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ELECTROLYSIS TESTING

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ABSTRACT

In 1916 the Bureau of Standards issued Technologic Paper No. 28 entitled "Methods of Making Electrolysis Surveys." This paper has been out of print for some time. Its place was taken to some extent by the publication of the 1921 Report of the American Committee on Electrolysis, in the preparation of which the Bureau of Standards took an active part.

This report pointed out several lines of investigation which needed further study, and the bureau has done considerable work on some of them. As a result of this work a new method of electrolysis testing has been developed which yields much more accurate and detailed information concerning localized electrolysis conditions than it is practicable to secure otherwise.

This method consists in measuring the intensity of discharge of current from a portion of a pipe line, which factor is the one most directly related to the rate of corrosion.

Experience with the new method indicates that the older methods do not directly determine the hazard of buried structures, and that under certain conditions some of the tests lead to erroneous conclusions.

It seems desirable, therefore, to issue a paper in which the various electrolysis tests are discussed in the light of the most recent data concerning them. The older methods of determining general electrolysis conditions are first discussed and then a detailed description of the new apparatus and methods for studying local conditions is given. This is followed by a description of tests for determination of track conditions and a discussion of the interpretation of electrolysis data.

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I. INTRODUCTION

1. NATURE AND PURPOSE OF ELECTROLYSIS TESTING

Shortly after the introduction of electric railways, the corrosion of underground pipes and cables resulting from stray electric currents began to be troublesome in many localities. As the trouble persisted to a greater or less degree it has become necessary from time to time to examine the pipes, cables, and other underground metallic structures to determine the extent of stray-current electrolysis and to detect the possibility of damage due to such currents. The various measurements and studies involved in electrolysis testing form the subject of this paper.

In general, the object of electrolysis testing is twofold: First, to determine the location and extent of the areas in which subsurface metallic structures may be in danger of corrosion by stray currents and to ascertain the degree of seriousness of the trouble; and, second, to collect the necessary engineering data upon which the design of proper mitigative measures may be based. In some cases simpler and more circumscribed electrolysis tests are made, but these, and the circumstances under which they are made, will be dealt with later.

2. CHARACTER OF INFORMATION REQUIRED

In deciding upon the engineering data necessary to a complete electrolysis survey, many factors must be taken into account and appropriate information regarding them obtained. The more important of these include the following:

(a) CAUSE OF DAMAGE

When underground metallic structures are found to show injury due to corrosion it is not uncommon to presume that such damage is caused by stray currents from electric railways. It is becoming more and more generally realized, however, that other factors may play an important part in the deterioration of such structures. The principal of these are, first, galvanic action resulting from currents which originate within the system affected; and, second, a direct corrosive action of the soil. This latter may be, and doubtless is, in some cases, the result of local galvanic action, but in many other cases other processes may be involved. These two factors may, under certain severe conditions, give rise to rates of deterioration of underground metallic structures comparable with those resulting from the presence of excessive stray currents. It is necessary, therefore, to determine in any case the cause of the damage, and this, in general, is to be regarded as the first step in an electrolysis investigation.

(b) SOURCE OF ELECTRIC CURRENTS

If it is found from the preliminary investigation just mentioned that electric currents are involved in the corrosion, it becomes necessary to determine the source of such currents and to distinguish between currents which originate within the system itself, as explained above, and currents which enter the system from some outside source. If current is found to come from some outside source it is often necessary to distinguish between two or more possible sources of the current.

(c) FACTORS IN RAILWAY SYSTEMS WHICH CONTRIBUTE TO ELECTROLYSIS

If it is found that stray currents from an electric railway system are responsible wholly, or in part, for the corrosion in progress, it then becomes one of the major phases of the electrolysis survey to determine what factors in the construction or operation of the railway system are mainly responsible in order that suitable steps may be taken to minimize their effects as far as practicable. Some of the more important factors usually encountered are improperly maintained rail joints, insufficient cross bonding, insufficient or improperly designed negative return, and excessive feeding distances. In general, these factors affect in greater or less degree the amount of stray currents leaving the electric railways. It is desirable also in many cases to make direct determinations of the extent of such stray currents.

(d) FACTORS RELATING TO PIPE AND CABLE SYSTEMS WHICH CONTRIBUTE TO ELECTROLYSIS

Among the factors which may affect in greater or less degree the electrolysis conditions may be mentioned such elements as high-resistance joints, soil resistance, location of pipes or cables with respect to railway tracks, and the use of various mitigative measures. All of the foregoing factors and others involving special local situations must be investigated in any general investigation of electrolysis troubles. It is important also to collect all the existing information as to the extent and location of damage already experienced on a pipe system, and to determine the general electrical condition of the affected structures by means to be described in detail in a subsequent chapter of this paper.

3. PRESENT ENGINEERING STATUS OF ELECTROLYSIS TESTING

It is customary to investigate electrolysis conditions on underground pipe and cable systems by making voltage measurements between various parts of the railway return system or on the affected metallic structures, or by voltage measurements between the affected structures and the earth or other subsurface structures and railway tracks, and to a certain extent by measuring current flow along the pipes or cables under investigation. Until recently these were the only measurements it was practicable to make with the methods available. Such measurements, when properly made and interpreted, will give considerable information bearing upon the general aspect of any local electrolysis situation. The tests do not, however, afford direct quantitive measurement, even roughly approximate, of the rate of corrosion. The reason for this is that the rate at which a pipe is being corroded at any point is a function of the intensity of electric current being discharged from the pipe to earth at the point in question, and it is only by measuring this intensity that the rate of corrosion can be determined. Obviously, voltage measurements between pipe and the earth or other structure give only one of the factors involved. The other factor, namely, the resistance, may vary a hundredfold or more, so that mere voltage measurements of this kind have absolutely no quantitative significance. This matter will be discussed in detail later.

Similarly, the measurement of current flow on an affected structure does not by itself tell the rate at which a structure may be deteriorating in consequence of the presence of such currents, since the rate of corrosion depends on the manner in which the current is discharged from the pipe, whether by metallic circuits or directly into the earth. In the latter case the injury to the structure depends also upon the distribution of the current discharge. For these reasons, current measurements on pipes or cables have also had nothing more than a qualitative significance. Much confusion has resulted and misleading conclusions have often been arrived at as a result of attaching too much quantitative significance to such voltage and current measurements.

Within the last few years these difficulties have in large measure been overcome by the development of means of measuring directly, in a quantitative way, the factor chiefly responsible for the corrosion of underground metallic structures, namely, the intensity of the current discharged into the earth from any small portion of the affected structure. This is accomplished by the use of the earth-current meter which has recently been made available for practical use and which, when properly utilized, will go far toward placing electrolysis testing on a more definite engineering basis than has been possible heretofore. The present paper aims to deal broadly with methods of procedure to be followed in securing all of the various classes of information outlined above and the factors which must be considered in making proper interpretation of such data in order that it may be used as a guide in determining both the seriousness of the trouble in particular cases and the procedure best adapted to improve conditions. The actual determination of modes of procedure in mitigating electrolysis, however, does not come within the province of this paper, but is to be discussed in considerable detail in another publication of the Bureau of Standards.

4. GENERAL PROCEDURE

The general procedure to be followed in conducting an electrolysis survey will depend largely on the purposes in view. If, as is sometimes the case, it is desired merely to make tests to determine whether the terms of an ordinance or set of regulations are being complied with, the survey then assumes the very simple form of procuring, by suitable instruments, the values of the various voltages or other factors specifically prescribed by the regulations.

A second type of survey, which usually involves considerably more testing than the one just mentioned, is one which may be called a maintenance survey. Such a survey is often made to determine whether electrolysis conditions have changed materially, as compared with conditions that existed at the time of some prior, and perhaps more complete, investigation. In making such a survey it is not necessary to obtain data having a definite quantitative significance when viewed by itself, but as a rule it is sufficient to take a representative number of measurements of voltages or currents at given places and compare them with corresponding values obtained at the same places during prior surveys. In this way fairly reliable information as to relative electrolysis conditions can be obtained with an amount of testing which is small compared to that usually required for a complete primary survey. Such surveys can be cheaply made, and many utility companies repeat them annually or even several times a year. It should be carefully kept in mind, however, that surveys of this character give, as indicated, only information as to relative conditions as compared with some previous surveys, and unless there has been a previous and thorough survey of such character as to give definite quantitative information concerning existing electrolysis conditions, the results may be of comparatively little value.

If general electrolysis conditions have never been determined for the system, or if extensive changes in the railway or underground utilities have been made, it often will be necessary to make a very thorough study of an entire district, using such means as will give as much quantitative data as can be obtained regarding the degree of hazard to the underground structures which exists. Such a survey may be called a complete survey. It usually involves not only the use of the methods and apparatus required for the other two types of surveys mentioned, but also additional methods and instruments designed to give more quantitative data. Complete surveys are at present very difficult to make and can only be carried out successfully by an engineer thoroughly experienced both in the methods of procedure to be followed in securing data, and in the interpretation of results of electrolysis tests. This phase of the matter can not be too strongly stressed and will be emphasized in a later chapter of this paper.

Electrolysis surveys of the first two types mentioned above can be made, as a rule, by anyone familiar with the use of ordinary electrical instruments, and they can, if necessary, be carried out by any one interest acting independently, although even here sometimes cooperation between interests is desirable. For making a complete survey, however, it is very essential that all the parties interested in a given locality cooperate actively in the investigation. Such a survey properly carried out requires that access be had to the properties of all the different utilities, since the presence of any one utility plant affects in greater or less degree the hazard that may be involved for any other utility. The use of telephone wires is often desirable and necessary for making certain types of tests. Access to the railway structures, as well as load data, car schedules, and other information, is likewise important. Further, if the investigation is carried out cooperatively, its educational value to the various utilities will be very greatly enhanced. The engineering representatives of the various utilities, by participating in the surveys, will become more or less familiar with the procedure to be followed in making later maintenance surveys that will be required.

Experience demonstrates that if utilities cooperate in making a complete electrolysis investigation, the acquaintanceship and mutual confidence established thereby will usually facilitate to an important extent the application of any remedial measures which may be found necessary. The results will be still further enhanced in value if the investigation can be carried out under the auspices of a joint committee representing all the utilities concerned, or of a consulting engineer selected by such a committee. Wherever a complete electrolysis survey of this character is to be made, every possible effort should be made to make it cooperative in character.

II. VOLTAGE AND CURRENT MEASUREMENTS

As previously stated, voltage measurements between various structures or between different points on the same structure, and also current measurements on underground structures, yield information of qualitative value only, and do not give adequate quantitative data on the degree of hazard involved. Such quantitative evidence as to the rate of corrosion at any given point can only be secured through the measurement of the intensity of current discharge from the subsurface structures into earth at that point. It is not to be inferred, however, that such voltage and current measurements should not be made. In fact, they are valuable and usually sufficient in the case of a maintenance survey, or of a survey made to determine whether the provisions of an ordinance are being complied with. Further, even in the case of a complete survey in which it is desired to establish quantitatively electrical condition of pipes, these measurements, and particularly the voltage measurements, are often of considerable value, and certain of them can always be made to advantage as a preliminary to the making of the more elaborate tests required for determining the intensity of current discharge from pipes at various points. These measurements comprise, for the most part, voltage measurements between different parts of the various utility systems, and current measurements, both on the subsurface metallic structures and, in many cases, on selected parts of railway systems. The present chapter will be devoted merely to a description of the different tests and the mode of procedure in making them, the question of determining the number and places for making such measurements being deferred to a later chapter.

1. VOLTAGE MEASUREMENTS

In the case of a complete survey where it is desired to secure all necessary information for designing mitigative systems, if any should be necessary, it is desirable as a rule to make measurements of maximum potential drops between the points of lowest potential in any feeding area and numerous points of approximately the highest potential in the same feeding area. It is also desirable to make similar measurements at many intermediate points in order that the distribution of this potential drop may be determined. Such measurements, when taken between the points of maximum and minimum potential, are quite commonly known as "over-all potential measurements." When taken between intermediate points, as, for example, 1,000 or 2,000 feet apart, and expressed as volts per unit length, they are known as "potential gradient measurements." These tests give information as to the adequacy of the railway negative return and, in conjunction with information as to rail insulation and soil conductivity, they indicate the general conditions as to magnitude of stray currents. In conjunction with certain load data they are used for making approximate calculations of energy losses in the negative return, which often have an important bearing when considering methods of mitigation.

Another class of voltage measurement consists of measurements of differences of potential between different underground structures and between such structures and the electric railway negative return system. These are commonly known as "potential difference measurements." They are valuable for indicating those areas in which trouble may be most logically expected and where detailed investigations should be made. It is, in general, desirable to make a considerable number of such measurements scattered throughout the entire area under investigation at the outset of the survey.

Another class of potential difference measurements is that made between a structure and a near-by point in the earth. Such measurements are subject to errors due to the contact resistance between the test electrode and the earth, to galvanic action between the test electrode and the structure, and to the gradient in the earth due to current flowing to or from structures other than the one under test. In the case of iron pipes in city streets these readings are especially unreliable, as will be explained more fully later. Where the pipe is remote from other structures, the potential differences, if more than 0.2 volt and taken over a sufficient period to show whether the reading varies with the movement of electric cars, may usually be depended upon to indicate polarity of the structure, and are of considerable value in determining whether the pipe is subject to electrolysis.

For cable testing, potential differences between the sheaths and a piece of lead in the earth at the bottoms of manholes are usually depended upon to indicate the electrolytic condition. The chance of drawing false conclusions is somewhat less because of the usually low potential difference between two pieces of lead, the probability of better contact between the test electrode and the earth, and the usually short distance over which the potential difference is measured. Where, however, the cable makes electrical contact with the earth only occasionally a very considerable earth gradient may be involved.

(a) OVER-ALL POTENTIAL MEASUREMENTS

In instituting an over-all potential survey in a city it is necessary first to decide upon the number and location of points between which the potentials are to be measured. The point of lowest potential in any power-house feeding area can usually be readily determined from an examination of the negative return-conductor system. It will generally be at the tracks where the shortest return feeder from the power house is connected. (If the feeder is not insulated, the reference point should be the bus.) It may, however, be at the terminal of a longer feeder, depending somewhat on the distribution of the load and the resistance of the feeders. The feeder on which the product of the average current and resistance is minimum will be the one which is connected to the tracks at the point of lowest potential.

By consulting a railway positive feeder map a list of the various power stations can be made and the approximate extreme feeding points can be determined by inspection with sufficient accuracy for most purposes. As a rule, it is desirable to measure the voltages between the points of lowest potential and the more remote points, but measurements should also be made between a considerable number of intermediate points in order that the distribution of the potential drop in the tracks can be determined and the location of any high-resistance section in the return circuit can be made evident.

When the points between which the voltages are to be measured have been determined, special wires may be run to these points or arrangements may be made with a telephone company for the temporary use of spare telephone wires for this purpose. The latter is usually feasible and much more economical, as well as requiring much less time than the running of special wires. It is preferable to have all of the wires terminate in one of the telephone central stations, but several central points may be used if necessary. It is advantageous, as a rule, to secure a large city map and mount it on a board, as shown in Figure 1. It is convenient to have the map show the railway lines and have binding posts, with connections on the back to the wires running to the corresponding parts of the city, and on the front for instrument leads. This will greatly expedite the work and insure greater certainty of correct connections, especially where measurements are to be repeated, as will often be desirable. After the correct connection of wires has been verified and freedom from grounds and crosses assured, one can readily connect a voltmeter between the wires leading to any part of the city without danger of error. At the outlying ends these wires should be connected to the rails so as not to be disturbed if the period of test may extend over several hours or longer.

If the pavement is of a character to preclude laying the wire under the surface, it should be protected by a covering to shield it from injury by traffic. In some cases it will be found that permanent connections can not be made for various reasons, in which cases temporary connections would have to be made. It is well to begin the readings by measuring the voltages between the various points near the power house or substation, in order to check the accuracy of the selection of the point of reference. Measurements can then be made from the lowest point to any other point, as well as between any two other points, as may be required.

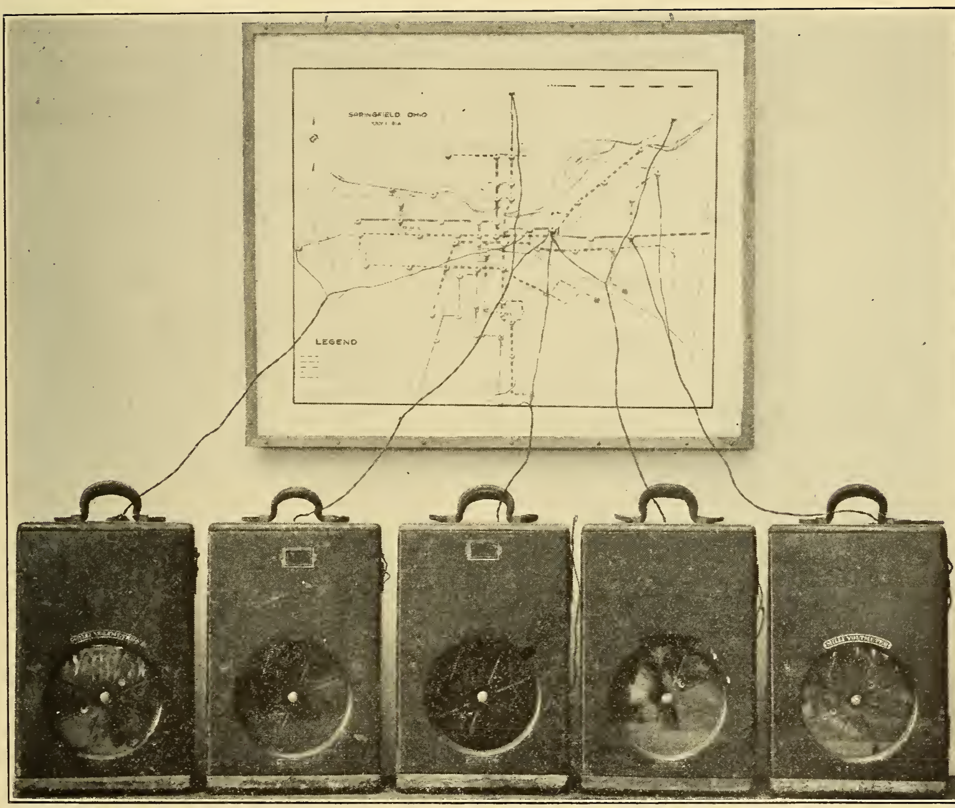

FIG. 1.—*Arrangement for over-all potential tests*

While making over-all potential measurements, as well as all other electrolysis tests described later in this paper, it is advisable wherever practicable to arrange to have the test data worked up and tabulated, and preferably laid out on maps as the work proceeds. In this way it is possible to keep in close touch with the progress of the work, and by making a study of the preliminary data before the work is finished it is often possible to modify the original plans in such a way as to obtain more complete and accurate data regarding electrolysis conditions. This plan has a further advantage in that it will bring to light any apparent inconsistencies in readings at various points in time for them to be checked and uncertainties eliminated.

