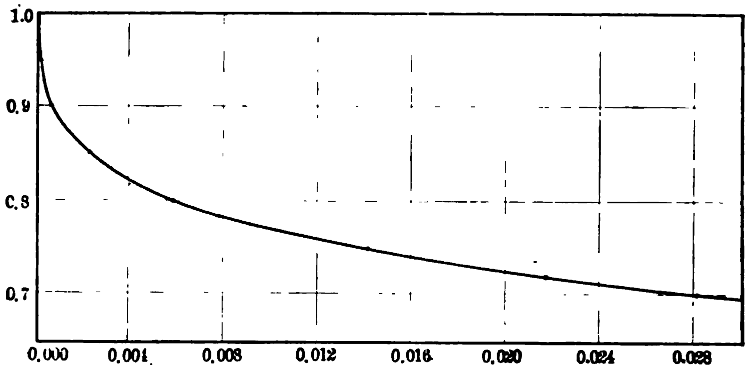

Fig. 4

thus

$$1 - q = 0.263,$$

and

$$t = \frac{737}{263} \times 3 \text{ mils},$$

$$= 8.4 \text{ mils}.$$

The induction is

$$\frac{2500}{0.737} = 3400 \text{ lines per sq. cm.}$$

Thus we see that both q and t are smaller than is usual.

If $t' = 2$ mils

$$\frac{(1-q)^3}{q^{1.6}(1+q)} = 0.00759.$$

Whence

$$q = 0.79,$$

$$1 - q = 0.21,$$

$$t = \frac{79}{21} \times 2 \text{ mils.}$$

$$= 7.5 \text{ mils.}$$

The induction is

$$\frac{2500}{0.79} = 3170 \text{ lines per sq. cm.}$$

Again suppose

$$B = 2000, \quad f = 50, \quad t' = 1.5 \text{ mils,}$$

$$\mathfrak{S} = 10^{-16}, \quad \eta = 0.002,$$

then

$$\frac{(1-q)^3}{q^{1.6}(1+q)} = 0.00196,$$

$$\therefore q = 0.857,$$

$$1 - q = 0.143,$$

$$t = \frac{857}{143} \times 1.5 \text{ mils} = 8.9 \text{ mils.}$$

And the induction is

$$\frac{2000}{0.857} = 2340 \text{ lines per sq. cm.}$$

t is of course the thickness of iron, and t' the distance between the iron of consecutive plates, so that it should include a little for rugosities of surface.

It thus appears that, with the same sized core and the same total flux, the diminution of hysteresis loss due to using plates, say 14 mils thick as against thinner ones, does not balance the increase of eddy-current loss, and to ensure minimum iron loss, the plates should be considerably thinner than is usual at present.

APPENDIX B.

CALCULATIONS FOR THE TRANSFORMER OF MAXIMUM EFFICIENCY

We will here give a more extended treatment of the solution of the equations of § x, in which, however, we will assume that the hysteresis loss varies as the εth power of the induction, in order to see how the proportions obtained depend on the index of this power.

The problem is, to make $\mathcal{C} + H + E$ a minimum, subject to the condition

$$\mathcal{C} = \frac{\varepsilon}{2} H + E,$$

where

$$\mathcal{C} = \mathcal{C}_1 \, a \, c \, (2 \, l + \pi \, \overline{b + c}),$$

$$H = H_1 \, (a + b + c) \, (a \, c)^{-\varepsilon} \, (b \, l)^{-\varepsilon + 1},$$

$$E = E_1 \, (a + b + c) \, (a \, c)^{-2} \, (b \, l)^{-1},$$

Thus, if W be the total energy wasted,

$$W = \mathcal{C} + H + E,$$

$$= \mathcal{C} + H + E + K \left(\mathcal{C} - \frac{\varepsilon}{2} H - E\right),$$

$$= \mathcal{C} \, (1 + K) + H \left(1 - \frac{\varepsilon}{2} K\right) + E \, (1 - K)$$

Thus

$$\frac{\delta W}{\delta l} = \frac{2}{2 \, l + \pi \, \overline{b + c}} (1 + K) \, \mathcal{C} + \frac{1 - \varepsilon}{l} \left(1 - \frac{\varepsilon}{2} K\right) H$$

$$- \frac{1}{l} (1 - K) \, E = 0,$$

or

$$\frac{2}{2\,l+\pi\,\overline{b+c}}\,(1+K)\;\Omega=\frac{\varepsilon-1}{l}\left(1-\frac{\varepsilon}{2}\,K\right)H$$

$$+\frac{1}{l}\,(1-K)\;E.$$

$$\frac{\delta\,W}{\delta\,a}=\frac{1}{a}\,(1+K)\;\Omega+\left(\frac{1}{a+b+c}-\frac{\varepsilon}{a}\right)\left(1-\frac{\varepsilon}{2}\,K\right)H$$

$$+\left(\frac{1}{a+b+c}-\frac{2}{a}\right)(1-K)\;E=0$$

or

$$\frac{1}{a}\,(1+K)\;\Omega=\frac{\varepsilon\,\overline{b+c}+\overline{\varepsilon-1}\,a}{a\,(a+b+c)}\left(1-\frac{\varepsilon}{2}\,K\right)H$$

$$+\frac{2\,\overline{b+c}+a}{a\,(a+b+c)}\,(1-K)\;E$$

$$\frac{\delta\,W}{\delta\,b}=\frac{\pi}{2\,l+\pi\,\overline{b+c}}\,(1+K)\;\Omega+\left(\frac{1}{a+b+c}-\frac{\varepsilon-1}{b}\right)$$

$$\left(1-\frac{\varepsilon}{2}\,K\right)H+\left(\frac{1}{a+b+c}-\frac{1}{b}\right)(1-K)\;E=0,$$

or

$$\frac{\pi}{2\,l+\pi\,\overline{b+c}}\,(1+K)\;\Omega=\frac{(\varepsilon-1)\,(a+c)-(2-\varepsilon)\,b}{b\,(a+b+c)}$$

$$\left(1-\frac{\varepsilon}{2}\,K\right)H+\frac{a+c}{b\,(a+b+c)}\,(1-K)\;E.$$

$$\frac{\delta\,W}{\delta\,c}=\left(\frac{\pi}{2\,l+\pi\,\overline{b+c}}+\frac{1}{c}\right)(1+K)\;\Omega+\left(\frac{1}{a+b+c}-\frac{\varepsilon}{c}\right)$$

$$\left(1-\frac{\varepsilon}{2}\,K\right)H+\left(\frac{1}{a+b+c}-\frac{2}{c}\right)(1-K)\;E=0,$$

or

$$\frac{2\,l + \pi\,\overline{b + 2\,c}}{c\,(2\,l + \pi\,\overline{b + c})}(1 + K)\,\mathfrak{Q} = \frac{\varepsilon\,\overline{a + b} + \overline{\varepsilon - 1}\,c}{c\,(a + b + c)}$$

$$\left(1 - \frac{\varepsilon}{2}\,K\right) H + \frac{2\,(a + b) + c}{c\,(a + b + c)}\,(1 - K)\,E.$$

Neglecting E for the time, these four equations can be written:

$$\frac{(1 + K)\,\mathfrak{Q}}{\left(1 - \frac{\varepsilon}{2}\,K\right)H} = \frac{(\varepsilon - 1)(2\,l + \pi\,\overline{b + c})}{2\,l} = \frac{\varepsilon\,\overline{b + c} + \overline{\varepsilon - 1}\,.\,a}{a + b + c}$$

$$= \frac{(2\,l + \pi\,\overline{b + c})\,(\overline{\varepsilon - 1}\;\overline{a + c} - \overline{2 - \varepsilon}\,b)}{\pi\,b\,(a + b + c)}$$

$$= \frac{(2\,l + \pi\,\overline{b + c})\,(\varepsilon\,\overline{a + b} + \overline{\varepsilon - 1}\,c)}{(2\,l + \pi\,b + 2\,c)\,(a + b + c)}$$

If for shortness, we write these

$$\frac{(1 + K)\,\mathfrak{Q}}{\left(1 - \frac{\varepsilon}{2}\,K\right)H} = [1] = [2] = [3] = [4],$$

from [1] = [3] we get

$$l = \frac{\varepsilon - 1}{2}\,\pi\,\frac{b\,(a + b + c)}{(\varepsilon - 1)\,(a + c) - \overline{2 - \varepsilon}\,b}, \qquad (1)$$

Substituting for l in the equation [1] = [4] we get

$$(\varepsilon - 1)\,b\,(a + b + c) + (b + 2\,c)\,[(\varepsilon - 1)\,(a + c) - \overline{2 - \varepsilon}\,b]$$

$$= b\,(\varepsilon\,\overline{a + b} + \overline{\varepsilon - 1}\,c),$$

or

$$2\,\overline{\varepsilon - 1}\,.\,c\,.\,\overline{a + c} = b\,(\overline{2 - \varepsilon}\,a + \overline{3 - \varepsilon}\,b + \overline{5 - 3\,\varepsilon}\,c). \qquad (2)$$

Again, from [1] = [2] we get, substituting for l from 1,

$$\frac{(\varepsilon-1)\,\pi\,\{\,\overline{e-1}\,b\,(a+b+c) + (b+c)\,(\overline{\varepsilon-1}\;\overline{a+c} - \overline{2-\varepsilon}\,b)\,\}}{(\varepsilon-1)\,\pi\,b\,(a + b + c)}$$

$$= \frac{\varepsilon\,\overline{b + c} + \overline{\varepsilon - 1}\,a}{a + b + c},$$

or

$$(\varepsilon - 1)\, b\, (a + b + c) + (b + c)\, (\overline{\varepsilon - 1}\ \overline{a + c} - \overline{2 - \varepsilon}\, b)$$
$$= b\, (\, \varepsilon\, \overline{b + c} + \overline{\varepsilon - 1}\, a),$$

or

$$\{\, (\varepsilon - 1)\, (a + c) - (3 - 2\, \varepsilon)\, b - \varepsilon\, b \,\}\, (b + c) = 0,$$

or

$$(3 - \varepsilon)\, b = (\varepsilon - 1)\, (a + c).$$

$$\therefore b = \frac{\varepsilon - 1}{3 - \varepsilon}\, (a + c)\, .$$

Hence, substituting for b in 2,

$$2\, (\varepsilon - 1)\, c = \frac{\varepsilon - 1}{3 - \varepsilon}\, [\overline{2 - \varepsilon}\, a + \overline{\varepsilon - 1}\ \overline{a + c} + \overline{5 - 3\, \varepsilon}\, c],$$

or

$$a = 2\, c.$$

Whence

$$b = \frac{\varepsilon - 1}{3 - \varepsilon} .3\, c,$$

and substituting in 1, we get

$$l = \frac{\varepsilon - 1}{2}\, \pi\, \frac{\frac{\varepsilon - 1}{3 - \varepsilon}\, 3 \left[2 + \frac{\varepsilon - 1}{3 - \varepsilon}\, 3 + 1 \right] c}{\overline{\varepsilon - 1}\, .3 - \overline{2 - \varepsilon}\, \frac{\varepsilon - 1}{3 - \varepsilon}\, 3},$$

$$= \frac{\varepsilon - 1}{3 - \varepsilon}\, .\, 3\, \pi\, c.$$

Whence

$$\frac{l}{3\, \pi\, \overline{\varepsilon - 1}} = \frac{a}{2\, \overline{3 - \varepsilon}} = \frac{b}{3\, \overline{\varepsilon - 1}} = \frac{c}{3 - \varepsilon}\, .$$

K is given by

$$\frac{(1 + K)\, \mathcal{Q}}{\left(1 - \frac{\varepsilon}{2}\, K\right) H} = \frac{(1 + K)\, \frac{\varepsilon}{2}\, H}{\left(1 - \frac{\varepsilon}{2}\, K\right) H} = \left[1\right]$$

$$= \frac{(\varepsilon - 1)\, (\, 6\, \overline{\varepsilon - 1} + 3\, \overline{\varepsilon - 1} + 3 - \varepsilon)}{6\, \overline{\varepsilon - 1}} = \frac{8\, \varepsilon - 6}{6},$$

$$\therefore \frac{(1 + K)\, \frac{\varepsilon}{2}}{1 + \frac{\varepsilon}{2}} = \frac{8\, \varepsilon - 6}{8\, \varepsilon},$$

$$\therefore K = \frac{(4\,\varepsilon - 3)\left(1 + \frac{\varepsilon}{2}\right)}{2\,\varepsilon^2} - 1 = \frac{5\,\varepsilon - 6}{4\,\varepsilon^2}.$$

We thus see that $l = \pi\, b$ and $a = 2\ c$ in general, but the ratio of b to c depends on ε, varying from 0.87 when $\varepsilon = 1.45$ to 1.45 when $\varepsilon = 1.65$.

For transformer iron ε seems, as a rule to lie between 1.5 and 1.6, for the range of the induction over which transformers are worked.

The following table gives the ratio of b to c, and the value of $\frac{\Omega_1}{H_1}\ c^{4\,\varepsilon}$ for different values of ε

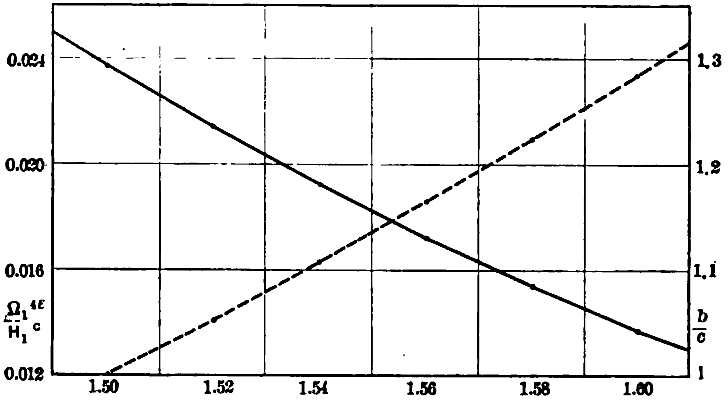

Fig. 5

TABLE I. (Fig. 5).

$\varepsilon =$	1.50	1.52	1.54	1.56	1.58	1.60
$\frac{b}{c} =$	1.000	1.054	1.110	1.167	1.225	1.286
$\frac{\Omega_1}{H_1}\ c^{4\varepsilon} =$	0.0238	0.0215	0.0193	0.0174	0.0155	0.0138

Where now

$$\Omega_1 = 2\,k\,\rho\,p\,\delta^2.$$

$$H_1 = 2\,q\,\eta\,j\,f\left\{\frac{\varphi.\,V.\,10^8.\sigma}{4\,f\,p\,q'}\right\}^{\varepsilon} \times 10^{-7}.$$

(§ XVII.)

These, together with the above table, and the relations $l = \pi\ b$ $a = 2c$, give us the first approximation to the dimensions of the core of the shell transformer which gives minimum losses.

A similar investigation will give us, for a transformer of the core type, (as in § XI).

$$\frac{l}{3\pi(\varepsilon-1)} = \frac{a}{4(3-\varepsilon)} = \frac{b}{3(\varepsilon-1)} = \frac{c}{2(3-\varepsilon)}$$

The following table gives us the ratio of b to c, and the value of $\frac{\Omega_1}{H_1} c^{4\varepsilon}$ for different values of ε, for this case.

TABLE II. (FIG. 6.)

$\varepsilon =$	1.50	1.52	1.54	1.56	1.58	1.60
$\frac{b}{c} =$	0.500	0.527	0.555	0.583	0.613	0.643
$\frac{\Omega_1}{H_1} c^{4\varepsilon} =$	0.0952	0.0884	0.0818	0.0756	0.0694	0.0633

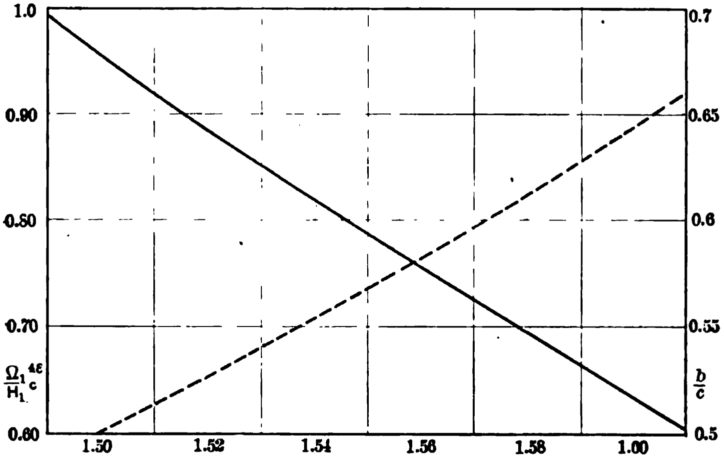

Fig. 6

Where Ω_1 and H_1 have the same values as the preceding case. (See also § XVIII).

If two specimens of transformer iron give about the same hysteresis loss at the same usual induction, (say 3000 lines per sq. cm.), and in one, ε is larger than in the other, it will be found that if transformers be designed, by the above methods to suit the iron, that in which ε is smallest will have least weight. The amounts of copper in the two transformers will not be very different, neither will the waste of energy, but the suitable amount of iron will be smaller when ε is smaller. The radiating surface will also be smaller, so that this transformer would get hotter, if both were used similarly.

APPENDIX C.

EFFECT OF EDDY-CURRENTS.

The equations

$$\frac{\delta W}{\delta l} = 0, \quad \frac{\delta W}{\delta a} = 0, \quad \frac{\delta W}{\delta b} = 0, \quad \frac{\delta W}{\delta c} = 0,$$

of Appendix B are,—

$$\frac{2}{2\,l + \pi\,\overline{b + c}}(1 + K)\,\Omega - \frac{\varepsilon - 1}{l}\left(1 - \frac{\varepsilon}{2}K\right) H - \frac{1}{l}(1 - K)\,E = 0, \quad \ldots .1$$

$$\frac{1}{a}(1 + K)\,\Omega - \left(\frac{\varepsilon}{a} - \frac{1}{a + b + c}\right)\left(1 - \frac{\varepsilon}{2}K\right) H - \left(\frac{2}{a} - \frac{1}{a + b + c}\right)(1 - K)\,E = 0, \quad \ldots .2$$

$$\frac{\pi}{2\,l + \pi\,\overline{b + c}}(1 + K)\,\Omega - \left[\frac{\varepsilon - 1}{b} - \frac{1}{a + b + c}\right] \left[1 - \frac{\varepsilon}{2}K\right] H - \left[\frac{1}{b} - \frac{1}{a + b + c}\right](1 - K)\,E = 0, \quad \ldots .3$$

$$\left[\frac{\pi}{2\,l + \pi\,\overline{b + c}} + \frac{1}{c}\right](1 + K)\,\Omega - \left[\frac{\varepsilon}{c} - \frac{1}{a + b + c}\right]\left[1 - \frac{\varepsilon}{2}K\right] H - \left[\frac{2}{c} - \frac{1}{a + b + c}\right](1 - K)\,E = 0, \quad \ldots .4$$

It is shown, in Appendix B, that if E is zero, these equations have the solution

$$\frac{l_o}{3\,\overline{\pi\,\varepsilon - 1}} = \frac{a_o}{2\,\overline{3 - \varepsilon}} = \frac{b_o}{3\,\overline{\varepsilon - 1}} = \frac{c_o}{3 - \varepsilon},$$

whilst

$$K = \frac{5\,\varepsilon - 6}{4\,\varepsilon^2},$$

which we will now write K_0; and the absolute values of l_0, a_0, b_0, and c_0, are given by

$$\mathcal{Q}_1\, a_0\, c_0\, (2\, l_0 + \pi\, \overline{b_0 + c_0}) = \frac{\varepsilon}{2}\, H_1\, (a_0 + b_0 + c_0)\, (a_0 c_0)^{-\varepsilon} (b_0 l_0)^{-\varepsilon+1},$$

or

$$\mathcal{Q}_0 = \frac{\varepsilon}{2}\, H_0, \text{ say.}$$

Suppose equations 1, 2, 3, and 4, together with the equation

$$\mathcal{Q} = \frac{\varepsilon}{2}\, H + E \qquad \ldots.5$$

are satisfied by.

$$l = l_0\, (1 + \lambda)$$

$$a = a_0\, (1 + a)$$

$$b = b_0\, (1 + \beta)$$

$$c = c_0\, (1 + \gamma)$$

whilst $K = K_0\, (1 + \delta\, K)$.

We will suppose that E is small, and neglect squares of small quantities.

To this order of approximation, we shall have

$$\mathcal{Q} = \mathcal{Q}_1\, a_0\, c_0\, (\, 2\, l_0 + \pi\, \overline{b_0 + c_0})\, \left[1 + a + \gamma + \frac{2\, l_0 \lambda + \pi\, \overline{b_0 \beta + c_0 \gamma}}{2\, l_0 + \pi\, \overline{b_0 + c_0}}\right]$$

$$= \mathcal{Q}_0\, \left\{1 + \frac{\overline{8\, \varepsilon - 6}.\, a + 3\, \overline{\varepsilon - 1}\, \beta + 7\, \overline{\varepsilon - 3}\, \gamma + 6\, \overline{\varepsilon - 1}\, \lambda}{8\, \varepsilon - 6}\right\}$$

or we may write

$$\delta\, \mathcal{Q} = \mathcal{Q}_0\, \frac{\overline{8\, \varepsilon - 6}\, a + 3\, .\, \overline{\varepsilon - 1}\, \beta + 7\, \overline{\varepsilon - 3}\, \gamma + 6\, .\, \overline{\varepsilon - 1}\, \lambda}{8\, \varepsilon - 6} \qquad (6)$$

again

$$H = H_1 (a_0 + b_0 + c_0) (a_0 c_0)^{-\varepsilon} (b_0 l_0)^{-\varepsilon+1}$$

$$\left\{ 1 - \varepsilon . \overline{a + \gamma} - \overline{\varepsilon - 1} . \overline{\beta + \lambda} + \frac{a_0 a + b_0 \beta + c_0 \gamma}{a_0 + b_0 + c_0} \right\}$$

$$= H_0 \left\{ 1 - \frac{\overline{8 \varepsilon - 6}\, a + 3 . \overline{\varepsilon - 1}\, \beta + \overline{7 \varepsilon - 3}\, \gamma + 6 . \overline{\varepsilon - 1}\, \lambda}{6} \right\}$$

thus

$$\delta H = - H_0 \frac{\overline{8 \varepsilon - 6}\, a + 3 . \overline{\varepsilon - 1}\, \beta + \overline{7 \varepsilon - 3}\, \gamma + 6 . \overline{\varepsilon - 1}\, \lambda}{6}$$

$$= - \mathfrak{Q}_0 \frac{\overline{8 \varepsilon - 6}\, a + 3 . \overline{\varepsilon - 1}\, \beta + \overline{7 \varepsilon - 3}\, \gamma + 6 . \overline{\varepsilon - 1}\, \lambda}{3 \varepsilon}$$

$$= - \frac{8 \varepsilon - 6}{3 \varepsilon} \delta \mathfrak{Q}, \qquad (7)$$

again

$$\left. \begin{aligned} 1 + K_0 &= \frac{4 \varepsilon^2 + 5 \varepsilon - 6}{4 \varepsilon^2} = \frac{(\varepsilon + 2) (4 \varepsilon - 3)}{4 \varepsilon^2} \\ 1 - \frac{\varepsilon}{2} K_0 &= \frac{8 \varepsilon - 5 \varepsilon + 6}{8 \varepsilon} = \frac{3 (\varepsilon + 2)}{8 \varepsilon} \\ 1 - K_0 &= \frac{4 \varepsilon^2 - 5 \varepsilon + 6}{4 \varepsilon^2} \end{aligned} \right\} \qquad (8)$$

Putting

$l = l_0 (1+\lambda)$, $a = a_0 (1+a)$, $b = b_0 (1+\beta)$, $c = c_0 (1+\gamma)$,

and

$$K = K_0 (1 + \delta K),$$

in equation 1, it becomes, by virtue of eqns. 6, 7, & 8,

$$\frac{2}{\pi (8 \varepsilon - 6)} \mathfrak{Q}_0 K_0 \delta K + \frac{\varepsilon - 1}{3 \pi (\varepsilon - 1)} \mathfrak{Q}_0 K_0 \delta K$$

$$- \frac{2}{(8\varepsilon - 6)\pi} \frac{6 . \overline{\varepsilon - 1}\, \lambda + 3 \overline{\varepsilon - 1}\, \beta + \overline{3 - \varepsilon}\, \gamma}{8 \varepsilon - 6} \frac{(\varepsilon + 2) (4 \varepsilon - 3)}{4 \varepsilon^2} \mathfrak{Q}_0$$

$$+ \frac{\varepsilon - 1}{3 \pi (\varepsilon - 1)} \mathfrak{Q}_0 \frac{2}{\varepsilon} . \frac{3 (\varepsilon + 2)}{8 \varepsilon} \lambda$$

$$+\left\{\frac{2}{\pi\,(8\,\varepsilon-6)}\cdot\frac{(\varepsilon+2)\,(4\,\varepsilon-3)}{4\,\varepsilon^2}+\frac{\varepsilon-1}{3\,\pi\,(\varepsilon-1)}\cdot\frac{3\,(\varepsilon+2)}{8\,\varepsilon}\cdot\frac{8\,\varepsilon-6}{3\,\varepsilon}\right\}$$

$$\frac{\overline{8\,\varepsilon-6}\;\alpha+3.\,\overline{\varepsilon-1}\;\beta+7\,\overline{\varepsilon-3}\;\gamma+6\,\overline{\varepsilon-1}\;\lambda}{8\,\varepsilon-6}\;\Omega_0$$

$$-\frac{1}{\pi\,(8\,\varepsilon-6)}\cdot\frac{4\,\varepsilon^2-5\,\varepsilon+6}{4\,\varepsilon^2}\,E=0,$$

Reducing to

$$\frac{4}{3}\,\varepsilon\;\alpha+\frac{1}{2}\,\overline{\varepsilon-1}\;\beta+\frac{7\,\varepsilon+3}{6}\,\gamma+\varepsilon\,\lambda$$

$$=\frac{4\,\varepsilon^2-5\,\varepsilon+6}{3\,(\varepsilon-1)\,(\varepsilon+2)}\,\frac{E}{\Omega_0}-\frac{8\,\varepsilon\,(5\,\varepsilon-6)}{3\,(8\,\varepsilon-6)\,(\varepsilon+2)}\,\delta\,K. \quad \ldots.9$$

Similarly equation 2 becomes

$$\frac{1}{2\,(3-\varepsilon)}\,\Omega_0\,K_0\,\delta\,K+\left[\frac{\varepsilon}{2\,(3-\varepsilon)}-\frac{1}{6}\right]\,\Omega_0\,K_0'\,\delta\,K$$

$$-\frac{1}{2\,(3-\varepsilon)}\,\Omega\,\frac{(\varepsilon+2)\,(4\,\varepsilon-3)}{4\,\varepsilon^2}\,\alpha$$

$$+\left\{\frac{\varepsilon\,\alpha}{2\,(3-\varepsilon)}-\frac{1}{6}\,\frac{2\,\overline{3-\varepsilon}\;\alpha+3\,\overline{\varepsilon-1}\;\beta+\overline{3-\varepsilon}\;\gamma}{6}\right\}\frac{3\,(\varepsilon+2)}{8\,\varepsilon}\cdot\frac{2}{\varepsilon}\,\Omega_0$$

$$+\left\{\frac{1}{2\,(3-\varepsilon)}\cdot\frac{(\varepsilon+2)\,(4\,\varepsilon-3)}{4\,\varepsilon^2}+\left[\frac{\varepsilon}{2\,(3-\varepsilon)}-\frac{1}{6}\right]\frac{3\,(\varepsilon+2)}{8\,\varepsilon}\,\frac{8\,\varepsilon-6}{3\,\varepsilon}\right\}$$

$$\left\{\frac{\overline{8\,\varepsilon-6}\;\alpha+3.\,\overline{\varepsilon-1}\;\beta+7\,\overline{\varepsilon-3}\;\gamma+6\,\overline{\varepsilon-1}\,\lambda}{8\,\varepsilon-6}\right\}\Omega_0$$

$$-\left\{\frac{2}{2\,(3-\varepsilon)}-\frac{1}{6}\right\}\frac{4\,\varepsilon^2-5\,\varepsilon+6}{4\,\varepsilon^2}\,E=0,$$

which reduces to

$$\frac{5\,\varepsilon-3}{2}\,\varepsilon\;\alpha+\frac{5\,\varepsilon-3}{4}\,(\varepsilon-1)\;\beta+\frac{9\,\varepsilon^2-2\,\varepsilon-3}{4}\,\gamma+2\,\varepsilon\,(\varepsilon-1)\,\lambda$$

$$=\frac{3+\varepsilon}{6\,(\varepsilon+2)}\,(4\,\varepsilon^2-5\,\varepsilon+6)\,\frac{E}{\Omega_0}-\frac{2\,\varepsilon\,(5\,\varepsilon-6)}{3\,(\varepsilon+2)}\,\delta\,K. \quad \ldots.10$$

Equation 3 becomes

$$\frac{1}{8\,\varepsilon-6}\,Q_0\,K_0\,\delta K+\left[\frac{\varepsilon-1}{3\,\overline{\varepsilon-1}}-\frac{1}{6}\right]\,Q_0\,K_0\,\delta K$$

$$-\frac{1}{8\,\varepsilon-6}\cdot\frac{(6.\overline{\varepsilon-1}\,\lambda+3\,\overline{\varepsilon-1}\,\beta+3\overline{-\varepsilon}\,\gamma)}{8\,\varepsilon-6}\cdot\frac{(4\,\varepsilon-3)\,(\varepsilon+2)}{4\,\varepsilon^2}\,Q_0$$

$$+\left\{\frac{\varepsilon-1}{3\,(\varepsilon-1)}\,\beta-\frac{1}{6}\,\frac{2.\overline{3-\varepsilon}\,\alpha+3.\overline{\varepsilon-1}\,\beta+\overline{3-\varepsilon}\,\gamma}{6}\right\}\frac{3.\overline{\varepsilon+2}}{8\,\varepsilon}\cdot\frac{2}{\varepsilon}\,Q_0$$

$$+\left\{\frac{1}{8\,\varepsilon-6}\cdot\frac{(4\,\varepsilon-3)\,(\varepsilon+2)}{4\,\varepsilon^2}+\left[\frac{\varepsilon-1}{3\,\overline{\varepsilon-1}}-\frac{1}{6}\right]\frac{3.\overline{\varepsilon+2}}{8\,\varepsilon}\cdot\frac{8\,\varepsilon-6}{3\,\varepsilon}\right\}$$

$$\left\{\frac{\overline{8\,\varepsilon-6}\,\alpha+3.\,\overline{\varepsilon-1}\,\beta+\overline{7\,\varepsilon-8}\,\gamma+6\,\overline{\varepsilon-1}\,\lambda}{8\,\varepsilon-6}\right\}Q_0$$

$$-\left\{\frac{1}{3\,(\varepsilon-1)}-\frac{1}{6}\right\}\frac{4\,\varepsilon^2-5\,\varepsilon+6}{4\,\varepsilon^2}\,E=0,$$

which reduces to

$$\frac{5\,\varepsilon-3}{6}\,\alpha+\beta+\frac{2}{3}\,\varepsilon\,\gamma+\frac{\varepsilon-1}{2}\,\lambda$$

$$=\frac{1}{6}\,\frac{3-\varepsilon}{(\varepsilon-1)\,(\varepsilon+2)}\,(4\,\varepsilon^2-5\,\varepsilon+6)\,\frac{E}{Q_0}-\frac{2\,\varepsilon\,(5\,\varepsilon-6)}{3\,(4\,\varepsilon-3)\,(\varepsilon+2)}\,\delta K \quad \ldots.11$$

Equation 4 becomes

$$\left[\frac{1}{8\,\varepsilon-6}+\frac{1}{3-\varepsilon}\right]Q_0\,K_0\,\delta K+\left[\frac{\varepsilon}{3-\varepsilon}-\frac{1}{6}\right]\,Q_0\,K_0\,\delta K$$

$$-\left\{\frac{1}{8\,\varepsilon-6}\,\frac{6.\,\overline{\varepsilon-1}\,\lambda+3.\,\overline{\varepsilon-1}\,\beta+\overline{3-\varepsilon}\,\gamma}{8\,\varepsilon-6}\right.$$

$$\left.+\frac{1}{3-\varepsilon}\,\gamma\right\}\frac{(4\,\varepsilon-3)\,(\varepsilon+2)}{4\,\varepsilon^2}\,Q$$

$$+\left\{\frac{\varepsilon}{3-\varepsilon}\,\gamma-\frac{1}{6}\,\frac{2.\overline{3-\varepsilon}\,\alpha+3.\overline{\varepsilon-1}\,\beta+\overline{3-\varepsilon}\,\gamma}{6}\right\}\frac{3.\overline{\varepsilon+2}}{8\,\varepsilon}\cdot\frac{2}{\varepsilon}\,Q_0$$

$$+\left\{\left[\frac{1}{8\,\varepsilon-6}+\frac{1}{3-\varepsilon}\right]\frac{(4\,\varepsilon-3)(\varepsilon+2)}{4\varepsilon^2}+\left[\frac{\varepsilon}{3-\varepsilon}-\frac{1}{6}\right]\frac{3.\overline{\varepsilon+2}}{8\,\varepsilon}\cdot\frac{8\varepsilon-6}{3\,\varepsilon}\right\}$$

$$\left\{\frac{\overline{8\,\varepsilon-6}\;\alpha+3.\,\overline{\varepsilon-1}\;\beta+\overline{7\,\varepsilon-3}\;\gamma+6.\,\overline{\varepsilon-1}\;\lambda}{8\,\varepsilon-6}\right\}Q_0$$

$$-\left[\frac{2}{3-\varepsilon}-\frac{1}{6}\right]\frac{4\,\varepsilon-5\,\varepsilon+6}{4\,\varepsilon^2}\,E=0,$$

which reduces to

$$(9\,\varepsilon^2-2\,\varepsilon-3)\,\alpha+4\,\varepsilon\,(\varepsilon-1)\,\beta+2\,(4\,\varepsilon^2-\varepsilon+3)\,\gamma+(\varepsilon-1)\,(7\,\varepsilon+3)\,\lambda$$

$$=\frac{9+\varepsilon}{2\,(\varepsilon+2)}\,(4\,\varepsilon^2-5\,\varepsilon+6)\,\frac{E}{Q_0}-\frac{4}{3}\,\frac{\varepsilon.(7\,\varepsilon-3)\,(5\,\varepsilon-6)}{(4\,\varepsilon-3)\,(\varepsilon+2)}\,\delta\,K \quad \ldots .12$$

Whilst equation 5, *i. e.*,

$$Q=\frac{\varepsilon}{2}\,H+E,$$

becomes

$$\delta\,Q=\frac{\varepsilon}{2}\,\delta\,H+E,$$

or

$$\delta\,Q\left[1+\frac{8\,\varepsilon-6}{3\,\varepsilon}\cdot\frac{\varepsilon}{2}\right]=E,$$

or

$$\overline{8\,\varepsilon-6}.\alpha+3.\overline{\varepsilon-1}\;\beta+\overline{7\,\varepsilon-3}\;\gamma+6.\overline{\varepsilon-1}\;\lambda=\frac{3\,(4\,\varepsilon-3)}{2\,\varepsilon}\,\frac{E}{Q_0}\quad\ldots .13$$

If we put $\frac{E}{Q_0}=S$, for brevity, we may write equations 9, 10, 11, 12 and 13, respectively as follows:

$$\tfrac{2}{3}\,(4\,\varepsilon-3)\,\varepsilon\,\alpha+\tfrac{1}{4}\,(4\,\varepsilon-3)\,(\varepsilon-1)\,\beta+\tfrac{1}{12}\,(4\,\varepsilon-3)\,(7\,\varepsilon+3)\,\gamma$$
$$+\tfrac{1}{2}\,(4\,\varepsilon-3)\,\varepsilon\,\lambda,$$
$$=\frac{(4\,\varepsilon-3)\,(4\,\varepsilon^2-5\,\varepsilon+6)}{6\,(\varepsilon-1)\,(\varepsilon+2)}\,S-\tfrac{2}{3}\,\frac{\varepsilon\,(5\,\varepsilon-6)}{\varepsilon+2}\,\delta\,K,\quad\ldots .14$$

$$\tfrac{1}{2}\,(5\,\varepsilon-3)\,\varepsilon\,\alpha+\tfrac{1}{4}\,(5\,\varepsilon-3)\,(\varepsilon-1)\,\beta+\tfrac{1}{4}\,(9\,\varepsilon^2-2\,\varepsilon-3)\,\gamma$$
$$+2\,\varepsilon\,(\varepsilon-1)\,\lambda$$
$$=\frac{(\varepsilon+3)\,(4\,\varepsilon^2-5\,\varepsilon+6)}{6\,(\varepsilon+2)}\,S-\tfrac{2}{3}\,\frac{\varepsilon\,(5\,\varepsilon-6)}{\varepsilon+2}\,\delta\,K,\quad\ldots .(15)$$

$$\tfrac{1}{6}(4\varepsilon-3)(5\varepsilon-3)\alpha+(4\varepsilon-3)\beta+\tfrac{2}{3}(4\varepsilon-3)\varepsilon\gamma$$
$$+\tfrac{1}{2}(4\varepsilon-3)(\varepsilon-1)\lambda$$
$$=\frac{1}{6}\frac{(4\varepsilon-3)(3-\varepsilon)(4\varepsilon^2-5\varepsilon+6)}{(\varepsilon-1)(\varepsilon+2)}S-\frac{2}{3}\frac{\varepsilon(5\varepsilon-6)}{\varepsilon+2}\delta K, \quad \ldots.(16)$$

$$\frac{1}{2}\frac{4\varepsilon-3}{7\varepsilon-3}(9\varepsilon^2-2\varepsilon-3)\alpha+2\frac{4\varepsilon-3}{7\varepsilon-3}\cdot\varepsilon(\varepsilon-1)\beta$$
$$+\frac{4\varepsilon-3}{7\varepsilon-3}(4\varepsilon^2-\varepsilon+3)\gamma+\frac{1}{2}\cdot\frac{4\varepsilon-3}{7\varepsilon-3}(7\varepsilon+3)(\varepsilon-1)\lambda$$
$$=\frac{(4\varepsilon-3)(\varepsilon+9)(4\varepsilon^2-5\varepsilon+6)}{6(\varepsilon+2)(7\varepsilon-3)}S-\frac{2}{3}\frac{\varepsilon(5\varepsilon-6)}{\varepsilon+2}\delta K, \quad \ldots.(17)$$

$$2(4\varepsilon-3)\alpha+3(\varepsilon-1)\beta+(7\varepsilon-3)\gamma+6(\varepsilon-1)\lambda$$
$$=\frac{3}{2}\frac{4\varepsilon-3}{\varepsilon}S. \quad \ldots.(18)$$

Subtracting eqn. 14 from 15 we get,—

$$\frac{3-\varepsilon}{6}\alpha+\frac{\varepsilon-1}{4}\beta+\frac{3-\varepsilon}{12}\gamma-\frac{1}{2}\lambda$$
$$+\frac{(2-\varepsilon)(4\varepsilon^2-5\varepsilon+6)}{6(\varepsilon-1)(\varepsilon+2)}S=0. \quad \ldots.(19)$$

Subtracting eqn. 16 from 14 we get,—

$$\frac{3-\varepsilon}{6}\alpha-\frac{5-\varepsilon}{4}\beta+\frac{3-\varepsilon}{12}\gamma+\frac{1}{2}\lambda$$
$$+\frac{(2-\varepsilon)(4\varepsilon^2-5\varepsilon+6)}{6(\varepsilon-1)(\varepsilon+2)}S=0. \quad \ldots.(20)$$

Now subtracting eqn. 20 from 19 we get,—

$$\beta=\lambda.$$

Thus equations 19 and 20 are equivalent to,—

$$2\alpha+\gamma-3\lambda+\frac{2(2-\varepsilon)(4\varepsilon^2-5\varepsilon+6)}{(3-\varepsilon)(\varepsilon-1)(\varepsilon+2)}S=0. \quad \ldots.(21)$$

Again, subtracting eqn. 16 from 17, we get,—

$$\tfrac{1}{3}(4\varepsilon-3)(3-\varepsilon)\alpha+(2\varepsilon^2-9\varepsilon+3)\beta+\tfrac{1}{3}(3-\varepsilon)(2\varepsilon+3)\gamma+3(\varepsilon-1)\lambda$$

$$+\frac{4\,\varepsilon\,(2-\varepsilon)\,(4\,\varepsilon^2-5\,\varepsilon+6)}{3\,(\varepsilon-1)\,(\varepsilon+2)}\,S=0,$$

or since $\beta=\lambda$

$$\tfrac{1}{3}\,(4\,\varepsilon-3)\,\alpha+\tfrac{1}{3}\,(2\,\varepsilon+3)\,\gamma-2\,\varepsilon\,\lambda$$
$$+\frac{4\,\varepsilon\,(2-\varepsilon)\,(4\,\varepsilon^2-5\,\varepsilon+6)}{3\,(\varepsilon-1)\,(\varepsilon+2)\,(3-\varepsilon\,)}\,S=0.\;\ldots.(22)$$

Eliminating λ between eqns 21 and 22 we get,—

$$3\,\alpha-3\,\gamma=0,$$

or
$$\alpha=\gamma.$$

Hence, from equations 21 or 22,—

$$\alpha-\lambda+\frac{2}{3}\,\frac{(2-\varepsilon)\,(4\,\varepsilon^2-5\,\varepsilon+6)}{(3-\varepsilon)\,(\varepsilon-1)\,(\varepsilon+2)}\,S=0,\ldots.\;(23)$$

and equation 18 becomes

$$(5\,\varepsilon-3)\,\alpha+3\,(\varepsilon-1)\,\lambda-\frac{1}{2}\,\frac{4\,\varepsilon-3}{\varepsilon}\,S=0,\;\ldots.(24)$$

whence

$$\left.\begin{aligned}\alpha=\gamma&=-\left\{\frac{(2-\varepsilon)(4\varepsilon^2-5\varepsilon+6)}{(3-\varepsilon)(4\varepsilon-3)(\varepsilon+2)}-\frac{1}{4\,\varepsilon}\right\}S,\\ \beta=\lambda&=\left\{\frac{1}{3}\,\frac{(2-\varepsilon)(4\varepsilon^2-5\varepsilon+6)}{(3-\varepsilon)(4\varepsilon-3\,(\varepsilon+2)}\cdot\frac{5\varepsilon-3}{\varepsilon-1}+\frac{1}{4\,\varepsilon}\right\}S.\end{aligned}\right\}\;(25)$$

Thus if $\varepsilon=1.6$ we have,—

$$\alpha=\gamma=-\,0.036\,\frac{E}{Q_0},\qquad\text{and }\beta=\lambda=0.691\,\frac{E}{Q_0},$$

whilst if $\varepsilon=1.5$ we get,—

$$\alpha=\gamma=-\,0.071\,\frac{E}{Q_0},\qquad\text{and }\beta=\lambda=0.881\,\frac{E}{Q_0}.$$

The values of α, β, γ, and λ, for other values of ε will be given with sufficient accuracy, by interpolation or extrapolation; for although α, β, γ, and λ, change considerably with change of ε, this change has but a small effect on the dimensions, when, as we have assumed in the calculations, the corrections to be made are small.