In overall potential measurements, as well as other electrical measurements made in connection with electrolysis surveys, it is desirable to take the readings at each point over as long a time as circumstances will permit. The variability of such readings, due to the fluctuating character of railway loads, is usually such that readings taken over a period of a few minutes only may give a very misleading impression as to the conditions which actually exist. This is particularly true where infrequent car schedules prevail giving rise to long load cycles. On a line on which a 15-minute schedule is maintained it will be found that certain of the readings, such, for example, as potential difference measurements between pipes and rails, will vary periodically between wide limits, depending on the location of the cars. Periods of several minutes may elapse during which the reading will be very small and these will be succeeded by a short period of a few minutes' duration during which the readings may be several times as great. Obviously, it is important in such cases to continue readings throughout a complete load cycle. Care should be taken that the period is either substantially one load cycle or an approximate multiple of a load cycle. It will be apparent that if a reading is taken, say, over one and one-half load cycles, the reading may include either two hollows and one peak of the voltage curve, or two peaks and one hollow, and in the latter case the average value will appear much larger than in the former case. Very large errors often will result in this way so that care should be taken to minimize such errors by determining the period of the load cycle before determining the length of time over which the reading is to be taken. Of course, if the load cycle is short, so that the reading can be continued over a considerable number of cycles, the error due to this cause will be negligible.

Wherever conditions will permit, it is desirable to continue the readings at any point for a period of about one hour, and in the case of very infrequent schedule, as on certain interurban lines, even a longer period should be adopted. Even then it will be necessary, if accurate conclusions are to be reached, to reduce these readings to some equivalent average values for a longer period, such as a day or longer. It is customary also to determine and tabulate the sustained maximum values; that is, the peak values that are maintained for several seconds or longer. Recording voltmeters should be used for over-all potential measurements, and it will usually be economical to have several such meters so that a number of readings can be taken simultaneously. This matter is discussed in detail in a later chapter of this paper, dealing with interpretation of electrolysis surveys.

When a series of over-all potential measurements, made as above described, have been obtained, it is important to make sure whether corrections in the readings are necessary and to make them when conditions require. A possible source of error that needs to be looked out for is the resistance of the wires extending between the various pairs of points between which measurements are made. Inasmuch as these wires are often several miles in length, and since the wires used in telephone cables are usually not larger than No. 19 A. W. G. for trunks and No. 22 or No. 24 for other cables, their resistance may be a considerable fraction of that of the voltmeter used for making the tests. No. 19 trunk cables have a resistance of about 44 ohms per wire-mile or 88 ohms per loop-mile. The resistance of No. 22 cable is double this figure. If the resistance of the voltmeter circuit is known and the resistance of the lead wires determined, the percentage correction can readily be calculated.

(b) POTENTIAL GRADIENT MEASUREMENTS

(1) Definition of Term.—A potential gradient is the rate of change of potential along a conductor. In electrolysis work it is generally expressed in volts per 1,000 feet, but this is intended to convey the idea of the rate per 1,000 feet at any point, although the length actually measured is generally only a few hundred feet or in some cases much shorter. Under "Potential gradients" should be included all potential measurements between two points on the tracks or between two points in the earth over distances materially less than the extremes of the power-house feeding area. In using the term "gradient" it must be borne in mind that the rate of change of voltage may not be regular, as, for example, if high-resistance joints or other irregularities in resistance of the circuit are encountered.

(2) Measurements of Potential Gradient in Tracks.—Potential gradient measurements are usually made on the railway tracks, but sometimes also on pipe systems and in the earth. The distances are generally short and may be spanned in a more convenient and economical manner than by the use of telephone wires. The points to be reached must be selected and a decision made as to

the types of leads best suited to reach these locations. If spans are quite long, such as 1,000 feet or more, telephone wires may be used to advantage, as in over-all potential tests, and in that case there would be no difference in procedure from that described above for making over-all potential measurements.

(3) Equipment.—The apparatus necessary in making rail gradient measurements includes voltmeters, leads, and suitable contact terminals. Since the gradient often ranges form a fraction of 1 volt to several volts per 1,000 feet, multiple range instruments are necessary. Instruments having ranges from 1 to 50 volts should be used. It is practicable to secure instruments of suitable ranges so that they can be used in both the over-all potential and potential gradient measurements, as well as for many other tests. Sush instruments are described later in this paper. The telephone lines used as leads and the rail contacts have been discussed, but in measurements of shorter spans, of 1,000 feet or less, a length of wire on a special reel and equipped with a crank and brake will expedite the work. The wire can be paid out from the reel along the side of the street and raised above crossings where traffic would cut the wires or insulation.

The contact terminals used will depend on whether the measurement is to be made between points on a track or pipe system or between points in the earth. For making measurements between points on the tracks or on a pipe system or other metallic structure any metallic terminals held firmly against a clean spot on the rail or pipe or a wire swedged in a slot may be used. Special electrodes must be used for measurements between points in the earth.

(c) POTENTIAL-DIFFERENCE MEASUREMENTS

(1) Definition and Purpose.—The term "potential difference" is used in reference to voltage measurements between two or more separate systems; for example, between pipes and rails, lead sheaths and rails, lead sheaths and ground, and a number of other combinations. The distinction made between gradients and potential differences is that gradients are values of voltages obtained between two points on a single system, while potential differences are measured between two different structures or between a structure and the earth.

A structure is said to be positive if a voltmeter deflects in the positive direction when its positive terminal is connected to the structure, the other terminal being connected to the structure of reference. On the assumption that the voltmeter current flows in the same direction with respect to the structure as the current in the earth, a discharge of current is indicated. If, however, the voltmeter current is due to galvanic action between the two materials interconnected through the voltmeter, there may be no current flow when the instrument is disconnected or the flow in the earth may be toward the structure in question if the instrument was placed in parallel with some other circuit. Thus a positive reading does not indicate the normal polarity of the structure with respect to the earth or the direction of flow of current with respect to the structure unless it is known whether the current is due to galvanic action.

To indicate that the structure discharges current to the earth it should be termed "anodic."

Potential-difference measurements are probably the ones most commonly made in electrolysis surveys, and have been and still are largely relied upon by many engineers in judging the seriousness of electrolysis conditions. They are, however, subject to serious inherent limitations. As a rule, potential-difference measurements alone are of no value as a quantitative measurement of the electrolysis condition, since they do not take account of the resistance of the path between the points of measurement. A low potential difference does not always indicate a safe condition, nor does a high potential difference necessarily indicate that corrosion has taken place. In the case of pipes a positive potential difference to rail or an adjacent pipe, or even to a point in the earth a few feet from the pipe, does not prove that the pipe is discharging current to earth, nor does a negative potential difference prove that it is safe. This matter will be discussed in detail later. In the case of lead cables, however, which are placed in conduit out of direct contact with the soil, a negative reading of the cable with respect to near-by earth may usually be regarded as a fairly definite indication that the cable is not discharging current to the earth to any considerable extent. Potential-difference measurements between cables and ground and other structures are usually relied upon to determine whether the cables are being corroded by stray currents. Such measurements are very valuable, since they can be made in large numbers economically, and serve to indicate where the earth-current measurements, to be described later, should be made.

(2) Equipment.—In case the potential-difference measurements are to be taken between metallic conductors the resistance of the voltmeter is not important, since spans and leads are usually short and the resistance of connections negligible. The ranges necessary do not differ greatly from those required for over-all potential measurements, although the readings are, in general, lower, and the same instruments are practically always used. In the potential-difference measurements, however, a zero center instrument is desirable because many of the measurements will show frequent reversals. Since the structures between which potential-difference measurements are made are usually close together, short leads are often all that are required, and for contact a wire swedged in a small slot should be used. This latter form is particularly convenient where contact

extending over a considerable time is to be made with a street-railway rail. For temporary connections use may be made of a clamp somewhat after the design shown in Figure 2. The clamp has a large spread between jaws, hardened points, and a binding post for attaching wire. It is especially valuable for making contact on fire hydrants and other large terminal points.

Figure 3 shows a very convenient form of contactor for use where a clamp is not suitable. The contact point is on a long wood handle which is provided with two hooks on which can be wound the excess wire not needed for the span under test.

In general, connections to water mains can best be made to fire hydrants where these are sufficiently close to the points at which it is desired to make tests. In connecting to a fire hydrant it is important to put the terminal directly in contact with the pipe. This will usually be obtained on the valve nut. Connections made to the top cap of a fire hydrant very often give incorrect results on account of high resistances between this cap and the pipe, which may result from corrosion at the imperfect contacts. When fire hydrants are not available at points where it is desired to make connections, connection to a pipe network can sometimes be made through house services. Gas services frequently contain high-resistance joints. These and the IR drop which may be present on services carrying current sometimes affect the reading obtained. Valve boxes should not be relied on. Where no services are available it may be necessary to bore a small hole with an auger down to the main and make contact to the main through a suitable metallic terminal. In such a case experience has shown that the mere putting of a metal rod down a hole and pressing it against a pipe surface, is not at all adequate because a pipe is often covered with a very tough and adherent coating of scale which it is impossible to penetrate with an ordinary metallic rod, even though it may be provided with a point. If the terminal does fail to penetrate the oxide coating, galvanic potentials may be set up which are sufficient to obscure entirely the true potential difference which it is desired to measure. In order to avoid this difficulty it has been found very satisfactory to use a special contact

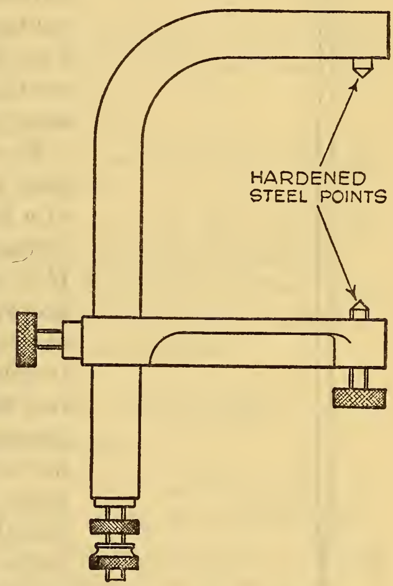

Fig. 2.—*Terminal clamp*

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terminal like that indicated in Figure 3. This consists chiefly of an insulated iron rod *1* about one-half inch in diameter and from 5 to 8 feet long, in the lower end of which a one-fourth inch hole is drilled and an ordinary one-fourth inch twist drill *2* inserted and thoroughly soldered. A binding post *3* is provided at the upper end for connecting the lead wire *4*. In use the rod is placed down in the hole until the drill point comes in contact with the pipe, and it is then turned a few turns until the drill point cuts through the scale and makes good metallic contact with the pipe. The drill must be kept sharp. It will soon become magnetized sufficiently to cause the iron cuttings to cling to it, and thus show when contact has been made with the metal. Use of two scales of the voltmeter will enable the observer to detect high-resistance contacts.

Fig. 3.—*Special drill point contact rod for making contacts with pipes*

1, insulated iron rod; *2*, twist drill; soldered into rod; *3*, binding post; *4*, lead wire.

In making connections to cables it is best to use a very blunt point on the end of a long rod where it is necessary to make connections without entering the manhole. If it is convenient to enter the manhole, however, it is better to scrape the surface of the cable before applying the contact terminal. Attention should be called to the fact that the steel drill terminal, described above for use on pipes, should not be used on cable sheaths, since on account of the extreme softness of lead sheaths, together with their thin walls, there is serious danger of puncturing the sheaths.

Potential differences, as a rule, are extremely variable both as to magnitude and polarity. For this reason it is desirable to make tests at any particular point for a long enough period to make sure of covering at least one load cycle, and preferably a number of cycles. Wherever such measurements are to be used for the purpose of deducing the seriousness of electrolysis troubles it is important, if possible, to use a recording meter. This has the advantage of giving a continuous automatic record. It is usually considerably more acurate than a number of individual readings taken with an indicating meter. It also gives a permanent record of the tests at each station. Suitable meters for making these tests are discussed later.

When measuring potential differences between points in the soil, special electrodes and instruments are necessary. These are described later under "Measurements of earth currents."

(3) Selection of Points of Measurement.—As indicated above, one of the primary purposes of potential-difference measurements is to serve as a guide as to where other and more definite quantitative readings should be made. It is desirable, therefore, to make potential-difference measurements at points well distributed throughout the area under investigation. In making a selection of these points, much must be left to the engineer in charge. In general, however, the following localities should be kept in mind as being the points where it is usually most important to take readings of this character:

Along streets having both underground pipes and street-railway lines, particularly in the regions of power-supply stations where pipes are most likely to be positive to tracks.

On pipes near manholes containing lead cables.

In localities where separate pipe systems not generally interconnected approach each other or other structures.

In locations where soil resistances may be very low, as in wet places, since here even small potential differences may be serious.

It is often profitable to measure potential differences in areas where the tendency is prevailingly negative, as well as in positive areas, as this will often throw light on a source of stray currents.

2. MEASUREMENT OF CURRENT IN STRUCTURES

(a) DEFINITION AND PURPOSE

Under the heading "Measurements of current in structures" are included all observations of current flow obtained by ammeter readings, or by a potential drop on a conductor, the resistance of which is approximately known. They do not include measurements of leakage current from pipes or cables to earth, this subject being discussed under "Measurement of earth currents."

The amount of current carried by underground structures is often a valuable index of the character and efficacy of the method of mitigation used, as well as of general conditions prevailing in the railway negative return. Such measurements, however, should be regarded as having only qualitative significance in indicating hazard to pipes, since in the absence of knowledge as to where current is being discharged from a pipe or cable to earth, they do not yield definite information concerning the location or severity of the corrosion. There are a variety of conductors in which it is at times desirable to measure the current, including copper feeders, railway rails, various kinds of pipe, and lead cable sheaths.

(b) MEASUREMENT OF CURRENT IN FEEDERS AND RAILS

(1) Purpose.—Measurement of current in feeders and rails is not necessary where it is desired to determine the degree of danger which exists to underground structures. When, however, it is desired to design a system of mitigation with a view of reducing the leakage of stray currents to the underground structures, it is necessary to secure complete data regarding the magnitude and distribution of the railway loads not only in positive feeders, but in the negative feeders and tracks also. Measurement of current in tracks is also useful because such measurements, when properly made and interpreted, often give a good idea as to the proportion of the total railway load that is leaking off into the earth. They also show at what points return feeders should be connected in order to prevent unduly large voltage drops in the track return. They further show the approximate amount of current that needs to be taken off at each point, and hence the size of the feeder that would be required. Such measurements are often of value also in estimating the losses in the negative return; and by measuring currents in different rails of a track, local bad bonding will be revealed by unequal distribution of currents between

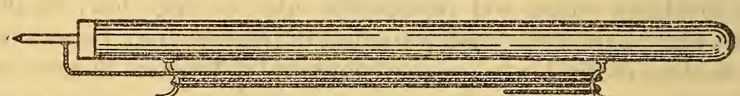

Fig. 4.—*Portable contact*

the different rails of the track. In fact, the quickest and most reliable way to get a good idea of the general condition of the track bonding is to test for equality of distribution of current in the rails at numerous places.

(2) Methods of Measurement.—An ammeter or shunt inserted in the feeder or rail circuit is the most accurate method of obtaining current measurements, but it is often the case that feeders, particularly negative feeders, are not provided with ammeters, and it is usually difficult and often impracticable to insert them. In such cases a potential-drop measurement on a portion of the cable or rail, together with data concerning the cross section and resistivity of the conductor, form the basis of a much more convenient and sufficiently accurate method of measurement. An instrument well suited for current measurements by the drop-of-potential method in all metallic conductors is an indicating or recording millivoltmeter of 10, 100, and 1,000 millivolt ranges. The lower ranges of the recorder, described elsewhere in this paper, are well adapted to this work.

Suitable terminals for connecting the instrument leads are shown in the accompanying illustrations. Figure 4 shows a contact well adapted to this work as well as to potential-difference testing, as described previously.

Figure 5 shows a rail spanner that has proven very convenient for measuring current in rails with indicating instruments. The spanner is a frame carrying two hardened points or portions of hack-saw blades at a fixed distance apart, preferably about 4 feet, and insulated from each other. A handle is provided for convenient application to rails on which it is designed to be used. It is made of aluminum, thin brass, and wood, is very light, and is made with a detachable handle so that it can be taken down and packed in a small space. This rail spanner has been found light and convenient enough so that one observer can handle it and an indicating voltmeter and get rapid and accurate results.

Where a recorder is to be used for taking measurements during a period of considerable length, swedged connections should be used. The data concerning the resistance of the rail or other conductor can be obtained by an electrical calibration at each point, or by a calculation from the cross section and specific resistance of such conductors. The latter is much more convenient, is accurate enough for most practical purposes, and is quite generally used. Where high accuracy is sought, however, a calibration is necessary and various methods for making calibration are described below.

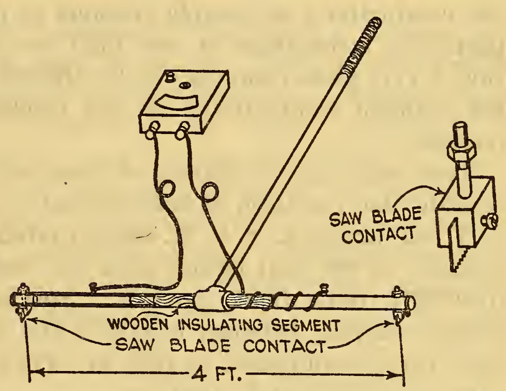

FIG. 5.—*Rail spanner for measuring voltage drop on short length of rail*

(3) CALCULATION OF CURRENT FROM VOLTAGE READINGS.—In the case of copper cables the cross section and resistivity are known so accurately that a calculation based on these data is sufficient for all purposes of electrolysis surveys. The formula for calculating the current is as follows:

$$I=\frac{EA}{10.4\ L\times 10^3}(1-0.0039\ (t-20)) \qquad (1)$$

where I is the current in amperes, E the potential drop in millivolts along a length, L, of the cable, measured in feet, A is the cross section in circular mils, and t is the cable temperature in degrees centigrade.

For ordinary practical work, except where cable temperatures are well above 40° C., the simpler formula

$$I=\frac{EA}{11\ L\times 10^3} \qquad (2)$$

meets all requirements. This value would generally be correct within a few per cent, since all the factors entering into the calculation are known or can be measured with an accuracy of at least 1 per cent. If the cable carries sufficient load to make it perceptibly hot and a high accuracy is desired, an allowance must be made for temperature coefficient of copper. When rails are the conductors, neither the cross section nor the resistivity are so accurately known as in the case of copper, since rails vary widely in weight, composition, and heat treatment. The composition and heat treatment of steels affect resistivity so decidedly that variations of from 9 to 20 microhms-centimeter[1] occur. Modern practice is tending toward greater uniformity of carbon and manganese content and also toward harder steel with higher resistivity. It is desirable, where convenient, that the conductivity of sample sections of rail be determined for each particular installation in case high accuracy is desired. In lieu of this, a very close estimate can be arrived at from the composition or the nominal conductivity for the product as given by the manufacturer.

Tests made by the Bureau of Standards on a number of rails show considerable variation in both resistance and weight. One specimen of T rail having A. S. C. E. section rated at 80 pounds per yard was actually 15 per cent lighter than this weight, and its resistivity was 0.0002975 ohm (foot, pound).[2] Specimens of rail having resistivities varying between 0.000275 and 0.00035 ohm (foot, pound) have been encountered in rails in service, but they represent rather extreme and unusual variations.

If the value of 0.0003 ohm (foot, pound) (which corresponds roughly to ten times the resistivity of copper) is used, the results can, in most cases, be depended upon to within 10 per cent, which is usually close enough when we consider the highly variable character of the quantities to be measured. As an example of a method of calculation using the values of the various quantities in terms of the units commonly obtained in observation, we take the following case: If the potential drop in the rail is E millivolts per foot, and the weight of the rail is W pounds per yard, the current I, in amperes, in the rail, will be given by the equation

$$I = 1.1\ E\ W$$

(c) MEASUREMENT OF CURRENT IN PIPES AND CABLE SHEATHS

(1) Purpose.—Measurements of current flow in pipes are frequently desirable for a number of reasons. Heavy currents set up high-potential gradients in the pipes, and thereby tend to produce

[1] This is the resistance of a piece of metal having a cross section of 1 square centimeter and a length of 1 centimeter.

[2] This is the resistance of a piece of metal of uniform cross section 1 foot long weighing 1 pound.

large potential differences between neighboring pipe systems, causing the one of higher potential to discharge current into the earth and onto the one of lower potential, resulting in injury to the former. Further, when heavy currents are flowing in a pipe there arises a certain amount of danger from arcing at points where pipes are opened for any reason, unless precautions are taken to provide a suitable shunt around the joint prior to opening it. This is true particularly in case of gas or oil pipes where an arc might give rise to fire or explosion. There is also the danger of arcing between two pipes of different potential when they make momentary mechanical contact. In rare cases small service connections have been overheated by current flowing in them. Where high-resistance joints occur in the pipe, the danger of corrosion on such joints is increased by heavy currents.

To guard against the above-mentioned conditions it is important to keep the current flow in pipes at as low a value as practicable; hence, the importance of making, in many instances, current measurements on buried pipes. Furthermore, the relative magnitude of current flow on pipe systems at given points, both before and after the installation of electrolysis mitigative measures on the railway system, offers a valuable index of the relative improvement in conditions resulting from the application of the mitigative measures. This is the most valuable use of current measurements on underground structures. Such measurements may also be used in many cases for determining the source of stray currents. The recording meter measuring the current flow in a pipe at the same time that another recorder measures the railway load supplying the district in which the pipe collects current will often afford through a similarity of records definite evidence regarding the source of stray current. Such measurements are particularly useful where two or more railway lines operate in the same vicinity.

(2) Selection of Points of Measurement.—It is important in making current measurements to select carefully the points at which measurements are to be made. Points of representative as well as of maximum current flow are usually desired in making observations, and since the tests are rather expensive, requiring excavations, a careful selection of locations is necessary. Other things being equal, the maximum current in pipe networks is to be found in mains which run in a general direction parallel to the earth gradients and particularly in or near neutral areas.

Pipes near drainage connections, regardless of potential difference conditions, and large mains which serve as interconnections between more or less extensive networks of pipe, may be expected to carry very heavy currents. In every case a careful study should be made of the pipe and cable networks and of their relation to the railway return system and railway load, and experienced judgment is the only satisfactory guide.

(3) METHODS OF MEASURING CURRENT FLOW.—Three general classes of methods for measuring current flow in pipes and other metallic structures have been used. The first of these, and the one used in a great majority of cases, is the ordinary drop-of-potential method. In this method the millivolt drop is taken on a measured length of pipe free from joints, and the current is calculated from the millivolt drop and the calculated resistance of that portion of pipe over which the potential drop is measured. The resistance per unit length and some other data regarding the common sizes of pipes used in practice, are given in Table 1.

TABLE 1.—*Resistance and current data for pipes*

CAST-IRON PIPE

Nominal inside diameter (inches)	Weight (pounds per foot)	Resistance (microhms per foot)	Current for 1 millivolt on 1 foot (amperes)	Weight (pounds per foot)	Resistance (microhms per foot)	Current for 1 millvolt on 1 foot (ampers)
	A. W. W. A. standard, class A			A. W. W. A. standard, class B		
3	13.04	94.0	10.6	14.6	84.0	11.9
4	18.03	68.0	14.7	20.06	61.0	16.4
6	27.90	44.0	22.7	31.14	39.4	25.4
8	38.74	31.7	31.6	42.68	28.8	34.8
10	51.95	23.6	42.3	58.80	20.9	47.9
12	66.90	18.3	55.0	76.44	16.1	62.0
14	82.33	14.9	67.0	94.82	12.9	77.0
16	98.75	12.4	81.0	114.7	10.7	94.0
18	118.1	10.4	96.0	137.7	8.9	112.0
20	137.2	8.9	112.0	163.2	7.5	133.0
24	186.5	6.5	152.0	217.1	5.7	177.0
30	265.1	4.63	216.0	312.6	3.93	255.0
36	357.8	3.43	292.0	419.0	2.93	342.0
42	465.6	2.64	379.0	541.5	2.27	441.0
48	607.7	2.02	495.0	688.5	1.78	560.0
54	730.2	1.68	600.0	842.8	1.46	690.0
60	835.6	1.47	680.0	1012.0	1.21	820 0
72	1169.0	1.05	950.0	1416.0	.87	1150.0
84	1441.0	.85	1170.0	1860.0	.66	1520.0
	A. W. W. A. standard, class C			A. W. W. A. standard, class D		
3	15.47	79.0	12.6	16.37	75.0	13.3
4	21.27	58.0	17.3	22.83	54.0	18.6
6	32.93	37.3	26.8	35.30	34.8	28.8
8	47.97	25.6	39.1	51.16	24.0	41.7
10	65.66	18.7	54.0	71.54	17.2	58.0
12	85.26	14.4	70.0	93.59	13.1	76.0
14	108.0	11.4	88.0	119.1	10.3	97.0
16	133.3	9.2	109.0	147.5	8.3	120.0
18	162.4	7.6	132.0	178.4	6.9	145.0
20	190.9	6.4	156.0	212.4	5.8	173.0
24	257.7	4.76	210.0	286.2	4.29	233.0
30	367.5	3.34	300.0	421.4	2.91	343.0
36	499.8	2.46	407.0	580.7	2.11	473.0
42	656.6	1.87	540.0	762.0	1.61	620.0
48	833.0	1.47	680.0	960.4	1.28	780.0
54	1041.0	1.18	850.0	1227.0	1.0	1000.0
60	1220.0	1.01	990.0	1458.0	.84	1190.0
72	1744.0	.70	1420.0			

TABLE 1.—*Resistance and current data for pipes*—Continued

CAST-IRON PIPE—Continued

Nominal inside diameter (inches)	Weight (pounds per foot)	Resistance (microhms per foot)	Current for 1 millivolt on 1 foot (amperes)	Weight (pounds per foot)	Resistance (microhms per foot)	Current for 1 millivolt on 1 foot (ampers)
	New England W. W. A. standard,[1] class A			New England W. W. A. standard,[1] class B		
4	14.89	82.0	12.1			
6	24.32	50.0	19.8			
8	35.58	34.5	29.0			
10	49.04	25.0	40.0	52.03	23.6	42.4
12	61.14	20.1	50.0	65.92	18.6	54.0
14	76.85	15.9	63.0	82.41	14.9	67.0
16	90.98	13.5	74.0	98.95	12.4	81.0
18	104.5	11.7	85.0	115.2	10.6	94.0
20	121.9	10.1	99.0	133.7	9.2	109.0
24	155.6	7.9	127.0	174.4	7.0	142.0
30	215.3	5.7	176.0	244.8	5.0	200.0
36	287.0	4.27	234.0	326.0	3.76	266.0
42	368.4	3.33	300.0	422.1	2.91	344.0
48	459.3	2.67	374.0	350.2	2.31	432.0
54	559.8	2.19	456.0	650.3	1.89	530.0
60	664.0	1.85	540.0	782.3	1.57	640.0
	New England W. W. A. standard,[1] class C			New England W. W. A. standard,[1] class D		
4	15.7	78.0	12.8			
6	26.72	45.9	21.8			
8	40.38	30.4	32.9			
10	54.99	22.3	44.8	57.94	21.2	47.2
12	70.67	17.4	58.0	75.39	16.3	61.0
14	87.97	14.0	72.0	94.85	12.9	77.0
16	106.9	11.5	87.0	114.8	10.7	93.0
18	127.4	9.6	104.0	138.0	8.9	112.0
20	147.6	8.3	120.0	161.4	7.6	132.0
24	196.3	6.2	160.0	215.3	5.7	175.0
30	277.7	4.42	226.0	307.3	3.99	250.0
36	373.3	3.29	304.0	412.3	2.97	336.0
42	481.1	2.55	392.0	538.9	2.28	439.0
48	608.0	2.02	495.0	678.9	1.81	550.0
54	749.5	1.64	610.0	839.9	1.46	680.0
60	911.5	1.35	740.0	1029.7	1.19	840.0
	A. G. I. standard gas					
4	17.3	71.0	14.1			
6	27.3	45.0	22.2			
8	38.0	32.3	30.9			
10	51.0	24.1	41.5			
12	67.0	18.3	55.0			
16	102.0	12.0	83.0			
20	139.0	8.8	113.0			
24	186.0	6.6	152.0			
30	256.0	4.79	209.0			
36	346.0	3.55	282.0			
42	453.0	2.71	369.0			
48	610.0	2.02	495.0			

[1] Resistivity=1227. Michroms (pound-foot.)

TABLE 1.—*Resistance and current data for pipes*—Continued

STEEL PIPE [1]

Nominal inside diameter (inches)	Weight (pounds per foot)	Resistance (microhms per foot)	Current for 1 millivolt on 1 foot (amperes)	Weight (pounds per foot)	Resistance (microhms per foot)	Current for 1 millivolt on 1 foot (ampers)
	Standard			Extra strong		
0.125	0.24	900.0	1.11	0.31	700.0	1.44
0.25	.42	510.0	1.95	.54	400.0	2.50
0.375	.57	379.0	2.64	.74	292.0	3.43
0.50	.85	254.0	3.94	1.09	198.0	5.0
0.75	1.13	191.0	5.2	1.47	147.0	6.8
1	1.68	129.0	7.8	2.17	100.0	10.1
1.25	2.27	95.0	10.5	3.00	72.0	13.9
1.50	2.72	79.0	12.6	3.63	60.0	16.8
2	3.65	59.0	16.9	5.02	43.0	23.3
2.50	5.79	37.3	26.8	7.66	28.2	35.5
3	7.58	28.5	35.1	10.25	21.1	47.5
3.50	9.11	23.7	42.2	12.51	17.3	58.0
4	10.79	20.0	50.0	14.98	14.4	69.0
4.50	12.54	17.2	58.0	17.61	12.3	82.0
5	14.62	14.8	68.0	20.78	10.4	96.0
6	18.97	11.4	88.0	28.57	7.6	132.0
7	23.54	9.2	109.0	38.05	5.7	176.0
8	24.70	8.7	114.0	43.39	4.98	201.0
8	28.55	7.6	132.0			
9	33.91	6.4	157.0	48.73	4.43	226.0
10	31.20	6.9	145.0	54.74	3.94	254.0
10	34.24	6.3	159.0			
10	40.48	5.3	188.0			
11	45.56	4.74	211.0	60.08	3.59	278.0
12	43.77	4.93	203.0	65.42	3.30	303.0
12	49.56	4.36	230.0			
13	54.57	3.96	253.0	72.09	3.00	334.0
14	58.57	3.69	271.0	77.43	2.79	359.0
15	62.58	3.45	290.0	82.77	2.61	383.0

WROUGHT-IRON PIPE [2]

0.125	0.24	870.0	1.15	0.29	720.0	1.39
0.25	.42	498.0	2.01	.54	387.0	2.58
0.375	.56	374.0	2.68	.74	283.0	3.54
0.50	.84	249.0	4.02	1.09	192.0	5.2
0.75	1.12	187.0	5.4	1.39	150.0	6.6
1.0	1.67	125.0	8.0	2.17	96.0	10.4
1.25	2.25	93.0	10.8	3.00	70.0	14.3
1.50	2.69	78.0	12.9	3.63	58.0	17.4
2.0	3.66	57.0	17.5	5.02	41.7	24.0
2.50	5.77	36.3	27.6	7.67	27.3	36.7
3.0	7.54	27.8	36.0	10.25	20.4	49.0
3.50	9.05	23.1	43.3	12.47	16.8	60.0
4.0	10.72	19.5	51.0	14.97	14.0	72.0
4.50	12.49	16.8	60.0	18.22	11.5	87.0
5.0	14.56	14.4	70.0	20.54	10.2	98.0
6.0	18.76	11.2	90.0	28.58	7.3	137.0
7.0	23.41	8.9	112.0	37.67	5.6	180.0
8.0	25.00	8.4	120.0	43.00	4.87	206.0
8.0	28.34	7.4	136.0			
9.0	33.70	6.2	161.0	48.73	4.29	233.0
10.0	32.00	6.5	153.0			
10.0	35.00	6.0	167.0			
10.0	40.00	5.2	191.0	54.74	3.82	262.0
11.0	45.00	4.70	215.0	60.08	3.48	287.0
12.0	45.00	4.70	215.0			
12.0	49.00	4.27	234.0	65.42	3.20	313.0

[1] National Tube Co. tables, 1913. Resistivity=215.8 microhms (pound-foot).
[2] Byers' table weights. Resistivity=209.3 microhms (pound-foot).

TABLE 1.—*Resistance and current data for pipes*—Continued

LEAD PIPE

Specimen No.	Card diameter (inches)	Card weight (pounds per foot)	Resistance (microhms per foot)	Current for 1 mv drop per foot (amperes)
1	0.25	0.5	1093.0	0.915
2	.25	.5	1101.0	.908
3	.25	.5	1062.0	.942
4	.75 (AA)	3.5	137.8	7.257
5	.75 (AA)	3.5	136.4	7.332
6	.75 (AA)	3.5	136.9	7.305
7	.75 (AA)	3.5	140.4	7.123
8	.75 (AA)	3.5	139.9	7.148
9	.75 (AA)	3.5	141.5	7.067
10	1.00 (C)	2.5	203.5	4.914
11	1.00 (C)	2.5	203.2	4.921
12	1.00 (C)	2.5	201.7	4.958
13	1.00 (AA)	4.75	102.2	9.785
14	1.00 (AA)	4.75	101.7	9.833
15	1.00 (AA)	4.75	102.4	9.766
16	2.00 (C)	6.0	84.70	11.81
17	2.00 (C)	6.0	85.09	11.78
18	2.00 (C)	6.0	84.94	11.77
19	2.00 (AA)	9.0	55.13	18.14
20	2.00 (AA)	9.0	55.21	18.11
21	2.00 (AA)	9.0	55.23	18.11
22	.25	.5	1093.0	.915
23	.25	.5	1095.0	.913
24	.25	.5	1093.0	.915
25	.75 (C)	1.75	302.8	3.302
26	.75 (C)	1.75	299.1	3.343
27	.75 (C)	1.75	301.0	3.322

A second class of methods comprises all those in which an auxiliary circuit is used to shunt out any or all portions of current in a section of pipe on which the millivolt drop is being measured, the current shunted out being measured by an ammeter and its percentage of the total current determined from the percentage change in the millivolt reading on the section from which the current is shunted. These methods have taken various forms and are described later under "Divided-circuit methods."

A third method consists of what is known as the direct-current ratio relay, used in a manner somewhat analogous to a current transformer in alternating-current measurements. These last two methods are sometimes recommended for calibrating a section of pipe so as to eliminate in some measure the uncertainties arising from the use of tables of resistance. They are desirable, however, only in exceptional cases. As a rule, these methods are more cumbersome and expensive than is warranted. These different methods of measuring current flow on pipes are described in detail below.

(*a*) *Drop-of-potential method.*—This method, which, as stated above, consists merely in connecting potential terminals to a section of pipe a few feet apart, measuring the millivolt drop, calculating the current from the voltage drop and the resistance of the section as determined from the accompanying tables, is very widely used and is accurate enough for most purposes. Its great simplicity especially adapts it to work of this kind. The accuracy of the method depends chiefly on the character of current flow and a knowledge of the resistance of the pipe. The data collected in the preparation of the accompanying pipe tables show that the resistance of a pipe can practically always be depended upon to be within 10 per cent of the value given in the table, and usually closer than this. Further, the currents usually found on underground pipes fluctuate between very wide limits so that when readings are taken with an indicating instrument it is usually quite impossible to determine the average value of the readings with an accuracy as good as 10 per cent. Even with a recording instrument, an accuracy as good as 10 per cent is rather difficult to obtain, particularly where a 24-hour record on an ordinary circular chart is used. It is evident, therefore, that it is hardly worth while in most cases to use a more complicated method in order to eliminate the possible error involved in calculating the resistance of a pipe when errors from other sources are likely to be even larger.

The working tables to which reference must be made for reducing the millivolt reading to amperes contain the nominal size of the pipe, the weight in pounds per foot, the resistance in microhms per foot of length, and the current corresponding to 1 millivolt drop on 1 foot of length. In using these tables it is necessary to take the millivolt drop E, on a portion of the pipe of length L, in feet, and then refer to the last column of the table under the particular kind and class of pipe used, and multiply the figure there found by the ratio of the observed voltage to the length, in feet. For example, suppose we are measuring the current flow in a 10-inch cast-iron pipe of class B, New England Water Works Association Standard. Referring to Table 1, it will be seen that for this class a current corresponding to 1 millivolt drop on 1 foot is 42.4 amperes. If we are measuring over a length of say 8 feet, and the observed potential drop is 3 millivolts, the current flow is the pipe will be

$$I = 42.4 \times 3/8 = 15.9 \text{ amperes}$$

In using this method it is necessary, first, to make an excavation at the point where the measurements are to be taken, and attach two leads to the pipe, preferably as far apart as practicable, without including a joint in the pipe. These connections can be made in any one of a variety of ways, such as by drilling a hole in the pipe and screwing in a plug to which a wire has been soldered. This is all right for a thick-walled pipe, especially cast iron. For thin-walled pipe, however, it has been the practice of the Bureau of Standards to use a swedged connection. Brazed or welded connections are satisfactory. Clamp connections a reliable to develop high resistance due to corrosion. If it is desired to use these connections for future measurements the leads should be brought underground to a point inside the curb and there terminated in an ordinary service box or other suitable receptacle so that they will be protected from traffic but be readily accessible for repeating the measurements at any future time. If it is desired to use these leads for making measurements over a period of several months or longer, it is important to protect the junctions between the wires and the pipes from corrosion by painting them over with a heavy asphalt paint or other waterproof coating. The observation of potential can best be made with a millivoltmeter of high sensitivity. A zero-center instrument having a range of 5 millivolts on either side of the zero is usually sufficient where the current density in the pipes is relatively high. In many cases, however, where the current is small and the pipe relatively large, and especially in the case of wrought-iron or steel mains, in which the resistivity of the pipe is low, a higher sensitivity instrument is often necessary. In such cases a portable galvanometer may be used. Where the currents are large enough to give a reading of 1 millivolt or more over the section spanned by the potential terminals, an ordinary recording instrument can be used.

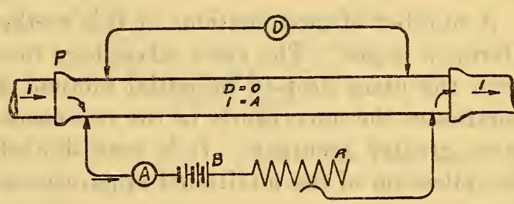

FIG. 6.—*Divided circuit method of measuring current in pipes*

I, Direction of current; *a*, ammeter; *b*, batteries; *d*, galvanometer; *p*, pipe; *r*, variable resistance

(*b*) *Divided-circuit methods.*—Divided-circuit methods in various forms have been used by a number of investigators for many years. Probably the first to use them was Professor Adams, of Columbus, Ohio, more than 25 years ago, and they have been used by a number of other investigators. Credit for having published a detailed description of the applications of various forms of the method and the procedure for the measurement of currents by it is due to Dr. Carl Hering.[3] The following description of the principle of the method is taken from Doctor Hering's paper:

The fundamental principle is as follows: Let *P*, Figure 6, be a part of an underground pipe which has been uncovered and through which an unknown current, *I*, is flowing, as shown. At first let it be supposed that this current is steady and, of course, a direct current. Let *D* be a sensitive galvanometer, millivoltmeter, or any other form of detector of small difference of potential, connected as shown; there should preferably be no variable resistance like an unbonded pipe joint between the two contact points. Let *A* be an ammeter, *B* a few cells of accumulators, and *R* an adjustable resistance; the shunt circuit

[3] Transactions of the American Institute of Electrical Engineers, 31, p. 1449; 1912.

containing them is connected, as shown. anywhere outside of the points of application of the voltage detector, the farther away the better—they may even be on the other side of a joint.