APPENDIX D.

PROOF THAT THE TRANSFORMERS DESIGNED HAVE MINIMUM LOSSES.

In §§ x and xi and in Appendices B and C we have shown how to find the proportions and size of the transformer having minimum waste of energy consistent with certain external restrictions. The method of procedure was to equate to zero the first differentials, with respect to the dimensions, of the expression for the energy wasted. This method, however, would equally well find us the dimensions, if such exist, which will make the energy wasted a maximum, and, for the sake of completeness, it is necessary to prove that the solution given corresponds to an absolutely minimum waste, that is, that no change in *any* of the dimensions will diminish the waste of energy.

In the first place, we may, for this purpose, neglect the effect of the eddy-currents, for, although this may somewhat change the dimensions corresponding to the stationary point, it will certainly not change a minimum point to a maximum or *vice versa.*

Using the same notation as in Appendix B the problem is to find the minimum value of $H + \Omega$, when Ω and H are connected by the relation

$$\Omega = \frac{\varepsilon}{2} H$$

This is the same as finding the minimum value of

$$\Omega \left[1 + K\right] + H \left[1 - \frac{\varepsilon}{2} K\right]$$

subject to the condition

$$\Omega = \frac{\varepsilon}{2} H$$

where K is any constant. If K has the value $\frac{5\,\varepsilon - 6}{4\,\varepsilon^2}$, then, the unique solution we obtain for the stationary value of

$$\Omega \left[1 + K\right] + H \left[1 - \frac{\varepsilon}{2} K\right],$$

satisfies

$$\Omega = \frac{\varepsilon}{2} H$$

naturally.

Consider now the problem of finding the minimum value of

$$\Omega\left[1+K\right]+H\left[1-\frac{\varepsilon}{2}K\right]$$

where

$$K' = \frac{5\,\varepsilon-6}{4\,\varepsilon^2},$$

and Ω and H are unconnected by any relation. We are able to find a single possible stationary value for the function, and the only question is whether this value is an absolute minimum or not. Since the variables are independent, we may consider the effects of their variations separately.

The function

$$X=\Omega\left[1+K'\right]+H\left[1-\frac{\varepsilon}{2}K'\right]$$

is continuous in all the variables. Let us consider the effect of the variation of a, supposing b, c, and l, to be fixed.

When a is large, Ω is large, and therefore X is large.

When a is small, H is large, and therefore X is large.

When a is of finite size, accordingly, X is smaller than when a is very large or very small, and it therefore passes through a minimum for some finite value of a, since it is continuous.

Similar argument precisely will apply to b, c, and l, and accordingly the unique solution obtained for the stationary value for X in Appendix B, must correspond to an absolute minimum, when Ω and H are not connected by any relation.

This solution is the same as that obtained for our problem of finding the minimum value of $H+\Omega$ when

$$\Omega=\frac{\varepsilon}{2}H,$$

that is, it gives us the stationary value of $H+\Omega$ consistent with the above condition.

Again, since, at the point obtained in this solution,

$$X\left[-\ \Omega\,\overline{1+K}+H\,1-\frac{\varepsilon}{2}K'\right]$$

increases with all changes in the variables it necessarily increases with those particular changes which are consistent with the condition

$$\Omega=\frac{\varepsilon}{2}H$$

that is, the solution given makes

$$\Omega\left[1+K'\right]+H\left[1-\frac{\varepsilon}{2}K\right]$$

an absolute minimum, when the variables are connected by the relation

$$Q = \frac{\epsilon}{2} H.$$

Accordingly the solution found makes $Q + H$ an absolute minimum subject to the condition

$$Q = \frac{\epsilon}{2} H.$$

DISCUSSION.

DR. M. I. PUPIN:—Mr. President, I do not think that there is much to discuss in connection with this paper. There is so much difference of opinion, and there naturally must be a great deal of difference of opinion in things depending on individual taste. The old Latin proverb, "*De gustibus non est disputandum*," applies eminently well to the design of any apparatus. The designing of machinery is a work of art, as well as of pure reasoning. A man may master the science of electricity and yet not be able to design a completely satisfactory piece of apparatus, because he lacks the artistic element. It is a thing that cannot be taught. It is just like the saying of the Greek philosopher Socrates, that you cannot teach a man virtue. It is a thing that has to be born in a man, and then developed by experience. The art of designing machinery has to be learned by practical experience, and a man will profit by his practical experience, and become a master of designing only if he has a taste for it. The experience will develop that which is in him. If he has it not in him, all the teaching in the world, and all the experience will not carry him very far. For that reason, I think, instructors in colleges do not insist very much upon the theory of design, because there is no clear cut theory relating to it. You have a theory of electricity. There are the fundamental principles and their generalizations, and you have the materials, and a man has to know the properties of materials and to combine his knowledge of electricity with his knowledge of materials to produce a method of design, and each man will have a different method; his own method of designing, but of course, all these different methods will lead to the same result. You see in this paper a calculation of what should be the dimensions of a transformer that should have the least loss. Taking a Westinghouse transformer as an example, it is found that this transformer has much less iron than this paper recommends. In another case, that of the Mordey transformer, a different relation is found. Again, the author finds that the thickness of the iron plates should be 7½ mils, and Prof. Bedell finds that it should be 16 mils. I think the American practice is to use 12 mils. So who is right? Probably they are all right, for each one of them had different conditions to fulfil, and it is impossible to design a transformer which will satisfy all conditions. On the whole I do not think that this paper will lead to anything that could be used as a standard for all cases. But at the same time it is a very good thing to have in a paper like this, filed away in our TRANSACTIONS, and ready for reference, the various steps, the essential steps of reasoning that a man has to go through in designing a transformer. We certainly who teach in colleges are very glad to have such a reference, because it saves us a great deal of tedious discussion. A student comes to us and says: "What am I going to do about this transformer design? What is the next step to take?" The teacher, you know, in a great many cases is not quite sure what the next step is, and he does not care to display his ignorance before the student. So he feels very much like saying to the eager student: "you will have to look that up in the electrical literature." I must say that so far, in electrical literature, there never was a convenient reference of this kind. The college professors of limited experience in transformer design (and their number is very large) can now say to students: "Read Mr. Carter's paper; it will give you all the essential points in transformer design." It takes a great deal of unnecessary, disagreeable work out of our hands; and it is disagreeable, to be sure, because not every teacher can be expected to know all the details of electrical apparatus design. Unless a man has been employed in some factory and made his living by designing, he cannot be expected to know much about it. As a mere scientific study the thing is dreadfully uninteresting. But it is a necessary evil, and very necessary indeed. In fact the success, sometimes of a company, depends on the appropriate design of its machinery. I was told some time ago that a man who was connected for a long time with a large electrical manufacturing company, stood very high with the company because he was a most eminent designer. He could design better than anybody else because he was a born artist in matters of design. That man could tell you more about a machine by merely looking at it than an ordinary electrician could by elaborate tests. The success of the company in a great measure depended on him. That shows how necessary a thing it is—this work of designing which to many of us appears dry. We ought to be very grateful to Mr. Carter for having taken the trouble to put down in this admirable, systematic way, the method of designing a transformer; and I only wish that somebody else who has had a large practical experience would come up and tell us all about designing an alternator, synchronous motors, induction motors and all that sort of thing. We would then be in a very fair position to train our young men and to develop their latent faculty of designing.

Prof. W. S. Franklin:—I wish to express my concurrence with the views of Dr. Pupin in the matter of teaching transformer design to students. The "cut and try" method is no doubt the method of practice, but it is not a method which lends itself with any convenience whatever to teaching. We have not had heretofore a mathematical statement of the principles of proportioning transformer parts, or in short we have had no method of design. We have known indeed precisely how transformers act, we have known how to calculate the secondary turns when the primary turns are given, we have known how to calculate losses, regulation, and every item of their behavior, but these are only the foundations of designing, and it seems to me that Mr. Carter's paper is the first that has been given on transformer design.

I may be permitted to say further that a consideration of limiting cost might easily be formulated and used in connection with Mr. Carter's method for determining rationally the absolute size of a transformer, instead of the choice of an arbitrary current density in the coils. This formulation is outlined as follows:

The cost, \$, is approximately:

$$\$ = ac + bi$$

where c is the weight of copper, i the weight of iron, and a and b are constants. The interest charge is proportional to \$ and may therefere be written

$$\% = a'c + b'i.$$

Take, now. Mr. Carter's expression for total loss, W, in terms of the yet undetermined dimensions of the transformer. The yearly value, Y, of this loss is at once known in the terms of the value of power, and the yearly total cost of the transformer is $Y + \%$ which is completely expressible, as above stated, in terms of the various items of the yet undetermined design, and these various items may then be determined so as to make the function $Y + \%$ a minimum. In this way the design would be determined without any arbitrary basis whatever. This method would always give a cheaper transformer than the transformer of maximum efficiency.

Mr. W. B. Jackson:—It seems to me that we have been discussing this matter wholly from a theoretical standpoint without giving sufficient consideration to its practical bearing. Having had some experience in the designing of transformers I feel competent to say that it is a mistake to suppose that the "cut and try" method is that now used exclusively in practice. When the transformer was made by the old uncertain methods we did not have what would be called, at present, a transformer at all; it was merely a bunch of copper and iron, and we were fortunate if able to make a reasonably good guess of the resultant action; it could not be calculated. When the transformer was made a reliable machine, it was by means of the most careful calculations, no less than we are requested to make in the paper we are discussing, and now when a transformer of a new design is brought out by a competent designer we feel assured if he has set himself the task of determining the loss in copper and in iron, the leakage current, and the drop, that when the transformer is completed it will very closely fulfil the conditions. The greatest difficulty, to my mind, we have not taken up to-night, and yet it is one that daily confronts us in practice, that is, the *heating* of the transformer. This must always be a determining factor in the proportioning of the copper and iron whether considered from a purely theoretical, or from a practical standpoint. Those who have made practical use of the various kinds of transformers now on the market have found a great part of the trouble experienced with them to be caused by defective design of the electrical and magnetic circuits considered apart from the insulation and building up of the apparatus; in some cases the copper heating too greatly for the normal load, and in others the iron. This fact demonstrates the futility of designing a transformer without due consideration of the heating factor.

Mr. Carter handles the subject most ably, theoretically, but of what value is the theoretical discussion unless it has clearly a practical bearing? Why should we not touch upon some of the principal points that interest those of us who have left for the time the designing of such appliances, and have taken up the use of them? There are one or two points of vital interest to every one of us who has to put a transformer on a pole or into a hole; for instance, shall we use an oil or a dry transformer? Also, how much added capacity do we get in an oil transformer over a dry one? Now these are points that are really worth careful investigation but, as far as I know, have never been taken up in a scientific manner, never having been worked out completely.

I know this, that where I can overload an oil transformer 10 per cent. without oil, that if I put in oil I can get just about as good results with an overload of 50 per cent. But is there any one here who has made the necessary tests to show us how much more capacity a transformer has when it has oil in it than when it has none? And should we, to get the best results, have the copper and iron in different proportions when designing for the use with oil or with no oil?

To my mind a design is not worth considering unless it is practical in the most thorough sense. I am a college man and I value very highly my college training, but I think our young men are not made to realize the practical significance of what they are taught; for instance, that such calculations as those of Mr. Carter's paper are of absolute importance, and that in our foremost electrical shops the result of formulæ just as complex as those of Mr. Carter are used in the successive steps of the manufacture of the transformer.

It is surprising that at the present day so many transformers are put upon the market that are not well designed. I can give a little experience in regard to one that was brought to my notice in the northwest. The manufacturer asked me to measure the leakage current. He said his transformer was "a dandy." I found it had over ten times as much leakage current as a standard transformer should have. At a low price this was a very expensive transformer. There are others equally expensive, and it is necessary to realize the importance, in buying, of choosing those of known low waste of energy.

I was interested to hear Prof. Franklin speak of this paper as probably not being worth very much because the Westinghouse transformer comes so near it in its calculations. But I think the paper is no less valuable because one make of transformer is similar in calculations, since there are hundreds of other makes that ought to be benefited by it.

There are several other questions relating to this subject that I should like to have discussed. I suppose all of us who are engaged in the electrical business have heard the question from a manufacturer "How much drop can you stand in your transformer?" "How much watt leakage?" As far as I know the answer can only be approximate. Can any one tell me what the drop *should* be? I do not see why our discussion should not take up both theory and practice. I suppose there are others interested, as I am, in considering this subject from all sides.

MR. TOWNSEND WOLCOTT:—The question as to whether transformers in use to-day are designed by "rule of thumb" or not seems to be still open. I know within the last year or two I have seen several statements, especially from English electricians;—(I think one was Mr. Swinburne, another was Prof. Fleming) —that owing to the fact that there is no simple mathematical expression, in fact even a complicated one, for the relation of magnetism in iron to the exciting current, it is impossible to design a transformer entirely on a scientific basis; the design is practically "rule of thumb." On the other hand, some other electricians, more particularly Prof. Carhart, last year said that he gets practically accurate results by assuming the sine form of wave of magnetism. In the first place, he may not have exactly a sine current, but assumes a sine form for both the current wave and also the wave of magnetism, and he says he gets results that are as accurate as you get in direct current machinery. It would seem that the "rule of thumb" practice is going out of designing at all events, if it is not already out.

PROF. FRANKLIN:—Mr. President, if I may impose upon the good nature of the INSTITUTE yet a few moments more, I may be allowed perhaps to say a word on that matter, as to what the design of transformers consists of at the present time. It seems to me—of course, I don't know very much about it, I will admit that--but it seems to me that the thing we know about transformers and the thing which practical men know about transformers is *how transformers act.* After a transformer is made, after you have decided upon the items in its design, you can calculate the ratio of electromotive force, you can calculate the magnetizing current, you can calculate the hysteresis and eddy current losses and the ohmic losses and all the details, without exception. That of course constitutes, as matter of fact, the basis of the paper to-day. Mr. Carter takes all that for granted. But the designing of a transformer is a matter of correlating these various items, and I think there can be no question but that the design heretofore has been a "cut and try" method of correlation and not a rational method of correlation. Of course it is not a matter of a single designer's beginning with Adam and working his own "cut and try" himself. He makes much of the practice as it exists at the present day, which represents the results of all the cutting and trying which has been done before him. A designer at the present time perhaps loses sight of the fact that the real essence of his design is "cut and try," because he does not carry out all of the cutting and trying himself and he is inclined to think that his knowledge of the action of the transformer is what he uses in designing. I think not. I think that he uses this merely in calculating what the transformer will do after he has designed it. Then he will design another with say two or three more turns of copper, and he will calculate what that will do. Then he will design another with two or three more sheets of iron and he will calculate what that will do. If that is not cutting and trying I don't know what cutting and trying is. Of course I may be mistaken in supposing that practical men design transformers in that way. I have designed a good many transformers, but they never were built, you know, so I cannot say anything from a practical point of view.

I cannot withstand the desire, Mr. President, to say one thing more, not in direct connection with the subject in hand, but in connection with the remark which was made by Mr. Jackson. He said that college men do not teach the actual practical methods of engineering, and the actual practical significance of the various points they take up. Now I think that as a rule no class of men understand better the worthlessness of what they teach than college men themselves. I think they appreciate the truth of a remark, if I may be allowed to quote German—a remark which occurs in Goethe's Faust, where Mephistopheles turning gravely on a student who has just come to confer with the professor: "Gray, my dear friend, is all theory, and green only is the tree of life."

Dr. Pupin:—If I may be permitted just to say one word more, I would like to supplement the quotation that Professor Franklin has made with reference to the teaching of design. Faust also says:

> "*So muss ich dem mit saurem Schweiss*
> *Euch lehrn, was ich selbst nicht weiss,*"

which I can translate for you in English, but of course not so as to produce Goethe's classical rhythm—"And so with the sweat of my brow I must teach you what I do not understand myself."

As far as I can see, this paper is just as practical as it can possibly be. It is limited to the design of a transformer under perfectly specified conditions. It does not speak of the oil transformer, because that is a separate matter. I do not see why the question of enclosing the transformer in oil is any more practical than the subject that this writer has discussed. Everything is practical, but of course we cannot take more than a certain number of steps at a time, and after we have taken those steps securely and safely we can take the next step. The question of whether we enclose the transformer in oil or not, is no more practical than giving the transformer the proper dimensions. A previous speaker admits that we consider also when we take up this question of oil: will not oil dropping from transformers hung upon poles, on the clothes of people bring the company into difficulties? That is a very practical question, but it is hardly within the limits of design. It brings in social questions and legal questions. In this connection it might be well to repeat a story told concerning a strange experience with the experiment in conveying power from Lauffen to Frankfort. The original design was all right, that is, the engineers thought it was all right, but they found it was all wrong, the thing would not work; and when they came to examine it they found that they made a mistake in making the insulators white, because the little boys in the fields had their attention attracted to those white insulators and thought they were good marks to throw stones at, so they threw stones at them and broke them, and that affected the whole plant and caused a tremendous leakage. The insulators were painted gray and the trouble was over. Well, that is hardly within the limits of designing conductors to transmit power, and yet it was of vital importance. At some date it may be of very great importance to know whether we should paint our transformers hung up on a pole, green or red or gray, but if we do it will be owing to some psychological or perhaps political reason. All questions are practical, but of course certain questions are more directly within the limits of transformer design than others, and I would not blame Mr. Carter for not spreading himself too wide. I think he has spread himself wide enough as it is.

MR. JACKSON:—I think I ought to say a word or two more, perhaps; Professor Pupin has not taken my meaning. I think what I said was, that this paper although theoretical was of practical value. I took issue with Professor Franklin in saying it was not practical. I think every figure in the mathematics used in designing a transformer is of practical value, and it is an interesting fact that our best transformers are based on very careful and minute mathematical calculations. I think also that Mr. Carter developed his theories far enough but why should we not apply them? The theoretical is so intimately related to the practical that we must have both to carry on a really valuable discussion. Why must we accept the mathematics and then drop the discussion? Up to within a comparatively recent time my business has been in connection with the designing of transformers and generators and similar work, consequently I am intensely interested in everything relating to these subjects.

I want to go a step farther than these discussions usually carry us and ask this society to help us who are working in practical lines to more definite knowledge. When I am told that a certain transformer is the one that will completely satisfy me and I state my objections to it I am not sure that I am right. I want such information that I can be absolutely certain that my opinions are properly based.

I have a very great respect for our college professors and their work. I think it is to them that we owe the fact that the number of well trained engineers is large, and is constantly increasing. It is up hill work for a man who has had no technical training to compete with the college trained man. But there is one thing in which the college is somewhat wanting, sufficient practicality. As I used to question in my calculus class, where is it possible that the "differential X" can be used in practical life? When out of college this question was soon fully answered and my only regret is that I could not realize its significance while under training. I believe more attention is now given to practical applications in college, and our later college graduates will be prepared to surmount difficulties that puzzle some of us older ones, but that will help us but little, and therefore I call upon our society to take up practical questions more fully in connection with the theoretical.

MR. WALTER S. MOODY:—As one who is actively engaged in every day practical design, I would like to make a few remarks.

First, I can assure these gentlemen who question the amount of use that is made of theory in every day design of electrical apparatus, that as far as my own work is concerned all the theory that college men develop for us finds ample use in every day practice.

There is no class of electrical apparatus designed to-day, I believe, by the best companies, whose proportions are not just as carefully analyzed as Mr. Carter's paper analyzes transformer proportions. But, of course, there are a great number of practical difficulties and considerations that modify the purely theoretical formula, or, more correctly speaking, our theoretical formula cannot be broad and complicated enough to include all the actual conditions presented. Mr. Carter's paper, for instance, while very complete on the points considered, leaves entirely out of consideration such essential facts as might entirely overpower the importance of the features which he discusses. Perhaps the most important factor which Mr. Carter does not in any way refer to is the question of heating, and the necessary radiating surfaces to dispose of the losses within the transformer. It would be perfectly possible to apply the formulæ developed by Mr. Carter, and which in themselves are undoubtedly perfectly correct, and yet obtain a design entirely impractical because of the lack of the necessary radiating surface to dispose of the heat.

Again, Mr. Carter's calculations all contain a constant which he designates as "p," and which expresses in per cent. the relation between the cross-section between the primary and secondary copper and the area of the wire space. In the calculations this figure is assumed, or rather it seems to be based on the actual per cent. found to express this relation in the transformers under consideration. Of course, in actual design this question has to be given careful study in order to make the percentage as high as possible, and still get the necessary insulation and the best distribution of it.

What I would like to bring out is that there is really great latitude in the choice of the best proportions for transformer design. One who has carefully figured the proportions of any piece of electrical apparatus, applying to the design a most careful analysis as to its proportions, and who has satisfied himself that he has a most thoroughly designed piece of apparatus, will often be surprised and disappointed to find that some one else's design which has been less carefully calculated, or perhaps worked out entirely by the "cut and try" method, is, as far as its proportions are concerned, nearly or quite as good as his own carefully developed design. In other words, as Mr. Carter himself points out at the bottom of page 667 of his paper, quite large changes in the proportions of the various dimensions of the transformer designed, affect but slightly the final results obtained, and consequently more practical considerations make advisable, or even necessitate, marked departures from the most economical proportions.

While I have not had an opportunity to carefully study the paper, yet I have hastily checked up some of the proportions found based on Mr. Carter's study with actual transformers of which I know the proportions, and find that these transformers had dimensions differing in their relation some 200 or 300 per cent. from those which the paper showed to be the most economical, yet these transformers are even more efficient (considering the value of the material in them) than the transformer which Mr. Carter develops to illustrate his formulæ. In other words, considerations which are in one sense purely details of shop practice or skill in workmanship, may modify the results to such an extent as to entirely outweigh the consideration of best theoretical proportions.

While I am speaking, I trust I may be pardoned for answering one of the more practical questions brought up by Mr. Jackson. I refer to his question as to the value of the use of oil in transformers. This is a question which has always been a subject of much discussion, and is one which sometimes is almost as hard for the manufacturer to settle as for the users of the transformers to decide upon. Many factors enter to determine one's decision in this matter, but in general it can be safely said that the use of oil transformers has vastly increased in the past few years.

The question as to just how much the capacity of the transformer can be safely increased by the use of oil is not one subject to direct answer, because the value of oil varies so much with different designs of transformers. Of course, we all understand that oil acts in a double manner in increasing the capacity of the transformer; first, by excluding air, and thereby preventing oxidation of the insulating material, and consequently increasing the temperature at which the transformer may be safely operated, and second, and more important, it acts as a heat conducting medium to carry the heat generated in the transformer to the transformer case. The space between the transformer and the case is small, and the air within this space consequently is too confined to allow any great amount of circulation, and therefore it acts as a poor conductor of heat. Oil will move much more freely under a slight difference of temperature, or, perhaps more correctly speaking, its specific heat is so much greater than that of air, that even with a slow motion it acts much more efficiently in conveying heat to the enclosing case. Just how much however oil will increase the safe capacity of a transformer can only be answered for each size and design of transformer independently. A small transformer may not have its capacity appreciably increased by its use, whereas a large one lacking in radiating surface on the coils and iron, but having a large exposed surface in its case, may easily have its capacity doubled, or even trebled by the use of oil.

THE PRESIDENT:—While we are indebted to the author for presenting to us propositions concerning the efficiency of a transformer, which are capable of analysis and application, it seems important to bear in mind that these propositions are necessarily limited by the conditions stated in their enunciation, and that many other conditions must be taken into account in the design and operation of commercial transformers. The deductions from these propositions probably require considerable modification to suit different conditions of practice. Cost, size, weight, excitation current, magnetic leakage, regulation and heating, are some of the factors which must be included in the design of a good commercial transformer, and the relation between these factors is so complex as to elude a general mathematical formula of design. Consequently, while I do not wish to undervalue the rules given in the paper for determining the design of the most efficient transformer, it seems important to bear in mind that the question of efficiency is not the only one which must be considered in practice, and that after all such rules have been taken into account, the method of trial and error must always be depended upon in arriving at the best design of a transformer at the present time.

MR. PHILIPPO TORCHIO:—Mr. President, one point which has not received attention in the discussion is on page 657, where the author alludes to the condition of work for which the transformer is designed. It is very important for the central station manager to get a transformer that will be most efficient under its special conditions of use. The author has in this diagram the daily load in amperes and also the ohmic transformer losses, proportional to the square of the amperes. The whole day ohmic losses represent a smaller or larger proportion of the total transformer losses according to the use of the transformer. If the transformer is going to operate at full load, say one hour a day, and be idle for 23 hours, the ohmic losses will be comparatively small; but if it operates 24 hours a day at full load, these losses will be large. Therefore, from the central station point of view, one transformer designed for a certain condition will not do as well under another condition. I think that this point of the load factor of the transformer is worth considering in the design of transformers. Of course, besides the condition of regulation, the cost of the transformer should also be included in the problem, together with the cost of energy in each special case, as the central station can afford to increase investment cost when the coal and running expenses are high; but when these are low, as, for instance, in water-power plants, the inducement is to reduce investment cost. I think this point of the transformer load factor brought out in the paper is very important for the design of the most economical transformer for actual operation.

MR. F. V. HENSHAW:—I think the last speaker has brought out a very salient point there in practical work, because I should rather imagine that most transformers are sold on their no-load consumption of energy, because if you get a transformer which wastes very little energy when the secondary is open, you will meet the conditions that probably at least nine-tenths of the central stations have, and for that reason it seems a little significant to me that the author finds the Westinghouse transformer has half as much iron as the "most economical design." While I have not gone into the thing very deeply, it seems to indicate that the author is going for full load efficiencies, rather than minimum wasted energy at no load, and in that case it is somewhat questionable whether the formulæ which we have every reason to be thankful to the author for putting in such good shape, could be followed in practical work with entire success. It seems to me rather, from the practical point of view of selling transformers to central stations, that we ought to have one that would run with very small light load losses and very small hysteresis losses, while at full load the ohmic losses might be as high as they could possibly be made without burning up the insulation. I do not know whether that is treating it very scientifically, but it seems to me it is rather a practical way of looking at it.

MR. JAMES HAMBLET:—Mr. President, I have been very much interested in the discussion this evening. I think it has been truly valuable in one sense more than in any other. Many of us present noticed two or three years ago quite an undercurrent of criticism unfavorable to the extreme mathematicians of the INSTITUTE. There has been, I think some will remember, quite a complaint coming to the surface, and a great deal of talk was made that we had too much mathematics. I want to congratulate those present, Mr. President, on the fact that we have seen evidence to-night of some harmony of feeling between the extreme mathematicians and the practical engineers. I move we adjourn.

[The motion was carried and the meeting adjourned.]

[REPLY COMMUNICATED BY THE AUTHOR.]

I will endeavor briefly to reply to some of the points that have been raised in the discussion on my paper. The chief objection that has been made to my method of design, is that it does not take account of certain practical considerations, such as the cost, the exciting current, etc., which, if they were discussed, might render useless the formulæ I have given. I should certainly have gone into these and other questions, had it not been that the paper was already lengthy, a fact which induced me to limit it to the consideration of its characteristic feature,—the direct method of design to give maximum efficiency. Some of the points, however, are mentioned in the introduction and shown to be implicitly taken account of by the method; others are more or less involved in the maximum current density assumed. In general, however, it would not be advisable to prescribe these quantities, but rather to give their limiting values; thus if the magnetic leakage is not excessive, it does not much matter what it is. Again, designers seem to be quite at variance as to what these limiting values should be. The table given on page 679 of the paper, enables one to see this immediately. The cost, weight, and size, of the Westinghouse transformer, are less than those of the two transformers corresponding to it, but of the Mordey transformer they are greater than those of its corresponding two. The exciting currents are probably less in my transformers than in the others; at any rate, they convey less power, as the no load losses are less. The magnetic leakage will be greater in the Westinghouse, and less in the Mordey than in my transformers, for the same subdivision of the coils. The regulation of the Westinghouse will not be as good as in my transformers, whilst that of the Mordey will be somewhat better than one of mine, and hardly so good as the other. The radiating surface per watt, is greater in mine than in the Westinghouse, and less than in the Mordey. Although the Westinghouse and Mordey transformers differ in output, they are nevertheless two ordinary transformers, by well credited makers intended to work under about the same conditions. Their respective designers, however, evidently had very different ideas as to the proper values for these supplementary quantities, so that the importance of the latter cannot be sufficient to render useless a method of design which need not bring any of them into objectionable prominence.

The modification of my method indicated by Professor Franklin,—that of including the interest charge on the outlay among the losses,—is certainly the most scientific way of performing the design, but is unworkable on account of its introducing another variable, (n), and very much complicating the equations. The relative importance of the capital charge and the wasted energy depends evidently on the proportion of time that the transformer is in circuit, so that if it is always, or nearly always, in circuit, the transformer of maximum efficiency will be very nearly the cheapest, as the value of the energy saved, will be of great proportional importance compared with the interest on a small difference of cost. The arbitrary quantity that I have assumed,—the maximum current density,—is the one quantity to be varied in finding the most suitable transformer by this method, so that I have not entirely eliminated the "cut and try" method, but have reduced it to the variation of one quantity. If the maximum current density is decreased, the losses are reduced, the radiating surface is increased, and the cost and size are increased. If we prescribe the cost, we can practically get rid of the "cut and try" methods, by finding the maximum current density to use as follows:

We may write the cost

$A \times$ volume of iron $+ B \times$ volume of copper, where A and B are constants.

This is of the form

$$A\, b\, l\, (a + b + c) + B\, a\, c\, (2\, l + \pi\, \overline{b + c}),$$

for a shell transformer,—using the notation of the paper. Now the ratios of a b c and l are known with sufficient accuracy, for we may assume values for the eddy current correction from former experience. Thus the cost may be written as a multiple of c^3, or of $\left(\frac{H_1}{\Omega_1}\right)^{\frac{3}{6.4}}$, and $\frac{H_1}{\Omega_1}$ is a known multiple of $\delta^{-3.6}$, thus the cost is a known multiple of $\delta^{-\frac{3 \times 3.6}{6.4}}$ or of $\delta^{-\frac{2.7}{1.6}}$ or of $\delta^{-1.69}$.

Hence an equation of the form $\delta^{-1.69} =$ a known quantity, gives us δ, — the maximum current density to be used. Of course it is not suggested that, as soon as the dimensions are found by the methods indicated, the transformer should be made without further consideration. Particularly it should be seen that the radiating surface is sufficient to dissipate the greatest continuous loss of energy. If the maximum current density be such as to make the cost of the transformer a prescribed amount, and if the prescribed cost be about that of a good commercial transformer of the type and output required, the radiating surface will, I think, be generally found sufficient. The maximum current density required to make as cheaply as possible a transformer designed in this way, which shall have not less than a certain amount of radiating surface per watt wasted at full load, might be found as follows. Assuming that we can approximately estimate, from former experience, the ratio of the eddy to the ohmic loss, (the so-called eddy current correction,) we may, taking account of the relation $\mathcal{Q} = 0.8\ H + E$, write the full load loss, — $\mathcal{Q}_{\max} + H + E$, — as a multiple of the maximum ohmic loss, ($\mathcal{Q}_{\max}$). This quantity varies as the volume of the copper, and as the square of the maximum current density, or as $c^3\ \delta^2$, using the notation of the paper. The area of the radiating surface varies as c^2, so that the energy dissipated per unit area of surface is a known multiple of $c^3\ \delta^2 \div c^2$ or of $c\ \delta^2$, or of $\delta^{2-\frac{3.6}{6.4}}$, (since c varies as $\delta^{-\frac{3.6}{6.4}}$), or of $\delta^{1\frac{7}{16}}$ or $\delta^{1.4375}$. If we put this dissipation equal to the maximum value allowed, we shall have δ given by an equation of the form $\delta^{1\frac{7}{16}} =$ a known quantity. This will make δ as great, and c as small, as we can permit it to be. Thus we can make either the cost or the heating determine the transformer,—and these are the chief extreme limitations. We see from this that the cost, weight, size and heating are implicitly involved in the maximum current density assumed.

I have not yet had an opportunity of seeing Prof. Bedell's work on the best thickness of core plates, but if anyone will go to the trouble of calculating the losses for two transformers having the same sized core, the same thickness of core insulation, and the copper circuits the same in all respects, he will find the advantage for efficiency is with that having the thinner plates, a point brought out in the table on page 679 of the paper.

Mr. Henshaw is wrong in supposing I am going for full load efficiencies, or for minimum wasted energy at no load either, but rather for minimum all day waste of energy, a point which I wished to bring out very clearly in the paper, and am sorry if I have left it liable to be misunderstood. I may point out, that, though my transformer has twice the iron of the Westinghouse, it has less no-load loss.

In conclusion I should like to take this opportunity of thanking the members for considering my paper, and Professor Franklin for the trouble he has taken in presenting it.

[COMMUNICATED AFTER ADJOURNMENT BY DUGALD C. JACKSON.]

The burden of the discussion of Mr. Carter's paper on "The Design of Transformers" which is published in the November issue of the TRANSACTIONS, is borne by university teachers; and the direction of the discussion naturally drifts into an expression upon methods of teaching. There are so many university teachers of electrical engineering who are not willing to subscribe to the discussion brought out by the paper, that it seems desirable to add something thereto.

As a further introduction to my remarks I desire to say that papers of the style of the one before us appeal to me as offering much of value, and the INSTITUTE is to be congratulated upon receiving Mr. Carter's presentation. On the other hand, it appears to me that the professors who entered into the discussion placed too much weight upon the immediate influence that such mathematical dissertations may carry in engineering matters, and the author himself appears to press his conclusions too far. The cost element seems to have been entirely omitted from consideration in the paper, and it does not appear to enter into the propositions for teaching the theory and practice in transformer design that are presented in the discussion. But, such an omission cannot be reconciled with the requirements; since the scientific and financial elements must equally enter into engineering design. We are often told that finances are not within the province of the engineer; but upon that reef, it is safe to assert, ruin has come to many excellent proposals.

In my view, the importance of the cost element should be borne in upon engineering students with a force equal to that given the presentation of the applied science involved. In applying the forces of nature to the welfare of man, the cost element is often of paramount importance; and, indeed, one of the principal differentiations between a scientist and the engineer lies in the fact that the latter must add to his store of science a due appreciation of the force of time, money, and human nature.

I am forced to strongly dissent from the attitude taken by Dr. Pupin in his remarks that are set down in the upper half of page 702. In my view—and I think this view will be upheld by the great majority of successful engineers whether they are in teaching or in practice,—the teacher who has charge of instruction in such a matter (for illustration) as the theory, construction, and use of transformers should have at least a reasonable knowledge of the usual practice in designing the appliances, and it is simply misguiding an inexperienced student to send him uncautioned to such a paper as the one under consideration. Design doubtless is "dreadfully uninteresting" as a "mere scientific study," *but as an engineering study it is of absorbing interest and exceeding importance.* True, it does bring in "social questions," but this adds to the interest. And it is of the utmost importance that engineering students shall give thought to social questions, as these are matters of the greatest importance to the profession.

Later remarks by Dr. Pupin, I must equally dissent from, as also from a portion of Professor Franklin's remarks. Engineering students must, indeed, be taught science in a thorough manner in order that they may be properly prepared for their profession; for every well trained engineer clearly understands that all knowledge in pure science in every branch ultimately comes as grist to his mill. But there must be mingled with the science proper instruction in common-sense and practice.

Mr. Carter has set forth what appears to be a very valuable law on page 641, which I will state a little differently from the way he has put it: *i. e., If the core of a transformer of given output has been fixed in dimensions, then, in order to make the* *energy wasted annually, bear a minimum percentage to the fixed annual output, the number of turns of wire in the coils must be such as to make the annual copper loss equal to the sum of the annual eddy-current loss and .8 of the annual hysteresis loss.* After a transformer design has been worked out so that it comes within the commercial requirements for costs, regulation, core and copper losses, insulation, etc., an application of this law may doubtless be made to show whether any changes may be made with advantage in the proposed winding. Even in this limited application there is difficulty, since the annual load factor of the ordinary transformer is entirely unknown, and judgment and experience in engineering must usurp the place of the scientific law which is thus relegated to the place of a suggestive pointer. In the case of special transformers designed for specific use this limitation in the applicability of the law need not exist. As, for instance, the conditions of operations for transformers for a plant such as is proposed by Mr. Wagner for St. Louis may be determined with considerable certainty in advance of the designing, and Mr. Carter's law may be usefully applied as a guide to the betterment of any proposed design.

The unfortunate effect of pressing the analysis further than is here indicated, with the object of determining the most efficient design for a special purpose, is shown by Mr. Carter's chosen illustrations. We will consider the Westinghouse 5 K.W. transformer. This is a transformer of fair capacity and perhaps of a reasonably recent date, though transformers of twice the output built to-day do not have core losses much exceeding those set down. In his computations based upon this transformer Mr. Carter assumes an annual load factor which, I venture to say, was beyond the thought of the designer of a stock transformer. If we use such an annual load factor as may be reasonably anticipated, to apply to this transformer when placed on a finely planned, economical central station distributing system, as we understand the terms, the extra cost of operating the commercial design as compared with Mr. Carter's first modification might amount to between $1.50 and $3.00 per year. On the other hand, Mr. Carter's design raises the first cost of the transformer so much that a reasonable increase in the fixed charges for this transformer on account of his design is from $1.50 to $2.00 per year. Thus, on the whole, no essential gain is brought about by the modification. Mr. Carter's second modification, in which thinner plates are proposed, makes a less favorable showing.