To find the current flowing in the pipe adjust the resistance *R* until *D* reads zero; then there will no longer be any current flowing in the shunted part of the pipe, hence the reading of the ammeter will give the current, *I*, in the pipe. The current may be said to have been sucked out of the pipe by the battery and made to flow through the ammeter where it can be measured; as far as the current in that short section is concerned the pipe circuit has, in effect, been electrically cut in two as though an insulating joint had been introduced.

If *D* is a galvanometer with proportionate deflections, instead of a mere detector, then by taking a deflection immediately after the shunt circuit has been opened, a reading proportionate to the drop of voltage for that current will be obtained. The instrument, *D*, is thereby calibrated to read the pipe currents directly and can be used for this purpose thereafter; the test with the battery current is, therefore, merely of the nature of a preliminary calibration and need be carried out only once for each station.

A number of modifications of this method are described in Doctor Hering's paper. The chief advantage for this method, as compared with the plain drop-of potential method described above, is that it eliminates the uncertainty of the resistance of the pipe, and therefore gives greater accuracy. It is very doubtful, however, whether the complication of the additional apparatus is justified except in special cases.

As previously stated, the resistance of the pipe can be determined from the tables with an accuracy of about 10 per cent, and the extremely variable current that is usually found on pipes can hardly be averaged with greater precision than this. Moreover, since the millivolt drop being measured in any practical case is usually very small (generally less than 1 millivolt) quite appreciable errors may be introduced by thermoelectromotive forces in the millivoltmeter circuit itself.

A difference of 3 or 4° in the temperature of the junctions would produce errors amounting to several per cent or larger, and this difference might readily occur, especially in gas pipes when they are excavated and one terminal is more or less damp and others relatively dry. Further, the temperature coefficient of iron pipe, particularly wrought iron or low-carbon steel, is very high, and seasonal changes in temperature of the pipe will produce variations of 5 to 10 per cent in the resistance. It appears, therefore, that accurate calibration of the pipe is very rarely justified in view of the complications of the apparatus required for this purpose.

(*c*) *Direct-current ratio relay.*—The direct-current ratio relay has sometimes been employed for measuring current in conductors which can not be opened for the insertion of ammeters or shunts. The ratio relay permits the measurement of variable continuous currents of relatively large magnitude by means of a small capacity d. c. ammeter.

This instrument was developed by Otto H. Knopp.[4] In its fundamental principle of operation the relay consists of a split iron ring (*r*) shown in Figure 7, which is slipped over the conductor (*C*), the current in which is to be measured. The iron ring need not be laminated. It carries a secondary winding (*W*), consisting of a large number of turns of fine wire in series with a low voltage battery (*B*), a variable resistance (*R*), and a direct-current ammeter (*A*). In the gap between the poles of the split ring is placed a small magnet (*M*). Current in the conductor (*C*) sets up a magnetic flux in the iron which may be neutralized by a current in auxiliary winding (*W*), from the battery (*B*). When this neutralization occurs, as indicated by the small magnet, the ampere turns of (*C*) and (*W*) are equal and the current in (*C*) is read on the ammeter (*A*), the reading being multiplied by the ratio of the turns (*W*) to the turns (*C*), which latter, in the case of the pipe, is unity. This ratio relay is manufactured in two forms, in one of which the secondary is made to follow automatically the fluctuations of the current (*C*). In the other form, known as the direct current-line current testing set, the current in the secondary is controlled by the observer.

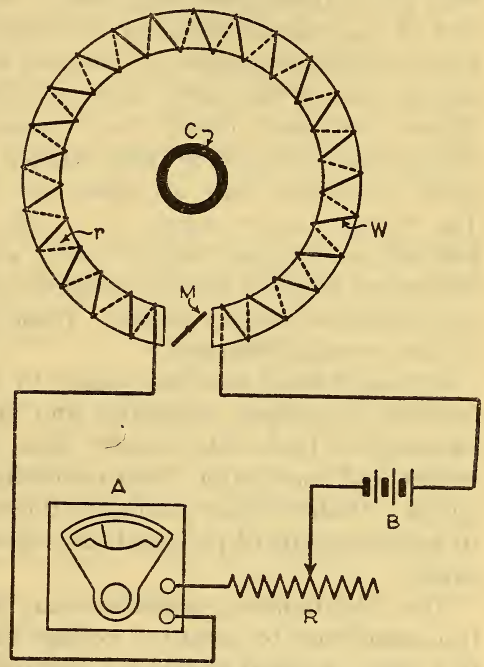

FIG. 7.—*Direct current ratio relay*

A, Ammeter; *B*, battery; *C*, conductor; *M*, magnet; *r*, split ring; *R*, variable resistance; *W*, secondary winding

The automatic instrument is most convenient for the measurement of rapidly fluctuating currents such as are usually found on pipe systems. The nonautomatic instrument is of simpler construction, cheaper, and considerably lighter in weight than the automatic relay, and where only average values of current are desired, which is usually the case, the former would often be preferable. This instrument can be used for making measurements of any value from about 25 amperes upward, although good accuracy even for electrolysis purposes can not be obtained with much less than 50 amperes flowing in the pipe. This greatly limits the field of application of this instrument.

[4] Electrical World, **61**, p. 632; 1913.

III. MEASUREMENT OF EARTH CURRENTS

In the field of electrolysis testing, especially quantitative testing, the greatest difficulty encountered until very recently has been our inability to measure directly the factor responsible for corrosion, namely, the density of current flowing from a pipe to earth at any particular point. In consequence of this it has not been possible, with the methods previously used, to make direct quantitative readings of the rate of corrosion of buried pipes and other structures. Prior to the development of methods for measuring the intensity of current flow in the earth, tests made to determine electrolysis conditions comprised chiefly two classes of measurements, namely, voltage measurements between various structures, and the measurement of current flow on pipes and other subsurface structures. The voltage measurements, as a rule, comprised measurements of over-all potential on railway tracks, and measurements of potential differences between various subsurface structures, and between such structures and railway tracks. These have been described in detail in the preceding chapters.

Attempts have also been made to measure potential differences between subsurface structures and adjacent earth, but with the exception of lead-cable sheaths, these have not yielded satisfactory results and have often been misleading as to the true polarity of a pipe. Under certain conditions this same consideration may apply to measurements of potential differences between cable sheaths and earth.

The chief difficulty about securing information regarding electrolysis conditions by means of voltage measurements grows out of the fact that, as stated above, the electrolytic corrosion at any point is determined directly by the intensity of current discharge from any particular point on the pipe surface. Other factors enter to a greater or less extent, but as shown in another publication of this bureau,[5] under practical conditions of buried pipes, current density is the controlling factor.

A voltage measurement between a pipe and any other structure constitutes only one of three factors affecting current flow, the other two being the resistance of the path traversed by the current through the earth, and the galvanic potentials existing at the surface of contact of the two structures with the earth. Experience has shown that the resistivity of the earth may vary between extremely wide limits, commonly in the ratio of 10 or 20 to 1, and not infrequently as high as 100 to 1, or even higher, due to the character of soil, variations in moisture content, temperature, and other factors. The galvanic potentials in the circuit also vary widely under a variety

[5] B. S. Tech. Paper No. 25, Electrolytic Corrosion of Iron in Soils; 1913.

of conditions. It will be apparent, therefore, that a mere voltage measurement has no reliable quantitative significance in determining the seriousness of electrolysis conditions in any particular locality.

A large amount of data has been accumulated, some of which will be presented later, which shows that such measurements often give erroneous indications as to whether a pipe is discharging or receiving current from the earth. It is not to be inferred, however, that voltage measurements are of no value, since they do have an important qualitative significance, and under certain circumstances, as pointed out in preceding chapters, such measurements can be used to determine relative conditions under different systems of mitigation, provided only a few days or weeks elapse between the two series of tests. They do not, however, permit of any quantitative interpretation.

The galvanic potentials which are always superposed on dynamic voltages that may result from a discharge of current into earth, may often be as large, or larger, than any dynamic voltage, thus entirely obscuring the quantity which it is sought to measure. On account of these galvanic potentials it was not possible to determine by any means heretofore available even the polarity of a pipe with respect to earth. It has been recently pointed out by Dr. Carl Hering that potential differences of considerable magnitude may exist between two adjoining subsurface structures identical in character, due to the polarizing effect of current previously impressed upon them, although there may be no interchange of current whatever between them at the time the tests are made. Experimental data are available which fully support this statement.

The measurement of current flow on pipes, which is very commonly made in connection with electrolysis surveys, may be of value in determining relative conditions under different systems of mitigation, but here again such measurements possess no definite quantitative significance. The amount of deterioration that may be caused by a given current on a pipe depends chiefly on its distribution as it leaves the pipe, and on whether it passes directly from the pipe to earth or leaves through metallic paths. That part of the current which may be removed from the pipe through metallic circuits will produce no corrosion upon leaving the pipe, only that portion of current which discharges directly from the pipe surface into adjoining earth being involved in the corrosive process. Further, even if it is known that all the current on a pipe ultimately leaks directly to earth, the degree of danger depends practically on the distribution of such current discharge, so that a mere measurement of current flow on a pipe at any particular point gives no definite information as to the degree of seriousness of the situation. Furthermore, where pipes are laid in regions in which the earth gradient in a direction transverse to the pipe is relatively high, as is frequently the case where pipes closely parallel other pipes or street-railway tracks, pronounced corrosion due to such transverse currents may occur on one side of the pipe, even though it carries no current at all in a longitudinal direction. A large amount of test data is available showing this fact, some of which will be presented later in this chapter. In consequence of the above-mentioned considerations, the only practical way at present available in which definite quantitative information can be secured, showing the degree of hazard to a pipe at any point, is by measuring the intensity of current discharge from a pipe at the point under consideration.

1. CURRENT-DISCHARGE MEASUREMENTS

Four methods of measuring current discharge from pipes to earth have been proposed, and to some extent used. These are: (*a*) Differential-current method, (*b*) Haber earth current collector, (*c*) polarization-potential method, and (*d*) the earth-current meter.

(a) DIFFERENTIAL-CURRENT METHOD

This method consists essentially in making accurate measurements of the actual current flow in a pipe at two points usually not very far apart. If these measurements are made with sufficient accuracy the difference between them will give the total current leaving the pipe between the two points of measurement. Since, however, it is usually the case that the actual leakage between two such points of measurement is but a very small percentage of the total current flow in a pipe, it will readily be seen that relatively small errors in measuring the flow of current will result in greatly magnified errors in the measurements of leakage current. Consequently, unless the current discharge between the two points is very large extremely high accuracy is required in the measurement of currents. Furthermore, if the measurements are to be of any value as indicating current discharge to earth, it is necessary to know definitely that there are no metallic connections, such as drainage cables, service pipes, or branch mains, attached to the pipes between the two points at which the current flow is measured.

The method of measuring current flow by the simple drop-of-potential method, described in the previous chapter, is by no means accurate enough to be applied to the determination of current discharge between the two points, unless the points are very remote from each other so that a large percentage of the current from the pipe leaks off between the two test stations. Furthermore, the method gives no indication as to the distribution of the leakage current in the region between the test stations. It merely gives the total leakage from which the average discharge per unit area may be estimated. Experience has shown that, as a rule, current discharge is by no means uniformly distributed and it is usually necessary to get some idea as to this distribution. It is sometimes desirable, however, to know this average value of leakage, and when such is the case, this method may be applied. In measuring the current it is necessary to resort to some form of the Hering method, described previously under "Current measurements," whereby the resistance of the pipe may be determined with considerable accuracy. It is also necessary to take precautions to avoid errors due to galvanic effects, temperature changes, and other factors.

(b) HABER EARTH-CURRENT COLLECTOR

The Bureau of Standards has experimented with a number of modified forms of the Haber earth-current collector, with a view to determining its possibilities and limitations for measuring current discharge in the earth. It has been found that the most satisfactory type is that shown in principle in Figure 8. This consists of a glass plate, *1*, placed inside an insulating tube, *2*, at right angles to the axis of the tube, the inside diameter of which is equal to the diameter of the plate. We have found a diameter of about 10 cm. (4 inches) satisfactory. The best results are obtained if the length of the tube is approximately equal to this diameter. It is necessary that the plate, *1*, be sealed in the tube with a thoroughly waterproof seal, *3*, such as pitch, in order that no current can pass the barrier formed by the plate. On either side of the plate there is placed a thin copper plate, *4*, from which insulated leads, *5*, are brought out to connect to a millammeter, *6*. On the outside of the copper plate are placed thin layers of some porous material, *7*, saturated with a strong solution of copper sulphate to prevent polarization. For this purpose several sheets of heavy blotting paper soaked in a saturated sulphate solution will give satisfactory results. Outside of these layers of blotting paper the insulating tube, *2*, is filled with fresh earth taken from the excavation in which the current is to be collected.

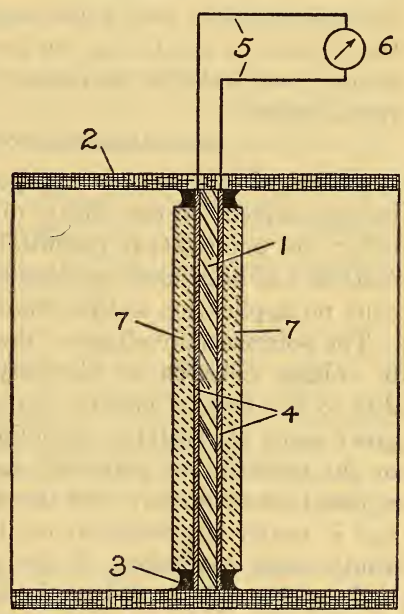

FIG. 8.—*Haber earth current collector*

1, Glass plate; *2*, insulating tube; *3*, pitch seal; *4*, copper plates; *5*, insulated leads; *6*, milliammeter; *7*, plates of porous material

The reason for using this length of tube filled with earth is that if this is omitted the resistance through the collector will be lower, as a rule, than that of the surrounding earth. It will therefore tend to draw more current than would normally flow through the same area. Using an elongated tube filled with earth from the trench in which the measurement is being made reduces this error somewhat, but by no means affords an accurate comparison. It is very important that the earth be packed into the collector as soon as taken from the excavation, when it has a normal moisture content. If it is permitted to dry out a little the resistance will increase enormously, and thus cause the indication to be low. One of the greatest objections to the use of this instrument lies in the fact that it is not possible to measure current flow in undisturbed earth. The making of an excavation and the refilling of the trench result in serious disturbance of local conditions, so that there is no assurance that conditions are the same as they were prior to making the excavation. Because of the difficulties mentioned we have not found the earth-current collector a very reliable instrument, although it may be useful in some special cases.

(c) POLARIZATION POTENTIAL MEASUREMENTS

A method that has been proposed for determining the intensity of leakage current on the surface of a pipe at any point is that of measuring the polarization potential at the surface of the pipe. This method has been used to some extent abroad, but has found practically no application in this country.

The polarization voltage at the surface of an electrode is the change in voltage between an electrolyte and electrode immersed therein due to the flow of electric current to or from the electrode. In a great many electrolytes, including some soils, this change in voltage, or the polarization potential, soon reaches a steady state after the application of current, and the magnitude of the polarization potential is nearly proportional to the intensity of the current flowing. Under such conditions, if the potential difference between a pipe and an electrode buried in the soil adjacent thereto be measured at a time of day when no current is flowing from or to the pipe, and again at a time when there is current flowing to or from the pipe, the sign and magnitude of the change of voltage will give a fair idea as to the intensity of the current discharge at the point under consideration. However, in many electrolytes and in certain soils the polarization potential is not by any means proportional to the intensity of current flowing, so that unless extraordinary care is exercised the results of polarization potential measurements may be decidedly misleading.

Furthermore, since it is usually impracticable to put the earthed electrode immediately adjacent to the pipe surface there will always be a certain amount of resistance drop superposed upon the true polarization potential. Earth resistances are usually quite large, and this resistance drop will, in most cases, be larger than the true polarization potential and will, therefore, usually obscure the latter.

Polarization potential measurements are not to be confused with measurements of potential differences between a pipe and adjacent earth when the electrode is placed a few feet or more from the pipe. The polarization potential results from changes in concentration in the electrolyte adjacent to the pipe surface, whereas potential differences between the pipe and a point in the near-by earth include both the polarization potential proper and the resistance drop through the relatively high-resistance soil.

(d) EARTH-CURRENT METER

This method of measuring current discharge from pipes to earth has proven of great practical importance. It is accordingly treated at some length below.

Engineers engaged in electrolysis research work have long felt the need of some more definite and accurate means of determining both the polarity of pipes with respect to earth and of measuring current density in the earth at any point, especially immediately adjoining pipes under investigation. The need of such an instrument was felt by the research subcommittee of the American Committee on Electrolysis throughout its investigations, and this need was expressed in its 1921 report in the following statement:

> The only accurate criterion of electrolysis damage is the intensity of current flow to earth at any point on the pipe or cable. If an accurate measure of this current flow from the pipe at any point could be made, it would come nearer giving a true indication of electrolysis conditions than any other measurement. At the present time there is no practical means available for making such measurements. The development of a simple, inexpensive, and accurate means for measuring such currents locally constitutes one of the chief needs in the field of electrolysis testing at the present time.

Realizing the vital importance of meeting this requirement, the Bureau of Standards conducted an extensive research into the whole subject of measurement of intensity of current discharge from pipes to earth, this research continuing over a period of several years. This investigation resulted in the development of an instrument known as the earth-current meter, which, although still subject to further development as to details, meets in its present form the essential requirements of a practical instrument for accomplishing this purpose. This instrument has been in practical use by a number of consulting electrolysis engineers, but no attempt has been made to introduce it commercially, pending a thorough demonstration of its true practicability in the hands of a few competent engineers. For this reason it is not well known to the engineering public and, therefore, a detailed description of its principle and mode of operation will be given below. At present the earth-current meter is adapted only to the measurement of current discharge from pipes or other structures embedded directly in the earth. It is not intended for measuring discharge from cables laid in conduit where contact with earth is highly localized. For pipe testing, however, it has proven a very valuable instrument, although because of the difficulties inherent in electrolysis testing it should be used under the direction of an engineer thoroughly experienced in electrolysis investigation.

(1) Theory of Earth-Current Meter.—It will be seen that if a measurement be made of the resistivity of the earth at any particular point without disturbing the earth in which the resistivity is to be measured, and if then a measurement be made of the voltage drop between two points a known distance apart within this same region in which the resistivity has been measured, these two measurements will permit a calculation of the current density in the earth in the region immediately under investigation. The new method described below involves the principle here stated, although in its actual carrying out neither the resistivity of the earth nor the true potential drop between two points need be determined.