The fault in Mr. Carter's argument, which is shown above, comes entirely from pressing his pure analysis too far, where the engineering conditions demand equal consideration from the side of science and the side of commerce.

There is a point in Mr. Carter's valuable paper that I must regret. That is his systematic use of "ohmic loss" as synonymous with copper or resistance loss. This use of the phrase is the natural result of adopting the term "ohmic drop" as synonymous with resistance or conductor drop. The use of the word "ohmic" in either case appears to be unfortunate. The impedance of a circuit is measured in ohms and therefore the fall of pressure through the circuit may be said to be "ohmic", as may also either the reaction or resistance drops be said to be "ohmic". And the term "ohmic", therefore, does not distinctively apply to true resistance. Neither does it distinctively apply to waste of power due to the resistance of conductors; as, for instance, if we measure by some means the power lost in a transformer and divide the watts by current^2 we get an equivalent resistance, R, which is in terms of ohms, and the total loss, I^2R, may be called "ohmic" with just as much propriety as the simple copper loss, I^2R, where R is the electrical resistance.

University of Wisconsin,
Madison, Wis., Feb. 11, 1899.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

New York, December 28th, 1898.

The 130th meeting of the INSTITUTE was held this date at 12 West 31st Street, and was called to order by the Secretary.

THE SECRETARY:—I received a telegram to-day from President Kennelly who is in Detroit. He hoped to be able to be with us to-night, but was delayed, and in his absence Mr. Lieb, one of the Managers, will preside.

Mr. Lieb took the Chair and called upon the Secretary to make announcements.

The Secretary read the following names of associate members elected at the meeting on this date of the Executive Committee.

Name.	Address.	Endorsed by
ALLAN, JOHN	Full Partner, H. H. Kingsbury & Co., 54 Margaret St., Sydney, N. S. W.	Jas.S. Fitzmaurice Gustave Fischer. Eugene Griffin.
BELLMAN, JOHN JACOB	Electrical Engineer, Crocker-Wheeler Electric Co.; residence, 90 King St., New York.	Gano S. Dunn. F. K. Vreeland. F. V. Henshaw.
CROWELL, ROBINSON	Electrical Tester, General Electric Co.; residence, 72 Washington Ave., Schenectady, N. Y.	A. L. Rohrer. D. C. Jackson. C. F. Burgess.
DATES, HENRY B.,	Professor of Electrical Engineering and Physics, Clarkson School of Technology, Potsdam, N. Y.	Chas. R. Cross. Wm. L. Puffer. F. N. Waterman.
FINNEY, JOHN C.,	Cashier, Wisconsin Trust Co.; residence, 34 Prospect Ave., Milwaukee, Wis.	A. S. Hibbard. D. McF. Moore. R. W. Pope.
GLADSON, WM. N.,	Professor of Electrical Engineering, Arkansas Industrial University, Fayetteville, Ark.	Chas. F. Scott. B. J. Arnold. B. F. Thomas.
HILDBURGH, LEO WALTER	Student, Columbia University; residence, 1 West 30th Street, New York.	G. F. Sever. D. R. Lovejoy. W. A. Anthony.

HODGE, WILLIAM B.,	Electrical Engineer, Elmer G. Willyoung & Co.: residence, 707 Spruce St., Philadelphia, Pa.	Jas. G. Biddle. E. G. Willyoung. W. M. Stine.
OI, SAITARO	Chief Engineer to the Bureau of Telegraphs, The Ministry of Communications, 16 Kamitomisakacho, Koishikawa, Tokyo, Japan.	John J. Carty. H. F. Thurber. Geo. A. Hamilton.
TYNG, FRANCIS E.,	Manager, Eastern Engineering Co., New York; residence, Cranford, N. J.	H. C. Cushing, Jr. T. D. Bunce. C. W. Rice.
WOOD, ARTHUR J.,	Associate Editor, *Railroad Gazette*, 32 Park Place, New York; residence, 162 Washington Park, Brooklyn, N. Y.	W. E. Geyer. C. J. Field. Joseph Wetzler.

Total 11.

THE CHAIRMAN:—(J. W. Lieb, Jr.) We are to be favored this evening, gentlemen, with a lecture by Mr. Arthur A. Hamerschlag, on the "Education of Electrical Apprentices and Journeymen."

A paper presented at the 130th Meeting of the American Institute of Electrical Engineers, New York, December 28, 1898. Manager J. W. Lieb, Jr. in the Chair.

THE EDUCATION OF ELECTRICAL APPRENTICES AND JOURNEYMEN.

BY ARTHUR A. HAMERSCHLAG.

I am leaving to a certain extent the beaten path of precedent by giving the INSTITUTE a lecture on a subject which is neither pure science nor engineering. It is because of the importance of the subject and the influence it will exert on the future of the electrical industry that I have been bold enough to broach it. I do so with the hope that some agitation and discussion will point out a solution of a problem which becomes of more vital importance each year:—That of securing the necessary skilled mechanics requisite to the execution of electrical engineering works in a satisfactory and efficient manner.

The world has watched with startled eyes the rapid and far-reaching strides the young electrical industry has made, and the numerous fields in which electricity has entered. Scarcely a decade has passed since the industry, with justice, was called an infant. From a total investment of a few thousand dollars, it has to-day grown to such proportions that it would be impossible to compute with accuracy the value of the various industries in which electricity plays a prominent part. It is almost as difficult to assimilate the figures of value in their proper proportion as it is to define the widening field they have developed for skilled electrical labor. From an industry that gave employment to a few hundred men, in a decade it has expanded until to day it demands the services of tens of thousands of men devoting their services exclusively to this work. It has also demanded men of intelligence of a comparatively high order, well equipped with mechanical skill. That we have made such astonishing progress is remarkable, but not nearly so wonderful as that we have found in the past, men in sufficiently large numbers capable of devising, developing and manufacturing electrical products on a marketable basis.

Should another generation find a proportional increase in the demand for electrical products and operations (and the prospects are good for such an increase) shall we be equally fortunate in finding the skilled men necessary? Is it just as certain these men will be found? It is the doubt that the condition will be so easily mastered that has given me the courage to speak to you to-night on this subject.

The birth of an industry is not the most potent factor in determining its development; it needs the nourishment and care of those engaged in it to enable it grow to maturity. With its growth it must develop and nurture the individuals upon whom it most depends. Merit alone will not enable it to be perpetuated and put upon a successful basis unless it is capable of placing its raw material in the hands of skilled workers upon whom absolute dependence can be placed.

It is to develop this most essential factor of future success that I believe it time that we give a thought to meeting the coming demand by educating the apprentices and journeymen to that point which will make it possible for our boldest conceptions in electro-technics to be skilfully and economically solved.

As we draw near the closing days of the century—a hundred years pregnant with progress and events, none is more notable in the world of science than electrical achievements. A thought and a backward glance will show American supremacy in this field. In order however to retain this supremacy we cannot afford to rest content with the laurels we have won, else they will be wrested from us.

The old world has given us excellent mechanics through its apprenticeship system: unfortunately even in those countries that system is dying out. This country has never had a well-developed apprenticeship system, and to-day it has almost entirely disappeared because of the peculiar restrictions placed thereon by the unions and associations, and the centralizations of the work under single financial heads, paying men by the hour or day, leading employees to shift from place to place as the demand for their services varies from busy to dull times. In fact to-day the apprenticeship system is almost impossible for financial and other reasons, so we must devise some other means of educating the youth who wishes to enter the electrical field.

It is true that three or four of the largest electrical concerns do apprentice young men but the number is comparatively small, and it requires considerable influence to secure such indentures. The number of applicants is, however, out of all proportion to the number that can be accommodated, and such openings are almost entirely out of the reach of the vast majority because of isolated location.

Electrical work as a trade and as a profession is now undergoing the same trials and tribulations regarding educational means that other trades and professions have undergone in the past, except that the problem in the electrical industry owing to its rapid growth is of vastly greater urgency. Because of this growth along scientific and mechanical lines, improvements succeed improvements so rapidly that what was considered good practice yesterday becomes obsolete and defective to-morrow. The men are mechanics who but a few years ago handled cleats and mouldings in wiring, but are to-day asked to use iron pipe and conduit requiring entirely different tools, materials and methods. And where do these men acquire the efficiency and facility for this work? They acquire it in the crudest and most wasteful method possible, by experimentally using their employers' material, and at his expense in the time during which he is compelled to pay for skilled labor. These improvements certainly result in the loss of the journeymen's efficiency, and result in "rule of thumb" mechanics. This type of mechanic is to be found in all trades, and sometimes he is exceptionally skilled in his work and thus causes a tendency on the part of employers to desire more of him or men like him, especially when he is placed side by side with the so-called theoretical mechanic who lacks the skill.

The fallacy of this reasoning is at once apparent when the "rule of thumb" mechanics come in competition with the well grounded and educated mechanics who possess an equal amount of skill. Then the efficiency of the latter is so much greater, that there can be no comparison. Oftentimes we meet men with such a vast preponderance of theoretical training, that it has removed the inherent practical skill, and this type of journeyman is almost useless when judged from the working standpoint. This latter condition is not a rare one by any means and just a few words concerning it may be appropriate.

A glance over a list of our numerous educational institutions causes us to feel proud of our achievements in this line. In almost every settlement or city throughout the country, some school, college or university is supported upon as lavish a scale as one could desire. Endless seem the opportunities which the young American has, to acquire the learning and higher education which are prized and cherished in the world to-day. We have schools for every conceivable purpose; we have colleges and universities for every profession, and we have technical institutions almost unmatched in efficiency. But we have only a very few practical trade schools, and for the education of electrical mechanics, fewer still. And yet, in which field can we utilize, at present and in the future, the greatest number of skilled men. In the engineering branch or in the skilled labor branch ? The answer must obviously be in the latter. Still, parents will persist in sending their children, regardless of their inherent qualities, to the colleges and universities to master a profession without giving a thought to the field in which their future labors must be conducted, without considering the compensation they will receive. And what is the result? There can be only one general reply.

After years of study and much money spent in acquiring the profession, and an early association with children of wealth and refinement, the born mechanic becomes ruined for the sake of posing as a genius, or a great engineer. The field for mediocre engineers is just as narrow and confined as it is for the mediocre artist, and the compensation for his labor is correspondingly curtailed. As a result, when the young man is thrown on his own resources, he must suffer that genteel poverty which his training in refined circles has bound him to. He can no longer look with pride upon the work of his hands, and his brain power being but the average he suffers acutely, and eventually becomes neither an excellent mechanic nor an excellent engineer.

Each year the colleges and universities are sending into the world large numbers of young men, who after years of work, take the title of "Electrical Engineer." How many of these will ever have an opportunity to do any genuine electrical engineering. How many of them are destined never to earn, in the electrical line, $1.000 or so a year, the pay of a skilled mechanic.

For every single opening for an electrical engineer, there are a hundred openings for the skilled journeyman, and for every successful engineer there are a hundred successful journeymen. And to be a journeyman does not mean to be debarred from engineering.

Who have made the notable inventions, who have carried out the greatest engineering problems? Not the trained engineer, but the journeymen who have started at the bottom and by their individual efforts raised themselves to the highest level. "By their deeds ye shall judge them," is true of men, whether they have been educated up to a high standard or not, and self-training is often the more effective.

The compensation for skilled electrical labor, such as journeymen bring into the market, has been on the increase, it will continue to increase, and in an unfair degree unless employers think in time of a method of supplying the increasing demand, or of making the labor which is offered, worth the increase, in results achieved.

Every new electrical equipment, each railroad equipped electrically, and each industry which depends on electricity, is taking some of our skilled men from the open market and retaining them permanently, and confining their energy to maintaining such equipment.

Whence will come the men to replace these defections. Has no one a solution to offer as to the best way of replenishing the supply? Many methods of solving this problem have been tried, some of them without proper consideration of the case.

Some have been the education of journeymen in other trades, such as carpenters, draughtsmen, etc., by means of actual experience during their employers' time, a poor means at best, and which places the burden directly on the shoulders of the employers, while the resultant mechanic leaves much to be desired in all around efficiency.

Oftentimes untried young men with the desire to be electrical artisans attend, in a desultory fashion, popular lecture courses, witness a few experiments in static and galvanic electricity and find them of such interest that even though they possess little or no qualifications, and have been educated and trained for other lines they determine to make electricity their life work. Their methods of securing the necessary instruction is usually a so-called apprenticeship in a shop manufacturing some article, which in itself gives them comparatively little instruction and which makes them eventually skilled in hand work without giving them any breadth of training, and merely enables them to fill the position of a simple automatic machine.

Sometimes they read electrical lectures and trade papers, in many instances finding themselves very much at sea because of the technical character of the papers and articles, which their previous training has done nothing to enable them to understand.

Sometimes as a final resort they become recipients of the training offered by correspondence schools, and these schools are certainly gathering an ever increasing clientele which their merit justifies.

In very rare instances they attend by far the best and most modern form of securing this training, and that through the trade school. There are however such a very few of the latter institutions in spite of their acknowledged merit, and they are so little known that only a very small percentage of the number who wish to become electrical craftsmen can reap their benefits.

The superiority of the trade school for educating and equipping young men for trade work is so vastly superior to any other form of acquiring the result, that to it in the future must we look to solve this very serious problem. Foreign countries have realized this fact for many years and profited by it. Is it not time that this progressive country began to realize it also and to stimulate and support such institutions? They certainly are bound to spring into existence, and those that exist and have an honorable record are bound to improve that record, and it is but a question of time when intelligent thinkers must give them their proper place and dues.

It has been my good fortune to have been connected with trade schools for some years, notably with the New York Trade School, St. George's Evening Trade School of New York, and the Highland Falls Trade School of Highland Falls, New York. They have taught me a lesson which I hope to profit by in the future, not alone concerning the electrical industry but concerning many trades. It is a lesson however which applies in an equal measure to them all, and that is that trade schools have an equally high aim and purpose as compared with any educational institution in the country. That their field cannot be covered in any other way, and if they were accorded the same support and encouragement by the fraternity and the public that other educational institutions receive, their effect and beneficent influence would be as widespread, if not felt in even a greater degree, because of the class which they aim to assist.

It seems strange to me that trade schools should be subject to such marked indifference by the employers, and by such intense persecution and criticism by the fraternity which they aim to assist, merely because of the possible future competition their graduates will cause when they have come to the journeyman's estate.

Was there ever a scientific institution aiming at higher education, a medical college, a law or an art school, but received the support and endorsement of the leaders of the respective professions, if its object was not to make money, but to benefit the respective branches?

Are the prominent lawyers, physicians, the artist or the men of any other profession less free from the thought of future competition than the journeymen and the employer, that the latter should be found wanting in that which tends to advance his profession?

The governing societies, the trade associations and the employers' associations must eventually see the wisdom of the trade schools, and perhaps when they realize the necessity for them and are compelled to support them, they will indeed see the error of their ways.

A society like the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, whose members comprise a very large number of the engineers engaged in electrical enterprises, can do much to bring this problem before the men of their line, and can materially assist in a solution of this problem of so much importance to the welfare of the electrical industry. The youth of the country imbued with the desire to become electricians will force their way in, and the inevitable is bound to occur. These young men will eventually enter the field of their choice. Why not help them and encourage them to enter under the best conditions and highest possible standard, instead of leaving them to drift in, unequipped, inefficient and lacking in essential requirements. Is it not the best for them to live up to the studies exacted by skilled artisans in other lines, so that they can not only become self-reliant and successful, but reflect credit on the fraternity to which they have given their allegiance.

Trade schools have in the past done much to assist young men to acquire the rudiments of trades in other lines; they have tended to raise the standard of the individuals styling themselves helpers and journeymen, by showing the capacity of the beginner, and they have put the highest premium on skill and efficiency.

What I wish to impress most seriously on my hearers, is that this question of educating apprentices and journeymen, bears a vital and urgent relation to the future success or failure of an industry in which we all feel commendable pride.

The New York Trade School, owing to the far-sightedness and philanthropy of its founder Col. R. Tylden Auchmuty, has been in the field to remedy this coming dearth of skilled mechanics and the crowding out of our home industries of the native born American workers by foreign skilled labor. Aided by the munificence of Mr. J. Pierpont Morgan and other gentlemen, it has been able to broaden its scope until to-day it ranks as the pioneer and largest trade school in the country. With its six thousand graduates it has demonstrated its utility and shown the way to those who wish to follow.

Three years ago it took cognizance of the electrical situation and immediately established a thoroughly practical course for electrical workers, which became at once an assured success. filling the class room to its fullest capacity and having a waiting list of young men eager to enter the classes.

The first year the class numbered thirty-two. The second year a large department was opened and fifty were accommodated, and still the waiting list continued to be as large. This year fifty are again at work and fully that number were turned away.

The course is thoroughly practical because nothing is taught which is not done by the students themselves and tested and proved before acceptance.

This year a course for journeymen workers in the form of practical lessons will be established. Its success is problematical, but should it show any signs of growth and interest it may lead to future results which cannot fail to be of interest to the whole electrical fraternity.

The lantern slides show the classes at work and a few samples of work, but give but a vague impression of the school, which all members of the INSTITUTE are cordially invited to visit.

DISCUSSION.

THE CHAIRMAN:—Gentlemen, I think we have all been very much interested in Mr. Hamerschlag's address, treating, as it does a subject which has not heretofore been discussed by the INSTITUTE.

It seems to me that Mr. Hamerschlag has sounded a timely note in calling attention to the great demand which the growth of the electrical industry is making upon the labor market, and the desirability of training young men to be satisfactory and efficient electrical workers This subject comes home to many of us who have had to meet the difficult problem of developing an efficient force to handle electrical work, and after listening to Mr. Hamerschlag's interesting address we shall be better prepared to give institutions of the character described by him our cordial support and co-operation. I think the subject is an extremely important one and well worthy of your careful consideration. I see we have with us this evening a number of members who have done effective work along parallel educational lines, and we should be glad to have them favor us with any remarks which the topic under discussion may suggest.

MR. JOSEPH WETZLER:—I believe Mr. Hamerschlag has stated his points so forcibly that a corroboration of his remarks is scarcely necessary. If we want to look for the right course to pursue in the education of men in strictly trade lines, I think, Germany presents the best example which the world affords. Its present commercial supremacy is certainly due to what the Germans call their "Gewerbeschulen," which are pure and simple trade schools. Nearly every important industry in Germany has its trade school, from which it graduates young men who are able to take up intelligently the work of that particular trade.

It is only within a day or two that I had occasion to read the report of one of our Consuls to the State Department at Washington, in which he mentions the results achieved by those German schools. He refers particularly, however, to the report made by an English commission which had been sent over to study the industrial education problem in Germany. I take the following quotation from the Consular Report.

"Under such mental and manual training, with steadily improving machinery, a class of highly intelligent workmen has been developed which in their several lines are nowhere surpassed, if equaled. This is true to such an extent, that a commission of Englishmen, which had been sent to Germany to inspect and report on German industry, lately delivered a report at Manchester in which they stated that, compared with these intelligent, skilful and frugal German workmen, the English factory hands were like semi-savages."

That we, in the United States, have got to come to the same thing there can be no doubt. All who have had occasion to work in engineering shops, as I have had myself, will have noticed the large proportion of foreign workers, especially Germans, Swedes, and the like. Now, that process of drawing our skilled mechanics from abroad, cannot go on forever. The time must come when we must produce them ourselves, and the trade school or the manual training school is the school which must produce them. We have begun that work in a small way; the school that Mr. Hamerschlag just described is a very promising example of the kind, and there are others growing up. I dare say that inside of twenty-five years there will hardly be a city, making any pretensions to being up to the times in this country, which will not contain its trade school.

I do not wish to say anything against the trades unions; they have their good points, no doubt. But to my mind one of the weak points in their system is the manner in which they discourage the taking and training of apprentices. Mr. Hamerschlag's illustration of the Horse Shoers' Union is a case in point. Five years is probably not too long a time for any young man to learn a trade properly. Indeed earlier in many of the arts, it was absolutely necessary to require a boy to work five years. But as a matter of fact to-day you cannot get the average boy to stay five years as an apprentice, and bind himself by a written agreement, as was formerly the case. He wants to get at results quicker than that. His refuge, therefore, will be to go to some trade school, like the Auchmuty school here in New York.

As to the establishment of a trade school adapted to the wants of the electrical worker, I do not see why the INSTITUTE cannot take up this subject. I do not mean to say that it should be the founder of such a school, but it can be of great service in starting a movement in that direction. I believe the subject discussed by Mr. Hamerschlag is of such importance that it ought not to be allowed to pass by without some action on the part of this INSTITUTE. Just what action ought to be taken I am not prepared at this moment to state. But I think it well worthy the attention of the Council.

THE CHAIRMAN :—The report to which Mr. Wetzler refers as having been made by a committee of the Manchester Council as the result of a visit to Germany by a commission delegated by it, is a document which has attracted much attention. The report caused a great deal of discussion in English producing centers, as it pointed out that England had not kept pace with Germany in developing trade schools for the training of intelligent labor. The committee visited in Germany particularly the prominent centers of textile industry, and it was evidently much impressed with the opportunities offered to young men in the trade schools, enabling them to become thoroughly familiar with all the branches of the textile industry, and although the report seemed to cast a reflection on the lack of attention which had been given in England to the subject of trade schools, it has had the healthy effect of bringing this matter prominently before the public and stirring up a discussion of the desirable methods of remedying what is evidently a serious weakness in the development of British industries.

Mr. Edward P. Thompson:—In reference to the point about the education of mechanics in Germany, I had a little experience in connection with the Singer Manufacturing Company, where in my early days of vacation at Stevens, I thought I would like to put myself in that position, and learn something about practical mechanics. I was in the tool room where there were lathes and different kinds of machines for doing work from drawings. I noticed that every man in that place was a German. Every man in that place had been educated as a mechanic in Germany. I could not find one who was educated for that work in America. And they seemed to be interested in me. From curiosity they asked me how much I had to pay to come there to learn how. Of course they could not help but notice how I made the holes too large in the little cranks for the sewing machine, how I broke one or two of the lathes, etc. They wanted to know how much I paid. I told them that the company paid me, and they were very much surprised, because they said they had to pay $100 a year for two or three years to learn how to do these things. I have often thought that the way in which artisans and mechanics are taught in America is a very loose way. The training is gained by accident, by rough experience, and by doing a great deal of harm in places where the learner is first engaged to work. Sometimes, we hear about too many people being educated for electrical engineers and professional men. I think one of the reasons is that many boys are not really fit to become engineers in the future, and really are adapted to become mechanics or artisans, but have had no suitable trade schools to go to. Of course, the next thing is to apply to some technical school with a probability of not even being able to get into the freshmen class. So that I appreciate very much the work that our lecturer is doing and that others are doing in that direction, in forwarding the interests of all kinds of schools for educating those who are to do hand work as distinguished from head work.

Mr. Hamerschlag:—I would like to say in relation to the remarks of my predecessor, that one of the most remarkable things I have found in connection with electrical work and the utilization of men, in conversation with them, asking them what they were before they became electrical workers, that it has been the rare exception that I have met a man who claimed that he had ever had any electrical instruction. It has always been the case that he had either been a carpenter or a draughtsman, or worker in some other line. In asking him how he happened to become a member of the electrical fraternity, he would state that there was the field where he got the most money for the least work, to which I replied that I agreed with him, judged by the standard of the New York mechanic. Very frequently I have asked "Why haven't you done something to improve your knowledge of electricity since you have become a member of the fraternity?" And the reply would be "It is not necessary for me to know anything more than I do know. I can do any work given to me"; always falling down, however, when the work was given to him. It seems to me that it is essential to open the eyes of the journeyman to the fact that to become an electrical artisan he must be just as well trained as to become a tool-maker. As I said in my address, there is now a new form of education for those who are confined to remote districts, who wish to improve themselves, and that is by means of correspondence. How effective that is, the future will show. But in speaking to men connected with the Scranton Correspondence School and the Electrical Engineer Correspondence Institute, I have become convinced that they are doing effective work. Personally, I have not had enough experience to be certain of it. But judging from reports and hearing from men who have engaged under this correspondence instruction, they are certainly receiving some benefit. It now remains for us to establish a sufficient number of institutions such as Germany has, in order to develop these two lines of education, those studying at home, and those that come and take practical lessons. Then we will be able to depend in the future upon excellent mechanics.

THE SECRETARY, [R. W. Pope]:—I had the pleasure of visiting the New York Trade School, a few days ago, and one thought that came up in connection with it was, that while it was very good, there was not enough of it. This school, large as it is, yet so small compared with the city, and so much smaller compared with the country, is turning away young men who are not able to join the classes. This is to my mind, a reflection upon our educational system. I have felt, and I presume many others will agree with me, that one of the principal reasons why more young men are not educated as mechanics is on account of the social prejudice against mechanical work. I would probably have made a pretty fair mechanic in various lines myself, if I had had an early training. My mother thought I ought to be a bookkeeper. I never became one, and what little knowledge I have of bookkeeping I picked up in the railroad and telegraph service. Since this school on the east side, referred to by the speaker, taught the trade of telegraphy, I suppose I can stand accused of being an electrical mechanic in that line, although it is not usually considered a trade. It has always been a source of pleasure to me that I learned telegraphy and that I am able to practice it to-day, and earn my living at it. And right here is where it appears to me that a great mistake is made, that people do not realize that young men when they learn a trade, if they have the necessary qualifications for progress, will either go higher in that line, or their experience may open up another course for them. I have yet to see the man who having first learned a trade, whatever his position might be in after life, was not proud of being able to do something that showed that he was skilled in some particular line—a skilled craftsman. I was riding through a city one day with a master mason, and he pointed out to me the different houses that he had either built or worked on. I said to him then, that I thought it was a source of gratification to a man through life that he could point to actual works of construction that were, as you may say, monuments to his skill, and I think that such a feeling prevails in every line of mechanical progress. I have a friend, the son of a neighbor of mine, who went through this New York Trade School in the plumbing department, and he is the only boy in the neighborhood out of perhaps half a dozen, who actually learned a trade. He went to this trade school and is considered a skilled workman. One of the astonishing things about it is, when we consider these old-time apprenticeships of five and seven years, that a young man will go to one of these trade schools and master some of the arts in a few months, because he is taught, although I am told that when graduated they are considered merely apprentices. His time is not occupied in sweeping out in the morning, going out after beer, and doing all the rough work in connection with the establishment for a year, or perhaps being kicked around and prevented from learning, rather than aided. Another point in regard to education that I think is worthy of consideration, is that before the boys arrive at the period when they realize the social prejudice against mechanics they should be given in the way of play, if you please, some mechanical work, as a diversion, and to relieve them from brain work, and you would find them glad to devote their time to building water wheels or boats, making their own toys instead of buying them, as is generally the case at present.

If a mechanic is at work in the city, within view of passers-by, you will frequently see a crowd of men and boys watching the operation, as if they enjoyed seeing the mystery of mechanical skill, as much as though they had paid to see a show. In one of those "Notes about town" appearing in a daily paper, it was stated that when a man was seen knocking a hole through a plate-glass window to put in a whirling ventilator, it would draw more people than a dog fight. I spoke of the early training of the boys, giving them these different trades to amuse themselves, you might say, because it has another practical bearing, revealing one of the most difficult problems a parent has to confront in the case of boys, and that is ascertaining what particular trade they are adapted for. Frequently boys come to us who are determined to learn about electricity. I have wondered what this same class of boys did before we had any electric work, and trades were comparatively few. It is difficult to tell what a boy's bent is unless he is a natural mechanic. A boy who has a mechanical turn of mind will generally show it by getting hold of a hammer, and perhaps doing as my brother did, driving the front door step full of nails. He did not become a carpenter after that but probably would, if he had been trained. His son became quite an efficient carpenter in a manual training class, but is now a traveling dry-goods salesman. If we could find out a little earlier than we do, what a boy is adapted for, and give him a chance to shift, in case he took up the wrong trade, we might save valuable time in the future; when he arrives at years of discretion, and spends four or five years of his valuable time in finding out that he is doing something that he is not fitted for. I made inquiry at the New York Trade School in regard to this point. It is found, that boys take a notion that they want to learn some one trade, and after they get there and try it a little while, they make up their minds they would rather not learn that trade, and change to something else. These are quite important points, and the whole question is a very large one. I was very glad to hear from Mr. Wetzler in regard to the German system, because I think that where we have an example to go by, it is well to profit by it, and there is little doubt that in this respect the German schools are far in advance of any other country.

Mr. Hamerschlag's reference to the fact that electrical workers are frequently drawn from other trades, as carpenters and draughtsmen, reminds me that wiremen were perhaps first generally recruited from the carpenter's trade about 1873, by my brother, Henry W. Pope, at that time General Superintendent of the American District Telegraph Co in this city. He saw that ordinary linemen were not well trained in the matter of doing neat work about buildings and found by experience that for the simple construction of that day it was easier to make a good wireman out of a carpenter, than to teach the existing craftsman how to make a neat job of running wires, especially in exposed work.

Mr. Wetzler:—Mr. Chairman, one has a natural hesitancy about speaking of work with which one is directly connected, and I feel some delicacy in speaking about the subject of correspondence schools which Mr. Hamerschlag adverted to. But there is no question in my mind that one of the great aids to the young apprentice who cannot, by any possibility, attend a school such as Mr. Hamerschlag described to us to-night, is the correspondence school. How many young men that are now growing up in trades are so situated that, even if such a school existed, they could attend it? I should say that the proportion is no greater than that which now exists between the men that are graduates of colleges in the United States, and those who are not; that is, about 1 to 100. For them, it appears to me, there is no other way of securing that theoretical training—when I say theoretical, I do not mean impractical, but rather the mental training, supplementary to their daily work, which is absolutely necessary to make them intelligent workers. I say this from experience. This experience which is fortified by the testimony of hundreds of letters, convinces me that the only way in which 99 out of 100 budding electrical workers can be reached to-day is by means of the correspondence schools.

THE CHAIRMAN:—I know that it has done me good to have been here this evening, as it will enable me in the future to reply more satisfactorily to the numerous applications for advice which I receive from fathers and relatives as to what they should do with their boys. It is usually the case that the boy has a mechanical turn of mind; puts up electric bells and burglar alarms about the house, showing a fondness for mechanical pursuits, and each fond father feels that he has in his home a born genius—an Edison, who needs only the opportunity to develop splendid latent talent. I must say that I have often been at a loss as to what counsel to give in such cases. The parents are in most cases unable to send their boys to the higher technical schools, and in pointing out the possibilities which the electrical industries open to young men, they feel satisfied that this is the line which they would have their boy follow. The difficult question immediately follows as to how the boy may obtain a start, and Mr. Hamerschlag's address this evening will go far toward enabling me to satisfactorily meet this question. I hope, however, that it may not have the effect of increasing the great difficulty Mr. Hamerschlag already experiences, in satisfactorily meeting the applications for admission to the trade school.

In regard to the correspondence schools, the question has often been asked me as to their efficiency and the extent to which young men were profiting by the advantages which they offered. The company with which I am connected, employing a number of young men, is of course an excellent field from which to recruit students for the correspondence schools and we had applications from all of them to be allowed to present their respective advantages to our employees. To have permitted their representatives to canvass our employees would have caused serious interference with their regular duties and if allowed during working hours, would have been incompatible with the station rules. At the same time it must be recognized that it is of the first importance to the employer that his employees should be as thoroughly instructed as possible, and it seemed a matter of regret that it was not feasible, without infringing the company's rules, to bring directly to the attention of the men the advantages which these correspondence schools seemed to offer. I therefore took occasion to make inquiries to find out to what extent the employees were informed as to the existence of these schools and the advantages which they offered, and I was surprised to find how well informed the men were on this subject—so well, indeed, that it did not seem necessary to bring the matter specifically to their attention by allowing direct canvassing by the representatives of the several correspondence schools.

MR. HAMERSCHLAG:—I would like to extend a cordial invitation to the members to visit the New York Trade School at any time that they can, and see the work done there in the various trades, and I would like to state that the electrical course is only in session on Monday, Wednesday and Friday nights. On other nights, and during the day, the other classes are in session. If any of the members are sufficiently interested, they will receive a very cordial reception if they merely mention that they are members of the INSTITUTE.

MR. WETZLER:—Before adjourning, I move you, sir, a very hearty vote of thanks to Mr. Hamerschlag for his interesting and important paper this evening. [Seconded.]

THE CHAIRMAN:—It gives me great pleasure to put this motion. It has been moved and seconded that a vote of thanks be extended to Mr. Hamerschlag for his interesting remarks this evening. Those in favor will please say aye; contrary, no. [Carried.]

On motion the meeting was adjourned.

OBITUARY.

BY TOWNSEND WOLCOTT.

CHARLES EDWARD EMERY, PH.D. (Associate Member, June 26th, 1891, member, April 19th, 1892,) was born at Aurora, New York, on March 29th, 1838, and died in Brooklyn, on June 1st, 1898. He was a descendant of a branch of the Emery family that came from England to Newbury, Massachusetts, in 1635. He attended the Canandaigua Academy, and at the same time lost no opportunity to acquire information from independent sources, by which means he early became acquainted with practical engineering. A branch of the Erie Railroad terminated at Canandaigua, and one of the engineers on that road took D. K. Clark's work on the locomotive, in numbers, which young Emery borrowed and read in detail, and then after thoroughly mastering the contents, he explained it to the enginemen at night in the roundhouse. The enthusiastic spirit which prompted such a course of study, soon found an opportunity for the practical application of the information thus gained, and carried the application to success. The engines on that division of the road had been running for over two years without repair, and the valves were working badly on account of lost motion. Young Emery recommended that the eccentrics be advanced to restore the lead, and the recommendation being adopted, he superintended the operation, school-boy as he was, while the gray-haired men pinched the engines along the track and reset the eccentrics as directed. He then ran one of the engines over the road, under the eye of the engineer, to try the effect of the new adjustment, which proved to be quite satisfactory. Incidentally it may be remarked that he was not strong enough to hook back for expansion, without assistance.

Another boyish exploit of our budding engineer, was the building of a steam engine with his own hands, and almost without tools. The majority of boys who have a natural liking for machinery, at some time during their youthful days, either build or attempt to build steam engines, and young Emery's engine and the process of construction thereof, bore many points of resemblance to the typical form. There was the usual poverty of tools and material, and wealth of more or less ingenious makeshifts, but in one respect this engine was differentiated from the usual form: it eventually ran with real steam, generated in its own boiler. The specifications of this remarkable engine were, so far as recorded, as follows. The fly-wheel spokes and connections were of wood, the cylinder was an old syringe made of type-metal or similar alloy; the cylinder ports were capped with an iron plate, which with the type-metal valve, was accurately laid out and finished, as our young engineer had advanced ideas in regard to valves and valve gear. The boiler was made from a length of stove-pipe, with wooden ends nailed in, and made tight by boiling bran inside, which in those days was the most approved method of stopping small leaks in steam boilers. The most remarkable thing about this engine, however, was the construction of the valve gear. Young Emery was an engineer on his own account, and not a mere imitator. He designed for this engine, a valve gear in which the principal motion was given by a link turning on a fixed center, the lead being obtained independently from the cross-head. This device was long afterward brought out in Germany and became well known under the name of the Waelschaert valve gear. It was used in the heavy pushing locomotives in Belgium, in the Fairlie type of engines built by the Mason Locomotive works at Taunton, Massachusetts, and in some steamships by Bryce Douglas. Another model contained the germ of one of the radial valve gears now in use.

After leaving school Mr. Emery was for a short time employed in the drafting room of a railroad company, and afterwards in a country foundry and machine shop, where he helped in the foundry, ran the engine, operated iron and wood-working tools, made drawings of machinery or prepared cases for the patent office, as circumstances required. This was a course of training of great value to an engineer, and Mr. Emery made the most of his opportunity. He took a special course of study in the office of Marvin Porter, C. E.; next at the solicitation of friends he entered the law office of Hiram Metcalf, Esq., where he studied law for two years, with a view of becoming a patent lawyer, and at odd times busied himself as a land surveyor, and in making maps and plans of buildings.

The first shot at Sumter found him on a sick bed, but soon after he organized a military company which was, however, disbanded without having seen service, owing to the premature proclamation of President Lincoln that no more troops were needed. A little later Mr. Emery entered the navy as an assistant engineer, and was on the steamer Richmond in the engagement at Fort Pickens, the capture of New Orleans, and the naval attacks of Vicksburg and Port Hudson. Some suggestions made by Assistant Engineer Emery as to experimental steam apparatus reached the ears of Engineer-in-Chief B. F. Isherwood, who ordered him to experimental duty at the Novelty Iron Works, New York, where he had unusual opportunities for several years. Mr. Emery resigned from the navy on January 1st, 1869, and was engaged for a year in making experiments for the Novelty Iron Works in connection with the proposed manufacture of steam engines, and prepared the elaborate circular afterwards published in book form by the vice-president, W. P. Trowbridge, entitled "Condensing and Non-Condensing Engines."

Mr. Emery was engaged in the fall of 1869 as the general superintendent of the American Institute Fair, it being at the time arranged that he should go back to the Novelty Iron Works as general superintendent. The establishment, however, was closed before his return, and Mr. Emery entered into business for himself as consulting engineer and patent expert, writing occasionally for the scientific papers. He had previously however been appointed consulting engineer of the United States Coast Survey and United States Revenue Marine, in connection with which he was also made superintendent of some work for the supervising architect of the Treasury Department. Mr. Emery built several vessels for the United States Coast Survey, and was actively interested in the revival of the compound engine in this country. The first engine built for the Coast Survey steamer Hassler, was probably the most economical engine of its size ever constructed. Reports on file show that the vessel, with a displacement of 400 tons, made with half boiler power, a speed of eight knots, most of the time running a line of soundings, on a consumption of two and one half tons of coal per day. While in the naval service at the Novelty Iron Works, Mr. Emery was employed as consulting engineer by the Hecker Brothers of this city, to initiate and superintend repairs to the engines and the construction of new boilers, with such success that the output was increased 50 per cent. in the larger mill. Mr. Emery was at this time a strong advocate of the compound engine and was criticized in some quarters on that account, but his judgment has been amply vindicated by the later performance of compound engines.

The Coast Survey appointment terminated when the naval engineers were ordered to the vessels; that to the Revenue Marine was continued some twenty-one years, until 1891. In this service the machinery for twenty new vessels was constructed under Mr. Emery's direction, and that of all the others several times repaired and remodeled. In 1874 an opportunity was embraced to place three different types of machinery in three hulls of the same size, one a long stroke, high pressure, condensing engine; another a short stroke, low pressure, condensing engine; and a third a fore-and-aft, compound, condensing engine. These vessels as well as a subsequent one, in which the cylinder of a high-pressure, condensing engine was jacketed, were thoroughly tested by a joint board of engineers from the Navy and Treasury departments, Chief Engineer Charles H. Loring, representing the former, and Mr. Emery the latter. The results were at the time the only reliable ones extant, and the printed reports and an analysis of the same by Mr. Emery were copied in the text books and technical literature at home and abroad. The degree of Doctor of Philosophy was conferred upon him soon afterward, by the University of the City of New York.

Dr. Emery was one of the judges at the Philadelphia Centennial Exhibition, on engines, pumps and mechanical appliances, and an associate member of the scientific committee on musical instruments, electrical and other scientific apparatus, and was assigned to the position of assistant to Lord Kelvin, then Sir William Thomson. He was also appointed one of the judges in the Electrical Department of the Columbian Exposition at Chicago in 1893, and was placed on the Committee to which was assigned the examination of dynamos and motors.