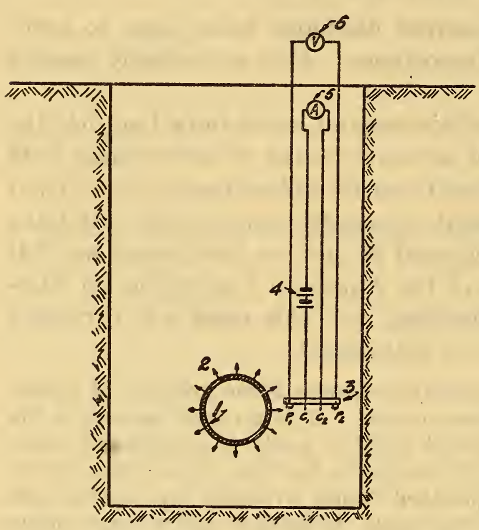

Fig. 9.—*Elementary principle of earth-current meter*

1, pipe; *2*, direction of current; *3*, insulating frame; *4*, battery; *5*, ammeter; *6*, voltmeter; C_1 C_2, current terminals; P_1 P_2, electrodes

The principle of the new method of measuring earth currents can best be understood by reference to Figure 9, which is a diagrammatic illustration of the elements of the apparatus. Let us assume that the pipe, *1*, of Figure 9 is discharging current in all directions as indicated by the arrows, *2*. Four electrodes P_1, C_1, C_2, and P_2 may be pressed against the wall of the trench immediately adjoining the pipe on whatever side the current density is to be measured. An excavation is here assumed tentatively to simplify the explanation of the principle of the method. It will later be shown how the method can be applied in many cases without making extensive excavations. For convenience, these several electrodes may be mounted on a single insulating frame, *3*.[6] Two of the electrodes P_1 and P_2 are connected to a

[6] This assembly of the four electrodes in a fixed relation to each other will hereafter be referred to as a contactor.

suitable voltage indicator, *6*, which need not read in any particular unit.

Suppose now a current I_c be caused to flow between the electrodes C_1 and C_2 through the earth from the battery, *4*, which current will be measured by an ammeter, *5*. It will be evident that this current distributes itself in all directions through the earth and produces a certain voltage drop between the electrodes P_1 and P_2 due to the resistance in the earth immediately surrounding the group of electrodes. This voltage drop between the terminals P_1 and P_2 will be indicated by the voltmeter, *6*, and will be proportional to the current flowing between the electrodes C_1 and C_2, to the resistivity of the surrounding earth, and to a constant depending on the size and arrangement of electrodes. If E_c is the voltage between the terminals P_1 and P_2 and if θ_c is the corresponding deflection of the voltage indicator, *6*, we have

$$\theta_c = K E_c \tag{1}$$

where K is the constant of the voltage indicator, *6*, which includes the effect due to the resistance in the leads and in and near the electrodes P_1 and P_2. This is sometimes an important consideration and will be discussed later. Further, it will be seen that E_c is proportional to the current I_c sent between the electrodes C_1 and C_2 and to the resistivity r of the surrounding earth, or

$$E_c = \frac{I_c r}{A} \tag{2}$$

where A is a constant depending upon the geometrical arrangement of the group of electrodes. Substituting the value of E_c as given by equation (2), in equations (1), we have

$$\theta_c = \frac{K I_c r}{A} \tag{3}$$

in equations (2) and (3) it is assumed that the voltage drop across the electrodes P_1 and P_2 is due solely to the current sent through the electrodes C_1 and C_2. In order that this may be true, conditions must be such that no other current flowing through the earth at the time measurement is made will in any way affect the apparatus. For the present we will assume that this is actually the case. It will be explained later how this is readily realized in practice.

After taking the above measurement of I_c and the corresponding Θ_c, the circuit of the battery, *4*, is opened, after which the voltage drop E_e between the voltage electrodes P_1 and P_2 will be solely due to the current i which is flowing through the earth, or

$$E_e = irL \tag{4}$$

where L is the distance between the electrodes P_1 and P_2, i is the mean current density in the region between the electrodes P_1 and P_2, and r, as above, is the resistivity of the earth.

The corresponding deflection of the instrument, *6*, is Θ_e, and we will then have

$$\Theta_e = KE_e = KirL \tag{5}$$

Dividing equation (3) by equation (5) we have

$$\frac{E_c}{E_e} = \frac{\Theta_c}{\Theta_e} = \frac{KI_c r}{KAirL} = \frac{I_c}{AiL} \tag{6}$$

Solving equation (6) for i, we have

$$i = \frac{I_c \Theta_e}{AL\Theta_c} = \frac{I_c E_e}{ALE_c} \tag{7}$$

As stated above, A is a constant depending upon the geometrical form of the electrode group P_1, C_1, C_2, and P_2. This can be determined once for all for a given contactor by immersing it in a medium, such as water through which a current density of known value is sent. Under these circumstances, if we perform the two measurements indicated above and substitute the values in equation (7) i being in this case known, we can calculate the value of the proportionality factor, $\frac{1}{AL}$. Calling this factor Q, for brevity, we have

$$i = \frac{QI_c\Theta_e}{\Theta_c} = \frac{QI_c E_e}{E_c} \tag{8}$$

In equation (8), i is the current per unit area, or the quantity which is to be measured, and Q is the known constant to be determined once for all by calibration under known conditions.

In brief summary, therefore, to obtain the value of i, we have to perform the two operations. One is to send a known current I_c through the two electrodes C_1 and C_2, and at the same time measure the corresponding deflection Θ_c of the instrument, *6*, this being done in a manner described below, such that the instrument, *6*, will not be affected by any earth current other than that which flows from the battery, *4*, through the electrodes C_1 and C_2. We then disconnect the battery, *4*, and measure the deflection Θ_e of the instrument, *6*, due solely to the earth current i. The three values Θ_c, I_c, and Θ_e are then substituted in equation (8) and the value of i calculated.

As stated above, the deflection of the voltage indicator, *6*, is a function of the resistance in series with its leads, and, therefore, of the resistance of the electrodes P_1 and P_2 and of the earth immediately surrounding them. In practice it is found that this resistance is often very high and quite variable so that the instrument, *6*, may not give a true value of the voltage impressed in the earth between the two electrodes P_1 and P_2. It will be observed, however, from equation (6) that the resistivity r of the earth in the region in which the test is being made and the constant k of the voltage indicator, *6*, disappear from the equation from which the earth current i is calculated. It will be seen, therefore, that in making this measurement, neither the resistivity of the earth nor the true value of the voltage drop between the electrodes P_1 and P_2 need be known. This constitutes one of the important advantages of this method of measuring earth currents.

(2) MEASUREMENT OF EARTH RESISTIVITY.—Equation (2) may be solved for r giving

$$r = A\frac{E_c}{I_c} \tag{9}$$

When the value of A has been determined for a contactor of any given size and form, the resistivity may readily be measured either by itself or as a by-product of the earth-current measurement.

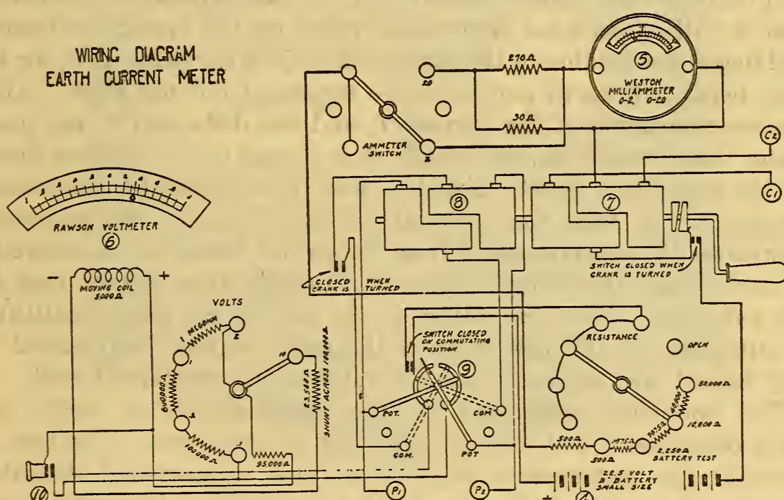

FIG. 10.—*Wiring diagram earth current meter*

4, Battery; *5,* milliammeter; *6,* voltmeter; *7–8,* commutators; *9,* switch; *10,* short-circuiting switch; C_1 C_2, current terminals; P_1 P_2, potential terminals

(3) PRACTICAL EMBODIMENT OF THE PRINCIPLE.—As stated above, in carrying out the first of the two operations described, it is essential that some arrangement be provided whereby the deflection θ_c will be due only to the current I_c which flows through the electrodes C_1 and C_2 and will not be influenced by any earth current already flowing. This can be accomplished in a very simple manner by an arrangement shown in Figure 10, which shows a complete wiring diagram of the test set.

In this arrangement two commutators, *7* and *8*, mounted on the same shaft are employed. These commutators are so mounted that commutation takes place on both at substantially the same instant, and are provided with a crank whereby they may be rotated by hand at a suitable speed. The commutator, *7*, is interposed between the battery, *4*, and the test electrodes C_1 and C_2 while the commutator, *8*, is interposed between the electrodes P_1 and P_2 and the voltage indicator, *6*. The switch, *9*, is in the position shown by the dotted lines during this part of the test. It will be seen that an alternating current flows through the earth from the electrodes C_1 and C_2 and impresses an alternating voltage on the electrodes P_1 and P_2 which are being commutated simultaneously with the current through the leads of C_1 and C_2 and gives rise to a unidirectional voltage on the voltage indicator, *6*. This instrument, being of the direct-current type, will, therefore, give a deflection Θ_c proportional to the current I_c sent through the electrodes C_1 and C_2. At the same time any unidirectional voltage impressed on the electrodes P_1 and P_2 due to a stray earth current will be commutated so frequently that it will exercise no appreciable effect on the voltage indicator, and hence the reading of the latter will be just the same as if, for the time being, the earth current to be measured did not exist. After the measurements of the current I_c and the deflection Θ_c are made under these conditions, the switch, *9*, is turned to the position shown by the solid lines, which, as will be seen from Figure 10, disconnects the battery, *4*, from the terminals C_1 and C_2 and at the same time eliminates the commutator *8* from the circuit between the electrodes P_1 and P_2 and the voltage indicator, *6*, which latter is then read for the value Θ_e. The three values Θ_c, I_c, and Θ_e are then substituted in equation (*8*) and the value of the earth current i calculated in any desired unit, depending on the value of the constant Q used.

The complete equipment for the measurement of earth currents comprises a test set and three sets of contactors. The test set contains the instruments and commutator arrangement described above and also the battery and other essentials. As shown in the diagram, Figure 10, the voltmeter, *6*, is provided with a multirange resistance unit giving full scale ranges from 0.1 to 10.0 volts, while the ammeter, *5*, is provided with two ranges, viz, 2 and 20 milliamperes. These are sufficient for all practical purposes. The complete test set is shown in Figure 11, and three types of contactors are shown in Figure 12. Here, *1*, is a type A or "trench" contactor, *2*, is a type B contactor designed to be placed down in a small hole over a pipe, and, *3*, two separate nonpolarizable electrodes for exploring voltage conditions at various points in the earth where the other two types are not readily applicable. The procedure to be followed in using the test set and the various contactors for the several classes of work to which they are adapted is set forth in detail in another publication[7] of the Bureau of Standards.

[7] B. S. Tech. Paper No. 351; 1927.

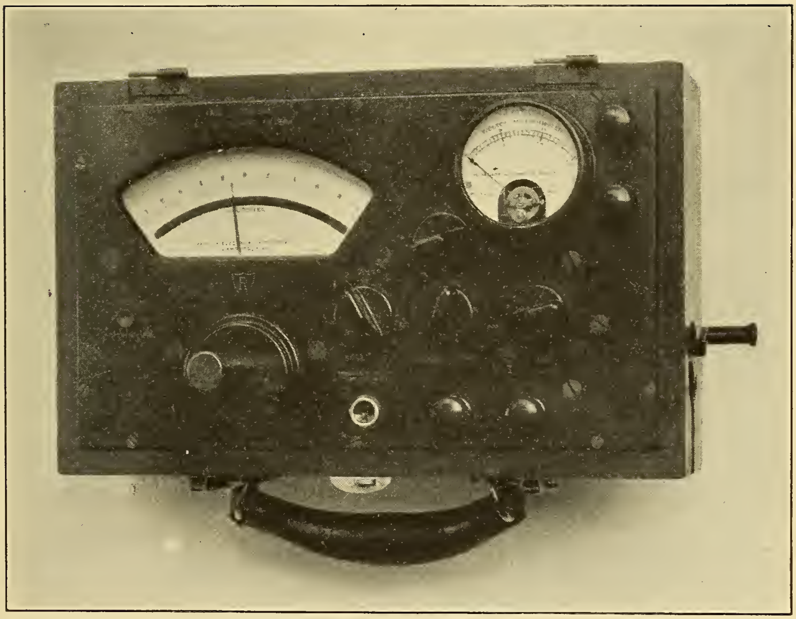

FIG. 11.—*Earth-current meter*

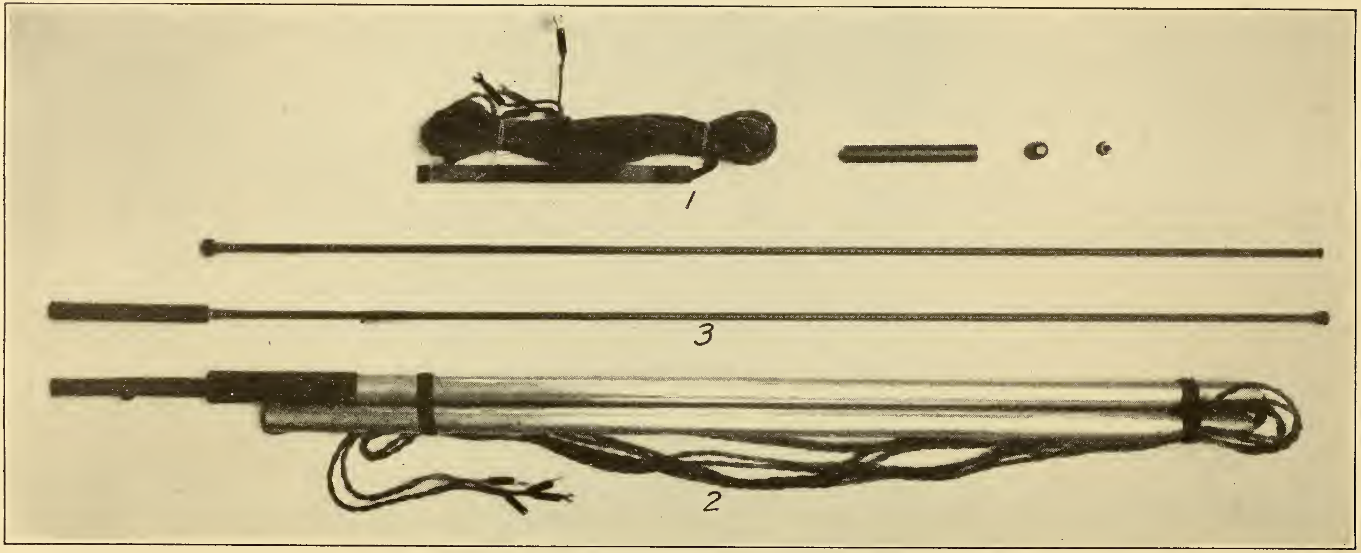

Fig. 12.—*Standard types of contactors*

1, Trench contactor; *2*, cantilever contactor; *3*, nonpolarizable electrode

IV. IMPORTANCE OF EARTH-CURRENT MEASUREMENTS

It has been previously stated in a number of instances that the only accurate criterion of the electrolytic corrosion of any particular pipe is the intensity of current discharge from pipe to earth in any locality. The mere measurement of potential differences between the structure under test and an auxiliary electrode in the earth does not give any indication, even qualitative in character, as to the condition of the pipe with respect to the discharge of current to earth. This is due to a variety of factors, such as varying resistivity of the earth from point to point, varying spacings and relative positions of subsurface structures, presence of galvanic potentials introduced by the auxiliary test electrode, and the biased character of current discharge due to the mutual reaction of adjoining structures.

1. GALVANIC VOLTAGES

The Bureau of Standards has collected a large amount of numerical data showing the galvanic potentials that may be encountered due to two dissimilar metals when buried in the ground. By "dissimilar metals" is meant not necessarily metals that are intended to be unlike in character, since it is often found that two pieces of metal cut from the same pipe, side by side, will show almost as marked potential differences as specimens of wholly unlike material.

It is sufficient here to summarize the data obtained by saying that in the case of tests made on lead cables using lead auxiliary electrodes in contact with soil or water, galvanic voltages as high as 50 to 100 millivolts are quite commonly encountered. In the case of pipe, considerably larger galvanic potentials frequently manifest themselves, values ranging from 0 to 0.3 volt being quite common between two pieces of iron nominally similar in character buried in the same kind of soil. Where differences in earth are superposed, values ranging as high as 0.4 volt may at times be obtained, although values ranging from 0.1 to 0.2 volt may be regarded as a fair average that is most likely to be encountered. In many cases, however, where an auxiliary electrode is placed in filled ground containing cinders or other foreign conducting materials, galvanic voltages materially higher than those mentioned may be obtained. These voltages, as a rule, are due to differences between the pipe under test and the auxiliary electrode, and exist only by virtue of the presence of the auxiliary test electrode, so that when the latter is removed there is nothing left to maintain the condition. Consequently, it does not follow that the pipe is being corroded even though a relatively large potential difference in the ground may have been observed.

Table 2 represents a typical set of voltage readings taken between representative specimens of ordinary pipe materials when placed in an alkali soil. The first column gives the laboratory reference number of the specimens used in combination, the first-named specimens in the combination being anodic. The second column gives the voltage of each combination within a few hours after the specimens were placed in the ground, and the third column gives corresponding voltages after the specimens had been buried almost a month. It will be seen that the values ranged from 0.11 to 0.23 when the specimens were first buried in the soil, and from a minimum of 0.15 to a maximum of 0.27 after they had been buried nearly a month. In general, there is a tendency for the voltage to increase with time in this series of tests. It should be added that this increase is not always observed by any means. The voltages may go either up or down, there apparently being no definite laws governing them. It should be added also that these values are somewhat larger than those observed in nonalkali soils, although as large or even larger values are at times obtained under practically all soil conditions.

TABLE 2.—*Galvanic potentials in alkali soil*

[The first-named specimen in the combination is anodic]

Combinations of specimens	Nov. 28	Dec. 20	Combinations of specimens	Nov. 28	Dec. 20
	Volts	*Volts*		*Volts*	*Volts*
y293–A300	0.230	0.270	Y297–A300	0.200	0.235
M293–A300	.210	.275	d297–A300	.190	.260
e296–A300	.210	.235	D294–A300	.220	.260
X295–A300	.140	.210	L286–A300	.112	.150
e296–A300	.130	.225			

2. RESISTIVITY EFFECTS

The resistivity of the earth varies enormously with the character of the soil, moisture content, temperature, and other effects. In Technologic Paper No. 25 of the Bureau of Standards entitled "Electrolytic Corrosion of Iron in Soils" it is shown that the resistivity of a given soil may vary in the ratio of 100 to 1, or more, with temperature changes varying from a few degrees above freezing to ordinary summer soil temperatures. In that paper it is also shown that the resistivity may vary several hundredfold with variations of moisture content usually encountered in the earth in different seasons. Obviously, with a given potential difference between a buried pipe and an adjoining structure, the current resulting therefrom will be subject to as much uncertainty as the resistivity, and consequently such a voltage measurement will not give even the roughest approximation to an indication of the amount of current that is passing between the structures on which potential-difference measurements are made.

This uncertainty as to resistivity is further accentuated by variations of spacings and relative positions of pipes and pipe networks in cities. Even if the resistivity of the soil were known, the actual resistance between two pipes at any point will vary greatly with distance and relative position. Pipes paralleling each other at a distance of 15 or 20 feet would not suffer as much interchange of current per unit area as those which approach each other within a foot or two, as at crossings and elsewhere. In view of the foregoing uncertainties, it is futile to attempt to attach any quantitative significance whatever to potential difference measurements, it being necessary to resort to actual measurement of intensity of current discharge from pipes to earth if an approximate idea of the rate of corrosion at any point is to be obtained.

TABLE 3.—*Relation of potential difference to leakage currents*

Potential difference, pipe-to-rail	Earth currents, extreme values	Ratio of earth current to potential difference	
		Maximum	Minimum
+0.77	+7.1 to −4.1	+9.2	−5.3
−.19	−.6 to −5.1	+25.2	+3.2
+.94	−2.3 to −16.5	−17.6	−2.4
−.78	−1.2 to −4.1	+5.3	+1.5
+.08	−2.1 to −28.5	−365.2	−26.2
+.55	−1.6 to −17.2	−31.2	−2.9
−.23	−.2 to −.6	+2.6	+.9
+1.23	+.8 to +.1	+.6	+.1
+.60	−.4 to −.8	−1.3	−.7
−.22	−.1 to −4.2	+9.1	+.5
+.12	−6.9 to −23.0	−192.0	−57.5
+.52	−.2 to −1.3	−2.5	−.4
−.42	+.2 to −.2	+.5	−.5
−1.29	−2.2 to −13.4	+10.4	+1.7
−1.85	+1.0 to −.9	−.5	+.5
+.59	+4.7 to −.4	+8.0	−.7
+2.70	+63.9 to +27.9	+23.6	+10.3
+.40	+.1 to −2.6	−6.5	+.3
+.66	+.9 to −.2	+1.4	−.3

3. DISCUSSION OF QUANTITATIVE DATA AND POLARITY DETERMINATIONS BASED ON PIPE-TO-RAIL MEASUREMENTS

The uncertainties involved in attempting to draw conclusions from potential-difference measurements are illustrated in Table 3, which gives in parallel columns for a representative group of stations taken at random, potential differences between a pipe and rail, the actual current discharge as obtained by an earth-current meter, and the ratios of the current discharge to the potential-difference measurements. Column 1 gives the potential differences obtained, the positive sign indicating that the pipe was positive to rail. Column 2 gives the earth-current measurements. In these cases the current discharge was taken in eight different directions around the pipe and there are recorded here only minimum and maximum values for the sake of brevity. If one is positive and the other negative, the largest negative numerical value is taken as the minimum, and the maximum positive value as the maximum. Column 3 gives the ratios of the maximum values of earth currents to potential differences and column 4 the ratios of the minimum values of earth currents to potential differences. Where earth-current readings and potential differences are of the same sign the ratios in columns 3 and 4 are marked positive. Where the current discharge is opposite in sign to the potential differences the ratios are recorded as negative; that is, where the ratios are positive the potential-difference measurements were a true indication of the polarity of a pipe, but where they are negative the potential-difference measurements were actually misleading as to pipe polarity. If potential-difference measurements gave any definite indication of pipe polarity a great majority of these ratios would be positive. An examination of the ratios in columns 3 and 4 shows, however, that of the 38 ratios recorded, 18 are negative and 20 positive, indicating that it is merely a matter of chance as to whether potential-difference measurements are consistent with the actual pipe polarity.

Furthermore, if the potential-difference measurements indicated, even roughly, the magnitude of earth-current discharge the ratios in columns 3 and 4 would not only have to be of the same sign but would all be of the same order of magnitude. Actually these ratios vary from less than unity to several hundred, showing that for a given potential difference the intensity of current discharge may vary in the ratio of several hundred to one. This table is representative of a great mass of accumulated data and could be extended indefinitely from experimental data already available. The figures herewith presented, however, are sufficient to illustrate the point repeatedly emphasized in this paper, namely, that potential differences afford no measure of the intensity of current discharge from a pipe to earth, nor even of the polarity of a pipe with respect to earth.

4. UNSYMMETRICAL CURRENT DISCHARGE

In making earth-current measurements to determine the degree of hazard that exists at any point, it is necessary to take into account the nonuniformity of discharge from a pipe. As a rule, a pipe located 15 or 20 feet, or more, from a neighboring structure when buried at a depth below the surface greater than four or five times its diameter will show a symmetrical distribution of current in all directions. If, however, other structures approach nearer to the pipe in question they will, if lower in potential than the pipe, tend to cause a discharge to earth in the direction of the neighboring structures, greater than that in the opposite direction, and if the neighboring structures are higher in potential the reverse may be the case.

This is illustrated very well in Figure 13, which shows earth-current readings taken in the vicinity of a 6-inch main paralleling a street-railway rail on one side and a telephone duct on the other. In the figure the rail is shown at the upper right from the water main and the telephone duct at the lower left. A dotted circle represents the zero line of the polar diagram on which the earth-current measurements are plotted. Negative earth-current readings are plotted inside the dotted circle and distant therefrom in proportion to the magnitude of the readings. Positive values of earth-current readings are plotted outside the circle and at a distance therefrom also proportional to the numerical values of the readings. Here it will be seen that on the side nearest to the rail the current flows toward the pipe, the value in the horizontal direction being 1.4 milliamperes per square foot. In the vertical direction the pipe is discharging current

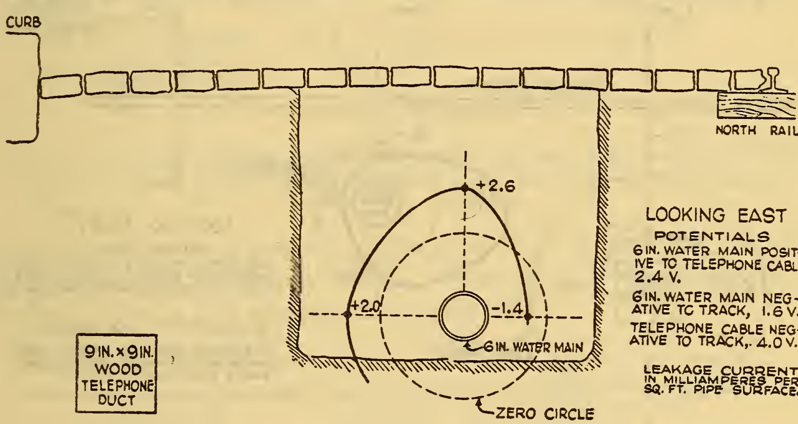

FIG. 13.—*Leakage current distribution around 6-inch C. I. water main showing mutual influence of utilities on one another*

at the rate of 2.6 milliamperes per square foot, and it is also discharging current toward the left in the direction of the telephone duct. It is interesting to note here that the 6-inch water main in question was negative to the railway track by 1.6 volts and positive to the telephone cable by 2.4 volts. In this particular case, therefore, potential-difference measurements between the pipe and both the rail and telephone cable would have given, qualitatively, an indication of the direction of current discharge to or from the pipe in their respective directions. It is clear here that the low potentail of the telephone cables produced a considerable tendency for the water main to discharge current in this direction.

Figure 14 shows a somewhat similar, but more aggravated condition. Here the 6-inch water main is 4 volts negative to the north rail shown at the upper right corner, and 2.6 volts positive to the telephone duct line shown at the left. It will be seen that the current flows toward the water main throughout approximately half of its area on the side next to the rail, the values ranging up to 3.8 milliamperes per square foot. On the opposite side toward the telephone duct the discharge rises to the high value of 9.3 milliamperes per square foot. At the same time measurements taken around the telephone duct show it to be taking current from the earth, the intake being especially heavy on the side next to the water main. These are very good examples of conditions that are the rule rather than the exception in city networks where several utilities occupy the same territory, and they show the very pronounced effect which one utility may exert on its neighbor. They also emphasize the importance of preventing too large a potential dif-

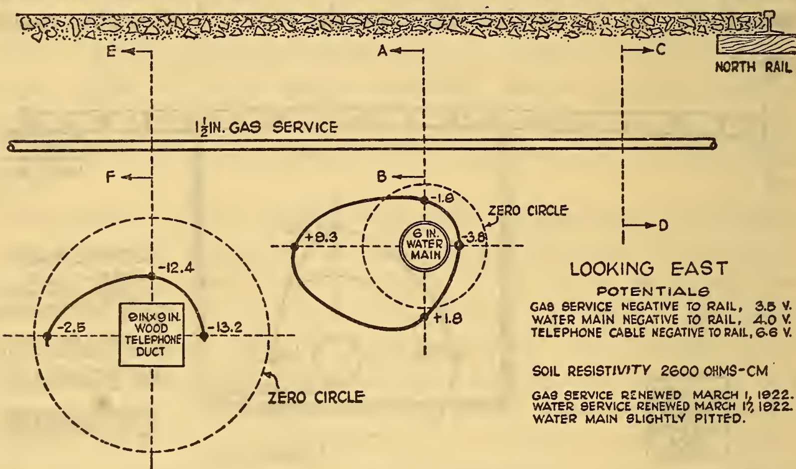

FIG. 14.—*Leakage current distribution around water main and around telephone duct showing influence of the several utilities on one another*

ference from being set up between neighboring utilities, by whatever method they may be caused.

Figure 15 is typical of what happens where a pipe is influenced only by a neighboring rail, there being no other utility in the immediate vicinity. Here it will be seen that the pipe is discharging current in all directions, but the discharge is relatively small on the side opposite the rail and relatively high in the direction of the rail. It is interesting here to note that the pipe was positive to the rail by only 0.1 volt, whereas the intensity of current discharge from the pipe toward the rail was of the order of 5 milliamperes per square foot. Potential differences of 0.1 volt are generally regarded as too small to be of much significance, but experience has shown that 5 milliamperes per square foot are sufficient to cause substantial injury to pipes within a few years.

Figure 16 is another typical case. Here the pipe is only 0.5 volt positive to the rail, a value generally considered quite small. It will be seen that the discharge is very slight on the bottom of the pipe,

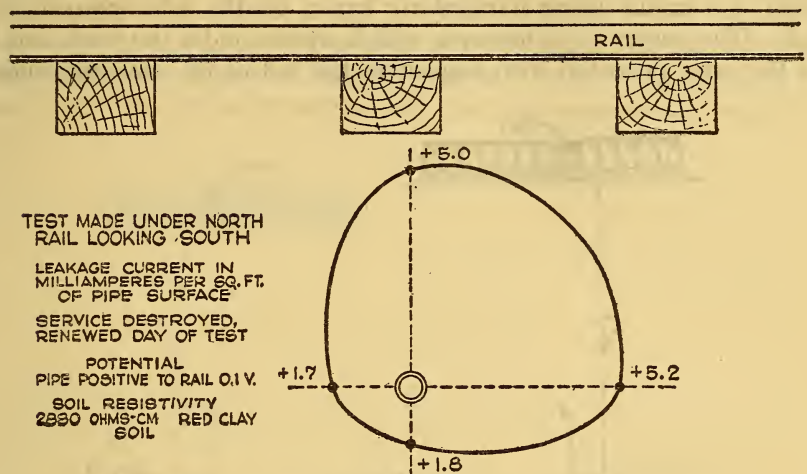

FIG. 15.—*Leakage current distribution around ¾-inch water service, showing case where very small potential difference gives rise to large current discharge from pipe*

but upward in the direction of the pipe there is recorded the very high value of 38.4 milliamperes per square foot, a value sufficient to destroy the pipe in a comparatively short time.

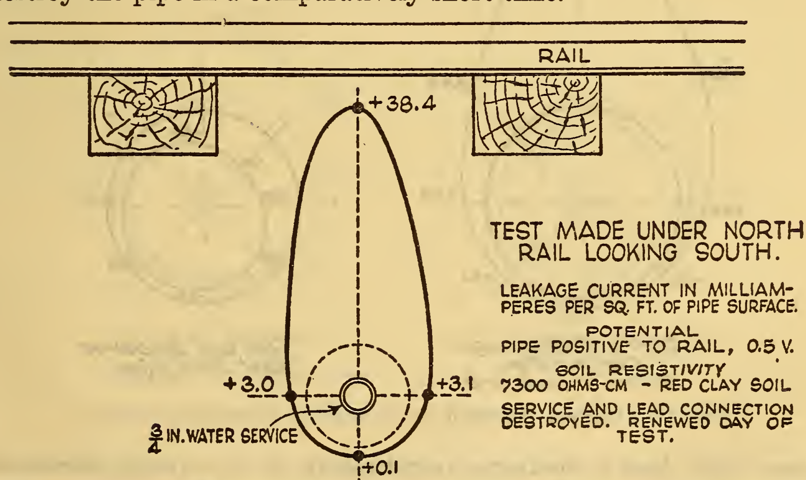

FIG. 16.—*Leakage current distribution around ¾-inch water service crossing under track*

Figure 17 also illustrates a very interesting condition commonly met with. Here the cast-iron main parallels the nearest street railway rail at a distance of about 6 feet, the main and the services in the vicinity being at an average of about 0.9 volt positive to the rail. The polar diagram of earth-current discharge about the cast-iron main shows the pipe to be taking on current from the earth on all sides, the intake being particularly heavy on the side opposite the rail. The service pipe, however, which crosses under the track and is at the same potential with respect to the rail as the cast-iron main,

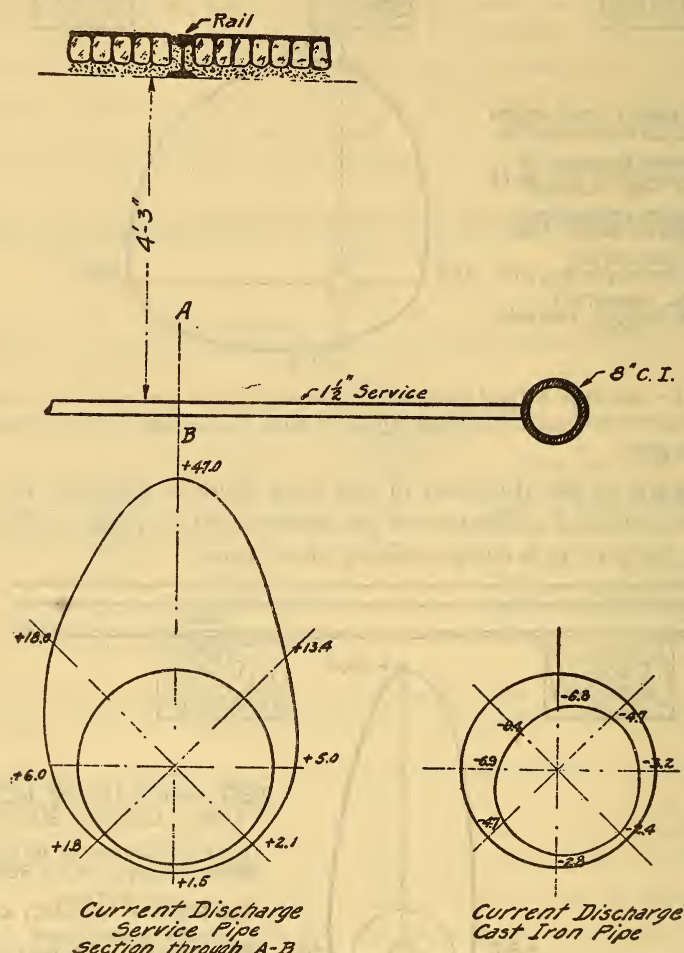

Fig. 17.—*Current discharge from main and connected service*

shows very heavy discharge, particularly in an upward direction toward the tracks. The current discharge around the service pipe was taken at the section A–B directly underneath the rail. The depth of the service pipe was about 4¼ feet below the rail. This illustrates a very common case of a cast-iron main paralleling a track, being itself entirely safe from electrolysis damage because of its negative condition with respect to earth, even though it may be positive to near-by tracks, while at the same time the services connected to this main and crossing under the tracks are being badly corroded.

In Figure 18 is shown a case in which a cast-iron main parallels the tracks in the same way as shown in Figure 17, but in this case both main and service are negative to rails by an average value of about 0.7 volt. Here it will be seen that the main is also negative

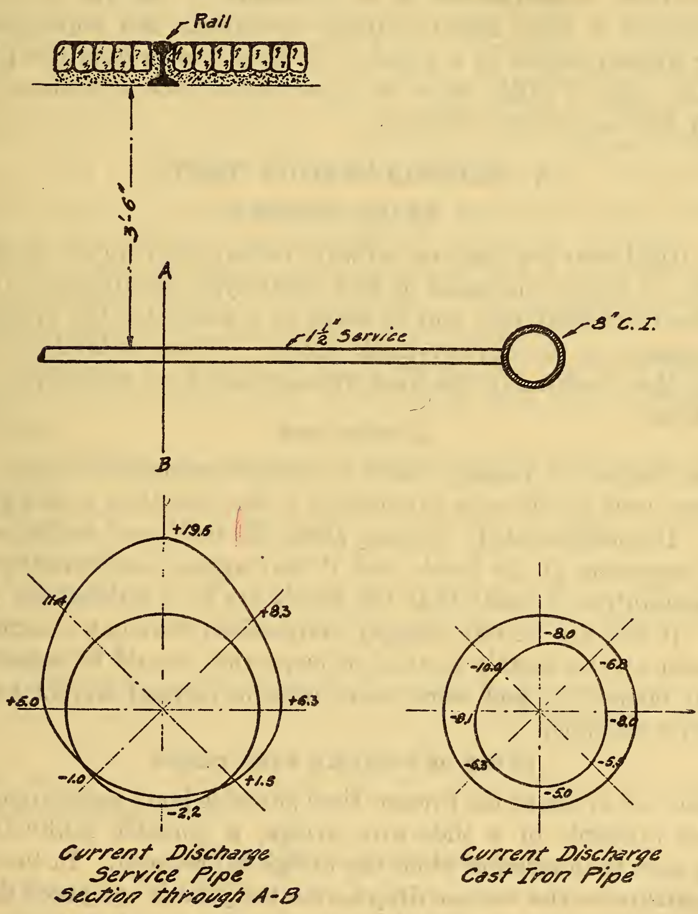

FIG. 18.—*Current discharge from main and connected service*

to the earth, but the service is discharging current toward the track with considerable intensity, notwithstanding its negative polarity the maximum being over 19 milliamperes per square foot at the pipe surface, a value sufficient to cause substantial deterioration of the pipe within a few years. The conditions described in the last two cases are made possible by the fact that the main and its connected service may be regarded as substantially an equipotential surface whereas the potential of the earth surrounding them varies greatly from point to point on account of the flow of transverse currents therein. In consequence, the earth at one point may be higher in potential than the adjacent pipe, while at another point 10 or 20 feet away the reverse may be the case.

The examples above are typical of large numbers of practical electrolysis tests and are sufficient to emphasize the importance of earth-current measurements as an indication of the true electrolysis condition of a pipe, and to further emphasize the importance of taking measurements in a number of directions around the pipe in case the pipe is fairly close to other subsurface structures, as is usually the case in city networks.