In 1879, Dr. Emery while continuing his connection with the Revenue service, became the chief engineer and finally manager of the New York Steam Company. He designed and built the entire plant, providing four stories of boilers, aggregating 16,000 horse-power at the Cortlandt street station, using wrought-iron pipes of the largest size it was then possible to obtain, (some fifteen inches and even sixteen inches in diameter), designing special expansion joints and other details, and making the work a complete mechanical success. Steam was supplied through service pipes, eight and ten inches in diameter, to buildings like the Produce Exchange, the Mutual Life building, and finally the New York Court House and Post Office, at distances of one half to three quarters of a mile from the station. The plant operated very satisfactorily and still continues to do so under the original pressure of eighty to eighty-five pounds. The steam company had the prospect of an enormous business before it, but the situation has been greatly changed by the subsequent growth of the electrical industries, especially the transmission of light and power over considerable distances. In consequence of this a great many power-users take electric power from central stations, who would otherwise take steam from the steam company. On the other hand however, there are office buildings in the district served by the steam company, which have their own plants including dynamos, engines and boilers complete, but which take steam for their engines from the steam company in preference to firing their own boilers. A smaller steam station was erected on Fifty-eighth Street near Madison Avenue. Dr. Emery resigned from the steam company in October, 1877, up to which time there had been expended on the work nearly two millions of dollars, and continued business as consulting engineer and engineering expert in relation both to practical matters of engineering and those arising from litigation in patent cases, condemnations of water power, etc. Dr. Emery has been consulting engineer for the terminal facilities of the New York and Brooklyn Bridge and several of the principal plants of the Edison Electric Illuminating Company. He was for a number of years consulting engineer for the City of Fall River, Massachusetts, and prominent in connection with the compromise of the difficulties between that city and mill owners; resulting in a novel agreement, based on his report, by which water was to be thereafter furnished to the city from the Watuppa ponds in consideration of the abatement of taxes on water power. He has been connected with the building of steam yachts, a subway company and a number of similar enterprises. He has lectured at Cornell University, and other educational institutions, and while in the government service was chairman of the engineering examining boards of the United States Revenue Marine. Many of his lectures were published in the *Scientific American Supplement.*

Besides being a member of this INSTITUTE, Dr. Emery was also a member of the following bodies. The American Society of Civil Engineers, the American Society of Mechanical Engineers, the American Institute of Mining Engineers, the American Association for the Advancement of Science, the British Institution of Civil Engineers, from which he received a Watt medal and a Telford premium for an approved paper, and the Brooklyn Institute of Arts and Sciences, in which institution he held the office of president of the department of engineering.

Dr. Emery always dwelt with much pleasure on his association with the New York Electrical Society, whose usefulness he held in high estimation. He was Vice-President from 1893 to 1894, and during that year of office he left an imprint on the counsels of the Society. In 1896 he was elected President, and his presidential term was distinguished by the same earnestness and wisdom which were apparent in all his relations to the Society. His inaugural address before the Society entitled "Reminiscences of Forty Years of Engineering Experience," was of more than ordinary interest and historical value.

In his official capacity of judge at the Centennial Exhibition at Philadelphia, Dr. Emery had an excellent opportunity to estimate the future possibilities of the various branches of applied science, and being impressed with the prospects of electricity, he determined to study that science, but several years elapsed before he had any business or professional connection with electrical matters. However, he never lost his personal interest in electricity, and as the different branches of the industry developed, he kept in touch with them. On June 26th, 1891, he was elected to this INSTITUTE, and on April 19th, 1892, he was transferred to full membership. On October 23d, 1895, he was appointed to the Board of Examiners, and at the next meeting of that body on November 6th, he was elected chairman, which office he held at the time of his death. Since his connection with the INSTITUTE, Dr. Emery has read four papers before the meetings, besides being a very frequent participant in the discussions. His papers were as follows; at the general meeting of the INSTITUTE at Chicago, June 6th, 1892, a paper on "The

Relation Between Magnetomotive Force and Magnetization" at the local meeting at New York, March 21st, 1893, a paper on "The Cost of Steam Power" at the general meeting at Niagara Falls, June 26th, 1895, another paper on the same subject and also a paper on "Alternating Current Curves." The papers on the cost of steam power are of great practical utility, and have become a standard of reference.

OLIVER BLACKBURN SHALLENBERGER.

A Memorial.

BY CHARLES A. TERRY.

Oliver Blackburn Shallenberger was born at Rochester, Pennsylvania, May 7th, 1860. His father, Dr. A. T. Shallenberger, is one of the leading physicians of western Pennsylvania, and a brother of the Hon. W. S. Shallenberger, formerly a member of Congress and now Second Assistant Postmaster General. Upon his mother's side he descended from the Bonbright family of Youngstown, Penna.

He received his early education at the public schools of Rochester, and at Beaver College in the neighboring city of Beaver. In 1877 he entered the Naval Academy at Annapolis, as cadet engineer. Out of the one hundred and twenty-six candidates examined, twenty-five were admitted and young Shallenberger entered at the head of his class. He held this position throughout the year. The work of his second and third years was seriously interfered with, first by an accident resulting in a broken arm and a dislocated wrist, and afterward by impaired eye-sight which compelled him to abandon night study. Notwithstanding these disabilities, he held third position in his class at the end of his course.

The department of physics at Annapolis occupied a prominent position in the curriculum at the time of Mr. Shallenberger's entrance, and particular attention was given to electricity. Mr. Shallenberger found in this line of work a field peculiarly congenial to his tastes, and was enabled to indulge his natural inclinations toward original experimental investigations. The systematic training and thorough knowledge of the fundamental principles of physics which he was thus able to acquire, formed the basis of his subsequent careful work, and enabled him to readily and accurately shape the directions of his investigations along lines in which he was always surprisingly free from erroneous conclusions and those deviations and vagaries which are characteristic of many inventive minds. After completing the three years' course at Annapolis, he took the customary two years' cruise upon a government vessel. He was assigned to the U. S. flag-ship *Lancaster*, and the greater portion of the time was spent in the Mediterranean. The most notable experience of these two years was that of witnessing the magnificent spectacle of the bombardment of Alexandria. The vivid pictures of different scenes of this event which Mr. Shallenberger's clear, concise style and remarkable command of language enabled him to give, were always full of fascinating interest to his friends. Among his contemporaries at the Naval Academy were Mr. Frank J. Sprague, Dr. Louis Duncan, Mr. W. F. C. Hasson, Mr. Gilbert Wilkes, and several others whose names are prominent among electricians.

In 1883 he returned to the United States, and in 1884 resigned from the naval service and thereafter devoted his entire attention to the science of electricity. The Union Switch and Signal Company, of Pittsburg, under the management of Mr. George Westinghouse, was at that time organizing an electric light department, and Mr. Shallenberger became associated with that work. His genius and executive ability were at once recognized, and he was selected to take charge of the experiments made the following summer and fall with the Gaulard and Gibbs alternating current apparatus which Mr. Westinghouse imported from Europe. During this period Mr. Shallenberger was associated with Mr. William Stanley and Mr. Reginald Belfield in the commercial development of the alternating current system. The results of the investigations made by the Union Switch and Signal Company led Mr. Westinghouse to organize the Westinghouse Electric Company, and Mr. Shallenberger was appointed Chief Electrician of that company and later of its successor, the Westinghouse Electric and Manufacturing Company. He was elected an associate member of the INSTITUTE September 7th, 1888, and was transferred to membership December 4th, 1888.

In 1889 he went abroad and spent a considerable time in visiting the central stations in many of the larger European cities. In 1891 failing health compelled him to resign his position as Chief Electrician, but the Westinghouse company, unwilling to part with his services, retained him as Consulting Electrician. The succeeding winters he was compelled to spend in Colorado, but the summer months were spent at his home in Rochester, where he continued his work at a well equipped laboratory near his residence.

In 1897 he organized the Colorado Electric Power Company, of which he was President at the time of his death. He returned to Colorado in October of 1897, accompanied by his wife, Mary Woolslair Shallenberger, whom he married November 27, 1889, and their two children, a son and a daughter. His strength gradually waned, and during the evening of January 23rd, 1898, he passed peacefully from among us.

Twenty-four years devoted to education, and fourteen years spent in giving to the world the fruits of his splendid intellect, span the brief period of his life, but each year of that short life witnessed the cultivation of a most lovable character, the development of a masterly mind, and lasting benefits to his fellowmen.

It would be interesting, indeed, to review many of Mr. Shallenberger's important contributions to the electrical art and to trace back to his engineering skill many of the essential features which are utilized in the modern systems of electrical distribution. He invented the street lighting system in which each of a series of incandescent lamps is shunted by a reactive coil having its winding so proportioned to the mass of iron in its core that upon the interruption of the current through any lamp, a normal current is allowed to flow through the corresponding coil to the remaining lamps by reason of the consequent high magnetic saturation of its core. The construction of converters with primary and secondary coils separately wound and insulated was originated by him. He also was the first, in this country at least, to connect alternating current generators in parallel circuit, and he devised ingenious methods and apparatus for that purpose. The compensating indicators for showing at the central station the condition of the consumption circuit were worked out by him. His latest work was in producing a series of alternating current recording and indicating wattmeters for accurately measuring the energy consumed upon inductive as well as non-inductive circuits, and compensating for variations in temperature and rates of alternation. But of all his inventions, the development of the current meter bearing his name is surrounded with the greatest interest, not alone because of its intrinsic value and importance, but because it illustrates the character and mental aptitude of the man. He was original in his conceptions, comprehensive in his grasp of ideas, conscientiously thorough in developing them, accurate in his conclusions, and complete in his final expression; these characteristics were abundantly evident in his development of the meter. While testing an experimental arc lamp upon an alternating current circuit, his attention was attracted by the rotation of a small spiral spring, which, dislodged from its position in the lamp, had fallen upon the brass head of the magnet-spool adjacent to a projecting core of iron wires. The motion was so slow as to be scarcely perceptible, but it did not escape his quick observation. He realized at once that he was in the presence of a new phenomenon. All his energies were immediately devoted to ascertaining the cause. Experiment followed experiment in rapid succession. Before he left the laboratory that night he developed from this accidental suggestion the complete conception of the alternating current meter, an object for which he, as well as many others, had for many months sought in vain. He pursued his further experiments with such zeal and good judgment that within a month he had produced a complete working meter, in essentially the same form that it is now manufactured after nearly ten years of extended use.

It is a curious but well recognized fact that important inventions and brilliant discoveries are often independently made by different people in widely separated localities, and the history of the production of the rotary field motor, an essential part of the Shallenberger meter, contains a striking instance of this phenomenon. While Mr. Shallenberger was producing his meter in Pittsburg, Mr. Tesla in New York was preparing to make public the wonderful discoveries which he had made in alternating current motors. Professor Ferraris, at Turin, contemplating with the delight of a profound scientist the beauty of a mathematical theory successfully demonstrated by the workings of physical apparatus, had prepared a paper descriptive of the theory of operation of a small motor which he had previously constructed, and suggesting its applicability to electric meters. Mr. Shallenberger's discovery was made during the week ending April 20th, 1888. Mr. Tesla presented to this INSTITUTE his memorable paper regarding his work on the evening of May 1st, 1888, the same day that his patents were issued. Professor Ferraris' article appeared in a journal which, while bearing a somewhat earlier nominal date, was actually published during either the last week of April or the early part of May. The results of the work of each of these three brilliant inventors was characteristic of their respective mental attributes, and while neither might have arrived at the special utilization of the others, they independently discovered the fundamental theory of the rotating field, one through an inventor's intuitive process of reasoning, another through pure mathematical calculations, and the third through a quick perception and intelligent appreciation of the presence of an unusual phenomenon.

The history of the first decade of the Westinghouse company's existence is full of the personality of Shallenberger. His ability to fashion apparatus in its simplest, most efficient form, was one of his prominent characteristics. The words of Prof. Tyndall, used in reference to another inventor, are peculiarly applicable to Mr. Shallenberger: "He had an inventor's power, and an inventor's delight in its exercise. Such minds resemble a liquid on the point of crystallization. Stirred by a hint, crystals of constructive thought immediately shoot through them. He had the penetration to seize the relationship of facts and principles, and the art to reduce them to novel and concrete combinations."

His lovable character, strong Christian manliness and capacity for warm friendship, endeared him to those who knew him best. The many who knew him by his works only, will gain some conception of the value of these qualities through the letters from some of his friends which it is my privilege to present with this brief tribute to his memory:

From Leonard E. Curtis.

Mr. Shallenberger was one of the most lovable men I ever knew. He had a singularly sweet and cheerful temper, a rare unselfishness and a sincere honesty of character that made friends of all who knew him. I do not think he ever had an enemy. His unfailing courtesy, his thoughtful consideration for the rights and feelings of others, in small things as well as great, his keen sense of humor, and a certain playfulness of imagination and quaintness of expression in his ordinary intercourse with his friends and associates, made him a most delightful companion for us who knew him well. His amiability did not, as is often the case, come from weakness, for he was a man of strong convictions, and when any question of right and wrong was involved, nothing could divert him from the strict line of duty. His cheerfulness of temper came largely from a nabiding faith that "somehow good shall be the final end of all," and also in large measure, I think, from a certain clearsightedness as to the facts of his environment and an uncomplaining acquiesence in what was inevitable.

Others will probably be able to speak from more direct knowledge with regard to his work as an engineer and as one of the executive officers of a great industrial organization, but I had an opportunity to see a good deal of his work as an expert and as an inventor. We worked together in a good many patent cases, some of which were very intricate and difficult, and I soon came to regard him as the strongest and most reliable electrical expert that I knew. His knowledge of the physical laws relating to electricity and magnetism was very thorough and practical, his powers of observation were acute and highly trained, he was an ingenious and careful experimenter, and he was, above all, a singularly clear thinker and close reasoner. In consultation he was especially helpful. Plausible fallacies and untenable positions that had at first more or less attraction for most of us did not detain his attention long. His mind seemed instinctively to reject any proposition that led to an illogical conclusion, and he did not take a position until he had worked out all the logical consequences of it. He was a very strong witness. His language was simple and direct, but clear and forcible, because he was a clear thinker. On cross-examination he never gave me any anxiety. He might amplify or explain on cross-examination the views he had expressed in his direct testimony, but he had no occasion to modify them because he had already thought the matter out fully and told the truth as he understood it.

Although he was severely practical in his work, he had a vivid imagination, and was fond of speculative discussion when more serious work was not pressing. I have spent many delightful hours with him in the intervals of our work, and later when we both had a good deal of leisure here, in discussing the unsolved problems of science and the greater problems of the supernatural world. It is one of the great sorrows of my life that there are to be no more such hours for me.

I have touched on a few points that especially impressed me in Shallenberger's character, but I feel that I can give no adequate expression to what he was to me and to others who were so fortunate as to know him well.

COLORADO SPRINGS, March 7th, 1898.

From ELIHU THOMSON.

Though it was not my fortune to meet Mr. Shallenberger frequently, I obtained at the outset a high appreciation of his fine character and genial disposition. To meet him was to admire and trust him. It is one of the great sorrows of life that such friends are so soon taken from us.

Mr. Shallenberger's electrical work is so well known and so highly valued as to need no praise from me. He held a high place among electrical engineers. The discovery of the principles of alternating current induction, upon which, in his hands, his beautiful induction meter and measuring instruments were founded, is sufficient evidence of his great ability and technical skill.

His work has left a lasting impression upon alternating current science and industry, and we cannot escape the conviction that had his life and health been spared he would have continued his successful work and would have won many fresh laurels.

SWAMPSCOTT, MASS., March 8th, 1898.

From Frank J. Sprague.

Mr. Shallenberger's life and character, his abilities and accomplishments, merit special record, the more so because of his own gentleness and modesty. His old naval associates feel a special pride in his work, much of which has become standard, and had his life and health been spared, it would have been still more for the lasting benefit of electrical science.

His friends will long miss a good fellow and a loyal companion of most lovable character, especially endeared to them by the pathetic ending of his career. Among those friends, I am more than glad to have been one.

New York, March 17th, 1898.

From Nikola Tesla.

I am glad that your letter gives me an opportunity to express how deeply I have regretted the death of Shallenberger. The electro-technical profession has lost in him one of its most gifted members. Many a bright idea is recorded in his numerous patents, and much of his work is embodied in the splendid machinery which, during a number of years, he has helped to develop. Although stricken down in the prime of life, he leaves a brilliant record in the profession.

Shallenberger has also made a record as an original discoverer ; for, although at a later date, he independently observed some rotations in a magnetic field, his merit is all the greater, as he did not stop at a laboratory experiment, but quickly applied the principle practically and produced his beautiful measuring instruments.

Shall we content ourselves to merely honorably mention the name of a man who has done so much ? I will not presume to make a suggestion in my capacity as one of his co-workers, but Shallenberger was a friend whom I have liked and esteemed highly, and particularly in this quality I would feel very gratified to see his name more fitly commemorated.

New York, March 17th, 1898.

From William Stanley.

Oliver Shallenberger was a delightful man to know—frank, fearless and positive, he possessed in an eminent degree that clear-headedness which made him sure of every step in his scientific work.

When he first began his practical alternating current work there was little available information on the subject. No alternating machinery had been constructed in this country, and the laws governing alternating current phenomena were but vaguely understood. In fact, the machinery for the transmission and transformation of energy by alternating currents was devised and put in practical use before the laws governing such machinery had been digested by engineers. Into this chaotic condition of affairs Shallenberger threw his whole strength. He quickly separated the logical and useful information from the unscientific and uncertain ; he made clear and simple many vexing and misty problems, and he probably did more than any engineer of the time in perfecting the so-called alternating system.

But, while Shallenberger's value as an engineer was known to many who came in contact with him, it was the privilege of but comparatively few to know him as I knew him; to know his charming personality and his high character. And while his inventions and engineering work have created a prominent place for his name in the development of practical electricity, his personality created friendships which his untimely death can but cause his friends to cherish the more.

PITTSFIELD, MASS., March 12th, 1898.

From ALEXANDER JAY WURTS.

It was my good fortune to be associated with Mr. Shallenberger as far back as 1887. I soon learned with others to admire his clear mind and wonderfully good judgment, but it was not so much these characteristics, together with his great inventions and the rapid progress he made in the science of electricity, which attracted my attention—there is not such a great lack of brilliant men in the world—what drew me to him more than anything else was his beautifully refined character. It was a real pleasure to greet him after a week's absence. I shall never forget his generous hand-shake and his always cheerful and pleasant "good mornings;" and he was just the same to all—everybody loved him.

I remember so well when Mr. Shallenberger first went to Colorado. It seemed as though the light and life of the laboratory had gone out; and as though we really could not get along without him. But now that he has gone from us, not to return, it is not so much his great inventions or his loss as a scientist that is talked about among his associates, but rather some phase of his character. The loss which we all feel is "O. B." Those who knew him will at once recognize what I mean and nothing else can possibly express it.

PITTSBURG, PA., March 9th, 1898.

From T. C. MARTIN.

The history of the alternating current in this country must always include Mr. Shallenberger's early work, for he not only did much to introduce the system for practical purposes, but was one of the first to address himself to the difficult problem of measuring that current. His success, in the beautiful instruments that bear his name, is a matter of record. It must not be forgotten that Mr. Shallenberger did his best work, in this direction, at a time when the alternating current was hardly known, harshly criticised and bitterly opposed; and hence he is entitled to double credit for the foresight and courage which led him to advocate its many solid claims to consideration.

Of Mr. Shallenberger personally, one can only speak in terms of admiration. He was a conspicuous member of that group of naval students who within the last fifteen years have made a deep mark on the electrical art in America; and he had a pleasant, breezy way that is associated in the popular mind with sea life. It was a pleasure to meet with him and talk with him. He not only was generous in his views but had insight into affairs, and ability to express well defined opinions in a clear, incisive manner.

NEW YORK, March 16th, 1898.

From Charles F. Scott.

Mr. Shallenberger's simple, clear, straight-forward way of thinking, impresses me as his preeminent characteristic. His mind was capable and discriminating, and he possessed a remarkable facility for transferring his ideas into physical forms His best known work—that on alternating current meters, well illustrates his clearness and keenness of thought and the direct and elegant way in which he expressed his thoughts mechanically. The meter work especially exemplifies his refinement and delicacy in both thought and manipulation. There was usually but a single step from the matured idea to the practical commercial form. It is not often that a new piece of apparatus remains unchanged for any considerable time. This has been especially true in electrical apparatus during the past decade when revolution and evolution have been common; but the original current meter was invented and developed and in the short period of a few months received a mechanical form which has been duplicated a hundred and thirty thousand times and is still being repeated daily with only minor changes. His recent work on alternating current measuring instruments shows at once a breadth of conception in taking a general survey of the theory of electrical instruments, and the minuteness and precision with which he cared for the minutest details.

It is difficult to realize now how truly work in the alternating current field a dozen years ago was pioneer work. But what was lacking in those early days in knowledge and experience, he made up in keen insight and generous common sense.

Upon meagre data, new types of apparatus, dynamos and transformers, measuring instruments and auxiliary apparatus, must be quickly designed and made ready for service. The success of that work contributed in no small measure to the subsequent extension and development of the alternating current system, and this success was due in no small measure to the clear insight, the sound judgment and the intelligent common sense of O. B. Shallenberger.

The symmetry of his character was a notable characteristic. In his theoretical study, in his method of experiment, in the apparatus which he produced, in his official relations with those under his direction, in his relations as personal friend and also in his home relations—there runs through all a consistent simplicity, integrity and sameness.

Pittsburg, Pa., March 13th, 1898.

From Reginald Belfield.

I am very glad to have this opportunity of adding my tribute to the fine character and great ability of my dear old friend, O. B. Shallenberger, whom I have had the privilege of knowing intimately for over twelve years, and have therefore had very many opportunities of appreciating his worth.

From every point of view Shallenberger was one among a thousand; he was a true friend, a great electrician, and altogether a type of manhood which is seldom seen. It is difficult, therefore, to confine oneself to any one of his particular attainments, as he was so many-sided that whether you consider his character, ability or work, the temptation is to stray away from that special subject, and contemplate them all.

Shallenberger, when first I knew him, was Electrician to the Union Switch and Signal Company of Pittsburg, Pa. Here, in the very early stages of electricity, his talents and inventive genius were most marked, his grasp of any new matter great, which, with his capacity for hard work and diligence, pointed him out as one of the most brilliant workers of the day in this subject. Even so early as this he had turned his attention to alternating current distribution—at that time quite in its infancy—and in the development of this system most of his later work has been devoted. All the earlier machines of the Westinghouse company, transformers, instruments, and the thousand and one other things which go to make up a system, were designed by him, and his fertile brain was never at a loss to work out new pieces of apparatus to overcome difficulties as soon as they presented themselves.

Despite the enormous amount of work which his position entailed, he was always experimenting, with most satisfactory results, as the Patent Office records amply testify, and the Westinghouse company has lost a most valuable and esteemed man by his early death.

Shallenberger was gifted with a very sound judgment, and he most fully considered all questions from every point before expressing an opinion. His experimental work was also directed with a clearness of perception, a full knowledge of the matter, and an exact idea of what he desired to obtain ; this enabled him to conserve his energies, and was the secret of the immense amount of work he was able to get through during his life. His grasp of a subject was very quick and thorough, and from a small experiment which to an ordinary observer would seem of little or no moment, he was often able to obtain results of great value.

LONDON, ENG., March 16th, 1898.

DIED.

Verley:—At his home in Kingston, Jamaica, March 3rd, 1898, Horace S. L. Verley, son of Louis Verley of that place. Mr. Verley was formerly laboratory assistant of Dr. Geyer at the Stevens Institute, and was elected an associate member of the Institute May 17th, 1892. He had been ill for over a year.

Perry:—In Brooklyn, N. Y., March 27th, 1898, Nelson Williams Perry, electrical and mining engineer. Mr. Perry was a son of Judge Perry of the Ohio Supreme Court, and was born in Columbus, Ohio, May 22nd, 1853. He joined the INSTITUTE May 17th, 1892, and was transferred to full membership March 21st, 1893. His death was due to the accidental drinking of a poisonous solution while working in his laboratory in darkness.

Gott:—In New York City, Monday, June 6th; Clarence P. Gott, formerly Chief Engineer and Electrician at the Grand Central Palace. Mr. Gott was elected an Associate Member of the INSTITUTE, November 20th, 1895.

Smith:—At Baltimore, Md., December 24, 1898, Captain Frederick H. Smith, City Engineer, of Baltimore, who was born in Pittsburg, Penn., November 10th, 1839, and elected an Associate Member of the INSTITUTE November 12, 1889. He had been in failing health for some time, but pneumonia was the immediate cause of his death. The early work of Captain Smith was with the Louisville and Nashville Railroad, from which he entered the service of the Southern Confederacy, continuing through the war. Latterly his work has been in bridge engineering in South America and this country. His leisure was largely devoted to scientific research. He was a gallant soldier, a bright and vigorous thinker, a deep student, a faithful friend, and a devoted husband and father.

American Institute of Electrical Engineers.

CATALOGUE OF MEMBERS.

May 1st, 1899.

HONORARY MEMBERS.

Name.	Address.	Date of Membership.
Kelvin, *Lord*,	*LL.D.*, *F.R.S.S.L.* and *E.* The University, Glasgow, Scotland,	H.M. May 17, 1892
Preece, **Wm. H.** *F.R.S.*	Electrician, General Post Office, London, Eng. Residence, Gothic Lodge, Wimbledon.	H.M. Oct. 21, 1884

Total, 2.

MEMBERS.

Abbott, Arthur V.	Chief Engineer, Chicago Telephone Co., 203 Washington St., Chicago, Ill.	A Oct. 21, 1890 M Jan. 16, 1895
Acheson, Edw. G.	President, The Carborundum Co., Niagara Falls, N. Y.	A Jan. 3, 1888 M May 1, 1888
Adams, Alton D.	Civil Engineer. Tremont Building, Box 1377, Boston, Mass.	A April 18, 1893 M Jan. 17, 1894
Ahearn, Thomas	Ahearn & Soper, Electrical Supplies, Ottawa, Ont.	A July 12, 1887 M Sept. 6, 1887
Albright, H. Fleetwood	Electrical Engineer, Western Electric Co., New York; residence, 60 Sayre St., Elizabeth, N. J.	A Sept. 27, 1892 M June 20, 1894
Almon, G. H.	Electrical Engineer and Contractor, Montpelier, Vt.	A Sept. 20, 1893 M Mar. 21, 1894
Andrews, Wm. S	Manager Central Station Sales, General Electric Co., Schenectady, N. Y.	A Mar. 5; 1889 M April 22, 1896
Anson, Franklin Robert	Secretary and Manager, Salem Light and Traction Co., Salem, Ore.	A Feb. 27, 1895 M Nov. 23, 1898
Anthony, Prof. W. A.	(*Past President.*) Consulting Electrician, Cooper Union; residence, 313 W. 33d St., New York, N. Y.	A Dec. 9, 1884 M Jan. 6, 1885
Armstrong, Chas. G.	Consulting Electrical Engineer, Fisher Building, Chicago, Ill.	A Sept. 27, 1892 M Aug. 31, 1898

Name.	Address.	Date of Membership.
Arnold, Bion J.	Consulting Electrical Engineer, 1541 Marquette Bldg. and 4128 Prairie Ave., Chicago, Ill.	A Oct. 25, 1892 M Nov. 15, 1893
Ayer, James I.	General Manager American Electric Heating Corporation, Franklin and Sidney Sts., Cambridge, Mass.	A May 19, 1891 M April 19, 1892
Ayres, Brown	Professor of Physics and Electrical Engineering, Tulane University, New Orleans, La.	A Dec 16, 1891 M Mar. 15, 1892
Badt, Lieut. Francis B.	Electrical Engineer, Firm of Meysenburg and Badt, 1522 Monadnock Block and 6506 Lafayette Ave., (Englewood), Chicago, Ill.	A April 19, 1892 M Mar. 25, 1896
Baillard, E. V.	Manufacturer of Electrical Instruments and Fine Machinery, 106 Liberty St., New York City.	A Dec. 3, 1889 M Jan. 16, 1895
Baldwin, Bert L.	Mechanical and Electrical Engineer, The Cincinnati Street R'way Co., 73 Perin Bldg., Cincinnati, O.	A April 22, 1896 M Nov. 18, 1896
Barstow, William S.	General Manager, Edison Electric Illuminating Co., 360 Pearl St., Brooklyn, N. Y.	A Feb. 21, 1894 M April 26, 1899
Batchelor, Chas.	Electrical Engineer, 33 West 25th St., New York City.	A June 8, 1887 M July 12, 1887
Bates. James H. *M. E.*	New York office, F. L. Smidth & Co., No. 66 Maiden Lane, N. Y. City. Box 118 Hoboken, N.J.	A Sept. 6, 1887 M Oct. 1, 1889
Baylis, Robert Nelson	The Baylis Co., 99 Cedar St., New York City.	A Oct. 1, 1889 M May 17, 1892
Bedell, Dr. Frederick,	Assistant Professor in Physics, Cornell University, Ithaca, N. Y.	A April 21, 1891 M May 19, 1896
Bell, Prof. A. Graham	(*Past President.*) 1331 Conn. Ave., Washington, D. C., and Baddeck, N. S.	A April 15, 1884 M Oct. 21, 1884
Bell, Dr. Louis	Electrical Engineer, Boston, Mass.	A May 20, 1890 M June 18, 1890
Benjamin, Park	Electrical Expert and Engineer, 203 Broadway, N. Y. City.	A Dec. 16, 1891 M Feb. 16, 1892
Bernard, Edgar G.	Electrical Engineer, President, E. G. Bernard & Co., 43 4th St., Troy, N. Y.	A. Jan. 5, 1886 M July 12, 1887
Berthold, Victor M.	Patent Department, American Bell Telephone Co., 125 Milk St., Boston; residence, 16 Upton St., Cambridgeport, Mass.	A May 17, 1892 M May 21, 1895
Betts, Philander 3d	Electrician, U. S. Navy Yard, Washington, D. C.	A Mar. 25, 1896 M Jan. 25, 1899
Billberg, C. O. C.	Electrical Engineer, 3300 Arch St,. Philadelphia. Pa.	A Mar. 21, 1894 M Feb. 27, 1895
Binney, Harold	Patent Solicitor and Expert, 31 Nassau St., New York City.	A Sept. 16, 1890 M Dec. 16, 1890
Birdsall, E. T. *M. E.*	Consulting Electrical Engineer, 26 Cortlandt St., residence, 56 West 38th St., New York City.	A June 8, 1887 M Nov. 1, 1887

Name.	Address.	Date of Membership.
Blades, Harry H.	Electrical Engineer, 419 Cass Ave., Detroit, Mich.	A April 19, 1892 M May 21, 1895
Blake, Francis	Auburndale, Mass.	A Sept. 3, 1889 M Oct. 1, 1889
Blodgett, Geo. W.	Electrical Engineer, B. & A. R. R. and Consulting Electrician, Boston, Mass.	A July 12, 1887 M Sept. 6, 1887
Blood, John Balch	Blood and Hale, Consulting Engineers, Room 22-A, Equitable Building, Boston, Mass.	A June 20, 1894 M Dec. 18, 1895
Boggs, Lemuel Stearns	The Union Light and Power Co., Ogden, Utah.	A Sept. 20, 1893 M May 17, 1898
Boileau, Willard E.	General Superintendent and Electrician, Brush Electric Light & Power Co., Consulting Engineer, Columbus R. R. Co., Columbus, Ga.	A Sept. 19, 1894 M Mar. 25, 1896
Bosch, Adam	Sup't Fire Alarm Telegraph, Newark, N. J.	A April 15, 1884 M Jan. 6, 1885
Bottomley, Harry	Electrical Engineer, 7 Bigelow St., Somerville, Mass.	A April 2, 1889 M Jan. 22, 1896
Bourne, Frank	Electrical Engineer, 26 Cortlandt St., New York City.	A April 21, 1891 M Nov. 15, 1892
Boyer, Elmer E.	Foreman, Testing Department, Lynn Works, General Electric Co., Lynn, Mass.	A Sept. 25, 1895 M Mar. 25, 1896
Boynton, Edward C.	Electrical Dep't, N. Y., N. H. & H. R. R., New Haven, Ct.	A Aug. 6, 1889 M Nov. 24, 1891
Bradley, Chas. S.	(*Vice President.*) Electrical Engineer, 44 Broad Street, New York City.	A May 24, 1887 M Dec. 6, 1887
Brenner, William H.	Constructing Engineer, Care of Frazar & Co., Yokohama, Japan.	A Sept 20, 1893 M Mar. 21, 1894
Brinckerhoff, Henry Morton	Electrical Engineer, Metropolitan West Side Elevated R. R.; 258 Franklin St., Chicago, Ill.	A Sept. 23, 1896 M Dec. 16, 1896
Brooks, Morgan	Professor of Electrical Engineering, University of Nebraska; residence, 419 Oak Grove St., Lincoln, Neb.	A May 20, 1890 M June 17, 1890
Brown, Alfred S.	Electrical Engineer, Western Union Telegraph Co., 195 Broadway, P. O. Box 856, New York City.	A Mar. 18, 1890 M Feb. 21, 1893
Brown, J. Stanford, *E.E.*, [Life Member.]	Consulting Electrical Engineer, Cor. Sec'y, Carpenter Steel Co., 1 Broadway; Vice-Pres't and Treas. Mutual Realty and Loan Corp; Treas., of the Realty-Loan Trust Co., 203 Broadway, New York City; residence, Park Hill, Yonkers, N. Y.	A Sept. 6, 1887 M Nov. 1, 1887

Name.	Address.	Date of Membership.
BROWNE, SIDNEY HAND.	Consulting Electrical Engineer, 810 Equitable Bldg., Baltimore; residence, Rider, Md.	A Apr. 28, 1897 M Nov. 23, 1898
BRUSH, CHAS. F.	Electrical Engineer, 453 The Arcade, Cleveland, O.	A April 15, 1884 M Oct. 21, 1884
BURCH, EDWARD P.	Electrical Engineer, Twin City Rapid Transit Co., 517 6th Av., S. E., Minneapolis, Minn.	A Jan. 28, 1898 M May 17, 1898
BURLEIGH, CHAS. B.	Electrical Engineer, General Electric Co., 180 Summer St., Boston, Mass.	A April 21, 1891 M Feb. 16, 1892
CAHOON, JAS. B.	Electrical Engineer; General Manager, The Elmira Municipal Improvement Co., 313 Columbia St., Elmira, N. Y.	A June 17, 1890 M May 19, 1891
CALLENDER, ROMAINE	Electrician, Ryton-on-Tyne, Eng.	A Sept. 27, 1892 M May 21, 1895
CARHART, HENRY S.	Prof. of Physics, University of Michigan, Ann Arbor, Mich.	A Sept. 25, 1895 M April 22, 1896
CARROLL, LEIGH	Algiers Waterworks and Electric Co., Bank of Commerce Bldg. New Orleans, La.	A Oct. 1, 1889 M Nov. 12, 1889
CARUS-WILSON, CHARLES A.	The Rise, Holford Road, Hempstead, London, Eng.	A April 18, 1894 M April 17, 1895
CHAMBERLAIN, J. C.	Manager, The Electric Launch Co., Morris Heights; residence, 1 West 81st St., New York City.	A Dec. 6, 1887 M Jan. 3, 1888
CHANDLER, PROFESSOR CHARLES F.	Columbia University, New York City.	A Jan. 20, 1891 M June 7, 1892
CHASE, HARVEY STUART	Mechanical and Electrical Engineer, 8 Congress St., Boston Mass.	A Sept. 19, 1894 M Jan. 22, 1896
CHENEY, W. C.	Electrical Engineer, Anaconda Copper Mining Co., Anaconda, Mont. Residence, Oregon City, Or.	A Sept. 22, 1891 M Nov. 21, 1894
CHILDS, ARTHUR EDWARDS, *B. Sc. M.E.E.E.*	Manager New England Office, The Electric Storage Battery Co., 23 Central St., Boston, Mass.	A June 20, 1894 M April 17, 1895
CHUBBUCK, H. EUGENE	Manager, Quincy Lighting Companies, Quincy, Ill.	A Dec. 4, 1888 M April 26, 1899
CHURCHILL, ARTHUR	British Thomson-Houston Co., 83 Cannon Street, London, E. C., Eng.	A April 15, 1890 M Jan. 17, 1893
CLARK, ERNEST P.	Electrical Engineer, B. Altman & Co, 19th St., and 6th Ave., New York City.	A Jan. 8, 1887 M Nov. 1, 1887
CLARKE, CHAS. L.	Electrical Engineer and Patent Expert, 31 Nassau St., New York City.	A April 15, 1884 M Jan. 6, 1885
COLBY, EDWARD A.	Consulting Engineer, Lock Box 113, Newark, N. J.	A April 2, 1889 M May 7, 1889
COLVIN, FRANK R.	Box 217, Roselle, N. J.	A April 18, 1894 M May 21, 1895
COMSTOCK, LOUIS K.	Electrical Engineer, Western Electric Co., Chicago, Ill.	A Dec. 20, 1893 M Nov. 20, 1895

Name.	Address.	Date of Membership.
Condict, G. Herbert	Electrical Engineer, Electric Vehicle Co., 1684 Broadway, New York City.	A July 12. 1887 M Sept. 6, 1887
Cornell, Charles L.	Electrical Engineer, Hamilton, O.	A Feb. 7, 1890 M June 27, 1895
Coster, Maurice	Manager, Westinghouse Elec. and Mfg. Co., N. Y. Life Bldg,, Chicago, Ill.	A Sept. 25, 1895 M Mar. 25, 1896
Cowles, Alfred H.	Technical Adviser to the Cowles Smelting and Aluminum Co., 656 Prospect St., Cleveland, O.	A Mar. 5, 1886 M May 7, 1889
Craig, J. Hally	New England Electrical Supply Co., 49 Federal St., Boston, Mass.	A May 16, 1893 M Feb. 27, 1895
Crandall, Joseph Edwin	Electrician, C. & P. Telephone Co., 619 Fourteenth St., N. W. Washington, D. C.	A April 18, 1892 M April 18, 1894
Crocker, Francis Bacon [Life Member.]	(*Past-President.*) Professor of Electrical Engineering, Columbia University, New York.	A May 24, 1887 M April 2, 1889
Cross, Charles R.	Thayer Professor of Physics, and Director of the Rogers Laboratory, Mass. Institute of Technology, Boston, Mass.	A April 15, 1884 M Oct. 21, 1884
Cushing, Harry Cooke, Jr.	Electrical Consulting and Constructing Engineer, 39 Cortlandt St., New York City.	A Sept. 19, 1894 M Nov. 18, 1896
Cutter, George	Dealer in Electrical Supplies, 100 Lake Street, Chicago, Ills.	A June 17, 1890 M May 19, 1891
Cuttriss, Chas.	Electrician, The Commercial Cable Co., 20 Broad St., New York.	A Nov. 1, 1887 M Dec. 6, 1887
Daft, Leo	Consulting Electrical Engineer and Contractor, Sydney, N. S. W.	A Dec. 9, 1884 M Jan. 6, 1885
Darlington, Frederic W.	Consulting Electrical and Mechanical Engineer. 931 Drexel Building, Philadelphia, Pa.	A Sept. 19, 1894 M Nov. 25, 1895
Davidson, A.	Cable Engineer and Electrician, Central and South American Telegraph Co, Lima, Peru.	A May 18, 1897 M Oct. 27, 1897
Davis, Charles H., *C. E.*	Consulting and Constructing Engineer, 99 Cedar St., 576 Lexington Ave., New York City, and 308 Walnut St., Philadelphia, Pa.	A Mar. 18, 1890 M June 17, 1890
Davis, Minor M.	Traffic Manager, Postal Telegraph-Cable Co., 253 Broadway, New York City.	A April 6, 1886 M May 16, 1893