V. MISCELLANEOUS TESTS

1. TRACK TESTING

Electrical tests are made on railway tracks chiefly for two purposes, namely, to locate the cause of bad electrolysis conditions that may have been encountered, and to serve as a guide for the systematic maintenance of the railway-track circuit. Three methods of determining the condition of the track system have been extensively used, as follows:

(a) INSPECTION

This method of testing bonds by simple inspection is one which has been used much more extensively in the past than at the present time. It consists chiefly in going along the track and making superficial inspection of the bonds and, if they appear mechanically good, the assumption is made that the bonds are in a satisfactory condition. It can not be too strongly emphasized that any examination of bonds by this simple method of inspection should be regarded as a poor makeshift, and some more reliable method should be used wherever possible.

(b) USE OF PORTABLE BOND TESTER

There are in use at the present time portable bond testers operating on the principle of a slide-wire bridge, a portable millivoltmeter being used to determine when the bridge is balanced. In the use of this instrument the voltage drop across the joint is compared directly by the bridge method with the voltage drop on a definite length of rail adjacent to the joint under test, so that the resistance of the joint is measured in terms of an equivalent length of rail. This method has the advantage of simplicity as it can be operated by one man, although one operator with a helper can work to much better advantage, and while somewhat slow and tedious, it is, perhaps, the cheapest method of testing bonds at present available. Where car service is infrequent or the bad bonds numerous the rails may not carry sufficient current to operate the bond tester except when a car is in the immediate neighborhood. In such cases it is advisable to supply current by connecting the trolley and rail through a suitable resistance at a convenient point. An additional man will then be required to remove the connection for the passage of cars and to prevent the curious from receiving a shock through contact with the resistance or connections.

(c) AUTOGRAPHIC METHOD OF BOND TESTING

The method which has been used quite extensively in recent years for testing bonds in railway tracks is that known as the autographic method. This method is like that of the portable bond tester in that it is based on a comparison of the potential drop across a certain length of rail, including the joint, with that across an equal length of adjacent solid rail. The two readings are taken and automatically recorded within a fraction of a second, and during this short time the current in the rail may be regarded as practically constant. The method, however, permits of a correction in case the current should vary appreciably between two readings. The autographic method has several advantages, chief of which are as follows:

(*a*) A special test current is employed so that one does not have to depend on the railway load which is uncertain and at times discontinuous.

(*b*) It eliminates the personal element entirely, all readings being autographic.

(*c*) It gives a permanent record which can be kept on file for future reference.

(*d*) A large amount of track can be covered in a short time so that the test of an entire railway system can be quickly made at any particular period.

The apparatus for this method of testing is quite expensive as a special car is required and sometimes another car is used to haul the test car. Since bonds can be tested much more rapidly by this method the total cost on a large job will not necessarily be greater than with manual testing.

(d) TESTING OF CROSS BONDS

In addition to testing the joint bonds above referred to, it is important also to test periodically the condition of cross bonds. This can best be done by means of a low-reading voltmeter having a range not exceeding about 1 volt, the method being to go along the track and at frequent intervals measure the potential difference between the two rails of the single track and also between the tracks of the double-track line. It is permissible, as a rule, to have considerably higher potential drops between rails and tracks than would be allowed on a single joint, but, in general, the drop of potential between rails in any particular location should not be greater than about 0.2 volt.

(e) PERIODIC TESTING OF BONDS[8]

It is highly desirable for the purpose of permanently maintaining good electrolysis conditions to adopt the practice of testing periodically all bonds and cross bonds on a railway system. If the track is once placed in good condition and the roadbed is, in general, of substantial construction so as to prevent excessive mechanical strains on the joint due to passing traffic, the testing of bonds once a year will probably be sufficient under most conditions. Where, however, the joints are known to be deteriorating rapidly, and particularly where the roadbed is such as to allow considerable movement of the joints under the weight of traffic, much more frequent bond testing will be necessary if the track is to be maintained at all times in reasonably good condition.

2. MEASUREMENT OF LEAKAGE RESISTANCE BETWEEN TRACKS AND EARTH

(a) IMPORTANCE OF TESTS

The determination of the average resistance of the leakage path between railway tracks and surrounding earth is often very desirable, particularly where it is necessary to determine what over-all potential drops may safely be permitted in the track return. It will be evident that if the resistance of the leakage paths is very high, it will be safe to allow higher potential drops on the track than if the leakage resistance be low, although the voltage drop which may be considered safe is not directly proportional to the average resistance of the leakage path. The relation between these is discussed in detail in other publications of the Bureau of Standards.[9]

(b) METHOD OF MEASURING ROADBED RESISTANCE

The Bureau of Standards has given considerable attention to tests of this character and a number of tests on various types of roadbeds have been made, during the course of which two methods have been found satisfactory. One of these consists of inserting insulating joints in the track at two points distant, 1,000 feet or more apart, and bonding these with a heavy bond designed to be conveniently opened at any time for testing. The test is made at night when no traffic is on the line, the shunt around the insulating joint being opened and then a low-voltage battery applied between the isolated section of track and a suitable earthed terminal giving a very low resistance to ground. For this purpose the railway track on either side of the isolated section can be used. These tracks have substantially the potential of a point on the earth quite remote from the track section under test. When this connection is made the current flowing from

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[8] See Technologic Paper No. 62, Modern Practice in the Construction and Maintenance of Rail Joints and Bonds of Electric Railways.

[9] B. S. Tech. Paper No. 63, Leakage Current from Electric Railways.

the battery to the isolated section of track must practically all pass off through the track roadbed in this section, the leakage around the insulating joints being very small compared to the total leakage through the roadbed of the section under test, and this current is measured simultaneously with the potential difference between the track and a second earth terminal which should be remote both from the isolated track section under test and from the earth terminal which is carrying the current of the battery. The resistance of the leakage path between the isolated track section and ground is then calculated from the ammeter and voltmeter readings.

The second method of testing which has given satisfactory results in some cases eliminates the necessity of inserting insulating joints in the track, a procedure often quite difficult especially where cross

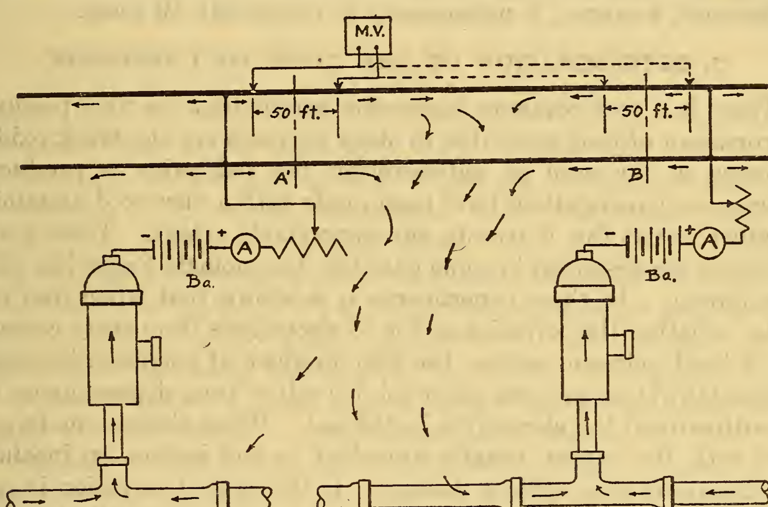

FIG. 19.—*Wiring diagram for track leakage test*

A, ammeter; *A'–B*, section lines; *Ba*, battery; *M V*, millivoltmeter

bonds or tie rods are close together. In this method two batteries are required and the arrangement is shown in Figure 19. The batteries are stationed from one to several thousand feet apart and connected as in the preceding test, one terminal being connected to the track and the other to an earthed terminal some distance away. It is desirable to connect the positive terminals of both batteries to the track and the negative terminals to earth, since this represents the polarity existing in practice where a current is leaking from the track into the earth. From an examination of the figure it will be seen that a great deal of current flowing from each battery will flow off in the directions away from the section under test (as indicated by the arrows), but a certain amount, corresponding to the total leakage of the current on the section between batteries, will flow into this section. If now, we measure the millivolt drop on a short length of the rails at points A and B, just inside the points at which the batteries are connected to the tracks, we can calculate from this millivolt drop on a measured length of rail of known weight the approximate current which is flowing into the section under test from each end. The sum of these two currents will then be the total leakage current fron the test section. At the same time a voltmeter is used to measure the potential difference between the section under test and a remote point in the ground, and from this voltmeter reading and the total leakage current the resistance of the section can be calculated. If high accuracy is sought the rails must be calibrated by one of the methods described above for calibrating pipe, in order to secure an accurate value of the resistance. This refinement, however, is unnecessary in practically all cases.

3. DETERMINATION OF THE CAUSE OF CORROSION

There is a very common impression extant that the final products of corrosion of iron when due to stray currents are the black oxides, whereas in the case of self-corrosion the red oxide is produced. Numerous investigations have been made with a view to determining whether or not this is true to any appreciable extent. These investigations are described in some detail in Technologic Paper No. 25 of this bureau. In these experiments it is shown that when iron corrodes, whether the corrosion is due to electrolysis from stray currents or to local galvanic action, the first product of corrosion is usually hydroxide of iron or some other soluble salt of iron, depending on the constituents of the electrolyte in the soil. When these come in contact with the oxygen usually prevalent in soil waters, an insoluble precipitate of iron oxide is formed. If the rate of corrosion is relatively rapid and the concentration of oxygen relatively low, the tendency will be to form ferrous oxides, and there may be expected a predominance of the black magnetic deposit often mistakenly called graphite. If, on the other hand, the rate of corrosion is relatively low and there is an abundant supply of oxygen in the soil water, the tendency will be for the ferric or red oxide to predominate. In most soils the amount of oxygen that can come in contact with the dissolved iron salt is usually quite limited, so where corrosion is very rapid there will be a definite tendency toward the formation of the black oxide. As a rule, especially in severe cases of electrolytic corrosion, corrosion takes place much more rapidly than in the case of soil corrosion. In general, therefore, we would expect the black oxide to result from corrosion due to this cause, whereas in a majority of cases, on account of the slowness with which self-corrosion proceeds, we would expect a predominance of red oxide. This rule is by no means infallible, however, because electrolytic corrosion sometimes takes place more slowly where the current discharged from the pipes is very small, and, further, special cases arise in which self-corrosion proceeds with great rapidity; for example, in certain very corrosive soils or in soils in which cinders, furnace slag, or other foreign materials exist which may form galvanic couples when in contact with iron. In such cases the end products of self-corrosion may be black oxides and appear identical in every respect to the end products of electrolytic corrosion. It is therefore impossible to tell with certainty from the examination of a corroded pipe whether or not the corrosion was caused by stray currents. Nevertheless, wherever a large predominance of black or magnetic oxide exists it may usually be regarded as a good indication that the rate of corrosion has been so great as to make it probable that stray currents have been largely responsible, unless corrosion tests under the same conditions which exist locally show that self-corrosion can take place with great rapidity. At the present time the only certain way of determining whether or not stray currents are causing corrosion in a particular case is to make proper electrolytic tests to determine whether the pipes are actually discharging current into the earth and to measure the strength of this current discharge. This can be done with the earth-current meter, as described above. In a case where serious corrosion has been caused by stray currents and the cause of stray currents later removed, the only way of determining whether the previous corrosion was caused by stray currents or by local influences is to make actual corrosion tests in the soil under the same average conditions of moisture, and using the same kind of iron as was previously found corroded. In the absence of a test of this kind it is not possible, at the present time, to fix with certainty the cause of damage that occurred under electrical conditions differing from those at present existing.

4. DETERMINATION OF THE SOURCE OF STRAY CURRENTS

Cases frequently arise in practice where it can be easily established that pipes or other underground structures in a given locality are being damaged by stray currents, but the question arises as to the source of the stray current causing the trouble. This question arises frequently where two or more electric railway sytems operate with grounded return in the same or near-by districts. There are, in general, two ways of determining the source of the stray current under such conditions. One method consists essentially in connecting voltmeters, preferably recording voltmeters, between the pipes or other structures which are discharging current into the earth and some other structure into which the currents are being discharged, which latter may be an auxiliary earth terminal if desired, and then shutting down momentarily first one and then another of the railway power houses and determining the effect of this on the reading of the voltmeter. In case the shutting down of one railway system makes practically no difference in the voltmeter reading, while the shutting down of the other results in marked reduction of the reading of the instrument, it indicates quite definitely that current from the second system is giving rise to the trouble.

It should be remembered that the shutting down of one substation not only removes the influence of the current from that substation but adds the conductivity of the tracks of that substation to the return circuit of the other system, thus under some circumstances materially improving conditions for the latter.

If the tracks of two street railway systems occupy the same territory, as they may in cities, interchange of current takes place and each system is affected by the other, often making it impossible to determine the responsibility for specific cases of electrolysis.

Another method which may often avoid the necessity of shutting down the power houses even temporarily consists in connecting one recording voltmeter in a suitable manner to the pipe structure, as described above, and connecting other recording voltmeters between the railway tracks and earth in all those sections of track which are known to be strongly positive to earth, and, therefore, discharging current into the earth. These instruments are allowed to run for a considerable period, preferably for several hours, and the shape of the curves giving the potential difference readings at different points on the railway system are compared with the shape of the voltage curve obtained in the underground structure under investigation. If the potential difference between the injured pipe and the earth varies widely and in a substantially similar manner, as potential differences between the tracks and earth in any particular section of the railway system, it affords a definite indication that it is leakage of current from this section which is giving rise to most of the damage. Sometimes it will be found that the damage in a given locality is caused chiefly by leakage from a single railway line or section of line, in which case the investigation is considerably simplified. More frequently, however, the corrosion at any point may be affected simultaneously by the leakage of current from a number of railway lines. Usually an examination of the local system will show which lines are likely to be affecting the district under investigation, and where two or more lines appear to be thus involved it is necessary to combine the readings of potential differences between tracks and earth of all these lines, thus giving a composite leakage curve, which is to be compared with the curve of potential difference on the pipe structure under investigation. As a rule, it will be found that enough disturbing influences are at work so that the potential-difference curves will not be of exactly the same shape, but it is usually possible to show whether or not they tend to increase or decrease simultaneously, and in a majority of cases the source of the greater part of the stray current can be definitely determined in this way.

5. LOCATING BURIED CONNECTIONS

During the course of electrolysis surveys it is frequently necessary to locate concealed metallic conductors, such as buried cross bonds in tracks, metallic connections between the pipes, and railway negative return, or even to determine the exact location of pipes themselves where such location is only approximately known. The most frequent and difficult case encountered is the location of unknown metallic connections between pipes and railway return. To locate these with a minimum of time and effort three classes of measurements are generally made.

Potential-difference measurements between pipes and railway tracks are made, and where these are much smaller than would be expected from over-all potentials and potential gradients which have been found to prevail throughout most of the railway area it indicates a strong probability of the existence somewhere of metallic connections between the pipe and railway negative return. These may not, however, be directly between the pipes and tracks, so that potential-difference measurements made at various points along the track will not reveal even the approximate location of such connections. Their existence having been indicated with considerable accuracy by potential-difference measurements, the next step is to measure potential difference between fire hydrants or, in the case of gas systems, between gas-service connections several hundred feet or so apart. The first such measurement will show in which direction the current is flowing in the main to which the hydrants or services are connected, and then the tester should proceed along the main in the direction in which the current is flowing and take a similar reading a few hundred feet farther on. In general, it will be found that the current will be flowing from all directions toward the point at which the metallic connection sought is made to the pipe, so if the tester continually proceeds in the direction of current flow, he will ultimately come to a point at which the direction of current flow is reversed, and in this way he can almost always locate the connection within 200 or 300 feet. It can often be much more closely located by measuring potential differences between adjacent house services, it being possible in this way to locate the connection within 30 or 40 feet. This, however, is not close enough to make it economical to find it by excavation, but an exact location can now be determined by the use of a special exploring coil similar to that used by telephone companies for locating crosses in telephone circuits in cable. The principle of this is shown in Figure 20. In this figure let A and B

represent a railway and pipe system which are connected at some point by the buried metallic conductor *C*, the location of which it is desired to find. A special high-frequency buzzer or other interrupting device *D* is connected between the pipe and railway systems at any convenient point, a battery being in series with the interrupter. This can be made to send an intermittent current between the systems *A* and *B*, a portion of which will return by way of the metallic connection *C*. An exploring coil *E*, connected to a telephone receiver, if carried along the surface of the earth in the vicinity of the pipes *A* or rail *B*, will give a sound in the telephone receiver due to electromagnetic induction. If the axis of the exploring coil *E* is held parallel to the pipes and track, the sound due to the current flowing along these structures will be a minimum, and can generally be made nearly negligible. When, however, the coil is moved along to a position

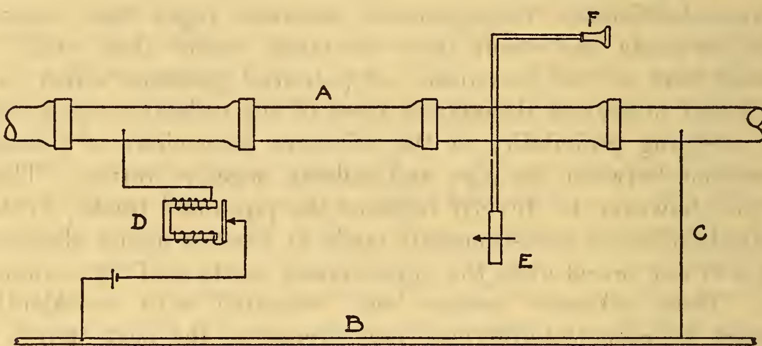

Fig. 20.—*Exploring circuit for locating invisible metallic connections*

A, pipe; *B*, rail; *C*, metallic conductor; *D*, buzzer; *E*, exploring coil; *F*, telephone receiver

above the connection *C*, a very loud sound will be heard in the receiver, which will be a maximum when the coil is directly above the metallic connection *C*. The hidden connection can then be uncovered and removed if desired. By following this procedure it is usually possible to locate a hidden connection within two or three hours, although in some cases where very complicated underground networks exist there may be so many disturbing influences and parallel paths for the current to follow that the definite location of the desired cross connection may be extremely difficult.