Name.	Address.	Date of Membership.
DAWSON, PHILIP	Associate and Chief Engineer with R. W. Blackwell, 39 Victoria St., Westminster, London, Eng.	A Sept. 25, 1895 M Feb. 17, 1897
DECKER, EDWARD P.	Assistant Chief Engineer, Sprague Electric Co., 20 Broad St., New York City; residence, 496 Second St., Brooklyn, N. Y.	A Feb. 26, 1896 M Oct. 27, 1897
DELAFIELD, A. FLOYD, *Ph. D.*	Electrical Engineer, Noroton, Conn.	A May 7, 1889 M Oct. 1, 1889
DELANY, PATRICK BERNARD	Inventor, South Orange N. J.	A April 19, 1884 M Nov. 24, 1891
DICKENSON, SAMUEL S.	Sup't, Commercial Cable Co., Hazel-Hill, Guysborough Co., N. S.	A Mar. 6, 1888 M Oct. 1 1889
DIEHL, PHILIP	Inventor, Singer Sewing Machine Co., 508 Morris Ave., Elizabeth, N. J.	A April 15, 1884 M Dec. 9, 1884
D'INFREVILLE, GEORGES	Electrical Engineer and Expert, 10 Desbrosses St., New York City.	A Nov. 1, 1887 M Dec. 6, 1887
DION, ALFRED A.	General Supt., The Ottawa Electric Co., Sparks St., Ottawa, Ont.	A Jan. 7, 1890 M Nov. 15, 1893
DOANE, SAMUEL EVERETT [Life Member.]	Sup't. Marlborough Electric Machine and Lamp Co., Marlborough, Mass.	A Aug. 6, 1889 M June 27, 1895
DODGE, OMENZO G., PROF.	U. S. Navy, 'Naval Academy, Annapolis, Md.	A Sept. 20, 1893 M April 17, 1895
DOIJER, H.	Consulting Electrical Engineer, 8 Choorstraat, Delft, Holland.	A Jan. 7, 1890 M Mar. 18, 1890
DOMMERQUE, FRANZ J.	Chief Draughtsman, Chicago Telephone Co.; residence, 496 N. Robey St., Chicago, Ill.	A Oct. 17, 1894 M Mar. 25, 1896
DONNER, WILLIAM H.	Electrical Eng'g Dept. International Correspondence School, Scranton, Pa.	A Nov. 18, 1890 M Dec. 16, 1890
DOW, ALEX	Manager, Edison Illuminating Co., Detroit, Mich.	A Sept. 20, 1893 M Dec. 18, 1895
DUDLEY, CHARLES B	Chemist and Scientific Expert, Penn. R. R. Co., 1219 Twelfth Ave., Altoona, Pa.	A Oct. 1, 1889 M Nov. 12, 1889
DUNBAR, F. W.	234 La Salle St., Chicago; residence Highland Park, Ill.	A Dec. 21, 1892 M May 16, 1893
DUNCAN, DR. LOUIS	(*Past-President*) Johns Hopkins University, residence, 139 E. North Ave., Baltimore, Md.	A July 12. 1887 M Sept. 6, 1887
DUNLAP, WILL KNOX	Electrical Engineer, Westinghouse Elec. and Mfg. Co., Niagara Falls, N. Y.	A Sept. 25, 1895 M June 24, 1898
DUNN, GANO SILLICK, *M.S., E.E.* (*Manager.*)	Chief Engineer, Crocker-Wheeler Electric Co., Ampere, N J.; residence. 223 Central Park, West, New York City.	A April 21, 1891 M June 20, 1894
DUNSTON, ROBT. EDWARD	General Manager, Saratoga Traction Company, Saratoga Springs, N. Y.	A Oct. 27, 1891 M Feb. 16, 1892

Name.	Address.	Date of Membership.
DYER, R. N.	Patent Attorney, 31 Nassau St., New York City.	A July 12, 1887 M Sept. 6, 1887
EDISON, THOMAS A.	Mechanician and Inventor, Orange, N. J.	A April 15, 1884 M Oct. 21, 1884
EDGAR, C. L.	General Manager and Chief Engineer, Edison Elec. Ill'm'g Co., 3 Head Place, Boston, Mass.	A Jan. 22, 1896 M May 19, 1896
EGGER, ERNST	Technical Director, Vereinigte Elektricitäts Actien Gesellschaft, Simmeringstr, 187, Vienna, X., Austria.	A Feb 21, 1893 M Mar. 21, 1894
EMMET, W. L. R.	Electrical Engineer, General Electric Co., Schenectady, N. Y.	A June 6, 1893 M Jan. 17, 1894
FARNHAM, ISAIAH H.	Electrical Engineer, N. E. Telephone & Telegraph Co., 125 Milk St., Boston, Mass.	A June 8, 1887 M July 12, 1887
FESSENDEN, REGINALD A.	Professor of Electrical Engineering, Western University of Pennsylvania, Allegheny, Pa.	A Oct. 21, 1890 M Dec. 16, 1890
FIELD, C. J., *M. E.*	Consulting and Constructing Engineer, 30 Broad Street, New York City.	A June 8, 1887 M Nov. 1, 1887
FIELD, HENRY GEORGE	Consulting Electrical Engineer, Field & Hinchman, 1203 Majestic Building, Detroit, Mich.	A April 22, 1896 M Dec. 16, 1896
FIELD, STEPHEN D.	Electrical Engineer, Stockbridge, Mass.	A April 15, 1884 M Oct. 21, 1884
FISCHER, GUSTAVE J.	Engineer for Tramway Construction, Public Works Department, Sydney, N. S. W.	A Jan. 20, 1891 M May 17, 1898
FISH, WALTER CLARK	Manager Lynn Works, General Electric Co., Lynn, Mass.	A June 26, 1891 M Feb. 26, 1896
FITZMAURICE, JAMES S.	Chief Engineer, The Electric Light Branch, 210 George St , Sydney, N. S. W.	A Sept. 20, 1893 M Mar. 21, 1894
FLACK, J. DAY	Electrical Engineer, 80 Carlton St., East Orange, N. J.	A Dec. 6, 1887 M May 21, 1895
FORTENBAUGH, S. B.	Asst. Prof. of Electrical Engineering, University of Wisconsin, Madison, Wis.	A April 17, 1895 M Dec. 16 1896
FOSTER, HORATIO A.	Electrical Engineer, Room 682, Ellicott Square, Buffalo.	A June 8, 1887 M Sept. 6, 1887
FOSTER, SAMUEL L.	Electrical Engineer, Market Street Railway Co. 19 Hobart Bldg.: residence, 3687 24th St., San Francisco, Cal.	A Feb. 26, 1896 M Nov. 18, 1896
FREEMAN, DR. FRANK L.	Attorney-at-Law, Solicitor of Patents, Electrical Expert, 931 F St , Washington, D. C.	A May 7, 1889 M Sept. 3, 1889

Name.	Address.	Date of Membership.
Freedman, William H.	Tutor in Electrical Engineering, School of Engineering, Columbia University; residence, 157 W. 119th St., New York City.	A Mar. 18, 1890 M Dec. 18, 1895
Gale, Horace B.	Mechanical and Electrical Engineer, Natick Mass.	A Nov. 15, 1892 M May 16, 1893
Gardanier, George W.	Assis't Electrical Engineer, Western Union Telegraph Co., 195 Broadway, New York City.	A April 18, 1893 M Jan. 22, 1896
Garratt, Allan V.	Chief Engineer, Lombard Waterwheel Governor Co., 61 Hampshire St., Boston; residence, 603 Centre St., Jamaica Plain, Mass.	A April 2, 1889 M May 7, 1889
Gerry, M. H., Jr.	Helena Water and Electric Power Company, Helena, Mont.	A April 18, 1893 M Oct. 21, 1896
Geyer, Dr. Wm. E.	Stevens Institute of Technology, Hoboken, N. J.	A June 5, 1888 M Sept. 7, 1888
Gharky, William David	Telephone Engineer, The Lorraine, Philadelphia, Pa.	A May 21, 1895 M Feb. 26, 1896
Gibbs, Lucius T.	Ass't Engineer, U S. N., Navy Dep't, Washington, D. C.	A Mar. 25, 1896 M Feb. 17, 1897
Gifford, Clarence E.	Electrical Engineer, Box, 292, Oil City, Pa.	A May 16, 1893 M Feb. 21, 1894
Goldsborough, Winder Elwell,	*M. E.*, Professor of Electrical Engineering, Purdue University, 113 South St., Lafayette. Ind.	A Mar. 21, 1893 M Jan. 25, 1899.
Goltz, William	1504 Monadnock Block, Chicago, Ill.	A Oct. 27, 1897 M Feb. 23, 1898
Gossler, Philip Green	Electrical Engineer, Royal Electric Co., 94 Queen St., Montreal, P.Q.	A June 20, 1894 M June 24, 1898
Gray, Dr. Elisha	Electrician and Inventor, Highland Park, Ill.	A Feb. 16, 1892 M May 17, 1892
Greene, S. Dana	Assistant General Manager, General Electric Co., Schenectady, N. Y.	A Sept. 20, 1893 M April 18, 1894
Gutmann, Ludwig	Electrical Engineer, 900 Knoxville Ave., Peoria, Ill.	A Sept. 14, 1888 M Mar. 21, 1893
Hadaway, W. S., Jr.	Electric Heating Engineer, 107 Liberty St., New York City.	A Nov. 21, 1894 M Oct. 21, 1896
Hall, Clayton C.	Attorney-at-Law, and Consulting Actuary, Room 40, Maryland Life Building, 10 South St., Baltimore, Md.	A April 15, 1884 M Oct. 21, 1884
Hall, John L.	C. and C. Electric Company, 45 North 7th. St., Philadelphia, Pa.	A Sept. 22, 1891 M Dec. 20, 1893
Hanchett, Geo. T.	Electrical and Technical Engineer, 123 Liberty St., N. Y.; residence, Hackensack, N. J.	A May 19, 1896 M Feb 15, 1899
Hamblet, James	Manager Time Service, W. U. Tel. Co., 195 Broadway, P. O. Box 856. NewYork City; residence, 20 Sidney Place, Brooklyn, N. Y.	A Nov. 1, 1887 M Dec. 6, 1887

Name.	Address.	Date of Membership.
Hamilton, Geo. A.	(*Treasurer.*) Electrician, Western Electric Co., 57 Bethune St., New York ; residence, 532 Morris Ave , Elizabeth, N. J.	A April 15, 1884 M Oct. 21, 1884
Hammer, Edwin W	Electrical Engineer, 46 Second Ave., Newark, N. J.	A Nov. 18, 1896 M June 23, 1897
Hammer, William J.	Consulting and Supervising Electrical Engineer, 1201 Havemeyer Bldg, 26 Cortlandt St., New York City.	A June 8, 1887 M July 12, 1887
Harrington, Walter E.	Electric Railway Engineer, 200 Market St., Camden, N. J.	A Mar. 17, 1891 M May 19, 1896
Harrison, Russell B.	Pres. and Electrical Engnieer, Terre Haute Electric Railway Co., Terre Haute, Ind.	A Sept. 25, 1895 M April 22, 1896
Hartwell, Arthur	Manager Chicago office, Westinghouse Electric and Mfg Co.; 171 La Salle Street, Chicago, Ill	A May 15, 1894 M Nov. 20, 1895
Haskins, Caryl D.	Electrical Engineer, General Electric Co., 180 Summer St., Boston, Mass.	A Mar. 18, 1890 M June 20, 1894
Haskins, Charles H.	Electrician, 70 Linwood Avenue, Buffalo, N. Y.	A April 15, 1884 M Oct. 21, 1884
Haskins, Clark Caryl	Electrical Engineer, 682a West Adams St., Chicago, Ill.	A Sept. 20, 1893 M Mar. 21, 1894
Hasson, W. F. C.	Honolulu, H. I	A Mar. 18, 1890 M May 15, 1894
Hayes, Hammond V.	Electrician, American Bell Telephone Co., 42 Farnsworth St., So. Boston, Mass.	A Nov. 12, 1889 M Mar. 18, 1890
Hayes, Harry E.	Asst. Electrician, American Telegraph and Telephone Co., 22 Thames St., New York City.	A April 18, 1893 M Dec. 20, 1893
Haynes, F. T. J.	Divisional Telegraph Engineer, Great Western Railway; residence, Belmont Villa, Cheddon Road, Taunton, Eng.	A Dec. 6, 1886 M Jan. 3, 1887
Heath, Harry E.	Electrical Engineer, Windsor, Conn.	A Mar. 21, 1893 M Mar. 25, 1896
Heinrich, Richard O.	General Manager, European Weston Electrical Instrument Co., 88 Ritterstrasse, Berlin, Germany.	A Oct. 1, 1889 M Oct. 25, 1892
Henshaw, Frederick V.	Electrical and Mechanical Engineer, 148 Henry St., Brooklyn, N.Y.	A Feb. 5, 1889 M Nov. 20, 1895
Herdman, Frank E.	Mechanical and Electrical Engineer, Crane Elevator Co., Winnetka, Ill.	A Dec. 18, 1895 M Oct. 21, 1896
Hering, Carl [Life Member.]	Consulting Electrical Engineer, 929 Chestnut St.; residence 124 E. Mt. Pleasant Ave., Philadelphia, Pa.	A Jan. 3, 1888 M June 5, 1888
Hering, Hermann S.	Associate in Electrical Engineering, Johns Hopkins University, residence, 1810 St. Paul St., Baltimore, Md.	A April 21, 1891 M April 18, 1893

Name.	Address.	Date of Membership
HERRICK, CHARLES H.	Superintendent Isolated, Lighting and Power Dep't., Edison Electric Illuminating Co., 3 Head Place, Boston; residence, 22 Herrick St., Winchester, Mass.	A April 21, 1891 M Jan. 17, 1893
HERZOG, F. BENEDICT, *Ph. D.*	President, Herzog Teleseme Co., Townsend Building, 1123 Broadway, New York City.	A May 24, 1887 M July 12 1887
HEWITT, CHARLES	Electrical Engineer, Union Traction Co., 820 Dauphin Street, Philadelphia, Pa.	A Sept. 16, 1890 M May 17, 1892
HIBBARD, ANGUS S.	General Manager, Chicago Telephone Co., 203 Washington St., Chicago, Ill.	A Nov. 24, 1891 M Feb. 16, 1892
HIGGINS, EDWARD E.	Editor, *Street Railway Journal*, 26 Cortlandt St., New York City.	A June 8, 1887 M July 12, 1887
HOLMES, FRANKLIN S.	Electrical Engineer, 108 Fulton St., New York City; residence 445a Macon St., Brooklyn, N. Y.	A April 21, 1891 M June 20, 1894
HOUSTON, EDWIN J., *Ph.D.* [Life Member.]	(*Past President.*) Prof of Physics, Franklin Inst., Firm of Houston & Kennelly, Crozer Bldg., 1420 Chestnut St.; residence, 1809 Spring Garden St., Phila., Pa.	A April 15, 1884 M Oct. 21, 1884
HOWELL, JOHN W.	Electrician, 20 Chestnut St., Newark, N. J.	A July 12, 1887 M June 5, 1888
HOWELL, WILSON S.	Lamp Testing Bureau Box, 114, Newark, N. J.; residence, 152 Prospect St., East Orange, N. J.	A Sept. 3, 1889 M Mar. 18, 1890
HUMPHREY, HENRY H.	Consulting Electrical Engineer, Bryan & Humphrey, 706 Lincoln Trust B'ld'g., St. Louis, Mo.	A Dec. 16, 1896 M April 28, 1897
HUNTER, RUDOLPH M.	Expert and Counsellor in Patent Causes, 926 Walnut St., Philadelphia, Pa.	A July 13, 1886 M May 17, 1887
HUNTING, FRED S.	Chief Engineer, Engineering Department, Fort Wayne Electric Co., 325 West Washington St., Fort Wayne, Ind.	A Nov. 15, 1892 M May 16, 1893
HUTCHINSON, DR. CARY T. [Life Member.]	(*Vice-President.*) Of Duncan & Hutchinson, Consulting Electrical Engineers, 71 Broadway, New York City.	A Feb. 7, 1890 M Dec. 16, 1890
HYDE, JEROME W.	Ass't Treasurer, The Springfield Steam Power Co., Wason Bldg. Springfield, Mass.	A June 8, 1887 M Nov. 1, 1887
INRIG, ALEC GAVAN	Globe Electrical Co., 44 White Post Lane, Victoria Park, London, Eng.	A Jan. 19, 1892 M May 17, 1892
IVES, EDWARD B.	Yuma, Arizona.	A April 2, 1889 M May 15, 1894
JACKSON DUGALD C.	(*Vice-President.*) Professor of Electrical Engineering, University of Wisconsin, Madison, Wis.	A May 3, 1887 M June 17, 1890

Name.	Address.	Date of Membership.
JACKSON, FRANCIS E.	Aylsworth & Jackson, Incandescent Filament Manufacturers, 128 Essex Ave., Orange; residence, 61 South Grove St., East Orange, N. J.	A Jan. 3, 1888 M June 17, 1890
JACKSON, HENRY	Telegraph Supt. and Engineer, The Lancashire & Yorkshire Railway Co., Horwich, Bolton-le-Moors, Lancashire, England.	A Mar. 21, 1894 M Dec. 19, 1894
JACKSON, JOHN PRICE	Professor of Electrical Engineering, Penn. State College, State College, Pa.	A Sept. 27, 1892 M Jan. 17, 1894
JACKSON, WM. B.	Chief Engineer, New York and Staten Island Electric Co., West New Brighton, N. Y.	A Aug. 13, 1897 M June 24, 1898
JANNUS, FRANKLAND	Attorney-at-Law, Solicitor of Patents, 149 Broadway, (Tel. 3565 Cortlandt), New York City.	A Nov. 12, 1889 M Mar. 18, 1890
JEHL, FRANCIS	VII Kazinczy-utczo 21, Budapest, Hungary.	A June 27, 1895 M Jan. 22, 1896
JENKS, W. J.	Secretary, Board of Patent Control, 120 Broadway, New York City.	A June 8, 1887 M Nov. 1, 1887
JOHNSTON, A. LANGSTAFF	Chief Engineer, Richmond Traction Co., 1112 E. Main St., Richmond, Va.	A April 21, 1891 M April 18, 1894
JONES, FRANCIS WILEY [Life Member.]	Assistant Gen'l-Manager and Electrician, Postal Telegraph-Cable Co., 253 Broadway, New York City.	A April 15, 1884 M Oct. 21, 1884
KEITH, DR. NATHANIEL S.	Electro-Metallurgist, 62 Nevada Block, San Francisco, Cal.	A April 15, 1884 M Jan. 17, 1894
KINSMAN, FRANK E.	Electrical Engineer, 120 Broadway, New York City; residence, 836 Sherman Ave., Plainfield, N. J.	A Sept 27, 1892 M May 16, 1893
KNOWLES, EDWARD R. *E. E., C. E.*	Sprague Electric Co., 20 Broad Street, New York City; residence, 82 Cambridge Place, Brooklyn, N. Y.	A June 8, 1887 M July 12, 1887
KNUDSON, A. A.	Electrical Engineer, Room 416, 32 Nassau St., New York City, Telephone 617 Cortlandt; residence, 127 Prospect Place, Rutherford, N. J.	A Dec. 6, 1887 M Jan. 3, 1888
LANGE, PHILIP A.	Superintendent Westinghouse Electric and Manufacturing Co., East Pittsburg, Pa.	A Mar 6, 1888 M June 5, 1888
LANGTON, JOHN	Electrical Engineer, Canada Life Building, Toronto, Ont., and 72 Trinity Place, New York, N. Y.	A Mar. 6, 1888 M June 5, 1888
LA ROCHE, FRED. A.	Senior Member of F. A. La Roche & Co., 652-660 Hudson Street; residence, 28 W. 25th St., New York.	A Sept. 19, 1894 M Nov. 20, 1895
LATTIG, J. W.	Electrical Engineer, residence, 335 West Broad St., Bethlehem, Pa.	A June 8, 1887 M July 12, 1887

Name.	Address.	Date of Membership.
LEMP, HERMANN, JR.	Electrician, 186 Allen Avenue, Lynn, Mass.	A April 2, 1889 M Feb. 21, 1893
LEONARD, H. WARD [Life Member.]	Electrical Engineer, Pres't. Ward Leonard Electric Co., Bronxville, N. Y.; residence, Lawrence Park, N. Y.	A July 12, 1887 M Sept. 6, 1887
LESLIE, EDWARD ANDREW	Vice-President and Manager, Manhattan Electric Light Co., Ltd., New York City; residence. 343 Hancock St., Brooklyn, N. Y.	A Jan. 16, 1895 M Feb. 17, 1897
LEVIS, MINFORD	Superintendent and Electrical Engineer, Novelty Electric Co., 54 North 4th St., Philadelphia, Pa.	A Feb. 21, 1893 M June 23, 1897
LIEB, JOHN W., JR.	(*Manager.*) General Mgr., Edison Electric Ill. Co.; Residence, 166 West 97th St., New York City.	A Sept. 6, 1887 M Nov. 1, 1887
LIGHTHIPE, JAMES A.	District Engineer, General Electric Co., Claus Spreckels Bldg., San Francisco, Cal.	A Feb. 21, 1894 M April 17, 1895
LINCOLN, PAUL M.	Electrical Supt. Niagara Falls Power Co., Niagara Falls, N. Y.	A Sept. 25, 1895 M June 24, 1898
LLOYD, HERBERT	(*Manager*) General Manager, Electrical Engineer and Chemist, The Electric Storage Battery Co., Drexel Bldg., Philadelphia, Pa.	A June 20, 1894 M May 21, 1895
LLOYD, JOHN E.	Chief Engineer and Acting General Manager Cape Town Tramways, 49 Sir Lowry Road, Cape Town, S. Africa.	A Jan. 22, 1896 M Mar. 25, 1896
LLOYD, ROBERT McA.	Electrician, 22 Broad St.; residence, 1 West 39th St., New York City.	A Oct. 21, 1890 M Nov. 15, 1893
LOCKWOOD, THOMAS D., [Life Member.]	Electrical Engineer, and Advisory Electrician, P. O. Drawer 2, Boston, Mass.	A April 15, 1884 M Oct. 21, 1884
LOOMIS, OSBORN P.	Electrical Engineer, Newport News Shipbuilding and Dry Dock Co., Newport News, Va.	A Sept. 16, 1890 M Dec. 16, 1896
LORRAIN, JAMES GRIEVE	Norfolk House, Norfolk St., London, W. C., England.	A May 16, 1891 M May 15, 1894
LOVEJOY, J. R.	General Manager, Supply Dept., General Electric Co., Schenectady, N. Y.	A April 21, 1891 M Feb. 21, 1894
MACFARLANE, ALEXANDER, *D. Sc., LL.D.*	(*Manager.*) Lecturer on Mathematical Physics Lehigh University, South Bethlehem. Pa.	A Jan. 19, 1892 M May 17, 1892
MAILLOUX, C. O.	(*Vice-President.*) Consulting Electrical Engineer, 150 Nassau St., Telephone 3985 Cortlandt, New York City.	A April 15, 1884 M Oct. 21, 1884
MANSFIELD, ARTHUR NEWHALL	Assistant Electrician, American Telephone and Telegraph Co., 22 Thames St., New York City.	A Dec. 20, 1893 M June 20, 1894

Name.	Address.	Date of Membership.
Marks, Louis B., *M. M. E.*	President, Marks Enclosed Arc Light Co., 689 Broadway; residence, 51 East 67th St., New York City.	A May 20, 1890 M Jan. 16, 1895
Marks, William Dennis, *Ph.B. C. E.*	President, The American Electric Meter Co., 9th and Montgomery Ave.; President, General Electric Automobile Co., Bourse Bldg., Philadelphia, Pa.	A Feb. 7, 1888 M May 1. 1888
Marshall, J. T.	Metuchen, N. J.	A Oct. 1, 1889 M Nov. 12, 1889
Martin, Julius	Electrical Engineer, 16 Oak St., Newark, N. J., Master Electrician, Equipment Dept., New York Navy Yard.	A Oct. 21, 1890 M Nov. 20, 1895
Marvin, Harry N.	Electrical Engineer and Manager, Marvin Electric Drill Co., Canastota, N. Y.	A April 19, 1892 M Jan. 17, 1893
Maver, William, Jr.	Electrical Expert and Consulting Electrical Eng'r, 120 Liberty St., New York City; residence, 227 Arlington Ave. Jersey City, N. J.	A July 12, 1887 M April 21, 1891
Mayer, George M.	Enterprise Block, 5th Floor, 79 Fifth Ave., Chicago, Ill.	A Dec. 16, 1890 M June 20, 1894
Maynard, Geo. C.	Smithsonian Institution, Washington, D. C.	A April 15, 1884 M Dec. 9, 1888
McCay, H. Kent	Electrical Engineer and Contractor, 106 E. German St., Baltimore, Md.	A Sept. 16, 1890 M May 19, 1891
McCluer, C. E.	General Manager, Richmond Telephone Co., Times Building, Richmond, Va.	A Mar. 21, 1893 M Jan. 17, 1894
McCrosky, James W.	Chief Engineer, La Capital Tramway Co. and Compaina de Luz y Fuerza Motriz de Cordoba, Reconquista 20, Buenos Aires, Argentina.	A Dec. 20, 1893 M Dec. 16, 1896
McCrossan, J. A.	Manager and Electrician, Citizens' Telephone and Electric Co., Rat Portage, Ont.	A Oct. 18, 1893 M Dec. 18, 1895
McMeen, Samuel G.	Engineer, Central Union Telephone Co., 1306 Ashland Block, Chicago. Ill.,	A Dec. 18, 1895 M Dec. 16, 1896
Mershon, Ralph D.	Westinghouse Electric and Mfg. Co., 120 Broadway, N. Y. City.	A Mar. 20, 1895 M Jan. 22, 1896
Millis, John	Captain of Engineers U. S. A., Willets Point, New York Harbor.	A July 7, 1884 M Mar. 3, 1885
Mitchell, James	Constructing Engineer and Agent, General Electric Co., Caixa do Correio No. 954, Rio de Janeiro, Brazil.	A Sept. 25, 1895 M Mar. 25, 1896
Mix, Edgar W.	Electrical Engineer, 12 Boulevard des Invalides, Paris, France.	A Sept. 3, 1889 M Mar. 20, 1895
Molera, E. J.	Civil and Electrical Engineer, 606 Clay St., San Francisco, Cal.	A Jan. 16, 1892 M June 7, 1892

Name.	Address.	Date of Membership.
Moore, D. McFarlan	Inventor, Moore Electrical Co., 52 Lawrence St., Newark, N. J.	A Dec. 20, 1893 M June 20, 1894
Morrow, John Thomas	Supt. Electrolytic Plant, Boston and Montana Consolidated Copper and Silver Mining Co., Great Falls, Mont.	A Dec. 21, 1892 M April 18, 1894
Neiler, Samuel G.	Consulting Electrical and Mechanical Engineer, Member of the Firm of Pierce & Richardson, Consulting and Designing Engineers, 1405–12 Manhattan Building, Chicago, Ill.	A April 18, 1894 M Dec. 18, 1895
Nichols, Dr. Edward L.	Professor of Physics, Cornell University, Ithaca, N. Y.	A Oct. 4, 1887 M Dec. 6, 1887
Nichols, Geo P.	Partner, Geo. P. Nichols & Bro., Elec. Engineers and Contractors, 1036 Monadnock Bldg., Chicago, Ill.	A Jan. 22, 1896 M Nov. 18, 1896
Nicholson, Walter W.	General Supt. Central N. Y. Telephone and Telegraph Co., Telephone Building, Syracuse, N. Y.	A May 15, 1894 M May 18, 1897
Noll, Augustus	Contracting Electrical Engineer, 8 East 17th St., Telephone, 62, 18th; New York City.	A Sept. 27, 1892 M April 18, 1893
Nunn, Paul N.	Consulting Engineer, San Miguel Cons. Gold Mining Co., Telluride, Colo.	A April 17, 1895 M Feb. 26, 1895
O'Connell, Joseph J.	Telephone Engineer, Chicago Telephone Co., Residence, 76 Eugene St., Chicago, Ill.	A Oct. 17, 1894 M Nov. 20, 1895
O'Dea, Michael Torpey	Professor of Applied Electricity, University of Notre Dame, Notre Dame, Ind.	A June 8, 1887 M Mar 25, 1896
Oudin, Maurice A.	Electrical Engineer, General Electric Co., Schenectady, N. Y.	A June 20, 1894 M Nov. 20, 1895
Owens, Robert Bowie	(*Vice-President.*) McDonald Professor of Electrical Engineering, McGill University, Montreal, P.Q.	A June 17, 1890 M Dec. 15, 1897
Paine, F. B. H.	Westinghouse Electric and Mfg. Co., 47 W. 43rd Street, New York, N. Y.	A Dec. 16, 1890 M Nov. 25, 1891
Paine, Sidney B.	General Electric Co., 180 Summer St., Boston, Mass.	A June 8, 1887 M Nov. 1, 1887
Parker, Lee Hamilton	The Buenos Aires and Belgrano Electric Tramways Co., Calle Santa Fé No. 2457, Buenos Aires.	A Aug. 5, 1895 M Dec. 16, 1896
Parks, C. Wellman	Civil Engineer, U. S. N., Bureau of Yards and Docks, Navy Department, Washington, D. C.	A July 12, 1887 M May 1, 1888
Parshall, Horace Field	Consulting Engineer, 83 Cannon St., London, Eng.	A Sept. 7, 1888 M Mar. 18, 1890
Pattison, Frank A.	Firm of Pattison Bros, Consulting and Constructing Electrical Engineers, 141 Broadway, New York City.	A Sept. 22, 1891 M Dec. 16, 1891
Pearson, F. S.	Engineer, Room 841, 621 Broadway, New York City.	A Oct. 25, 1892 M Feb. 21, 1893

Name.	Address.	Date of Membership.
Pedersen, Frederick Malling	Office Engineer, Crocker-Wheeler Electric Co., 39 Cortlandt St ; residence, 39 Washington Square, New York City.	A Sept. 20, 1893 M June 24, 1898
Perot, L. Knowles	President of The Schuylkill Valley Illuminating Co., Phœnixville, Pa.	A Mar. 15, 1892 M Dec. 18, 1895
Perrine, Frederic A. C., *D. Sc.*	(*Manager.*) Professor of Electrical Egineering, Leland Stanford, Jr., University, Palo Alto, Cal.	A Sept. 16, 1890 M Dec. 16, 1890
Pickernell, F. A.	(*Manager.*) Chief Engineer, Amer. Tel. & Tel. Co., 22 Thames St., New York City.	A Feb. 7, 1890 M Mar. 18, 1890
Pierce, Richard H.	Pierce & Richardson, Electrical Engineers, 1409 and 1410 Manhattan Bldg., Chicago ; residence. 5434 Monroe Ave., Hyde Park, Ill.	A April 18, 1893 M Dec. 20, 1893
Pike, Clayton W., *B.S.*	Electrical Engineer, Falkenau Engineering Co., 711 Reading Terminal, Philadelphia, Pa.	A Dec. 16, 1891 M Oct. 25, 1892
Porter, Joseph F.	Manager, Alton Railway and Illuminating Co., Alton, Ill.	A Sept. 6, 1887 M Nov. 1, 1887
Potter, Wm. Bancroft,	Engineer Railway Dept., General Electric Co., Schenectady, N. Y.	A Jan. 22, 1896 M Mar. 25, 1896
Pratt, Robert J.	Rensselaer, N. Y.	A July 12, 1887 M Sept. 6, 1887
Puffer, Wm. L.	(*Manager.*) Assistant Professor of Electrical Engineering, Mass. Institute of Technology, Boston ; residence, West Newton, Mass.	A Dec. 20, 1893 M April 17, 1895
Rae, Frank B.	Electrical Engineer, 804 Fort Dearborn Bldg., 134 Monroe St., Chicago, Ill.	A April 15, 1884 M Oct. 25, 1892
Reber, Samuel	Lieut. Col. Signal Corps, U. S. c/o. Chief Signal Officer, Washington, D. C.	A Sept. 20, 1893 M Jan. 22, 1896
Reckenzaun, Frederick,	Electrical Engineer, 44 Pine St., New York City.	A Mar. 6, 1888 M June 5, 1888
Redman, Geo. A.	General Supt., Electric Dept., Brush Elec. Light Co., and Rochester Gas and Elec. Co., Rochester, N. Y	A Feb. 27, 1895 M May 17, 1898
Reid, Thorburn	Consulting Electrical Engineer, 120 Liberty St., New York City.	A Oct. 21, 1890 M June 24, 1898
Reist, Henry G.	Designing Engineer, General Electric Co., 5 South Church St., Schenectady, N. Y.	A June 17, 1890 M Dec, 19, 1894
Rice, Calvin Winsor	Electrician, Kings County Electric Light and Power Co., Brooklyn. Electrician, Consolidated Telegraph and Electrical Subway Co., 59 Wall St., New York City.	A Jan. 20, 1897 M April 28, 1897
Rice, E. Wilbur, Jr.	Technical Director, The General Electric Co., Schenectady, N. Y.	A Dec. 6, 1887 M Jan. 3, 1888
Richardson, Robert E.	Electrical Engineer, Pierce & Richardson, 1409 Manhattan Building; residence, 3910 Calumet Ave, Chicago, Ill.	A Sept. 19, 1894 M May 18, 1897

Name.	Address.	Date of Membership.
Ridley, A. E. Brooke	Electrical Engineer, Agent, Siemens & Halske Electric Co., and Electric Storage Battery Co., 598 Parrot B'ldg. San Francisco, Cal.	A Nov. 21, 1894 M Nov. 23, 1898
Ries, Elias E.	Electrical Engineer and Inventor, 1242 New York Life Insurance Bldg.; residence, 4 W. 115th St., New York City.	A July 12, 1887 M Sept. 6, 1887
Riker, Andrew L. [Life Member.]	Electrical Engineer, The Riker Electric Motor Co., 45 York St., Brooklyn; residence, Stamford, Conn.	A Nov. 1, 1887 M Dec. 18, 1895
Robb, Russell	With Stone & Webster, 4 P. O. Square, Boston, Mass.	A Oct. 18, 1893 M May 21, 1895
Robb, Wm. Lispenard	Professor of Physics, Trinity College, Hartford, Conn.	A Dec. 16, 1891 M Mar. 15, 1892
Roberts, E. P.	E. P. Roberts & Co., Electrical and Mechanical Engineers, Brainard Block, Telephone 2656, Cleveland, O.	A Jan. 6, 1885 M Feb. 3, 1885
Rodgers, Howard S.	Electrical Engineer, care General Electric Co., 420 W. 4th Street, Cincinnati, O.	A Sept. 27, 1892 M May 16, 1893
Rohrer, Albert L.	Electrical Engineer, with General Electric Co., Schenectady, N. Y.	A Nov. 1, 1887 M May 1, 1888
Roller, John E.	Lieut. U. S. N., in charge of Inspection and Installation, U. S. Navy Yard, New York; residence, Cranford, N. J.	A Sept. 19, 1894 M May 19, 1896
Rosa, Edward B.	Professor of Physics, Wesleyan University, Middletown, Conn.	A Feb. 17, 1897 M May 18, 1897
Ross, Norman N.	Electrical Engineer, The Royal Electric Co., Montreal, Can.	A Sept. 20, 1893 M Nov. 21, 1894
Ross, Robert A.	Mechanical and Electrical Consulting Engineer, 17 St. John St., Montreal, P. Q.	A Sept. 27, 1892 M April 18, 1893
Rouquette, William F. B. [Life Member.]	Proprietor, Rouquette & Co., 47 Dey St., New York City.	A Mar. 21, 1894 M Dec. 19, 1894
Ryan, Harris, J.	Professor of Electrical Engineering, Cornell University, Ithaca, N. Y.	A Oct. 4, 1887 M April 17, 1895
Sachs, Joseph	Electrical Engineer, The Johns-Pratt Company; residence, 220 Collins St., Hartford Conn.	A Mar. 15, 1892 M Dec. 15, 1897
Salomons, *Sir* David Lionel, *Bart. M. A.* [Life Member]	Engineer and Barrister, Broomhill, Tunbridge Wells, Kent, and 49 Grosvenor St., London, W. England.	A Feb. 7, 1888 M May 1, 1888
Sampson, F. D.	Manager, Charlotte Electric Light and Power Co., Charlotte, N. C.	A Aug. 5, 1896 M Oct. 27, 1897
Sands, H. S.	Consulting and Constructing Electrical Engineer, 1153 Market St., Wheeling, W. Va.	A Feb. 21, 1893 M Nov. 21. 1894
Sargent, William D.	General Manager, N. Y. & N. J. Tel. Co., 81 Willoughby St., Brooklyn. N. Y.	A April 15, 1884 M Feb. 21, 1894
Scheffler, Fred. A.	General Factory Manager, Sprague Electric Co., Bloomfield, N. J.; residence, Passaic, N. J.	A May 16, 1893 M Jan. 26, 1896

Name.	Address.	Date of Membership.
Schmid, Albert	Superintendent, Westinghouse Electric and Mfg. Co., Pittsburg, Pa.	A Oct. 21, 1890 M April 17, 1895
Schoen, A. M.	Electrician, South Eastern Tariff Association, Norcross Building, Atlanta, Ga.	A Sept. 20, 1893 M Dec. 16, 1896
Scott, Charles F.	Chief Electrician, Westinghouse Electric and Mfg. Co., Pittsburg, Pa.	A April 19, 1892 M Jan. 17, 1893
Scott, James B.	Consulting Electrical, and Mechanical Engineer, 227 East German St.; residence, 847 Ducatel St,, Baltimore Md.	A Aug. 5, 1896 M May 17, 1898
Sever, George F.	(*Manager.*) Instructor in Electrical Engineering, Columbia University, New York City.	A Jan. 17, 1894 M May 19, 1896
Shaw, Edwin C.	Mechanical Engineer, The B. F. Goodrich Co., Akron, O.	A May 17, 1892 M Feb. 27, 1895
Shea, Daniel W.	Professor of Physics, Catholic University of America, Washington, D. C.	A Dec. 20, 1893 M June 20, 1894
Sheldon, Samuel, *A. M., Ph.D.*	(*Manager.*) Professor of Physics and Electrical Engineering, Polytechnic Institute, 198½ Schermerhorn St., Brooklyn, N.Y.	A Dec. 16, 1890 M Oct. 27, 1891
Shepardson, George D.	Professor of Electrical Engineering, University of Minnesota, Minneapolis, Minn.	A April 21, 1891 M Jan. 22, 1896
Sinclair, H. A.	Electrical Engineer, The Tucker Electric Co., 950 Bedford Ave., Brooklyn, N. Y.	A June 17, 1890 M Feb. 26, 1896
Smith, Frank Stuart	Supt. Lamp Factory, Sawyer-Man Electric Co., Pittsburg, Pa.	A Sept. 27, 1892 M April 18, 1893
Smith, Jesse M.	Expert in Patent Causes, Consulting Electrical and Mechanical Engineer, 36 Moffat Block, Detroit, Mich., and 218 Broadway, New York City.	A April 15, 1884 M June 26, 1891
Smith, T. Carpenter	Mechanical and Electrical Engineer, 650 Drexel Building, Philadelphia, Pa.	A Oct. 27, 1891 M Dec. 16, 1891
Spaulding, Hollon C.	Electrical Dep't., H. W. Johns Mfg. Co., Siemens & Halske Electric Co., 77 Pearl St., Boston, Mass.	A April 21, 1891 M June 20, 1894
Sperry, Elmer A.	Electrical Engineer, Sperry Electric Railway Co., Mason and Belden Sts.; residence, 855 Case Ave., Cleveland, O.	A April 19, 1892 M Feb. 21, 1893
Sprague, Frank J.	(*Past-President.*) Vice-Prest. Sprague Electric Elevator Co., Postal Telegraph Bldg., 22 Broad St., and 182 West End Ave., New York City.	A May 24, 1887 M Feb. 17, 1897
Stanley, William	(*Vice-President.*) Electrical Engineer and Inventor, Pittsfield, Mass.	A Dec. 6, 1887 M Oct. 26, 1898
Stearns, Charles K. *E.E.*	60 State Street, and 85 Westland Avenue, Boston, Mass.	A Aug. 6, 1889 M May 16, 1893
Stearns, Joel W., Jr.	Treasurer, Mountain Electric Co., Box 1545, Denver, Col.	A June 20, 1894 M Nov. 20, 1895

Name.	Address.	Date of Membership.
STEBBINS, THEODORE	Engineer of Committee on Local Companies, General Electric Co., Schenectady, N. Y.	A July 9, 1889 M June 17, 1890
STEINMETZ, CHARLES P.	(*Manager.*) Electrician, General Electric Co., Schenectady, N. Y.	A Mar. 18, 1890 M April 21, 1891
STEPHENS, GEORGE	General Supt., Canadian General Electric Co., Ltd., Peterboro, Ont.	A June 20, 1894 M Dec. 18, 1895
STIERINGER, LUTHER	Electrical Expert, Beard Building, 120 Liberty St., New York City.	A June 8, 1887 M Nov. 1, 1887
STILLWELL, LEWIS B.	(*Manager.*) Electrical Director, Niagara Falls Power Company, and the Cataract Construction Co., Niagara Falls, N. Y.	A April 19, 1892 M Nov. 15, 1892
STOTT, HENRY G.	Electrical Engineer, Buffalo Gen'l Electric Co., Buffalo, N. Y.	A Sept. 25, 1895 M April 22, 1806
TAINTOR, GILES	Sup't. Right of Way, and Statistical Department, New England Telephone and Telegraph Co., 125 Milk St., Boston, Mass.	A June 26, 1891 M Dec. 16, 1891
TALTAVALL, THOS. R.	Associate Editor, *Electrical World, and Electrical Engineer* 9 Murray St., New York City.	A Jan. 20, 1891 M Oct. 27, 1891
TERRY, CHARLES A.	Lawyer, Westinghouse Electric and Mfg. Co., 120 Broadway, New York City.	A April 5, 1887 M May 17, 1887
THEBERATH, THEODORE E.	Pacific Coast Engineer, Stanley Electric M'f'g Co, 300 California Street, San Francisco, Cal.	A Mar. 23, 1898 M June 24, 1898
THOMAS, BENJAMIN F.,	Professor of Physics, Ohio State University, Columbus, O.	A June 7, 1892 M Nov. 15, 1892
THOMSON, PROF. ELIHU	(*Past President*). Electrician, General Electric, and Thomson Electric Welding Companies, Lynn, Mass.	A April 15, 1884 M April 21, 1891
THOMPSON, EDWARD P.	Consulting Electrician and Solicitor of Patents, 81 Fulton Street, New York City.	A April 15, 1884 M Dec. 3, 1889
THRESHER, ALFRED A.	Electrical Engineer and Proprietor Thresher Electric Co., Dayton, O.	A April 22, 1896 M June 24, 1898
THURNAUER, ERNST	Manager, Thomson-Houston International Elec. Co., 27 Rue de Londres, Paris, France.	A Oct. 14, 1887 M Dec. 6, 1887
TISCHENDOERFER, F. W.	Electrical Engineer, Schückert & Co., Nuremberg, Germany.	A April 19, 1892 M Nov. 21, 1894
TRAFFORD, EDWARD W.	Electrical Engineer, Richmond Railway and Electric Co., Foot of 7th St., Richmond, Va.	A Feb. 21, 1894 M Dec. 19, 1894
TURNER, WILLIAM S.	Consulting and Constructing Electrical and Mechanical Engineer, Room 1408, 141 Broadway, New York City.	A Dec. 7, 1886 M Oct. 2, 1888
UEBELACKER, CHAS. F.	The Peckham Motor Truck and Wheel Co., 262 Broadway, Kingston, N. Y.	A Feb. 7, 1890 M Nov. 15, 1893
UHLENHAUT, FRITZ, JR.	Whitestone, L. I.	A May 7, 1889 M Dec. 19, 1894
UPTON, FRANCIS R	Edison Laboratory, Orange, N. J.	A May 17, 1887 M Mar. 15, 1892

Name.	Address.	Date of Membership.
Vail, J. H	Engineer-in-Chief, Philadelphia Manufacturing Light and Power Co., and Edison Electric Light Co., 10th and Sansom Sts., Philadelphia, Pa.	A June 8, 1887 M Nov. 1, 1887
Vansize, William B.	Solicitor of Patents and Expert, 253 Broadway; residence, Hotel Grenoble, New York City.	A April 15, 1884 M Oct. 21, 1884
Van Trump, C. Reginald	Engineer and Manager, Wilmington City Electric Co., Wilmington, Del.	A Feb. 5, 1886 M Feb 21, 1894
Waddell, Montgomery	Consulting Engineer, 72 Trinity Place, New York City.	A Feb. 7, 1888 M May 1, 1888
Wait, Henry H.	Assistant Electrical Engineer, Western Electric Co., 4919 Madison Ave., Chicago, Ill.	A Sept. 20, 1893 M June 20, 1894
Waldo, Dr. Leonard	Electrical Engineer, Secretary, The Waldo Foundry, 57 Coleman St., Bridgeport, Conn.	A June 5, 1888 M Dec. 4, 1888
Walker, Sydney F.	Electrical Engineer, 195 Severn Road, Cardiff, Wales.	A June 2, 1885 M May 17, 1887
Waring, John	Ovid, N. Y.	A Dec. 16, 1890 M April 17, 1895
Warner, Ernest P.	Electrical Engineer, Western Electric Co.; residence, 402 Belden Ave., Chicago, Ill.	A Sept. 20, 1893 M June 20, 1894
Waterman, F. N.	Electrical Engineer, Westinghouse Electric and Mfg. Co., 120 Broadway, New York City.	A Feb. 21, 1893 M June 20, 1894
Weaver, W. D.	Editor *Electrical World, and Electrical Engineer*; residence 7 West 26th Street New York City.	A May 17, 1887 M May 17, 1887
Webb, Herbert Laws	(*Manager*) 18 Cortlandt St.; residence, 253 West 42d St., New York City.	A Oct. 21, 1890 M Dec. 16, 1890
Weeks, Edwin R.	706 Wall St., Kansas City, Mo.	A Sept. 6, 1887 M Nov. 1, 1887
Weller, Harry W.	Electrical Engineer, Room 206, Equitable Building, Boston, Mass.	A Oct. 21, 1890 M Nov. 24, 1891
Weston, Edward	(*Past President.*) Vice-President Weston Electrical Instrument Co, 120 William St., and 645 High St., Newark, N. J.	A April 15, 1884 M Oct. 21, 1884
Wetzler, Joseph	President, The Electrical Engineer Institute of Correspondence Instruction, 120 Liberty St., New York City.	A April 15, 1884 M Dec. 9, 1884
Wharton, Chas. J.	Palace Chambers, Westminster, London, Eng,	A Jan. 3, 1888 M May 1, 1888
Wheeler, Schuyler Skaats, *Sc.D.* [Life Member.]	President, Crocker-Wheeler Electric Co., 39 Cortlandt St., N. Y., and Ampere, N. J.; residence, 4 West 33d St., New York City.	A June 2, 1885 M Sept. 1, 1885

Name.	Address.	Date of Membership.
WHITE, WILL F.	Electrical Engineer, 1st Vice-President and General Manager, New Omaha T.-H. Electric Light Co., 309 So. 13th St., Omaha, Neb.	A Feb. 7, 1890 M July 27, 1898
WHITE-FRASER, GEO.	*Mem. Can. Soc. C. E.*; 18 Imperial Loan Building, Toronto, Ont.	A Sept. 22, 1891 M Dec. 18, 1895
WIENER, ALFRED E.	Chief Instructor, The Electrical Engineer Institute of Correspondence Instruction, 120 Liberty Street, New York.	A May 16, 1893 M May 15, 1894
WILCOX, NORMAN T.	Sup't Chattanooga Light and Power Co., Chattanooga, Tenn.	A May 21, 1895 M Jan. 22, 1896
WILKES, GILBERT	Consulting Electrical Engineer, 1112 Union Trust Building, Detroit, Mich.	A Jan. 7, 1890 M Mar. 18, 1890
WILLYOUNG, ELMER G.	E. G. Willyoung & Co., Scientific Instruments and Apparatus, 938 Market St., Philadelphia.	A Nov. 24, 1891 M Dec. 20, 1893
WILSON, CHARLES H.	General Manager, Southern Bell Telephone Co., 26 Cortlandt St., New York City.	A Nov. 24, 1891 M Feb. 16, 1892
WILSON, FREMONT	Electrician, 66 Maiden Lane, (Telephone, 1651 Cortlandt) New York City; residence, Yonkers, N. Y.	A Mar. 6, 1888 M June 5, 1888
WILSON, HARRY C.	Supt. of P. O. Telegraph with the Government, Kingston, Jamaica, West Indies.	A Jan. 19, 1891 M June 7, 1892
WINCHESTER, A. E.	Consulting Engineer and Designer of Electric Systems, South Norwalk, Conn.	A June 8, 1887 M Nov. 1, 1887
WINSLOW, GEORGE HERBERT	Consulting Electrical Engineer, 82 & 83 Schmidt Building, 339 Fifth Ave., Pittsburgh, Pa.	A April 17, 1895 M Feb. 26, 1896
WOLCOTT, TOWNSEND	Electrician, 455 Bowling Green Building, New York City. Residence 329 Clinton St., Brooklyn, N. Y.	A Mar. 6, 1888 M Dec. 16, 1890
WOLVERTON, B. C.	Electrician, N. Y. & Pa. Telephone and Telegraph Co., Elmira, N. Y.	A Mar. 18, 1890 M Feb. 21, 1895
WORDINGHAM, CHAS. H.	City Electrical Engineer, The Manchester Corporation Electric Light Station, Dickinson Street, Manchester, England.	A July 27, 1898 M Oct. 26, 1898
WRIGHT, PETER	President, Virginia Electric Company, Norfolk, Va.	A May 16, 1889 M Jan. 16, 1895
WURTS, ALEXANDER JAY	Westinghouse Electric & Mfg. Co., Pittsburg, Pa.	A April 19, 1892 M Nov. 15, 1892
YOUNG, C. GRIFFITH	Electrical Engineer, J. G. White & Co., 706 Equitable Building., Baltimore, Md.	A Jan. 3, 1889 M April 21, 1891

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ASSOCIATE MEMBERS.

Name.	Address.	Date of Election.
ABBE, CLEVELAND	Professor of Meteorology. The Weather Bureau, residence 2017 I St., N. W. Washington, D. C.	Nov. 23, 1888
ABBOTT, HENRY	President, Calculagraph Co., 2 Maiden Lane, N. Y.; residence, 32 So. Clinton St., East Orange, N. J.	Apr. 28, 1897
ABELLA, JUAN	Director General of Public Lighting, Buenos Aires; residence, 691 Calle Bolivar. Buenos Aires, Argentine Republic.	Aug. 5, 1896
ADAE, CHAS. FLAMEN	67 Madison Ave., P. O. Box, 2809; New York City	Dec. 16, 1896
ADAMS, COMFORT A., JR.	Assistant Professor of Electrical Engineering. Harvard University, 13 Farrar St., Cambridge, Mass.	Jan. 17, 1894
ADAMS, ERNEST K.	Graduate Student, Columbia University; residence, 455 Madison Ave., New York City.	July 27, 1898
ADAMS, FRANK PIERCE	Electrician, Stockton Gas & Electric Co., residence, 171 N. El. Dorado, St., Stockton, Cal.	Feb. 15, 1899
ADAMS, JULIUS LE ROY	Chief Engineer, Hartford, Manchester & Rockville Tramway Co., Manchester, Conn.	Feb. 15, 1899
ADAMSON, DANIEL	Manager Joseph Adamson & Co., Hyde, Cheshire, England.	Feb. 26, 1896
AGNEW, CORNELIUS R.	Electrical Engineer, 7 Nassau St., 23 West 39th St., New York City.	Mar. 21, 1894
ALBANESE, G. SACCO	Electrical Engineer, Tramways Electriques de Nice, Nice, France.	Sept. 20, 1893
ALBERT, HENRY	Electrical Engineer, 815 Main St., Jacksonville, Fla.	Feb. 21, 1893
ALDEN, JAMES S.	Assistant Manager, with L. H. Alden, 486 River Drive, Passaic, N. J.	May 19, 1891
ALDRICH, WILLIAM S.	Professor of Mechanical Engineering West Virginia University, P. O. Box 256, Morgantown, W. Va.	Mar. 15, 1892
ALEXANDER, HARRY	Electrical Engineer, General Manager and Vice Prest. Alexander-Chamberlain Electric Co., 25 West 33rd St., and 18 and 20 W. 34th St., Telephone 3767–38th, New York City.	April 21, 1891
ALLAN, JOHN	Full Partner, H. H. Kingsbury & Co., 54 Margaret St., Sydney, N. S. W.	Dec. 28, 1898
ALLEN, WYATT H.	Care H. F. Allen, 202 California St., San Francisco, Cal.	Apr. 27, 1898
ALLEN, WALTER CUMMINGS,	Electrical Engineer of the Government of District of Columbia, District Building, Washington, D. C.	June 24, 1898

Name.	Address.	Date of Election
ANDERSON, HENRY S.	General Manager and Electrician, United Electric Light Co., Springfield, Mass.	Jan. 16, 1895
ANDREWS, WILLIAM, C.	Electrical Engineer, Hotel Margaret, Brooklyn, N. Y.	May 21, 1895
ANTHONY, WATSON G.	Electrician, 32½ Webster St., Newark, N. J.	Feb 24, 1891
APPLEYARD, ARTHUR E.	Manager and Engineer, Natick Gas and Electric Co., Natick, Mass.	Aug. 5, 1896
ARCHBOLD, WM. K.	Westinghouse Electric and Mfg. Co. 120 Broadway, New York City.	June 20, 1894.
ARCHER, GEO. F.	Electrical Engineer, 31 Burling Slip, New York City.	Nov. 21, 1894
ARMSTRONG, ALBERT H.	Electrical Engineer, General Electric Co., Schenectady, N. Y.	June 24, 1898
ASHLEY, FRANK M.	Master Mechanic, Ashley Engineering Co., 95 Liberty St., New York.	Nov. 21, 1894
ATKINS, HAROLD B.	Draughtsman, Electrical Vehicle Company, 1684 Broadway, New York City; residence, Roselle, N. J.	June 23, 1897
ATWOOD, GEORGE F.	The Atwood Power and Speed Gage Company. 95 Liberty St., New York City; residence, 20 Hurlbut St., Orange, N. J.	Sept. 16, 1890
AUSTIN, SYDNEY B.	Hadaway Electric Heating and Engineering Co., 107 Liberty Street; residence, 110 E. 18th Street, New York.	Sept. 25, 1895
AUERBACHER, LOUIS J.	Electrical Engineer, 39 Cortlandt St., New York City.	Sept. 20, 1893
BABCOCK, CLIFFORD D.	[Address unknown.]	Feb. 21, 1894
BADEAU, ISAAC F.	General Electric Co.; residence, 815 Locust Ave., Schenectady, N. Y.	Feb. 26, 1896
BALCOME, HERBERT A.	With The B. F. Sturtevant Co., Jamaica Plain Station, Mass.	Oct. 27, 1897
BALDWIN, ALFRED DE V.	Selling Agent, Crocker-Wheeler Electric Co, P. O. Box, 267; residence, 206 W. 81 St., New York.	Aug. 13, 1897
BALDWIN, JAS. C. T.	Superintendent Bell Telephone Co., of Mo.; 10th and Olive Sts., St. Louis, Mo.	April 17, 1895
BALL, WM. D.	Consulting Electrical Engineer. Nagle and Ball, New York Life Building. Chicago, Ill.	Nov. 20, 1895
BALSLEY, ABE	Chief Electrician, Terre Haute Electric Railway Co., 514 No. Center Street. Terre Haute, Ind.	Oct. 27, 1897
BANCROFT, CHAS. F.	Electrical Engineer, Lowell and Suburban Street Railway, Lowell, Mass.	Dec. 18, 1895
BANGS, CHAS. R.	Special Agent, American Telephone and Telegraph Co., 15 Dey St., New York.	Jan. 26, 1898

Name.	Address.	Date of Election.
Banks, William C.	Electrician, Gordon-Burnham Battery Co., 594 Broadway, New York City.	May 18, 1897
Barbour, Fred Fiske	Manager, Power and Mining Department, Pacific District, General Electric Co., Claus Spreckels Bldg., San Francisco, Cal., and 1673 Valdez St., Oakland, Cal.	May 16, 1893
Barnes, Chas. R.	City Electrician and Electrical Expert to State R. R. Commission, Rochester, N. Y.	Aug. 13, 1897
Barnes, Edward A.	Electrical Expert, Fort Wayne Electric Co., Fort Wayne, Ind.	Sept. 20, 1893
Barry, David	Electrician and Superintendent, Amherst Gas Co., Amherst, Mass.	Aug. 5, 1896
Barton, Enos M.	President Western Electric Co., 227 South Clinton St., Chicago, Ill.	July 12, 1887
Bates, Frederick C.	Electrical Engineer, General Electric Co., 44 Broad St., New York City.	Jan. 20, 1891
Bates, Putnam A.	Engineering Department, Crocker-Wheeler Electric Co., 39 Cortlandt St., New York City.	Jan. 20, 1897
Beames, Clare F.	Ingeniero, Mexican General Electric Co., Apartado 403, City of Mexico.	May 21, 1895
Beattie, John, Jr.	Manager and Superintendent, The Beattie Battery, Zinc and Electric Co., Fall River, Mass.	Sept. 6, 1887
Bechtel, Ernest J.	Superintendent Construction, Toledo Traction Co., Toledo, O.	Mar. 24, 1897
Beebe, Murray. C.	Instructor in Electrical Engineering, University of Wisconsin; residence, 271 Langdon St., Madison, Wis.	Jan. 26, 1898
Bell, Ora A.	Electrical Engineer, Western Electric Co., 22 Thames St., New York; residence, 921 St. Nicholas Ave., New York.	Aug. 5, 1896
Bellman, John Jacob	Electrical Engineer, Crocker-Wheeler Electric Co.; 1515 Old Colony Building, Chicago, Ill.	Dec. 28, 1898
Bennett, Edwin H., Jr.	Electrician and Engineer, Diehl & Co., Elizabethport, N. J., and 19 West 33d St., Bayonne, N. J.	June 20, 1894
Bennett, John C.	Electrician, General Electric Co., 44 Broad St., New York City.	Mar. 18, 1890
Benoliel, Sol. D., *B. S.*, *E. E.*, *A. M.*	Consulting Electrical Engineer, Adelphi College, Brooklyn, N. Y.	Oct. 21, 1896
Bentley, Merton H.	Chicago Telephone Co.; residence, 221 Scoville Ave., Oak Park, Ill.	Oct. 18, 1893
Berg, Ernst Julius	Engineer, General Electric Co.; residence, 243 Liberty St., Schenectady, N. Y.	Sept. 19, 1894

Name.	Address.	Date of Election.
Berg, Eskil	Electrical Engineer, Gen'l Electric Co., Schenectady, N. Y.	Nov. 20, 1895
Bergholtz, Herman	Secretary and Treasurer, Ithaca Street Railway Co., Ithaca, N. Y.	April 2, 1889
Berliner, Emile	Inventor, Columbia Road, between Fourteenth and Fifteenth Sts., Washington, D. C.	April 15, 1884
Berresford, Arthur W., *B. S.*, *M. E.*	Vice-Pres't and Supt. Iron Clad Resistance Co., Westfield, N. J.	May 15, 1894
Best, A. T.	Electrical Engineer, Florida East Coast Hotel System, St. Augustine, Fla.	April 19, 1894
Bethell, U. N.	General Manager, The New York Telephone Co., 15 Dey St., New York City.	Jan. 17, 1894
Betts, Hobart D., *E. E.*	Room 517, 141 Broadway, New York, N. Y.; residence, Englewood, N. J.	Aug. 5, 1896
Biddle, James G.	Drexel Bldg., Philadelphia, Pa.; residence, 264 Rittenhouse St., Germantown, Pa.	Aug. 5, 1896
Bijur, Joseph, *A. B.*, *E. E.* [Life Member.]	Electrical Engineer, 20 Broad St.; residence, 172 West 75th St., New York City.	May 15, 1894
Black, Chas. N.	Westinghouse Electric and Mfg. Co., Land Title Building, Philadelphia, Pa.	April 19, 1890
Black, Howard D.	With Blackall & Baldwin, 39 Cortlandt St.; house, 340 Manhattan Ave., New York, N. Y.	Sept. 15, 1897
Blackall, Frederick, S.	P. O. Box, 267; office, 39 Cortlandt St.; residence, 51 Manhattan Ave., New York.	Sept. 15, 1897
Blake, Henry W.	Editor, *Street Railway Journal*, 26 Cortlandt St., New York City.	Nov. 13, 1888
Blake, Theodore W.	Electrical Engineer, 410 Bleecker St., New York, N. Y.	Sept. 20, 1893
Blanchard, Charles M.	Winterburn, Pa.	Sept. 19, 1894
Blaxter, Geo. H.	Vice-President and General Manager, Allegheny County Light Co., Westinghouse Building, Pittsburg, Pa.	Sept 25, 1895
Bliss, William L., *B. S.*, *M. M. E.*	Electrical Engineer, 128 Front St., New York City; residence, 505 Throop Ave., Brooklyn, N. Y.	Mar. 21, 1894
Blizard, Charles	Manager of New York Office. Electric Storage Battery Co., 22 Broad St.; residence, 30 W. 25th St., New York City.	Nov. 21, 1894
Blunt, Willam W.	Engineer, Westinghouse Electric Co., Ltd., 32 Victoria St., London, Eng.	Dec. 16, 1896
Bogue, Charles J.	Manufacturer and Dealer in Electrical Supplies, 206 Centre St., N.Y. City.	Dec. 3, 1889
Bohm, Ludwig K., *Ph.D.*	Consulting Electrical and Chemical Expert, 320 Broadway, N. Y. City.	Nov. 15, 1892

Name.	Address.	Date of Election.
Bolan, Thomas V.	Supervising and Constructing Engineer, General Electric Co., 509 Arch St.; residence, 869 N. 41st St., Philadelphia, Pa.	Aug. 5, 1896
Boyles, Thomas D.	Electrical Engineer, General Electric Co.; residence, 58 Washington Ave., Schenectady, N. Y.	Mar. 20, 1895
Brackett, Byron B.	408 A St., S. E., Washington, D. C.	Nov. 30, 1897
Brackett, Prof. Cyrus F.	Princeton, N. J.	April 15, 1889
Braddell, Alfred E.	Electrical Inspector, Underwriters' Association, Middle Department, 316 Walnut St., Philadelphia, Pa.	Sept. 1, 1890
Brady, Frank W., *M. E.*	Professor of Engineering and Physics, New Mexico College of Agriculture and Mechanic Arts, Mesilla Park, N. M.	June 20, 1894
Brady, Paul T.	Manager, Central N. Y. Agency, Westinghouse Electric and Mfg. Co., Syracuse, N. Y.	July 12, 1887
Bragg, Charles A.	Manager Phila. Agency, Westinghouse Electric and Mfg. Co., 302 Girard Building, Philadelphia, Pa.	Sept. 20, 1893
Brayshaw, I.	Telegraph Inspector Great Southern Railway, City of Buenos Aires.	Aug. 5, 1896
Brixey, W. R.	Proprietor and Manufacturer, Day's Kerite Wire and Cables, 203 Broadway, New York City.	Sept. 20, 1893
Broich, Joseph	Superintendent and Electrician, with F. Pearce, New York City; residence, 1622 8th Ave. Brooklyn, N.Y.	Jan. 17, 1894
Broili Frank	Electrical Engineer, California Elec. Works; residence, 328 Eddy St., San Francisco, Cal.	Feb. 23, 1898
Brophy, William	Electrician to the Wire Department, 12 Old Court House, Boston; residence, 17 Egleston St., Jamaica Plain, Mass.	Mar. 5, 1889
Browd, Paul K.	Chief Engineer, The Russian Electric Company, "Union" St. Petersburg, Russia.	Feb. 15, 1899
Brown, Chas. L.	Gen'l Manager and Sec'y, Chicago Mutoscope Co., 1309 Monadnock Block, Chicago, Ill.	Nov. 20, 1895
Brown, Hugh Thomas	Electrical Engineer, General Electric Co., Schenectady, N. Y.	Jan. 26, 1898
Bubert, J. F.	Supervising and Contracting Electrical Engineer, 402 Exchange Bldg., (Telephone 1379) Boston, Mass.	June 7, 1892
Buck, Harold W.	107 Union St., Schenectady, N. Y.	Jan. 16, 1895
Buckingham, Chas. L.	Patent Attorney, Western Union Telegraph Co., 195 Broadway, P. O. Box 856, New York City.	April 15, 1884
Bunce, Theodore D.	President, The Storage Battery Supply Co., 239 E. 27th St., New York City.	May 20, 1890
Burgess, Chas. Fred'k.	Instructor in Electrical Engineering, University of Wisconsin, Madison, Wis.	Mar. 25, 1896

Name.	Address.	Date of Election.
BURKE, JAMES	Klopstack Strasse, 15; Berlin, Germany.	May 16, 1893
BURNETT, DOUGLASS, *B.S.*	Edison Illuminating Co., Inspection Dept., 55 Duane St., New York City; residence, 42 Livingston St., Brooklyn, N. Y.	Feb. 21, 1893
BURROUGHS, HARRIS S.	Commonwealth Electric Co., 667 Lincoln Ave., Chicago, Ill.	Nov. 30, 1897
BURT, BYRON T.	Vice-President and General Manager, Charleston Edison Light and Power Co., Charleston, S. C.	Sept. 25, 1895
BURTON, PAUL G.	Switchboard Dep't. Western Electric Co.; residence, 149 Lenox Ave, New York City.	Nov. 20, 1895
BURTON, WILLIAM C.	With White-Crosby Co., 29 Broadway, New York, N. Y.	Sept. 20, 1893
BUTLER, WILLIAM C.	President, The Puget Sound Reduction Co., Everett, Washington.	Mar. 21, 1893
BUYS, ALBERT	Electrical Engineer, The Rahway Electric Light and Power Co., Rahway, N. J.	Feb. 7, 1890
BYRNS, ROBERT A.	Ohio Brass Company, 20 Broad Street, New York City.	Dec. 16, 1896
CABOT, FRANCIS ELLIOTT	Supt. of Inspection and Electrician, Boston Board of Fire Underwriters, 55 Kilby Street; residence, East Milton, Mass.	April 17, 1895
CABOT, JOHN ALFRED	124 W. 127th St., New York City.	May 16, 1893
CALDWELL, EDWARD	President Empire Advertising Co, 150 Nassau St., New York City; residence, 407 E. 5th St., Plainfield, N. J.	Jan. 20, 1891
CALDWELL, FRANCIS C.	Associate Professor of Electrical Engineering, Ohio State University, Columbus, O.	June 20, 1894
CANFIELD, MILTON C.	Electrical Engineer, The Cleveland City Railway Co.; residence, 18 Clinton St., Cleveland, O.	Feb. 21, 1893
CANFIELD, MYRON E.	Western Electric Co.; residence, 404 W. 44th St. New York City.	May 21, 1895
CAPUCCIO, MARIO	Raimondo & Capuccio, Consulting Engineers and Patent Agents, Piazza Statuto 15, Turin, Italy.	Dec. 20, 1893
CARICHOFF, E. R.	Electrical Engineer, Sprague Electric Co., Bloomfield, N. J.	Mar. 21, 1894
CARPENTER, CHAS. E.	Vice-President, Carpenter Enamel Rheostat Co., Bronxville, N. Y.	Aug. 5, 1896
CARTER, FREDERICK WILLIAM	Lecturer in Electrical Technology, City and Guilds of London Institute, Exhibition Road, London, S. W.	Sept. 28, 1898
CARTER, HENRY W.	Attorney and Expert in Patent Causes, Carter & Graves 810 Reaper Block, Chicago, Ill.	Apr. 28, 1897

Name.	Address.	Date of Election.
Carty, J. J.	Engineer, New York Telephone Co., 15 Dey St., New York City; residence, Cranford, N. J.	April 15, 1890
Case, Willard E.	196 Genesee St., Auburn, N. Y.	Feb. 7, 1888
Casper, Louis	Electricial Engineer and Contractor, 3122 Wabash Ave., Chicago, Ill.	April 21, 1891
Cassidy, John	Superintendent Mutual Telephone Co., Honolulu, Hawaiian Islands, U.S.A.	Nov. 23, 1898
Chadbourne, Henry R., Jr.	Electrical Engineer, 130 Bedford St., Boston, Mass.	May 15, 1894
Chapman, A. Wright	Electrical Engineer, 160 Hicks St., Brooklyn, N. Y.	Mar. 25, 1896
Cheney, Frederick A.	Maple Avenue, Elmira, N. Y.	Oct. 1, 1889
Chermont, Antonio Leite	Engineer, Firm of Chermont, Silva and Miranda, Box 252, Para, U. S. Brazil.	Mar. 18, 1890
Chesney, C. C.	Electrician, Stanley Laboratory, Pittsfield, Mass.	June 20, 1894
Childs, Sumner W.	c/o R. W. Pope, 26 Cortlandt St., New York, N. Y.	May 15, 1894
Childs, Walter H.	Brattleboro, Vt.	Sept. 6, 1887
Clark, Chas. M., *E. E.*,	Clark & MacMullen, 42 E. 23d St., residence, 831 Madison Ave., New York City.	April 22, 1896
Clark, LeRoy, Jr.	Electrical Engineer of the Safety Insulated Wire and Cable Co., 229 West 28th St., residence, 208 West 85th St., New York City.	May 15, 1894
Clark, William J.	General Manager, Railway Dept. General Electric Co., 44 Broad Street, New York City.	April 22, 1896
Clement, Edward E.	Attorney-at-Law, McGill Building, Washington, D C.	May 18, 1897
Clement, Lewis M.	1013 12th St., Oakland, Cal.	April 21, 1891
Clough, Albert L.	Box 114, Manchester, N. H.	Feb. 21, 1894
Codman, John Sturges,	Consulting Engineer. Associated with R. S. Hale, 31 Milk St.; residence, 57 Marlborough St., Boston, Mass.	Feb. 15, 1899
Cody, L. P.	Manager and Engineer, Grand Rapids Electric Co., 9 South Division St., Grand Rapids, Mich.	Aug. 5, 1890
Coffin, Chas. A.	General Electric Co., 180 Summer St., Boston, Mass.	Dec. 6, 1887
Cogswell, A. R.	Electrician and Superintendent, Halifax Illuminating and Motor Co., Ltd., 34 Bishop St., Halifax, N. S.	April 21, 1891
Coho, Herbert B.	Electrical Engineer, 143 Liberty St., New York City.	Mar. 21, 1894
Coleman, Walter H.	Supt. and Treasurer, Andover Electric Co., Andover, Mass.	Sept. 28, 1898
Coles, Edmund P.	Resident Engineer, Manáos Electric Lighting Co, Manáos, U. S. Brazil.	Oct. 23, 1895

Name.	Address.	Date of Election
Collett, Samuel D.	Eastern Manager, Elevator Supply and Repair Co., 136 Liberty St., New York City; residence, Van Pelt Manor, N. Y.	Feb. 26, 1896
Compton, Alfred G.	Professor of Applied Mathematics, College of the City of New York, 17 Lexington Ave.; residence, 40 W. 126th St, New York City.	Nov. 1 1887
Coolidge, Charles A.	Electrical Engineer, Portland Ceneral Electric Co, 12 Selling-Hirsch Bldg. Portland, Ore.	April 19, 1892
Copeland, Clement A.	Acting Professor of Electrical Engineering, Stanford University, Cal.	June 23, 1897
Corey, Fred Brainard	Mechanical Engineer, The Stilwell-Bierce and Smith-Vaile Co., 1425 N. Main St., Dayton O.	Dec. 20, 1893
Cornell, John B.	Supt. of Construction, with Chas. L. Cornell, Hamilton, O.	Sept. 25, 1895
Corson, William R. C.	Superintendent, The Eddy Electric Mfg. Co., Windsor, Conn.	Jan. 17, 1893
Cory, Clarence L.	Professor of Electrical Engineering, University of California, Berkeley, Cal.	April 19, 1892
Cosgrove, James Francis	Head of Locomotive Engineering Dept., International Correspondence School, 631 Madison Ave., Scranton Pa.	Nov. 23, 1898
Crain, John Jay,	225 49th St., Newport News, Va.	Dec. 16, 1896
Crandall, Chester D.	Assistant Treasurer, Western Electric Co., 227 South Clinton St.; residence, 4558 Ellis Ave. Chicago, Ill.	Sept. 27, 1892
Crane, W. F. D.	Electrical and Mechanical Engineer, Electric Vehicle Co., New York City; residence, 24 Reynolds Terrace, Orange, N. J.	Feb. 7, 1888
Crawford. David Francis	Ass't to Supt. Motive Power, Penn'a Co., Fort Wayne, Ind.	Sept. 25, 1895
Crawford, L. G.	Sup't, Repair Dep't General Electric Co., Chicago, Ill.	Oct. 23, 1895
Creaghead, Thomas J.	President and General Manager, Creaghead Engineering Co., 802 Plum St., Cincinnati, O.	Sept. 20, 1893
Crehore, Albert C., *Ph.D.*	Assistant Professor of Physics, Dartmouth College, Hanover, N. H.	Dec. 21, 1892
Criggal, John E.	Mechanician with the Weston Electrical Instrument Co.: Newark, N. J.	June 20, 1894
Crocker, Eben Clinch	Electrical Engineer, American Ordnance Co., 29 Harriet Street, Bridgeport, Conn.	Jan. 26, 1898
Crosby, Oscar T.	White-Crosby Co., 1417 G Street, Washington, D. C.	Mar. 18, 1890
Crowell, Robinson	c/o Chas. H. Crowell; office, Laurel Hill Cemetery, San Francisco, Cal.	Dec. 28, 1898
Cumner, Arthur B.	1805 Wallace St., Philadelphia, Pa.	Feb. 27, 1895
Cunningham, E. R.	Sup't Fort Dodge Light and Power Co., Fort Dodge, Iowa.	Jan. 22, 1896

Name.	Address.	Date of Election.
CUNTZ, JOHANNES H.	325 Hudson St., Hoboken, N. J.	Mar. 5, 1889
CURRIE, N. M.	Santiago, Chili.	Feb. 15, 1899
DACUNHA, MANOEL IGNACIO	Manager of the Electrical Section, Emprera Industrial Gram-Para, Para, U. S. of Brazil.	May 16, 1893
DAGGETT, ROYAL BRADFORD	Electrical Engineer, Electric Storage Battery Co., Marquette Building, Chicago, Ill.	Jan. 25, 1899
DAME, FRANK L.	General Sup't, Tacoma Railway and Motor Co., Tacoma, Wash.	June 26, 1891
DAMON, GEO. A.	With B. J. Arnold, Electrical Engineer, 1541 Marquette Building, Chicago, Ill.	Jun. 24, 1898
DAMON, GEO. B.	Westinghouse, Church, Kerr & Co., 26 Cortlandt St. New York City.	June 23, 1897
DANA, R. K.	Agent, Washburn and Moen Mfg. Co., 16 Cliff St., New York City.	April 15, 1884
DANIELSON, ERNST	Consulting Electrician, Vestra Trãdgȧrdsgatan 1513, Stockholm, Sweden.	June 27, 1895
DARROW, ELEAZAR	Professor M. E. Dept. Washington Agr. College, Pullman, Wash.	Aug. 5, 1896
DATES, HENRY B,,	Professor of Electrical Engineering and Physics, Clarkson School of Technology, Potsdam, N. Y.	Dec. 28, 1898
DAVENPORT, GEORGE W.	61 Ames Bldg., Boston, Mass.	June 4, 1889
DAVIDSON, EDW. C.	Patent Lawyer, 141 Broadway, New York City.	Feb 7, 1890
DAVIS, ALBERT G.	Acting Manager, Patent Dep't, General Electric Co., Schenectady, N.Y.	Mar. 23, 1898
DAVIS, DELAMORE L.	Superintendent, Salem Electric Light and Power Co., 299 Lincoln Ave., Salem, O.	April 2, 1889
DAVIS, JOSEPH P.	Engineer, American Bell Telephone Co., 113 W. 38th St., New York City.	April 15, 1884
DAVIS, W. J., JR.	Electrical Engineer, General Electric Co., Schenectady, N. Y.	Mar. 20, 1895
DEGEN, LEWIS	c/o. M. E, Levering, 1414 Chestnut St., Philadelphia, Pa.	Sept. 25, 1895
DEKHOTINSKY, CAPT. ACHILLES	Late Chief Electrician and Torpedo Officer, Imperial Russian Navy, Room 860, No. 334 Dearborn St.; residence, 1457 Newport Ave., Chicago, Ill.	Oct. 27, 1891
DEMPSTER, THOMAS	Electrical Engineer, General Electric Co., Schenectady, N. Y.	May 17, 1898
DENTON, JAMES E.	Professor of Experimental Mechanics, Stevens Institute of Technology, Hoboken, N. J.	July 12, 1887
DEREDON, CONSTANT	Consulting Engineer, 27 Thames St., New York City.	May 18, 1897
DEWAR, JOHN THOMAS	Electrical Expert, Western Electric Co.; residence, 33 Rue Bouewijns, Antwerp, Belgium.	May 21, 1895

Name.	Address.	Date of Election.
Dexter, Frank H.	Draughtsman, Nassau Electric Co., 268 23d St.; residence, 391 8th St., Brooklyn, N. Y.	June 24, 1898
Dey, Harry E.	393 Classon Ave., Brooklyn, N. Y.	Dec. 19, 1894
Dickerson, E. N.	Attorney-at-Law, 141 Broadway; residence 64 E. 34th St., New York City.	April 15, 1884
Dinkey, Alva C.	Supt. Electric Dept., Homestead Steel Works, Munhall, Pa.	Feb. 17, 1897
Dobbie, Robert S.	Electrical Engineer, Riding Mill-on-Tyne, Northumberland, Eng.	Feb. 5, 1889
Doherty, Henry L.	40 Wall Street, New York City.	Sept. 28, 1898
Doolittle, Clarence E.	Manager and Electrician, Roaring Fork Electric Light and Power Co., Aspen, Colo.	May 15, 1894
Doolittle, Thomas B.	Engineering Department, American Bell Telephone Co., 125 Milk St., Boston, Mass.	May 16, 1893
Doremus, Charles Avery	*M.D. Ph.D.* 59 W. 51st St., New York City.	July 7, 1884
Downing, P. M.	Supt. Electrical Dept. Blue Lakes Water Co., Palo Alto, Cal.	June 24, 1898
Dressler, Charles E.	17 Lexington Ave., New York City.	Dec 16, 1890
Drysdale, Dr., W. A.	Consulting Electrical Engineer, Hale Building, Philadelphia, Pa.	Sept. 19, 1894
Du Bois, Julian	Chief Electrician, Mohawk Division N. Y. C. & H. R. R. R. 24 So. Hawk St., Albany, N. Y.	Nov. 20, 1895
Duncan, John D. E.	18 Sidney Place, Brooklyn, N. Y.	Mar. 20, 1895
Duncan, Thomas	Electrician, Laboratory Fort Wayne Electric Corporation, 407 Broadway, Fort Wayne, Ind.	Oct. 17, 1894
Dunn, Clifford E.	Patent Attorney, 229 Broadway, New York City, residence, 12-a Monroe St., Brooklyn, N Y.	Feb. 15, 1899
Dunn, Kingsley G.	British Columbia Electric Railway, L't'd., 37 John Street, Victoria, B. C.	Oct. 17, 1894
Durant, Edward	Chief Electrical Engineer, Manhattan State Hospital of the State of New York, Ward's Island, N. Y.; residence, 115 East 26th St., New York City.	Nov. 15, 1892
Durant, Geo. F.	Vice-Pres't Bell Telephone Co., of Mo., 511 No. 4th St., St. Louis, Mo.	April 15, 1884
Dyer, Francis Maron	Associate Engineer with Chas. L. Eidlitz, 1012 St. James Bldg., 26th St., and Broadway; residence, 355 Lenox Ave., New York City.	Sept. 19, 1894
Eddy, H. C.	Electrical Engineer and Contractor, Lees Building, Chicago, Ill.	June 20, 1894
Eden, Morton Edward	Electrical Inspector, Western District the Underwriters' Association of the Middle Department, 245 Fourth Ave., Pittsburg; residence, Warren Pa.	Sept. 19, 1894

Name.	Address.	Date of Election.
Edmands, I. R.	Construction Engineer, General Electric Co., 315 Buffalo Ave., Niagara Falls, N. Y.	June 23, 1897
Edwards, James P.	Consulting Electrician, Augusta, Ga.	April 19, 1892
Eglin, Wm. C. L.	Chief of Electrical Department, Edison Electric Light Co., 909 Walnut St.; residence, 4230 Chester Ave., Philadelphia, Pa.	Sept. 19, 1894
Ekstrom, Axel	Electrical Engineer, General Electric Co.; Schenectady, N. Y.	June 17, 1890
Ellard, John W.	Treasurer, Edison Electric Illuminating Co., 15 South Street, Baltimore, Md.	June 23, 1897
Elias, Albert B.	1310 Washburn Street, Scranton, Pa.	Jan. 26, 1898
Ellicott, Edward B.	Superintendent of City Telegraph, Union League Club, Chicago, Ill.	Sept. 19, 1894
Ellis, R. Laurie	Assistant to Superintendent, Augusta R'way & Electric Co., 230 Dyer Building, Augusta, Ga.	April 26, 1899
Elmer, William, Jr.	Electrical Engineer, 1330 12th Ave., Altoona, Pa.	Mar. 18, 1890
Ely, Wm. Grosvenor, Jr.	Ass't Supt. Construction, General Electric Co., 849 Union Street, Schenectady, N. Y.	Mar. 21, 1893
Emerick, Louis W.	Electrical Engineer, The Solvay Process Co., Syracuse, N. Y.; residence The Kenyon, Warren St., Syracuse, N. Y.	Aug. 13, 1897
Emmet, Herman L. R.	Publisher and Printer, 106 Liberty St., New York City.	April 15, 1884
Ende, Siegfried H.	121 E. 77th St., W. New York City.	Jan. 17, 1894
Entz, Justus Bulkley	Electrical Engineer, Electric Storage Battery Co., 19th St., and Allegheny Ave., Philadelphia, Pa.	Jan. 7, 1890
Erickson, F. Wm.	Electrical Engineer, The Erickson Electric Equipment Co., 71 Federal St., Boston, Mass.	Sep. 19, 1894
Esty, William	Professor in charge of Dept. of Electrical Engineering, University of Illinois, Urbana, Ill.	Mar. 20, 1895
Etheridge, Locke	Chicago Telephone Co.; residence, 44 E. 50th St., Chicago, Ill.	Oct. 17, 1894
Evans, Edward A.	Acting Chief Engineer, The Quebec, Montmorency and Charlevoin Railway, Quebec, Canada.	Jan. 22, 1896
Eyre, M. K.	Duncan and Eyre, Consulting Engineers, 1514 Empire Building, 71 Broadway, New York City	Oct 17, 1894
Farnsworth, Arthur J.	Chief Engineer, Larchmont Electric Co., Mamaroneck, Conn.; residence, 30 Beechwood Ave., New Rochelle, N. Y.	Jan. 16, 1895
Fielding, Frank E. [Life Member.]	Chemist and Assayer, Virginia City, Nev.	Sept. 6, 1887
Finney, John C.	Cashier, Wisconsin Trust Co.; residence, 34 Prospect Ave, Milwaukee, Wis.	Dec. 28, 1898

Name.	Address.	Date of Election.
FIRTH, WM. EDGAR	Chief Engineer, The Midvale Steel Co., Nicetown, Philadelphia; residence, 7203 Boyer St., Germantown, Pa.	Mar. 25, 1896
FISH, MILTON L.	Colvin Park, Ill.	Oct. 21, 1896
FISHER, HENRY W.	Electrician and Director of Elec. and Chem. Laboratories; The Standard Underground Cable Co., Pittsburg, Pa.	Jan. 16, 1895
FITZHUGH, WM. H.	Supt. Bay City Electric Plant, Bay City, Mich.	April 27, 1898
FLATHER, JOHN J.	Professor of Mechanical Engineering, University of Minnesota; residence, 316 10th Ave., S. E., Minneapolis, Minn	April 19, 1892
FLEMING, JOHN BRECKENRIDGE,	M. M., and Elec. Engineer, Silver King Mill, Park City, Utah.	April 27, 1898
FLESCH, CHARLES	Electrical Engineer, Allgemeine Elektricitats-Gesellschaft, 22 Schiffbauerdamm, Berlin, N. W. Germany.	Sept. 27, 1892
FLIESS, ROBERT ANTON	Student of Electrical Engineering, Columbia University: residence, 201 W. 55th St., New York City.	Mar. 23, 1898
FLOOD, J. F.	Sup't Steubenville Traction Co., Steubenville, O.	Mar. 18, 1890
FLOY, HENRY	Consulting Electrical and Mechanical Engineer, 220 Broadway, New York City.	May 17, 1892
FOOTE, THOS. H.	Electrical Engineer, C. & C. Electric Co., Garwood, near Westfield, N. J.	April 21, 1891
FORBES, FRANCIS	Lawyer, 32 Nassau St., New York City.	Sept. 16, 1890
FORBES, GEORGE	Electrical Engineer, 34 Great George St., London, Eng.	Feb. 21, 1894
FORD, ARTHUR HILLYER,	Western Electric Co., 503 W. Adams St., Chicago, Ill.	Mar. 24, 1897
FORD, FRANK R., *M. E.*	Consulting Engineer, Ford, Bacon & Davis, 149 Broadway, New York City.	Mar. 25, 1896
FORD, WM. S.	Assistant to Chief Engineer, The American Bell Telephone Co., room 73, 125 Milk St., Boston, Mass.	June 7, 1892
FRANCISCO, M. J.	President and General Manager, Rutland Electric Light Co., Rutland, Vt.	June 17, 1890
FRANK, GEO. W., JR.	c/o. J. G. White & Co., 29 Broadway, New York City.	Sept. 28, 1898
FRANKENFIELD, BUDD	1007 S. Hill St., Los Angeles, Cal.	Feb. 17, 1897
FRANKLIN, W. S.	Lehigh University, South Bethlehem, Pa.	Jan. 22, 1896
FRANTZEN, ARTHUR	Electrical Engineer and Contractor, 225 Dearborn St., Chicago, Ill.	Feb. 21, 1894
FRENCH, PROF. THOMAS, JR. *Ph.D.*	713 Ridgway Ave., Cincinnati, O.	Sept. 20, 1893

Name.	Address.	Date of Election.
Frenyear, Thomas C.	Westinghouse Electric and Mfg. Co., 782 Ellicott Sq., Buffalo, N. Y.	Sept. 25, 1895
Fridenberg, Henry Leslie, *M. E.*	44 E. 61st St., New York City.	Jan. 16, 1895
Friedlaender, Eugene	Electrician, Carnegie Steel Company, Duquesne, Pa.	Nov. 20, 1895
Frost, Joseph W.	Secretary, National Automatic Fire Alarm, 335 Broadway, New York City.	Mar. 20, 1895
Fry, Donald Hume	Electrical Engineer and Sup't. Mt. Whitney Power Co., Visalia Cal.	Nov. 23, 1898
Gallaher, Edward B.	The Pneumatic Supply and Equipment Co., 120 Liberty St.; residence, 137 W. 116th St., New York City.	Jan. 19, 1895
Gallatin, Albert R.	Student at Columbia University, residence 58 W. 55th St., New York City.	Mar. 23, 1898
Ganz, Albert F.	Assistant Professor, Physics and Applied Electricity. Stevens Institute: residence 612 River St., Hoboken, N. J.	April 26, 1899
Garrels, W. L.	4531 West Pine Boulevard, St. Louis, Mo.	Mar. 20, 1895
Garfield, Alex. Stanley	Engineer, Cie Thomson-Houston, 27 Rue de Londres, Paris, France.	Jan. 26, 1898
Gaytes, Herbert	Electrical Engineer, Oakland Transit Co., Oakland, Cal.	Mar. 23, 1898
Gerry, James H.	Superintendent, The Self-Winding Clock Co., 163 Grand Ave., Brooklyn, N. Y.	April 18, 1894
Gherardi, Bancroft, Jr.,	Assistant in the Engineering Dept. New York Telephone Co.; 15 Dey St., New York City; residence, 21 South Arlington Ave., East Orange, N. J.	June 27, 1895
Gilliland, E. T.	Pelham Manor, N. Y.	April 15, 1884
Gilmore, Lucien H.	Prof. of Physics and Electrical Engineering, Throop Polytechnic Institute, Pasadena, Cal.	Mar. 20, 1895
Githens, Walter L.	Manager, H. P. Elec. Light and Power Co., Cor. 55th & Halsted Sts.; residence, 5101 Kimbark Ave., Chicago, Ills.	Jan. 22, 1896
Glading, Frank W., *M. A., M. E., M. S.*	Edison Manufacturing Co., Orange, N. J.; residence, Caldwell, N. J.	May 15, 1894
Gladson, Wm. N.	Professor of Electrical Engineering, Arkansas Industrial University, Fayetteville, Ark.	Dec. 28, 1898
Gladstone, James Wm.	Manager, Edison Mfg. Co., 110 East 23d St., New York City; residence, West Orange, N. J.	April 18, 1894
Goddard, Chris. M.	Secretary and Electrician, New England Insurance Exchange. Sec'y Underwriters' National Electric Ass'n, 55 Kilby St., Boston, Mass.	April 22, 1896
Goldmark, Chas. J.	Electrical Engineer, 29 Broadway, and 473 Park Ave., New York City.	June 5, 1888
Gorton, Charles	Civil Engineer, Belmont, N. Y.	Nov. 12, 1889

Name.	Address.	Date of Election.
Gordon, Reginald	Tutor in Physics, Columbia University, New York City.	Feb. 24, 1891
Gorrissen, Ch.	With Siemens & Halske, Franklinstrasse 29, Charlottenburg, Ger.	Mar. 25, 1896
Graham, George Wallace	80 Decatur St., Brooklyn, N. Y.	Dec. 19, 1894
Granberry, Julian H.	*Jun. Am. Soc. C. E.;* residence, Elmora, Elizabeth, N. J.	Aug. 5, 1896
Graves, Chas. B.	Marblehead, Mass.	Sept. 15, 1897
Greenleaf, Lewis Stone	Electrician, Hudson River Telephone Co., Albany, N. Y.	Aug. 5, 1896
Green, Elwyn Clinton	Supt., Gosport Electric Light Co., Gosport, Ind.	Mar. 25, 1896
Greenwood, Fred. A.	Secretary California Electric Works, 409 Market St., San Francisco, Cal.	April 28, 1897
Gregg, Tom Howard	Supt. Electrical Construction, U. S. Light House Board, Tompkinsville, S. I., N. Y.; residence, New Brighon, S. I.	Mar. 22, 1899
Griffen, John D.	Inventor, Electric Conduit and Electric Signaling Apparatus, 60 Broadway ; residence, 304 West 90th St., New York.	Aug. 13. 1897
Griffes, Eugene V.	Electrical Engineer, 518 South Broadway, Los Angeles, Cal.	Feb. 26, 1896
Griffin, Capt. Eugene	First Vice-President, General Electric Co., 44 Broad St., New York City.	Feb. 7, 1890
Gross, S. Ross	Electrician, Tennessee Coal, Iron and R.R. Co., Ensley, Ala.	May 17, 1892
Grower, George G.	Electrician and Chemist, Ansonia Brass and Copper Co., Ansonia, Conn.	Mar. 18, 1890
Guy, George Heli	Secretary, The New York Electrical Society, 120 Liberty St., New York City.	May 16, 1893
Hadley. Arthur L.	Assistant Electrician to Chief Electrician and Gen'l Supt., Fort Wayne Electric Corporation, 174 W. Craighton Ave., Fort Wayne, Ind.	Oct. 17, 1894
Hadley, Fred'k W.	Electrical Eng'r, Arlington Heights, Mass.	Aug. 5, 1896
Hakonson, Carl Harold	Electrical Engineer, with the Union Elektricitäts Gesellschaft, Dorotheeastr 43, Berlin, N.W., Ger.	Sept. 25, 1895
Hall, Edward J.	Vice-President and General Manager, American Telephone and Telegraph Co., 15 Dey St., New York City.	April 18, 1893
Hall, J. P.	Electrical Contractor, 22 Thames St.; residence, 200 W. 136th St., N. Y.	Aug. 5, 1896
Hall, William P.	President, The Hall Signal Co., Vice-President The Johnson Railroad Signal Co., 44 Broad St., New York City.	Sept. 16, 1890

Name.	Address.	Date of Election.
HAMERSCHLAG, ARTHUR A.	Electrical Expert, and Owner Hamerschlag & Co., 100 Maiden Lane, New York City.	Mar. 25, 1896
HAMILTON, JAMES	Patent Attorney and Expert in Patent Causes, 53 State St., Boston, Mass.	Nov. 23, 1898
HAMMATT, CLARENCE S.	Manager, Jacksonville Electric Light Co., Jacksonville, Fla.	Sept. 20, 1893
HANCOCK, L. M.	Supt., Nevada County Electric Power Co., P. O. Box 151, Nevada City, Cal.	May 19, 1891
HARDING, H. McL.	20 Broad Street, New York City.	May 24, 1887
HARRIS, GEORGE H.	Electrical Engineer, Birmingham Railway and Electric Co., Birmingham, Ala.	June 20, 1894
HARRIS, W. C., JR.	[Address unknown.]	April 17, 1895
HARTMAN, HERBERT T.	Pennsylvania Heat, Light and Power Co., Cor. 10th and Sansom Streets, Philadelphia, Pa.	Mar. 21, 189
HARVEY, ROBERT R. [Life Member.]	10 So. Franklin St., Wilkes-Barre, Pa.	Sept. 25, 1895
HATHAWAY, JOSEPH D., JR.	Assistant in Cable Dep't Western Electric Co., 57 Bethune St., N. Y. City.	Aug. 5, 1896
HATZEL, J. C.	Electrical Engineer and Contractor, 114 Fifth Ave., New York City.	Sept. 3, 1889
HEALY, LOUIS W.	Treasurer, East Liverpool Railway Co., East Liverpool, Ohio.	June 26, 1891
HEDENBERG, WM. L.	Manager and Editor, *Electricity*, 136 Liberty Street, New York City.	Nov. 21, 1894
HELLICK, CHAUNCEY GRAHAM	Department of Electrical Engineering, Lafayette College, Easton, Pa.	Jan. 26, 1898
HENDERSON, ALEX.	Electrician, New York Fire Dept.; residence, 321 West 118th St. N. Y.	Nov. 30, 1897
HENDERSON, HENRY BANKS	Riverside, Cal.	May 21, 1895
HENRY, GEO. J., JR.,	Engineer for The Pelton Water Wheel Co., 143 Liberty St , New York and 121 Main St., San Francisco, Cal.	April 27, 1898
HERMESSEN, JOHN LOUIS	83 Cannon St., London, E. C., England.	Jan. 20, 1897
HESSENBRUCH, GEORGE S.	*E.E. Ph.D.* 4214 Delmar Boulevard, St. Louis, Mo.	June 27, 1895
HEWITT, CHARLES E.	Electrician, Hyer-Sheehan Electric Motor Co., 139 Chamber St., Newburgh. N. Y.	Sept. 25, 1895
HEWITT, WILLIAM R.	Superintendent, Fire Alarm and Police Telegraph, 9 Brenham Place, San Francisco, Cal.	May 15, 1894
HEWLETT, EDWARD M.	Designing Engineer, Switchboard Dept., General Electric Co., Schenectady, N. Y.	May 19, 1891

Name.	Address.	Date of Election.
HILDBURGH, WALTER LEO	Student, Columbia University; residence, 1 West 30th St., New York.	Dec. 28, 1898
HILL, ERNEST ROWLAND	Electrical Engineer, Westinghouse E. & M. Co., Pittsburg, Pa.	Jan. 25, 1899
HILL, GEORGE, *C.E.*	Consulting Engineer, 150 5th Ave., Tel. 2326 18th., New York City.	April 19, 1892
HILL, GEO. HENRY	Chief Engineer, Elevator Department, Sprague Electric Co., Bloomfield, N. J.; residence, New York City.	Jan. 25, 1899
HILL, H. P.	Washington Loan and Trust Building, Washington, D. C.	Nov. 18, 1897
HILL, NICHOLAS S., JR.	Manufacturers' Record Bldg., Baltimore, Md.	Aug. 5, 1896
HOAG, GEO. M.	City Electrician, City of Cleveland, 113 City Hall: residence, 3 Dorchester Ave., Cleveland, O.	April 28, 1897
HOBART, HENRY M.	Engineer, care British Thomson-Houston Co., 83 Cannon St., London Eng.	April 18, 1894
HODGE, WILLIAM B.	Electrical Engineer, Foundry Dep't. Anaconda Copper Mining Co.; Anaconda, Mont.	Dec. 28, 1898
HOFFMANN, BERNHARD	New York Telephone Co., 15 Dey St., New York City.	Nov. 23, 1898
HOLBERTON, GEORGE C.	Chief Engineer and Electrician, Bangkok Electric Light Syndicate, Bangkok, Siam.	May 15, 1894
HOLBROW, HERMAN L.	With New York Telephone Co.; residence, 421 West 20th St, New York City.	Mar. 24, 1897
HOLT, MARMADUKE BURRELL	Mining and Electrical Engineer, Silverton, Col.	April 15, 1890
HOMMEL, LUDWIG	Supt. of Construction, Standard Underground Cable Co., 1225 Betz Building, Philadelphia, Pa.	Jan. 20, 1897
HOOD, RALPH O.	Electrical Engineer, General Electric Co., Baltimore, Md.	April 18, 1894
HOPEWELL, CHAS. F.	Inspector of Wires, Supt. of Lamps, Fire Alarm and Police Telegraph, City of Cambridge, City Hall; residence, 82 Magazine St., Cambridgeport, Mass.	Aug. 13, 1897
HOPKINS, NEVIL MONROE	Electrical Engineer, 1730 I Street, Washington, D. C.	Nov. 20, 1895
HOPKINS, N. S.	Ass't Engineer, General Electric Co. Lynn, Mass.	April 27, 1898
HORN, HAROLD J.	Electrical Engineer, John A. Roebling's Sons' Co; residence, 36 W. State St., Trenton, N. J.	Mar. 22, 1899
HORNSBY, HARRY H.	Electrical Inspector, 16 City Hall, Chicago, Ill.	June 27, 1895

Name.	Address.	Date of Election
Hosmer, Sidney	Sup't. Underground Cable Dep't, Boston Electric Light Co, Ames Building, Boston, Mass.	May 18, 1897
Howson, Hubert	Patent Lawyer, 38 Park Row, New York City.	June 8, 1887
Hubbard, Albert S.	Electrical and Mechanical Engineer, The Electro Chemical Storage Battery Co., Belleville, N. J.	Nov. 20, 1895
Hubbard, William C.	Vice-President, Electric Arc Light Co., 120 Liberty St., New York City; residence, 427 West 7th St., Plainfield, N. J.	April 18, 1894
Hubley, G. Wilbur	Electrical Engineer, Louisville Electric Light Co.; residence, 717 Fourth Ave, Louisville, Ky.	Sept. 19, 1894
Hubrecht, Dr. H. F. R.	Director, Nederlandsche Bell Telephone Co., Amsterdam, Holland.	Oct. 4, 1887
Hudson, John E.	President, The American Bell Telephone Co., 125 Milk St., Boston, Mass.	Dec. 20, 1893
Huggins, N. W.	Salesman, etc., General Electric Co., Seattle, Wash.	Aug. 5, 1896
Huguet, Chas. K.	Electrical Engineer, 1216 Carondelet St., New Orleans, La.	June 27, 1895
Hull, S. P.	Chief Electrician of Hudson Div. N. Y. C. & H. R. R. R. Co., Poughkeepsie, N. Y.	May 19, 1896
Hulse, Wm. S.	Electrical Engineer, Union Electricitäts Gesellschaft, Berlin, Germany.	Mar. 25, 1896
Humphreys, C. J. R.	Manager, Lawrence Gas Co., and Edison Electrical Ill. Co., Lawrence, Mass.	Sept. 6, 1887
Hunt, Arthur L.	Harrisburg Foundry and Machine Works, 203 Broadway, New York City.	Sept. 19, 1894
Huntley, Chas. R.	General Manager, Buffalo General Electric Co., 40 Court St., Buffalo, N. Y.	Sept. 25, 1895
Hutton, Chas. William	Chief Electrician, Sacramento Electric Gas and Railway Co., Sacramento, Cal.	Feb. 15, 1899
Hutchinson, Frederick L.	Electrical Engineer, Westinghouse Electric and Mfg. Co., Pittsburg, Pa.	June 20, 1894
Idell, Frank E.	Havemeyer Building, 26 Cortlandt St., New York City.	July 12, 1887
Ihlder, John D.	Electrical Engineer, Otis Electric Co., Yonkers, N. Y.	Oct. 2, 1888
Iijima Zentaro,	Electrical Engineer, 89 Shinhanacho, Hongo Tokyo, Japan.	Jan. 22, 1896
Ingold, Eugene	Consulting Engineer and Expert, 1669 Second Ave., Pittsburg, Pa.	April 18, 1894
Insull, Samuel	President, Chicago Edison Co., 139 Adams St., Chicago, Ill.	Dec. 7, 1886
Irvine, Drew W.	[Address unknown.]	Sept 25, 1895

Name.	Address.	Date of Election.
Iwadare, Kunihiko	Electrician, Nippon Electric Company, 2 Shikokumachi Mita Shibaku, Tokyo, Japan.	Sept. 20, 1893
Jackson, Wm. Steell	4th Assistant Examiner, Patent Office; residence, 325 Spruce St., N. W., Washington, D. C.	April 22, 1896
Jaeger, Charles L.	Inventor, Maywood, N. J., Electric Recording Ship Apparatus, Laboratory, 132 Mulberry St., New York, N. Y.	Dec. 20, 1893
James, Harry D.	Expert Draughtsman, Otis Bros. & Co., residence, 100 Buena Vista Ave., Yonkers, N. Y.	Nov. 23, 1898
Johnson, Howard S.	Engineer and Sales Agent, Morgan-Gardner Electric Co.; residence, 70 Jefferson Ave., Columbus, O.	Mar. 22, 1899
Johnston, W. J.	*The Electrical World*, 9 Murray St., New York City.	April 15, 1884
Jones, Arthur W.	Care of Gibbs, Bright & Co., Melbourne, Australia.	Oct. 17, 1894
Jones, F. R.	Professor of Machine Design, University of Wisconsin, Madison, Wis.	May 20, 1890
Jones, G. H.	Agent, General Electric Co., Casilla 1317 D Santiago, Chile.	April 17, 1895
Jones, Henry C.	Member of Firm, the Electric Construction and Supply Co., Montgomery, Ala.	Mar. 20, 1895
Jones, M. E.	Contractor, and Student in Senior Class, Cornell University, Ithaca, N. Y.	Oct. 27, 1897
Joslyn, Howard.	Assistant Engineer, Snoqualmie Falls Power Co., Seattle, Wash.	May 17, 1898
Judson, Wm. Pierson	Oswego, N. Y.	June 8, 1887
Kammerer, Jacob A.	General Agent, The Royal Electric Co., Toronto; residence, 87 Jameson Ave., Toronto, Ont.	April 28, 1897
Keefer, Edwin S.	Supt. of Electric Light Construction, Western Electric Co., 57 Bethune St., New York City; residence, Elizabeth, N. J.	April 18, 1894
Keilholtz, P. O.	U. S. Electric Power and Light Co., Holliday and Centre Sts., and 330 N. Charles St., Baltimore, Md.	Mar. 21, 1893
Keller, E. E.	Vice-Prest. and General Manager, Westinghouse Machine Co, Pittsburg, Pa.; Mailing address, Edgewood Park Pa.	Sept. 20, 1893
Keller, Edwin R., *M.E.*	Mechanical and Electrical Engineer, Falkenau Engineering Co., Ltd., 727 Reading Terminal, 4823 Springfield Ave., Philadelphia, Pa.	Mar. 21, 1894
Kellogg, James W., *M.E.*	General Electric Co, Lighting Dept., Schenectady, N. Y.	June 26, 1891
Kelly, William F.	Manufacturers' Electric Co., American and Somerset Sts., Philadelphia, Pa.	Mar. 24, 1897

Name.	Address.	Date of Election.
KENAN, WM. R. JR.	Chemist and Electrical Engineer, Lake Superior Carbide Works, Sault Ste., Marie, Mich.	Jan. 20, 1897
KENNELLY, ARTHUR E. [Life Member.]	(*President*) Electrician, Firm of Houston & Kennelly, 1203-4 Crozer Bldg., 1420 Chestnut St.; residence, The Landsowne, N. 41st St. and Parkside Ave., Philadelphia, Pa.	May 1, 1888
KER, W. WALLACE	Instructor of Electricity, Hebrew Technical Institute, 36 Stuyvesant St., New York City. Residence, 626 Pavonia Ave., Jersey City, N. J.	Sept. 25, 1895
KING, VINCENT C., Jr.	With V. C. & C. V. King, 517 West St.; residence, 110 East 16th Street, New York.	Aug. 5, 1896
KINSLEY, CARL	Box 357, Johns-Hopkins University, Baltimore, Md.	May 18, 1897
KIRKLAND, JOHN W.	Electrical Engineer, General Electric Co., Schenectady, N. Y.	Mar. 21, 1894
KITTLER, DR. ERASMUS	Professor at the Technical High School, Darmstadt, Germany.	Dec. 16, 1896
KLAUDER, RUDOLPH H.	Electrical Engineer, The Electric Storage Battery Co., Philadelphia, Pa.	Aug. 13, 1897
KLINCK, J. HENRY	Dept. Electrical Engineering, Lehigh University, South Bethlehem, Pa.	Jan. 16, 1895
KNOX, FRANK H.	15 Esplanade St., Alleghany Pa.	June 20, 1894
KNOX, GEO. W.	Electrical Engineer, Chicago City Railway Co., 2020 State St., Chicago, Ill.	Nov. 18, 1896
KNOX, S. L. G.	Mechanical Engineer, Stilwell-Bierce and Smith-Vaile Co., Dayton, O.	Nov. 23, 1898
KREIDLER, W. A.	Editor and Publisher, *Western Electrician*, 510 Marquette Building, Chicago, Ill.	Oct. 4, 1887
LABOUISSE, JOHN PETER	*M.E.* Electrical Engineer, General Electric Co., 40 Park St., Lynn, Mass.	Aug. 5, 1896
LAMB, RICHARD	Chief Engineer, in charge business of the Lamb Electrical Cableways, The Trenton Iron Co., No. 1 Broadway, New York City.	Dec. 18, 1895
LAND, FRANK	Sec'y and Treas., I. A. Weston Co., residence, 221 Green St, Syracuse, N. Y.	Sept. 22, 1891
LANE, VANCE	Manager and Superintendent Construction, Nebraska Telephone Co., Omaha, Neb.	Dec. 19, 1894
LANPHEAR, BURTON S.	Instructor in Experimental Engineering, Cornell University, Ithaca, N.Y.	Jan. 16, 1895

Name.	Address.	Date of Election.
LANMAN, WILLIAM H.	Board of Patent Control, 120 Broadway, New York City.	June 6, 1893
LARDNER, HENRY ACKLEY	Borough of Manhattan Electric Co., 33 Gold St., New York City.	Dec. 19, 1894
LARNED, SHERWOOD J.	Superintendent, Chicago Telephone Co., 203 Washington St., Chicago, Ill.	Oct. 17, 1894
LARRABEE, ROLLIN N.	Western Electric Co., 242 Jefferson St., Chicago, Ill.	Mar. 20, 1895
LATHAM HARRY MILTON	In Engineering Department, American Bell Telephone Co., 42 Farnsworth St., South Boston, Mass.	Dec. 16, 1896
LAWRENCE, W. H.	Assistant Superintendent, Second District, Edison Electric Illuminating Co., 49 West 26th St., New York, N. Y.	April 26, 1899
LEBLANC, CHARLES	Ingenieur en Chef, de la Compagnie Generale de Traction, 24 Boulevard des Capucines, Paris, France.	April 17, 1895
LECLEAR, GIFFORD,	Electrical and Mechanical Engineer, Partner Densmore & Le Clear, 7 Exchange Place, Boston, Mass.; residence, Cambridge, Mass.	Oct. 27, 1897
LECONTE, JOSEPH NISBET	Instructor in Electrical Engineering, State University, Berkeley, Cal.	Feb. 27, 1895
LEDOUX, A. R., *M. S.*, *Ph.D.*,	99 John St., New York City.	Dec. 7, 1886
LEE, FRANCIS VALENTINE T.	Engineer, (Pacific Coast Dept.) Stanley Electric M'f'g. Co., 300 California St., San Francisco, Cal.	Mar. 23, 1898
LEE, JOHN C.	Chemist and Electrician, American Bell Telephone Co., Mountfort St., Longwood, Brookline, Mass.	Mar. 18, 1890
LEITCH, HOWARD WALLACE	Switchboard Regulator. The Edison Elect. Illuminating Co., residence, 373 Madison St., Brooklyn, N. Y.	Nov. 23, 1898
LEMON, CHARLES,	Hon. Sec'y for New Zealand for the Institution of Electrical Engineers, Palmerston, North, New Zealand.	Jan. 22, 1896
LENZ, CHARLES OTTO	Electrical Engineer, 150, Camp Street, Providence, R. I.	Mar. 15, 1892
LE PONTOIS, LEON.	Electrical Engineer, The Westinghouse Elec. and Mfg. Co., Pittsburg, Pa.	Dec. 18, 1895
LETHEULE, PAUL	Electrical Engineer, Commissioned by French Government, 27 Rue de Londres, Paris, France.	May 17, 1898
LEVY, ARTHUR B.	Assistant Engineer, Arc Light Dept., General Electric Co., 810 Lexington Ave., New York City.	Jan. 20, 1891
LEWIS, HENRY FREDERICK WILLIAM,	Redlands, 48 Sydenham Road, Croydon, Surrey, England.	Mar. 5, 1889
LIBBY, SAMUEL BYINGTON	Supt. N. Y. & S. I. Electric Co., West New Brighton, N. Y.	Feb. 23, 1898
LILLEY, L. G.	Electrical Inspector, Underwriters' Association of Cincinnati, S. W. Cor. 3d and Walnut Sts., Cincinnati, O.; residence, Wyoming, O.	June 20, 1894

Name.	Address.	Date of Election.
Lindsay, Robert	General Supt. The Cleveland Elec. Ill. Co., 717 Cuyahoga Building, Cleveland, Ohio.	April 27, 1898
Lindsay, Wm. E.	Consulting Mechanical and Electrical Engineer, Anglo-American Provision Co., Union Stock Yards, Chicago, Ill.	April 17, 1895
Little, C. W. G.	Engineer, British Thomson-Houston Co., 83 Cannon Street, London, Eng.	April 22, 1896
Livingston, Johnston Jr.	56 E. 49th St., New York City.	May 17, 1898
Loewenherz, Herman	Electrical and Mechanical Engineer, 1376 Lexington Ave., New York City,	Feb. 27, 1895
Loewenthal, Max	Manager, Publication Dep't. *The Electrical World and Electrical Engineer*; residence, 1057 Lexington Ave., New York City.	Mar. 23, 1898
Lohmann, R. W.	32 University Ave., Ithaca, N. Y.	Nov. 23, 1898
Lorimer, Geo. Wm.	Superintendent of Construction, The Callender Telephone Exchange Co., Troy, O.	Aug. 5, 1896
Lorimer, James Hoyt	Electrical Engineer. The Callender Telephone Exchange Co., Troy, O.	Aug. 5, 1896
Louis, Otto T.	Manager of New York Branch, Queen & Co., Inc.; residence, 340 East 119th St., New York City.	Feb. 23, 1898
Lovejoy, D. R.	Assistant in Electrical Engineering, Columbia University; residence, 222 East 49th St., New York, N. Y.	April 28, 1897
Low, George P.	Editor and Proprietor, *Journal of Electricity*, 427 Tenth Ave., San Francisco, Cal.	Jan. 17, 1893
Lozier, Robert T. E.	Electrical Engineer, Member of Firm of Bullock Electric Co., St. Paul Bldg., New York City.	May 20, 1890
Ludlam, Harry W.	With Western Electric Co., 57 Bethune St., New York City.	Dec. 18, 1895
Lundell, Robert	Electrical Engineer, 20 Broad St., residence, 109 W. 69th St., New York City.	Feb. 7, 1890
Luquer, Thatcher, T. P.	New York Telephone Co., 15 Dey St., residence, Bedford, N.Y.	June 26, 1891
Lyman, Chester Wolcott, *M. A.*	30 Broad St., New York, N. Y.	Sept. 19, 1894
Lyman, James [Life Member.]	839 Union Street, Schenectady, N. Y.	Sept. 19, 1894
Lynn, Wm. A.	Assistant in Electrical Engineering, University of California, Berkeley, Cal.	Jan. 25, 1899
Lyons, Joseph,	Patent Solicitor, with Gustav Bissing 908 G. St., Washington, D.	June 24, 1898
Maccoun, Andrew Ellicott	Supt. of the Electrical Dep't., The Carnegie Steel Co., Braddock, Pa.	Nov. 20, 1895
MacCulloch, Robert C.	Manager, Jos. Lough Electric Co., 503 Fifth Ave.; resideuce, 209 W. 81st St., New York City.	Feb. 27, 1895

Name.	Address.	Date of Election.
MACFADDEN, CARL K.	Consulting Engineer, Geneva, Ind.	Sept. 27, 1892
MACGREGOR, WILLARD H.	General Eastern Agent, Cutler-Hammer, Mfg. Co. of Chicago. 136 Liberty St.; residence, 359 W. 27th St., New York City.	Jan. 20, 1897
MACKIE, C. P.	30 Broad St., New York City; residence, Englewood, N. J.	Mar. 21, 1893
MACKINTOSH, FRED'K.	Electrical Engineer, General Electric Co.; residence, 225 Union St., Schenectady, N. Y.	Mar. 25, 1896
MACLEOD, GEORGE	Superintendent and Engineer, Kentucky and Indiana Bridge Co., 29th and High Sts.; residence, 1913 4th Ave., Louisville, Ky.	Aug. 5, 1896
MACMULLAN, ROBERT HEATH,	Lafayette, Ind.	Sept. 22, 1891
MAGEE, LOUIS J.	Electrical Engineer, Director, der Union Elektricitats Gesellschaft, Grosse Quer Allee 1., Berlin, Germany.	April 2, 1889
MAHONEY, JAMES J.	Engineering Assistant to Manager Railway Dep't General Electric Co., 115 W. 47th St., New York City.	May 17, 1898
MAKI, HEIICHIR	Chief Engineer, Hōshyū Traction Co., Beppu, Oitaken, Japan.	Aug. 5, 1896
MALIA, JAMES P.	Electrician, Armour & Co., 5316 Union Ave., Chicago, Ill.	June 20, 1894
MANSFIELD, R. H. Jr.,	President, Iron Clad Resistance Co., Westfield, N. J.	Sept. 28, 1898
MARTIN, FRANK	Superintendent, Universal Lock Co., Woodbine, N. J., and 56 Liberty St., New York City.	Oct. 21, 1890
MARTIN, JAMES A.	[Address Unknown.]	May 19, 1896
MARTIN JOHN	Agent, Stanley Electric M'fg. Co., 300 California Street, San Francisco, Cal.	July 27, 1898
MARTIN, T. COMMERFORD	(*Past-President.*) Editor, *The Electrical World and Electrical Engineer*, 9 Murray Street, N. Y. City.	April 15, 1884
MASON, JAMES H.	Electrical Expert, 10 Fifth Ave., Brooklyn, N. Y.	May 19, 1891
MATHER, EUGENE HOLMES	Central Railway and Electric Company, New Britain, Conn.	April 28, 1897
MATTHEWS, CHARLES P.	Associate Professor, Electrical Engineering, Purdue University, Lafayette, Ind.	May 16, 1893
MAXWELL, EUGENE	c/o. General Electric Co., Seattle, Wash.	Aug. 5, 1896
MAURO, PHILIP	Counsellor at-Law in Patent Causes (Pollock & Mauro), 620 F. St., Washington, D. C.	Dec. 21, 1892
MAYER, MAXWELL M.	Mfr. of Plating Dynamos, 2d Ave. and 121st St.; residence 433 East 116th St., New York City.	Feb. 27, 1895

Name.	Address.	Date of Election.
Mayrhofer, Jos. Carl	Electrical Engineer, 165 W. 82d St., New York City.	June 20, 1894
McCarthy, E. D.	McCarthy Bros. & Ford, 45 North Division St.; residence, 382 West Ferry Street, Buffalo, N. Y.	Nov. 18, 1896
McCluer, Chas. P.	District Inspector, So. Bell Tel. and Tel. Co., Richmond, Va.	Apr. 22, 1896
McClurg, W. A.	Manager, Electrical Dept., Plainfield Gas and Electric Light Co., 207 Madison Ave., Plainfield, N. J.	Dec. 20, 1893
McElroy, James F.	Consulting Engineer, Consolidated Car Heating Co., 131 Lake Ave., Albany, N. Y.	Nov. 15, 1892
McKibbin, George N.	Reed & McKibbin, General Street Railway Contractors, 30 Broad St New York City.	June 8, 1887
McKissick, A. F.	Professor of Electrical Engineering, The A. & M. College of Ala., Auburn, Ala.	Feb. 16, 1892
McRae, Austin Lee	Consulting Electrical Engineer, 306 Oriel Bldg , St. Louis, Mo.	May 17, 1892
Meadows, Harold Gregory	Associate Engineer (Elec.) with Newcomb Carlton, 109 White Building; residence, 238 Elmwood Ave., Buffalo, N. Y.	Sept. 23, 1896
Medina, Frank P.	Electrician, Pacific Postal Telegraph Co., 534 Market St., San Francisco, Cal.	Sept. 19, 1894
Meredith, Wynn	Electrical Engineer, Benjamin, Hunt, and Meredith, 331 Pine St., San Francisco, Cal.	Jan. 17, 1893
Merrill, E. A.	Manager, New York Office, MacIntosh and Seymour, 26 Cortlandt St., New York City.	Sept. 20, 1893
Merrill, Josiah L.	Electrical Engineer, c/o. General Electric Co., New Orleans, La.	Sept. 25, 1895
Merritt, Ernest	Assistant Professor in Physics, Cornell University, Ithaca, N. Y.	Sept. 16, 1890
Merz, Chas. H.	The British Thomson-Houston Ltd., 83 Cannon St., London, E.C.; residence, The Quarries, Newcastle-on-Tyne, England.	Sept. 25, 1895
Meyer, Hans S.	Electrical Engineer, General Electric Co., residence, Hotel Edison, Schenectady, N. Y.	July 27, 1898
Meyer, Julius	Consulting Engineer, 55 Broadway, New York City.	Oct. 25, 1892
Miller, Herbert S.	Electrical Engineer, Diehl Mfg. Co.; residence, 1025 E. Jersey St., Elizabeth, N. J.	Mar. 22, 1899
Miller, Kempster B.	Electrical Engineer and Patent Expert, Box 323, Scranton, Pa.	Sept. 28, 1898
Miller, Wm. C., *M. S.*	Electrical Engineer, 3 South Hawk St , Albany, N. Y.	Oct. 21, 1890

Name.	Address.	Date of Election.
MITCHELL, SIDNEY Z.	Manager, Oregon, Washington and Idaho Agency, General Electric Co., Fleischner Building, Portland, Ore.	Nov. 12, 1889
MOLE, HARVEY EDWARD	Ass't in Engineering Dept. J. G White & Co., 29 Broadway; residence, 320 West 58th St., New York City.	Nov. 30, 1897
MONTAGU, RALPH LECHMERE	Chief of Electrical Department, The Gold Dredging Co., Bannack, Mont.	Feb. 26, 1896
MOORE, WM. E.	General Superintendent and Electrician The Augusta Railway & Electric Co., Augusta, Ga.	Jan. 22, 1896
MORA, MARIANO LUIS	General Electric Co., 44 Broad St., New York City.	Mar. 20, 1895
MORDEY, WM. MORRIS	Consulting Electrician, 82 Victoria St., Grosvenor Mansions. Westminster, London, Eng.	Sept. 22, 1891
MOREHOUSE, H. H.	Morehouse and Morrill, General Electric Installation and Contracting Work, Apartado No 44, Quezaltenango, Guatemala, C. A.	Feb. 21, 1894
MORGAN, CHAS. H.	1015 13th Street, Altoona, Pa.	Aug. 5, 1896
MORGAN, JACQUE L.	Electrical Inspector, Kansas City Fire Dep't.; residence, 1702 Locust St., Kansas City, Mo.	Jan. 26, 1898
MORLEY, EDGAR L.	Sup't Hatzel & Buehler, 114 5th Ave., New York City.	Sept. 25, 1895
MORRISON, J. FRANK	Manager, The Northern Electric Co. 15 South St., Baltimore, Md.	April 15, 1884
MORSE, GEORGE H.	Electrical Engineer, St. Joseph and Benton Harbor Electric Railway and Light Co., St. Joseph, Mich.	May 15, 1894
MORSS, EVERETT	Vice-President, Simplex Electric Co., 303 Marlboro St., Boston, Mass	Sept. 22, 1891
MORTLAND, JAMES A.	Sergeant 12th Co., U. S. V., Signal Corps, Official Photographer, 3d Army Corps, Montezuma, Iowa.	Feb. 23, 1898
MORTON, HENRY, *Ph.D.*	President of Stevens Institute of Technology, Hoboken, N. J.	May 24, 1887
MOSES, DR. OTTO A.	Electrician, 1037 Fifth Ave., New York City.	May 17, 1887
MOSES, PERCIVAL ROBERT, *E. E.*	Electrical Engineer, 35 Nassau St.: residence, 46 West 97th St., New York City.	Dec. 19, 1894
MOSSCROP, WM. A., *M.E.*	Electrical Engineer, 189 Montague St., Brooklyn, N. Y.	May 7, 1889
MUNNS, CHAS. K.	Electrical Engineer, Corning, Iowa.	Nov. 21, 1894
MURPHY, JOHN McL.	Electrical Engineer, Safety Third Rail Electric Co., 5 Beekman St., Room 223, N. Y.	Oct. 26, 1898
MUSCHENHEIM, FRED'K A.	Electrical Engineer, Western Electric Co., 57 Bethune St., residence, 41 W. 31st St, N. Y. City.	April 27, 1898

Name.	Address.	Date of Election.
Neilson, John	Sup't. of Interior Wiring Department, Larchmont Electric Co., Larchmont, N. Y.	May 18, 1897
Newbury, F. J.	Manager Insulated Wire Department, John A. Roebling's Sons Co., Trenton, N. J.	Sept. 23, 1896
Nimis, Albert A.	Electrical Contractor, Nimis & Nimis, 59 East 5th Street, St. Paul, Min. and 204 E. 86th St., N. Y. City.	Aug. 13, 1897
Nock, Geo. W.	Chief Engineer, in charge of Steam and Electric Plant Westinghouse Elect. and Mfg. Co., Pittsburg, Pa.	Aug. 5, 1896
Noxon, C. Per Lee	Manufacturer, High-Frequency X-Ray Apparatus, Dynamos and Motors, 500 East Water Street, Syracuse, N. Y.	Oct. 17, 1894
Nunn, Richard J., *M.D.*	Physician, 119½ York St., Savannah, Ga.	July 12, 1887
Nyhan, J. T.	Superintendent and Electrician, Macon and Indian Spring Electric Railway, Macon, Ga.	Feb. 27, 1895
Ockershausen, H. A.	Electrical Engineer, 65 Madison Ave., Jersey City, N. J.	Sept. 6, 1887
Oi, Saitaro	Chief Engineer to the Bureau of Telegraphs. The Ministry of Communications, 16 Kamitomisakacho, Koishikawa, Tokyo, Japan.	Dec. 28, 1898
Olan, Theodor, J. W.	[Address unknown.]	May 16, 1893
Olivetti, Camillo	Ingegnere Industriale, Ivrea, Italy.	Oct. 17, 1894
Ormsbee, Alex. F.	Electrical Engineer, with N. Y. and N. J. Telephone Co., 81 Willoughby St.; residence, 183 Joralemon St., Brooklyn, N. Y.	June 27, 1895
Osborne, Loyall Allen	Assistant to 2nd Vice-President Westinghouse Electric and Mfg. Co., Pittsburg, Pa.	Oct. 18, 1893
Osterberg, Max, *E.E.*, *A.M.*	Consulting Engineer, and Electrical Expert, Bowling Green Building, New York City.	Jan. 17, 1894
O'Sullivan, M. J.	Superintendent, Electric Light, B. & O. R. R. Co., 202 Hazelwood Ave., Pittsburg, Pa.	Mar. 20, 1895
Otten, Dr. Jan D.	Director, Batavia Electrische Tram-Maatschappij, Van Baerlstraat 80, Amsterdam, Holland.	Nov. 18, 1890
Page, A. D.	Assistant Manager, General Electric Co. Lamp Works, Harrison, N. J.	Jan. 19, 1892
Parker, Herschel C.	Tutor in Physics, Columbia University, 21 Fort Green Pl., Brooklyn, N. Y.	April 19, 1892
Parmly C. Howard, *S.M.*, *E.E.*	College of the City of New York, 17 Lexington Ave.; residence, 344 W. 29th St., New York City.	Feb. 21, 1893

Name.	Address.	Date of Election
Parry, Evan	Engineer, The British Thomson-Houston Ltd., Sunningdale, Fitzgerald Ave., Mortlake, London, Eng.	Sept. 25, 1895
Parsell, Henry V., Jr.	31 E. 21st St., New York City.	Nov. 12, 1889
Patton, Price I.	Sheble & Patton, Ltd., 1026 Filbert St.; residence, The Bartram, 33d and Chestnut St., Philadelphia, Pa.	Mar. 20, 1895
Pearson, Fred'k J.	Supt. of Construction. Western Electric Co., 1510 Howard St., Omaha, Neb.	July 27, 1898
Peck, Edward F.	187 Montague St.; residence, 700 Nostrand Ave., Brooklyn, N. Y.	May 20, 1890
Peckham, W. C.	Prof. of Physics, Adelphi College, Brooklyn; residence, 406 Classon Ave., Brooklyn, N. Y.	Nov. 30, 1897
Peirce, Arthur W. K.	Consulting Electrical Engineer to the Consolidated Gold Fields of South Africa, Ltd., Johannesburg, S. A. R.	June 27, 1895
Perkins, Frank C.	Electrical Engineer and Contractor, 774 Prospect Ave., Buffalo, N. Y.	Oct. 21, 1890
Petty, Walter M.	Superintendent Fire Alarm Telegraph, Rutherford, N. J.	May 16, 1893
Pfund, Richard	With Western Union Telegraph Co., 195 Broadway, New York City.	April 18, 1893
Phelps, Wm. J.	Electrical Engineer and Contractor; residence, Elmwood, Ill.	Mar. 25, 1896
Philbrick, B. W.	Electrical Engineer for J. J. Astor, Rhinecliff, N. Y.	May 15, 1894
Phillips, Eugene F.	President, American Electrical Works, Phillipsdale, R. I.	July 13, 1889
Phillips, Leo A.	Superintendent, New York and Queens Light and Power Co., 66 Lawrence St., Flushing, N. Y.	Mar. 21, 1894
Phisterer, Fred'k William	188 State St., Albany, N. Y.	Nov. 20, 1895
Pillsbury, Chas. L.	City Electrical Inspector, City Hall, Minneapolis, Minn.	Aug. 13, 1897
Pinkerton, Andrew	Electrical Engineer, The Apollo Iron and Steel Co., Vandergrift Pa.	Sept. 25, 1895
Plumb, Charles	Proprietor and Electrician, The Chas. Plumb Electrical Works, 70 West Swan St., Buffalo, N. Y.	June 20, 1894
Pomeroy, William D.	Electrician, Akron Electric Mfg. Co., 1106 So. Main St., Akron, O.	Mar. 22, 1899
Poole, Cecil P.	Editor Electrical Dep't., *Power*, Pulitzer Building; residence, 206 W. 80th St., New York City.	Jan. 3, 1888
Pope, Henry W.	Traffic Manager Southern Bell Telephone & Telegraph Co., residence, 200 W. 83d St., New York City.	Mar. 23, 1898
Pope, Ralph Wainwright	Secretary to the American Institute of Electrical Engineers, 26 Cortlandt St., (Telephone, 2199 Cortlandt), New York City; residence, 570 Cherry St., Elizabeth, N. J.	June 2, 1885

Name.	Address.	Date of Election.
Porter, H. Hobart, Jr.	Agent, Westinghouse Elec. and Mfg. Co., 120 Broadway, New York; residence, Lawrence, L. I.	Mar. 25, 1896
Powell, Percy Howard	*M. E.*, Bridgeport Brass Co.; residence, 344 State St., Bridgeport, Conn.	Sept. 25, 1895
Price, Chas. W.	Editor the *Electrical Review*, 41 Park Row, New York City; residence, 223 Garfield Place, Brooklyn, N. Y.	Sept 19, 1894
Price, Edgar F.	Electricial Engineer, Carbide Works, Niagara Falls, N. Y.	June 27, 1895
Prince, J. Lloyd	Edison Illuminating Co., New York City; residence, 868 Flatbush Ave., (Flatbush Station), Brooklyn, N. Y.	Feb. 27, 1895
Privat, Louis	Electrician, Cicero Water, Gas and Electric Light Co., Oak Park, Ill.	Dec. 19, 1894
Proctor, Thos. L.	General Manager, Riker Electric Motor Co., Brooklyn; residence, Newtown, L. I., N. Y.	April 18, 1894
Prosser, Herman A.	Electrician, c/o Baltimore Copper Works., Keyser Bldg.; Baltimore, Md.	Jan. 26, 1898
Pupin, Dr. Michael I.	(*Vice President*) Adjunct Professor in Mechanics, Columbia University; residence, 7 Highland Place, Yonkers N. Y.	Mar. 18, 1890
Randall, John E.	Columbia Incandescent Lamp Co., 1912 Olive St., St. Louis, Mo.	May 7, 1889
Randolph, L. S.	Professor of Mechanical Engineering, Blacksburg, Va.	Feb. 21, 1893
Rathenau, Erich	Electrical Engineer. Allg. Electricitats Gesellschaft, Berlin, Germany.	Nov. 20, 1895
Ray, William D.	General Manager G. P. Magann Air Brake Co., 46 Campau Building, Detroit, Mich.	Sept. 27, 1892
Read, Robert H.	Patent Attorney, 44 Broad St., New York City.	Jan. 19, 1892
Reed, Chas. J.	Electrician, 3313 N. 16th St., Philadelphia, Pa.	Mar. 5, 1889
Reed, Harry D.	Electrician, Bishop Gutta Percha Co., 420 East 25th St., New York City; residence, 88 North 9th St., Newark, N. J.	Sept. 19, 1894
Reed, Henry A.	Secretary and Manager, Bishop Gutta-Percha Co., 422 East 25th St., New York City; residence, 88 North 9th St., Newark, N. J.	June 4, 1889
Reichmann, Fritz	Ryerson Physical Laboratory, University of Chicago, Chicago, Ill.	Mar. 23, 1898
Reid, Edwin S.	General Sup't of Construction, National Conduit and Cable Co, 17 Times Building; residence, 112 Madison Ave., New York City	Feb. 26, 1896

Name.	Address.	Date of Election.
Reilly, John C.	General Supt., N. Y. & N. J. Tel. Co., 16 Smith St., Brooklyn, N. Y.	April 15, 1884
Rennard, John Clifford,	*A. B. E. E.* Consulting and Supervising Electrical Engineer, 15 Dey St., New York City.	Jan. 16, 1895
Reno, C. Stowe	Electrical Engineer, Triumph Electric Co., 620 Baymiller Street, Cincinnati, Ohio.	Nov. 23, 1898
Requier, A. Marcel	Electrical Engineer, Westinghouse Electric Co., (L't'd.) 32 Victoria St., London, S. W. Eng.	Dec. 20, 1893
Rice, Arthur L.	Professor of Steam and Electrical Engineering, Pratt Institute, Brooklyn, N. Y.	Oct. 21, 1896
Rich, Francis Arthur	Manager, Woodstock G. M. Co., Karangahake, Auckland, New Zealand.	Jan. 20, 1897
Richards, Chas. W.	C. W. Richards & Co., 64 Federal St., Boston; residence, Needham, Mass.	Sept. 23, 1896
Richey, Albert S.	Electrician, Citizens' Street Railway Co., 403 W. Adams Street, Muncie, Ind.	May 18. 1897
Ricker, Charles W.	Electrical Engineer, 702 Ellicott Square, Buffalo, N. Y.	May 15, 1894
Rideout, Alexander C.	*LL. D.*, Consulting Electrical and Mechanical Engineer, Rideout & Gage, 101 Randolph St., Chicago, Ill.	Aug. 5, 1896
Ripley, Wm. Howe	605 Lexington Avenue, New York City.	Feb. 17, 1897
Rittenhouse, Chas. T.	247 W. 138th St., New York City.	Feb. 21, 1894
Roberson, Oliver R.	Electrician, Western Union Telegraph Co., 195 Broadway, P. O. Box 856, New York City.	Dec. 20, 1893
Robinson, Almon	Webster Road, P. O. Box 943, Lewiston, Me.	Sept. 6, 1887
Robinson, Dwight Parker	Manager, Edison Illuminating Co., 15 South St., Baltimore, Md.	Sept. 25, 1895
Robinson, Francis George	With Metropolitan Street Railway Co.; residence, 138 E. 61st Street, New York City.	Nov. 21, 1894
Rodman, Samuel, Jr.	(Late 1st Lieut., 2nd U. S. Artillery), Electrician and Expert in High Explosives. Room 106, Pullman, Bldg., Chicago, Ill.	Sept. 16, 1890
Roebling, Ferdinand W.	Manufacturer of Electrical Wires and Cables, Trenton, N. J.	June 8, 1887

Name.	Address.	Date of Election.
Roller, Frank W. *M.E.*	Electrical Engineer, Machado & Roller, Electrical Machinery, 203 Broadway, N. Y.; residence, Cranford, N. J.	May 21, 1895
Roper, Denney W.	Edison Illuminating Co. of St. Louis, Mo., Alton, Ill.	June 6, 1893
Rosebrugh, Thomas Reeve	Lecturer in Electrical Engineering, School of Practical Science, Toronto, Ont.	June 26, 1891
Rosenbaum, Wm. A.	Electrical Expert and Patent Solicitor, 177 Times Building, New York City.	Jan. 3, 1889
Rosenberg, E. M., *M. E.*	Residence, 138 W. 85th St., New York City.	Oct. 21, 1890
Rosenbusch, Gilbert	Engineer, Sprague Electric Co., South Orange, N. J.	Sept. 28, 1898
Ross, Taylor William	Second Assistant Engineer, U. S. Revenue Cutter Service, Revenue Cutter "Perry," Astoria, Or.	Mar. 25, 1896
Rowland, Arthur John	Professor of Electrical Engineering, Drexel Institute: residence, 3220 Spencer Terrace, Philadelphia, Pa.	Sept. 19, 1894
Rowland, Henry A.	Professor of Physics, Johns Hopkins University, Baltimore, Md.	Mar. 21, 1894
Royce, Fred W.	Electrician and Patent Solicitor, 1423 New York Ave., Washington, D. C.	April 15, 1884
Rushmore, David B.	Wendell Hall, Pittsfield, Mass.	Sept. 25, 1895
Rutherford, Walter	Manager Electric Traction Dep't, Dick Kerr & Co., Ltd., 110 Cannon St., London E. C., England.	Sept. 22, 1891
Sage, Henry Judson	Sage & Co., Electrical Engineers, Rochester, Pa.	Dec. 20, 1893
Sahulka, Dr. Johann	Docent of Electrotechnics, Technische Hochschule, Vienna, Austria.	Dec. 20, 1893
Sanborn, Francis N.	Ass't Master Mechanic, Coe Brass and Mfg. Co., Torrington, Conn.	Nov. 24, 1891
Sanderson, Edwin N.	Of Sanderson & Porter, Engineers and Contractors, 120 Broadway, New York City.	Oct. 17, 1894
Sargent, Howard R.	Electrical Engineer, General Electric Co.; residence, 706 East Liberty St., Schenectady, N. Y.	Mar. 25, 1896
Satherberg, Carl Hugo	Chief Engineer, The Midvale Steel Co., Nicetown, Phila., Pa.; residence 1752 N. 26th St., Philadelphia, Pa.	Aug. 5, 1896
Sawyer, Fred. W.	68 Mount Vernon St., Fitchburg, Mass.	June 27, 1895
Saxelby, Frederick	Electrical Engineer, 288 Summer Ave., Newark, N. J.	June 5, 1888

Name.	Address.	Date of Election
SCHEIBLE, ALBERT	Secretary, George Cutter Co., 100 Lake Street, Chicago, Ill.	June 20, 1894
SCHLOSSER, FRED. G.	Superintendent of Electric Dept., Laclede Gas Light Co., 411 N. 11th St. Louis, Mo.	Sept. 22, 1891
SCHREITER, HEINR. *C. E.*	Counsellor and Attorney, 20 Nassau St, New York City.	Jan. 17, 1893
SCHUM, CHAS. H.	Electrical Engineer, F. A. La Roche & Co., 216 Third Ave., New York City.	Feb. 23, 1898
SCHWAB, MARTIN C.	Electrical Engineer, with Northern Electric Co., 15 South St.; residence, 1729 Madison Ave., Baltimore, Md.	Nov. 18, 1896
SCHWABE, WALTER P.	Superintendent, Rutherford, Boiling Springs and Carlstadt Electric Co., Carlstadt, N. J.	May 19, 1896
SCHWEITZER, EDMUND OSCAR	Electrical Inspector, Chicago Edison Co., 139 Adams St.; residence, 1906 Oakdale Ave., Chicago, Ill.	Feb. 15, 1899
SCIDMORE, FRANK L.	With N. Y. C. & H. R. R. R. Co., office of A. F. A.; residence, 21 Highland Ave., Yonkers, N. Y.	Dec. 18, 1895
SCOTT, WM. M.	Electrical Engineer. The Cutter Electrical and Mfg. Co., 1112 Sansom St., Philadelphia, Pa.; residence, 108 West Johnson St, Germantown, Pa.	June 23, 1897
SEARING, LEWIS	Consulting, Mechanical, and Electrical Engineer, Denver Engineering Works, Denver, Col.	April 3, 1888
SEARLES, A. L.	Engineering Dept., Fort Wayne Electric Corporation, Fort Wayne, Ind.	April 18, 1894
SEDGWICK, C. E.	Agent at San Francisco Office, General Electric Co, 15 First St.; residence, Berkeley, Cal.	Feb. 23, 1898
SEE, A. B.	A. B. See Manufacturing Co., 116 Front St.; residence, 107 East 19th St, (Flatbush), Brooklyn, N. Y.	Jan. 17, 1893
SEITZINGER, HARRY M.	Consulting and Constructing Engineer, 6 Northampton St., Wilkes-Barre, Pa.	Sept. 20, 1893
SERRELL, LEMUEL WM.	Mechanical and Electrical Engineer, 99 Cedar St., New York City; residence, Plainfield, N. J.	Nov. 1, 1887
SERVA, A. A.	With Fort Wayne Electric Corporation, 150 Devonshire St., Boston, Mass.	Dec. 20, 1893
SHAFFNER, S. C.	Supt. and Electrician. Electric Lighting Co. of Mobile, Box, 234, Mobile, Ala.	Aug. 13, 1897
SHARPE, E. C.	John A. Roebling's Sons' Co., 25 Tremont St, San Francisco, Cal.	Feb. 26, 1896
SHAW, HOWARD BURTON	Assistant Professor Electrical Engineering, Missouri State University, Columbia, Mo.	April 28, 1897

Name.	Address.	Date of Election.
SHIELDS. W. J.	Consulting Engineer, New Wilmington, Pa.	Sept. 19, 1894
SHOCK, THOS. A. W.	Gen'l Sup't Portland General Electric Co., Portland, Or.	Mar. 20, 1895
SIMPSON, ALEXANDER B.	Electrical Engineer, 54 Maiden Lane, N. Y. City; residence, Whitestone, L. I.	May 21, 1891
SIMPSON, J. MANLEY	Assistant Superintendent, Nortwestern Grass Twine Co., P. O. Box 2513, St. Paul, Minn.	Jan. 25, 1899
SISE, CHARLES F.	President, Bell Telephone Co., of Canada, P. O. Box 1918, Montreal, Canada.	June 8, 1887
SKIRROW, JOHN F.	Ass't Manager, Postal Telegraph Cable Co., New York City; residence, 183 N. 19th St , East Orange, N. J.	Sept. 25, 1895
SLADE, ARTHUR J., *Ph.D.*	Engineer, 44 Broadway; residence, 62 East 66th St., New York City.	Sept. 19, 1894
SLATER, FREDERICK R.	Designing Department, Otis Bros. & Co., 153 Warburton Ave., Yonkers, N. Y.	Oct. 17, 1894
SMITH, FRANK E.	Chief Electrician, San Francisco Gas and Electric Co., 229 Stevenson St.; residence, 418 Eugenia Ave., San Francisco, Cal.	Sept 19, 1894
SMITH, HAROLD BABBITT	Professor of Electrical Engineering, Worcester Polytechnic Institute; residence, Trowbridge Road, Worcester, Mass.	Nov. 24, 1891
SMITH, J. BRODIE	Supt. and Electrician, Manchester Electric Light Co., 142 Merrimack St., Manchester, N. H.	Mar. 21, 1894
SMITH, J. ELLIOT	Superintendent Fire Alarm Telegraph, 122 W. 73d St., New York City.	April 15, 1884
SMITH, OBERLIN	President and Mechanical Engineer, Ferracute Machine Co., Lochwold, Bridgeton, N. J.	May 19, 1891
SMITH, T. JARRARD	Manufacturers and Inventors' Electric Co., 96 Fulton St., Tel. 838 John, New York City; residence, Roselle, N. J.	April 19, 1892
SPEED, BUCKNER	Fort Pickens, Pensacola, Fla.	Apr. 22, 1895
SPENCER, PAUL	Gen'l Sup't, People's Light and Power Co., Newark, N. J.; residence, Montclair, N. J.	Nov. 30, 1897
SPENCER, THEODORE	With Bell Telephone Co., 406 Market St., Philadelphia, Pa.	Mar. 21, 1893
SPERLING, R. H.	Assistant Engineer, British Columbia Electric Railway Co., Ltd., Victoria, B. C.	Nov. 23, 1898
SPROUT, SIDNEY S.	Electrical Engineer, 328 Montgomery St., San Francisco, Cal.	Jan. 17, 1894
SQUIER, GEORGE O., *Ph.D.*	1st Lieut., 3d Artillery, Chief Signal Office, War Department, Washington, D. C.	May 19, 1891

Name.	Address.	Date of Election.
STADELMAN, WM. A.	Agent, Elwell-Parker Co., 26 Cortlandt St., New York City.	Feb. 7, 1890
STAHL, TH.	Ingenieur des Usines du Creusot, 34 Avenue Thiers, Grenoble, France.	Nov. 15, 1892
STAKES, D. FRANKLIN	Electrical Expert and Salesman, The Fort Wayne Electric Corporation, 101 The Bourse, Philadelphia, Pa.	Jan. 20, 1897
STANTON, CHAS. H.	With C. H. & H. Stanton Electrical Contractors, 1517 Walnut St.; residence, 134 S. 3d St., Philadelphia, Pa.	Mar. 20, 1895
STEVENS, J. FRANKLIN	Manager, Keystone Electrical Instrument Co., 9th St. and Montgomery Ave.; residence, 1610 Spruce St., Philadelphia, Pa.	Sept. 19, 1894
STEWART, ROBERT STUART	Westinghouse Electric and Mfg., Co., 440 Jefferson Ave., Detroit, Michigan.	Dec. 20, 1896
STEWART, W. M.	District Inspector, New York Telephone Co., 30 Gold St., New York City.	Mar. 25, 1896
STINE, WILBUR M.	Professor of Engineering, Swarthmore College, Swarthmore, Pa.	May 15, 1894
STOCKBRIDGE, GEO. H.	Patent Attorney, 120 Broadway; residence, 2514 11th Ave., near 187th St., New York City.	May 24, 1887
STONE, CHARLES A.	With Firm of Stone & Webster, 4 P. O. Sq., Boston, Mass.	May 19, 1891
STONE, JOSEPH P.	Electrical Engineer, Bailey, Walker, & Co., Buenos Aires, A. R.	Dec. 18, 1895
STORER, NORMAN W.	Electrical Engineer, Westinghouse Electric and Mfg. Co., residence, Amber Club, Pittsburg, Pa.	Dec. 18, 1895
STORRS, PROF. H. A.	Professor of Electrical Engineering, University of Vt., Burlington, Vt.	Mar. 21, 1893
STRATTON, ALEX.	Assistant Electrical Engineer, C. & C. Electric Co., Garwood, N. J.; Box 516 Westfield, N. J.	Mar. 20, 1895
STRAUS, THEODORE E.	Electrical Engineer, residence, 1213 Linden Avenue, Baltimore, Md.	Nov. 18, 1896
STRAUSS, HERMAN A.	Consulting Electrical Engineer and Electrical Expert, 54 Maiden Lane and 29 Liberty St; residence, 201 W. 121st St., New York	Oct. 17, 1894
STRONG, FREDERICK G.	Box, 959, Hartford, Conn.	Oct. 27, 1891
STURTEVANT, CHARLES L.	Patent Attorney, Atlantic Building, Washington, D. C.	Dec. 20, 1893
SULLIVAN, EDWARD	Electrical Inspector, Municipal Building, Brooklyn, N. Y.	Feb. 26, 1896
SUMMERS, LELAND L.	Electrical Engineer, 441 The Rookery, Chicago, Ill.	Feb. 16, 1892
SWANN, JOHN JOSEPH	Assistant Editor, *Engineering News*, 220 Broadway; residence, 12 East 47th Street, New York.	Jan. 26, 1898

Name.	Address.	Date of Election.
Sventorzetzky, Capt. Loudomir	Military Engineering Academy, St. Petersburg, Russia.	Sept. 20, 1893
Swenson, Bernard Victor	Assistant Professor of Electrical Engineering, University of Wisconsin, 606 Francis St., Madison, Wis.	Feb. 27, 1895
Sweet, Henry N.	Chief of Patent Bureau, Thomson Electric Welding Co., 4 Spruce St., Boston, Mass.	May 20, 1890
Swoope, C. Walton	Instructor, Electrical Engineering, Spring Garden Institute; residence, 12 North 38th St., Philadelphia, Pa.	Jan. 26, 1898
Sykes, Henry H.	Chief Engineer, Bell Telephone Co., of Mo., Telephone Bldg., St. Louis, Mo.	Oct. 18, 1893
Tachihara, Jin	Electrical Engineer, Mining Dep't, Mitsu Bishi Co., Tokyo, Japan.	Jan. 26, 1898
Tait, Frank M.	Superintendent, The Somerset Lighting Co., Somerville, N. J.	Sept. 19, 1894
Tapley, Walter H.	Electrician in Government Printing Office, care of Public Printer, Washington, D. C.	Oct. 25, 1892
Taylor, Irving A.	Lachine Rapids Heating and Lighting Co., McCord and Seminary Sts., Montreal, P. Q.	May 17, 1898
Temple, William Chase	Mechanical and Electrical Engineer, Bank of Commerce Bldg., Pittsburg, Pa.	May 3, 1887
Tesla, Nikola	Electrical Engineer and Inventor, 46 E. Houston St., The Gerlach, 53 W. 27th St., New York City.	June 5, 1888
Thayer, George Langstaff, *M. E.*,	Manager, Belle Plaine Electric Light Co, Belle Plaine, Ia.	Aug. 5, 1896
Thomas, Robert McKean, *E. E.*	Member of the firm of Thomas & Betts, 141 Broadway; residence, 135 Madison Ave., New York City.	April 22, 1896
Thompson, Alfred J.	Manager, Electrical Dep't. Krajewski-Pesant Company, O'Reilly 15, Havana, Cuba.	Jan. 25, 1899
Thompson, John West	Supt, Cia de Luz'y Fuerza Motriz Electrica, Guadalajara, Mexico.	Sept. 28, 1898
Thompson, Silvanus P.	Morland, Chislett Road, West Hampstead, London, N. W., England.	Oct. 27, 1897
Thompson, Thos. Perrin	Electrical Laboratorian, Brooklyn Navy Yard; residence, 217 Cumberland St., Brooklyn, N. Y.	Jan. 25, 1899
Thordarson, Chester H.	Manufacturing Electrican, 327 Dearborn St.; residence, 6415 Lexington Ave., Chicago, Ill.	Dec. 18, 1895
Thurber, Howard F.	General Superintendent, New York Telephone Co., 18 Cortlandt Street, New York City; residence, 49 Sidney Place, Brooklyn, N. Y.	Mar. 25, 1896
Toerring, C., Jr.	Electrical Engineer, Helios Electric Co., 3214 Arlington Avenue., Philadelphia, Pa.	April 18, 1894
Tolman, Clarence M,	Electrical Engineer, with Edw. G. Stoiber, Silverton, Colo.	April 27, 1898

Name	Address.	Date of Election.
TORCHIO, PHILIPPO	Engineering Dep't, The Edison Elec. Illuminating Co., 53 Duane Street, New York City.	June 27, 1895
TOWER, GEORGE A.	Electrical Engineer, The Sherwood Land Co., and The Jefferson Hotel Co., 704 E. Main St., Richmond, Va.	May 15, 1894
TOWNSEND, HENRY C.	Attorney and Expert in Electrical Cases, 141 Broadway, New York City.	July 10, 1888
TOWNSEND, SAMUEL G. F.	Assistant in Electrical Engineering, Columbia University; residence, 131 Fifth Ave., New York City.	Jan. 20, 1897
TREADWELL, AUGUSTUS, JR.	*E. E.*, Ass't. Business M'g'r. New York Office, Electric Storage Battery Co., 20 Broad St, New York City; residence, 488 3d St., Brooklyn, N. Y.	Feb. 21, 1894.
TRIPIER, HENRI	Counsel and Technical Engineer, of the Compagnie des Transports Electriques de l'Exposition. Paris, France; residence, 16 rue Ganneron, Paris, France.	Sept. 28, 1898
TROTT, A. H. HARDY [Life Member.]	Beer, near Axminster, Devonshire, Eng.	Jan. 20, 1891
TRUESDELL, ARTHUR E.	Assistant to General Superintendent. Peoples Light and Power Co, 443 4th Ave. Newark, N. J.	Feb. 15, 1899
TURNBULL, WALLACE RUPERT.	Foreman of Experimental Room, General Electric Lamp Works; residence, 29 S. Arlington Ave., East Orange, N. J.	May 17, 1898
TYNG, FRANCIS E.	Manager, Eastern Engineering Co., New York; residence, Cranford, N. J.	Dec. 28, 1898
VAIL, THEO. N.	26 Cortlandt St., New York City.	April 15, 1884
VAN BUREN, GURDON C.	Electrician and Electrical Contractor, 9 & 11 Green St., Albany, N. Y.	Oct. 25, 1892
VANDEGRIFT, JAMES A.	Sawyer-Man Electric Company, 125 Robinson St., Allegheny, Pa.	Nov. 24, 1891
VAN DEVENTER, CHRISTOPHER	626 Lexington Ave., New York City.	Feb. 17, 1897
VAN VLECK, FRANK	President, Van Vleck Tramway Co., Wells Fargo Bldg., Los Angeles, Cal.	Nov. 16, 1886
VAN VLECK, JOHN FALCONER	Constructing Engineer, The Edison Electric and Illuminating Co. of New York; residence, Glenridge, N. J.	Aug. 5, 1896
VAN WYCK, PHILIP V. R., JR.	Plainfield, N. J.	April 21, 1891
VARLEY, THOMAS W.	Electrician, United Electric Light and Power Co., 210 Elizabeth St., New York City.	Sept. 19, 1894
VARNEY, WILLIAM WESLEY	City Commissioner of Baltimore, office, City Hall; residence 712 N. Carey St., Baltimore, Md.	Nov. 21, 1894

Name.	Address.	Date of Election.
Venable, Wm. Mayo	Headquarters 2d U.S. Vol. Engineers, Camp Columbia, Marianao, Cuba.	Nov 30, 1897
Vinten, Ernest Stiles	Draughtsman, Walker Co., New Haven, Conn.; residence 89 Pearl St., New Haven, Conn.	April 27, 1898
Voit, Dr. Ernst	Professor of Electricity, Technical University, Schwanthalerstrasse, Munchen, Germany.	Mar. 21, 1894
Vosmaer, Alexander	Electrical, Mechanical, Chemical Engineer, Director Electrical Research Laboratory, Zijlweg 49, Haarlem, Holland.	Nov. 18, 1896
Vreeland, F. K.	Ass't Engineer, Crocker-Wheeler Electric Co, residence, 228 Orange Road, Montclair, N. J.	Oct. 26, 1898
Wagner, Herbert A.	Gen. Supt., Missouri, Edison Electric Co., and also with Wagner Electric Mfg. Co., 415 Locust St., St. Louis, Mo.	Sept. 28, 1898
Walker, Arthur F.	Sup't and Electrical Engineer, Edison Light Co., Grand Rapids, Mich.	Oct. 23, 1895
Wallace, Chas. F.	Engineer, Stone and Webster, 4 P. O. Square, Boston, Mass.; residence, 62 Forest Street, Roxbury, Boston, Mass.	Nov. 18, 1896
Wallace, William	Washington, D. C.	April 15, 1884
Wardlaw, George A.	[Address unknown.]	Jan. 17, 1894
Waring, Richard S.	Standard Underground Cable Co., 61 Westinghouse Bldg., Pittsburg, Pa.	April 15, 1884
Warner, Chas. H.	Consulting Electrical Engineer, Bowling Green Building, New York City.	Dec. 20, 1893
Warren, Aldred K.	Proprietor, A. K. Warren & Co., 451 Greenwich St., New York; residence New Brighton, N. Y.	Nov. 20, 1895
Wason, Chas. W.	President and Purchasing Agent, Cleveland, Painesville and Eastern R. R., Purchasing Agent Akron, Bedford and Cleveland R. R., 616 Garfield Bldg., Cleveland, O.	May 19, 1891
Waterman, Marcus B.	Electrical Engineer, Brewster Engineering Co., New York City; residence, 177 Lefferts Place, Brooklyn, N. Y.	Feb. 15, 1899
Waters, Edward G.	General Electric Co., 44 Broad St., New York City.	Mar. 18, 1890
Webb, Henry Storrs	Department Electrical Engineering, Lehigh University, South Bethlehem, Pa.	Nov. 20, 1895
Webster, Edwin S	Firm of Stone & Webster, 4 P. O. Sq., Boston, Mass.	April 21, 1891
Weise, Will M. T.	Manager, Weise Bros., Library Building, Davenport, Iowa.	Aug. 13. 1897

Name.	Address.	Date of Election
Welles, Francis R.	Manufacturer, 46 Avenue de Breteuil, Paris, France.	Sept. 6, 1887
Wells, Dana Clemmer	Assistant in Physics, Columbia University, New York; residence, 109 Willow St., Brooklyn; N. Y.	April 28, 1897
West, Julius Henrik	Engineer, Handjery St., 58 Friedenau, Berlin, Germany.	Sept. 20, 1893
Whitaker, S. Edgar	Electrical Engineer andContractor, 135 Shurtleff St., Chelsea, Mass.	Aug. 5, 189
White, Chas. G.	Public Schools Sup't, and Instructor in Physics and Chemistry, Lake Linden, Mich.	Sept. 23, 1896
White, J. G.	J. G. White & Co., Electrical Engineers and Contractors, 29 Broadway, New York City.	April 2, 1889
Whiting, Allen H.	Electrical Engineer, Riker Electric Motor Co., 45 York St., Brooklyn, N. Y.; residence, Stamford, Conn.	Nov. 18, 1896
Whitmore, W. G.	Electrical Engineer, General Electric Co., Edison Building, Box 3067, New York City.	Mar. 18, 1890
Whitney, Henry M. [Life Member.]	81 Milk St., Boston, Mass.	July 12, 1887
Whitted, Thos. Byrd	Electrical Tester, The General Electric Co.; residence, 211 State St., Schenectady, N. Y.	Mar. 22, 1899
Wiederhold, Oscar	Electrical Engineer, 48 Cliff Street, New York; laboratory, 329 Orange St., N. J.	Aug. 13, 1897
Wiese, Gustav Adolph	City Electrician of Alameda, 718 Haight Ave., Alameda, Cal.	Sept. 25, 1895
Wightman, Merle J.	Electrical Engineer, The Staten Island Midland Railway Co., Room 102, Times Building, N. Y. City.	Mar. 5, 1889
Wiley, Walter S.	Engineer, with the American Waterworks, 1107 No. 40th St.. Omaha, Neb.	April 18, 1894
Wilkinson, James	Station Manager, Chief Engineer, Consolidated Electric Light Co., 812 South 19th St., Birmingham Ala.	Nov. 23, 1898
Wiley, Wm. H.	Scientific Expert, 53 E. 10th St., New York City.	Feb. 7, 1888
Williams, Arthur	General Inspector, The Edison Electric Illuminating Co., of New York; residence, 155 Linden Boulevard, Brooklyn, N. Y.	June 23, 1897
Williams, Charles Jr.	Electrician, 1 Arlington Street, East Somerville, Mass.	April 15, 1884
Williams, Geo. Henry	District Supt. The Edison & Swan United Electric Co., Ltd., 134 Royal Avenue; residence, Culmore, Glenburn Park, Belfast, Ireland.	Oct. 27, 1897
Williams, William Henry	Professor of Mechanical and Electrical Engineering. Montana State College, Bozeman, Mont.	Sept. 28, 1898

Name.	Address.	Date of Election.
Willis, Edward J.	Supt. Richmond Traction Co., Richmond, Va.	Nov. 30, 1897
Wilson, Chester P.	Chief Engineer, The Milwaukee Electric Railway and Light Co., 451 Broadway, Milwaukee, Wis.	Sep. 25, 1895
Wilson, Robert M.	Faculty of Applied Science, McGill University; residence, 113 Shuter St., Montreal, P. Q.	Jan. 25, 1899
Winand, Paul A. N.	Engineer and Supt., Schleicher, Schumm & Co., 3200 Arch St., Philadelphia, Pa.	June 20, 1894
Winchester, Samuel B.	9 Laurel St., Holyoke, Mass.	May 15, 1894
Winfield, James H.	Sup't Eastern Division, Nova Scotia Telephone, Ltd., New Glasgow, N. S.	May 17, 1898
Winslow, I. E.	The General Traction Company, Ltd., 35 Parliament Street, Westminster, London, Eng.	Nov. 12, 1889
Wintringham, J. P.	Theorist, 36 Pine St., Cable address, "Atlantic Scrip," New York City, and 153 Henry St., Brooklyn, N.Y.	May 7, 1889
Wirt, Herbert C.	Engineer, Supply Department, General Electric Co., Schenectady, N. Y.	June 26, 1891
Wise, John Shreeve, Jr.,	Electrician The Pa. Mfg. Light and Power Co.; residence, 2023 Mt. Vernon St., Philadelphia, Pa.	Feb. 15, 1899
Wood, Arthur J.	Associate Editor, *Railroad Gazette*, 32 Park Place, New York City.	Dec. 28, 1898
Wood, Fred. W.	General Manager, Los Angeles Railway Co., Los Angeles, Cal.	May 17, 1898
Woodbridge, J. E.	Editor *American Electrician*, 120 Liberty St., New York City.	Oct. 26, 1898
Woodward, W. C.	Electrical Engineer, Narragansett Electric Lighting Co.; residence, 21 Arlington Ave., Providence, R. I.	Nov. 18, 1896
Woodworth, Geo. K	Office of the Engineering Commission, District Building; residence, 1424 S St., N. W., Washington, D. C.	Feb. 17, 1897
Woolf, Albert E.	Electrician and Inventor, The Electrozone Co, 415 Lexington Ave., New York City.	Sept. 16, 1890
Worswick, A. E.	Departamento de Construction, F. C. D., 12 Santa Clara, Mexico City.	Sept. 20, 1893
Wotton, James A.	Electrician, Southern Bell Telephone and Telegraph Co., P. O. Box, 218, Atlanta, Ga.	Oct. 27, 1897
Wray, J. Glen	Assistant Engineer, Chicago Telephone Co., 1651 Fletcher Ave., Chicago, Ill.	Sept. 20, 1893
Wybro, Harrison C.	Electrical Engineer, Wybro-Hendy Co., 38 Fremont St., San Francisco, Cal.	Dec. 18, 1895

Name.	Address.	Date of Election.
YARNALL, VERNON H.	Superintendent of Construction, Metropolitan Electric Construction Co., 20 Broad St., New York City.	May 16, 1893
YOUNG, CHARLES I.	Electrical Engineer, Westinghouse Elec. & Mfg. Co., Land Title Bldg., Philadelphia, Pa.	June 27, 1895
YSLAS, CARLOS	Electrician of Railway in Jalapa, Vera Cruz, Mexico.	Nov. 18, 1896
ZAHM, A. WILFORD	Electrical Engineer and Supt., Manhattan Light, Heat and Power Co., Manhattan Building, St. Paul, Minn.	Nov. 23, 1898
ZALINSKI, EDMUND L.	Captain of Artillery, U. S. A., (retired), The Century, 7 West 43d St., New York City.	May 17, 1887
ZIMMERMAN, LAURENCE J.	Electrical Engineer and Inventor, 232 Schenck Street, Brooklyn, N. Y.	Mar. 21, 1893

(6)

Associate Members, - - - - 768.

OFFICIAL STENOGRAPHER

RYAN, RICHARD W., Room 178, Post Office Building, Telephone, 2787 Cortlandt. Residence, 125 W. 80th St., New York City.

SUMMARY.

Honorary Members, - - - - - - - - - -	2
Members, - - - - - - - - - - - - -	363
Associate Members, - - - - - - - - - -	768
Total - - -	1133