In a similar manner the same apparatus can be used for locating buried pipes or other conductors. The general arrangement for this is shown in Figure 21. Here an ordinary buzzer, *1*, preferably of high frequency, is connected in series with a dry cell, *2*, and these are connected between the pipe to be located and any other available conductor. The usual method when services connected to the pipe are not available is to connect between a rail, *3*, if one is available, and a fire hydrant, *4*, which is known to be connected to the pipe, *5*, which it is desired to locate. If no rail is available, a simple ground rod driven into the earth can be used as a substitute, provided the ground is fairly moist, and a service pipe may be used as a connection to the main instead of a fire hydrant. This sends an interrupted current through the pipe, *5*, and produces a pulsating magnetic field in the vicinity. An exploring coil, *6*, connected to a telephone receiver, *7*, is then carried about over the surface with its plane approximately parallel to the pipe, *5*. When the noise heard in the telephone receiver is maximum the exploring coil, *6*, will be directly over the pipe. In many cases where the pipe carries considerable railway current the pulsations of this current,

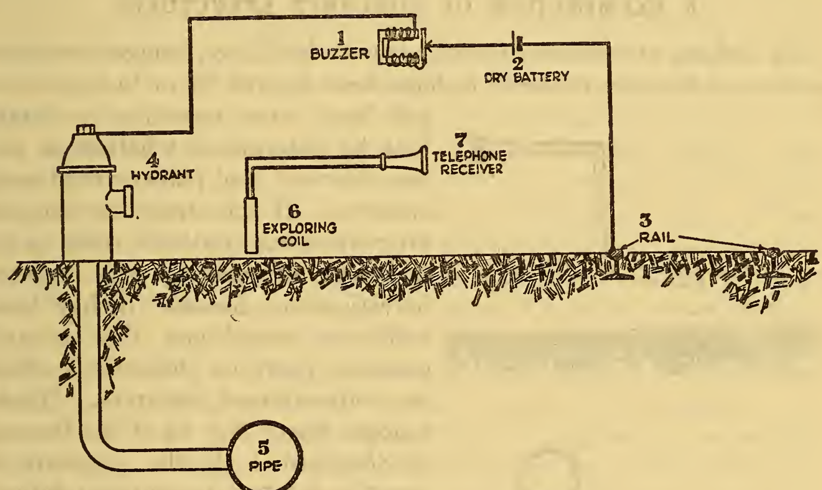

Fig. 21.—*Exploring circuit for locating pipe*

due to commutation and pulsations of field magnetism in both generators and motors, will be sufficient to produce an audible noise in the telephone receiver, and in a large percentage of cases the exploring coil, *6*, and telephone receiver, *7*, are all that are needed, the buzzer, battery, and all connections being dispensed with. If the pipe being located is at a considerable distance, say 5 or 6 feet or more from any other parallel pipe, its location can usually be obtained with considerable accuracy. If, however, there are other pipes paralleling within 2 or 3 feet, or less, these pipes will carry a part of the current and the indicated position of the pipe will then be somewhere in between the actual locations of the two pipes. This not infrequently causes much difficulty in making an accurate location and renders necessary exploring for the pipe within narrow limits by driving a bar until it strikes the pipe.

A modified procedure in using the exploring coil is shown in Figure 22. Here, instead of holding the coil in a vertical plane, as shown in Figure 21, when exploring for a maximum sound in the receiver, the coil is held in a horizontal plane and moved about over the surface until the noise in the telephone is minimum. Under these conditions the axis of the coil will be pointing in the direction of the pipe. In many cases this will give a more sensitive and accurate location than the method previously described. It is, however, subject to the same difficulty from the presence of other pipes near the one being looked for, and may give somewhat erroneous indications. In most cases, however, these methods are quite useful.

6. EXAMINATION OF CONCRETE STRUCTURES

In making an examination of concrete buildings, bridges, or other structures that are reported to have been injured by or to be in danger from stray currents, it should first be determined whether or not the structure is of plain or reinforced concrete. If the structure contains no reinforcing material there is no necessity of making any further investigation, because it has been definitely established that electric currents exert no deleterious effect on nonreinforced concrete. (Technologic Paper No. 18 of the Bureau of Standards.) If the structure in question is found to contain reinforcing material an inspection should first be made to see whether there are any cracks or rust stains such as may result from corrosion of the reinforcing material in the concrete.

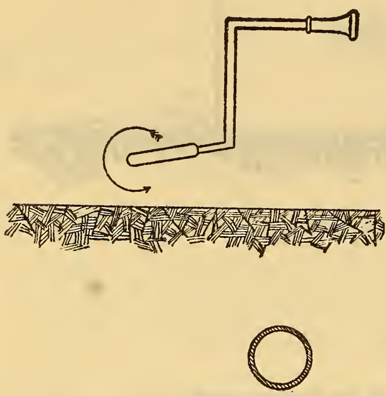

Fig. 22.—*Method of pipe finding*

The existence of electric current in any particular structure can be determined by measuring potential drops between selected points on the structure, spaced a considerable distance apart. If the reinforcing material is accessible, the instrument terminals should be connected directly to it, but if the terminals of the instrument have to be directly connected to the concrete, a nonpolarizable terminal similar to that described above in this paper should be used. It is important in making such measurements to bear in mind that with sufficiently delicate instruments a potential difference will be indicated between any two points selected at random on a building or any other conducting structure, but the existence of such potential differences should not be accepted as evidence that any serious stray currents are flowing. If such readings are found to be of the order of magnitude of a few millivolts, they should not be regarded as of any consequence. Where, however, readings of a few tenths of a volt or more between points comparatively close together are found, the source of these had best be determined.

In general there are three possible sources from which stray electric currents may get into a building or other structure. First, from a private power plant within the building; second, through leaks from light or power mains which enter the building; and, third, from stray currents from electric-railway lines. It can readily be determined which of these possible sources may be giving rise to stray currents in any particular case by connecting a voltmeter between points in the building which exhibit appreciable potential differences and momentarily shutting down the private plant or cutting off the outside source of electrical power. If the stray current comes from either of these sources, there will be sudden changes in the voltmeter reading when the sources of supply are shut off. If switching these sources on or off makes practically no difference in the voltmeter reading, steps should be taken to see whether stray currents are entering the building on the grounded circuits of railway or other power lines. Where stray currents of this kind get into the building they usually enter or leave through water or gas pipes or cable sheaths which enter the building, or in rare cases through the bases of columns or foundations. It is a simple matter to determine whether or not currents are entering or leaving the building through any metallic pipes or cables which enter the building by merely taking potential-drop readings on a short length of such conductors, and the question as to whether currents are entering or leaving through columns of the building can be determined by similarly making potential-drop measurements on a suitable length of column near its base.

If current is found to be entering the building through pipes or cables, substantially the same amount of current may be found to be leaving through other pipes or cables at other points, in which case it would usually be improbable that any serious danger would be set up. Where, however, more current flows into the building on metallic structures than is flowing out on similar metallic structures, the difference might be expected to be leaving the building through the columns and foundations, in which case some damage might result. In such cases the simplest and most obvious remedy would be to insert insulating joints in the pipes or cables which are conveying current into the structure.

In making investigations it should be constantly borne in mind that ordinary concrete is an excellent preventive of corrosion of embedded iron, not only as regards self-corrosion, but also as regards electrolytic corrosion, and unless the potential differences between various parts of the building are of considerable magnitude, no fears should be felt regarding the safety of the structure. In particular, great care should be exercised not to be misled by the presence of inevitable galvanic differences of potential which can be found in practically every structure of this kind, but which cause absolutely no harm.

VI. INTERPRETATION OF RESULTS OF ELECTROLYSIS MEASUREMENTS

1. GENERAL CONSIDERATIONS

The interpretation of the results of electrolyses tests requires long experience and thorough familiarity with the subject of electrolysis from stray currents. No specific key to the interpretation of the test data can be given, but below are discussed some of the fundamental principles involved as well as some of the difficulties encountered in making a correct interpretation of electrolysis survey data.

As a rule no single set of readings, such as over-all potential measurements or measurements of current flow in pipes, can be interpreted by itself alone, but other factors must be taken into account. For instance, very high over-all potentials may at times be accompanied by, and in some measure casued by, high-leakage resistance between track and ground. This resistance is sometimes so high that even very high over-all potentials would not cause sufficient current to leak from the tracks into the earth to give rise to any serious electrolysis conditions. On the other hand, where the leakage resistance between tracks and ground is very low, the current delivered to the track in outlying portions will readily leak off into the earth, thereby reducing greatly the current in the rails and correspondingly reducing the voltage drop in the track. As pointed out in another part of this paper, different types of roadbeds commonly encountered in electric-railway work exhibit widely different characteristics as to leakage resistance between tracks and earth, some showing a resistance many times greater than other types of construction. In some cases when a large percentage of the total current returns by way of the earth and underground structures, the over-all potential drops may be low, whereas if all the current was returned by the rails, much higher over-all potentials would prevail, although electrolysis conditions would be decidedly better in the latter case. Hence, while high over-all potentials under average conditions indicate bad electrolysis conditions, nevertheless, under certain conditions where leakage resistance is very high, such would not be the case; and, conversely, low over-all potentials may result from very bad electrolysis conditions, due to low-leakage resistance between tracks and earth. It frequently occurs that the direction of the gradient on suburban lines is toward the end of the line on account of the high resistance of the rail circuit and a comparatively low resistance between the suburban track and the earth. Under such circumstances an over-all potential measurement taken to the end of the track will show a lower value than a similar measurement to a point on the same track somewhat nearer the substation. Similarly when the line is operated with one or more sections of the trolley negative the voltage between the end of the line and the substation may be considerably less than that between two intermediate points.

Similar considerations apply to potential difference measurements between pipes and tracks. High values of leakage resistance tend, in general, to produce high-potential differences, whereas if the leakage resistance is low, a much larger current may flow from pipe to tracks even with considerably smaller potential differences. Hence, potential-difference readings alone can not be accepted as an indication of the amount of current discharged, and before even approximate conclusions can be drawn from them some definite idea regarding the leakage resistance between pipes and tracks near the points of measurement must be obtained. This depends not alone on the character of the roadbed. The location of the pipes is an important factor in estimating both the amount of leakage current and also the distribution of such leakage current. Further, because of the effect of location of pipes on the distribution of leakage current, it is not sufficient to determine the total amount of current which the pipes may be discharging, but it is important also to know where and how the current leaves the pipes. If a main parallel to a railway line is at all points 20 or 30 feet distant, the current discharge will generally be distributed over a large area, so that a considerable amount of current may be discharged from the pipes without serious corrosion developing at any point. On the other hand, if the pipe comes very close to the track at a few points, as, for instance, where the main or services cross directly under the track and within a few feet of the surface the current discharge will be greatly concentrated at such points, thereby giving rise to very rapid deterioration of the pipe. It is not to be inferred from the above that pipes 30 feet or any other specified distance from the tracks are safe since other factors may control. Again, even though it may be determined that the current is not doing any damage to the pipes at the point at which it is leaving them; for example, where pipe drainage is installed and the current is practically all removed from the pipe through metallic connections, it can not be concluded, with certainty, that such currents are not doing damage to the pipe system on which they may be flowing, since there may be joints of sufficiently high resistance in the system to cause considerable corrosion on the positive side of the joints at unsuspected places throughout the system. This trouble is not common where lead joints are exclusively used, but in case drainage is applied to a system containing isolated insulating joints damage at such joints may occur.

In addition to the above considerations, it must be borne in mind that current flow on any one pipe system may injure not alone the pipe system on which the current is found, but it may be causing even grater injury to some other pipe or a cable system from whence it may be discharging into the system in which it is actually measured. Therefore, where considerable amounts of current are found on any pipe system, it is important to find out whether it is producing trouble in any other pipe system from which it may be drawn. This is particularly important in cases where drainage is applied to one or more of the pipe systems in any given locality. Even if drainage is applied to all the systems, care must be exercised to balance the drainage as well as possible, since by failing to do so considerable injury to the systems of higher potential may be produced. For this reason it is desirable to measure potential differences between the different systems of underground structures occupying the same general locality, as pointed out in an earlier part of this paper.

It will be evident from the foregoing considerations that the very low potential differences in the positive areas which accompany most installations of pipe-drainage systems may induce a false sense of security unless due consideration is given to the secondary conditions which may be set up by the pipe-drainage connections.

2. USE OF REDUCTION FACTORS

In most cases it is not practicable to take readings of current and potentials at any point over a sufficiently long time to get a fair average value of readings at that point. Such readings should always be taken as long as circumstances permit, but in making electrolysis surveys it is usually necessary to take a large number of readings scattered over a wide area so that each reading can be continued only for a comparatively short time. Such short-time readings can not, in general, be used directly as a basis for determining electrolysis conditions. The great variability of railway loads generally causes the readings to fluctuate decidedly from time to time, and in order to interpret properly the results of the survey the readings must be reduced to some common basis; for example, either the potential for average scheduled traffic, the all-day average, the operating-day average, the average for the maximum hour, or the maximum average value for any 10-minute period. Each of these has certain advantages and disadvantages, and the method of procedure will often differ, depending on the method to be followed in interpreting the results. All are affected by such factors as heavy or light days, unusual weather conditions, electric heaters in cold weather, morning and evening peak loads, and other causes, and these factors must be considered. Electrolytic damage is determined by average conditions over long periods, but danger from arcing and overheating are more closely related to maximum values. Since electrolytic damage is by far the most important because of its more general occurrence, while only exceptional cases of arcing and overheating have been observed, the average values over long periods give a much more accurate index of the seriousness of the condition than any short-time readings.

The great unreliability of short-time readings for determining electrolysis conditions is especially noticeable when comparing the load curve of a line having a 5, 10, or 15 minute schedule, with that of hourly interurban service, or when comparing that of a station having a 45 per cent load factor with one having a load factor of 10 per cent. Because of this great variation and uncertainty in short-time measurements, and for the purposes of interpretation and comparison, it is desirable that all short-time readings be reduced to values for some representative period, preferably the all-day average.

(a) TEN-MINUTE BASIS

Some engineers prefer to determine directly the highest average value for a period of about 10 minutes and use this as an index to electrolysis conditions, while some even attach importance to momentary peak values. The maximum 10-minute potential is a peak-load value and must be measured at the time of peak, it being too variable to be derived from a value observed during another part of the day and corrected by means of the load curve, as suggested later for readings over longer periods. Reading the actual value with no correction from a load curve has the advantage of greater simplicity and is free from one source of error due to the possibility of the load curve being different on the line measured from the load curve used in calculations, which would probably be that of the station supplying that line. On the other hand, the 10-minute value during peak load fluctuates between much wider limits than the average for a longer period, and results from one day to another will lack concordance to a much greater extent than in case of readings taken over longer periods, due to the irregular and widely fluctuating character of the load.

Numerous investigations have shown that the actual amount of corrosion which takes place is much more nearly proportional to the average all-day load than to any short-time peak value.[10] For this reason it is undesirable to place undue significance on high-peak values of voltage or current readings which are of short duration, provided the average value of such readings throughout the day is

[10] B. S. Tech. Paper No. 25.

small. Voltage readings taken during such high-peak periods or during another hour of the day should be referred to the load curve for the district under consideration in order to determine the approximate value of the all-day average. Better still, as pointed out above, readings should be taken over a longer period of time where practicable.

Our experience in attempting to interpret results of surveys by means of short-time peak values has convinced us that not only is this procedure objectionable on the ground that even if readings are accurately obtained they are not a true index of the electrolysis situation, but also because an accurate determination of such peak values requires as much time as the taking of measurements over periods of an hour or longer. This is due to the fact that in order to make sure of getting a reading during the maximum 10-minute period of any particular day, it will usually be necessary to continue the reading over a period of at least one-half hour, and preferably longer, and, further, on account of the variations of the 10-minute maximum from day to day such readings would have to be repeated on a number of different days in order that either the highest maximum value, or the average maximum value, may be obtained.

(b) HOURLY BASIS

(*b*) The time which can be allotted to individual measurements will vary greatly with conditions and nature of the information sought and must be determined by the engineer in charge. It may be said, however, that in the majority of cases readings taken over a period of one hour, either during peak load or for average scheduled traffic, give values that can be repeated from day to day with a fair degree of consistency. Peak values of this duration usually occur at a fairly definite time each day so that one-hour readings during peak load can generally be determined with fair accuracy. It would obviously be most logical to take the readings for an hour or somewhat longer during peak load. However, for ordinary survey work designed to determine the actual condition which exists with respect to the pipes, the one-hour values have something of the same weakness, although to a much less extent, as the 10-minute maximum values possess, in that they are not an accurate index to the magnitude of the corrosion due to electrolysis. If, however, the load curve of the station or principal feeders supplying the district under consideration is at hand, a reading taken over a period of one hour during practically any time of the day will permit the determination of the average value throughout the entire day with sufficient accuracy for practically all purposes. In general, we would urge the taking of a large number of one-hour readings rather than a relatively small number of readings of a longer period, the one-hour readings being later reduced to average all-day values through reference to a typical load curve. It frequently happens that the street-railway load throughout the period between the end of the morning and the beginning of the evening peak, the period in which most of the electrolysis tests are made, is nearly constant and approximately equals the all-day average load. Under such conditions the reduction of readings to all-day average values may not be justified, since the

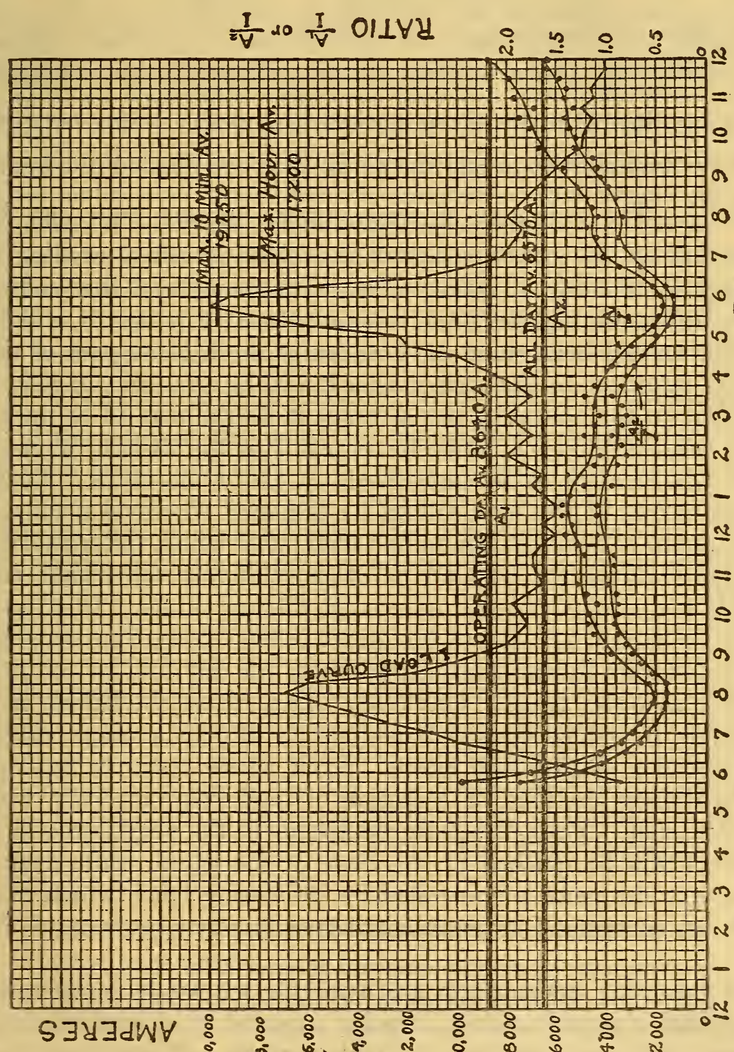

Fig. 23.—*Load curves illustrating method of reducing short-period readings to all-day averages*

accuracy of the final results is limited by the variations in weather and operating conditions rather than by the accuracy of the observations with respect to conditions on a given date.

The method of making this reduction is illustrated by curves in Figure 23. In this figure, curve *I*, with the two high peaks, is the load curve of a power station supplying the area under test. From this load curve either the operating-day average represented by the line, A_1, can be determined, or the all-day or 24-hour average represented by the line, A_2. If the reading at any point is taken during any particular hour of the day, its value reduced to the operating average would be the actual reading of the instrument, multiplied by the ratio of the operating-day average to the ordinate of the load curve during the period when the reading was being taken. These ratios between the operating-day average and the actual value of the load are plotted in the curve marked $\frac{A_1}{I}$ and the ratios between the 24-hour average values and the actual load are plotted in a curve marked $\frac{A_2}{I}$. The ordinates of these curves for any hour can be used directly as the reduction factor to reduce an actual reading to an average for the day on either basis. For example, if the reading has been taken during the hour between 5 and 6 p. m., it will be very high, having been taken at practically the highest part of the load. By reference to the ratio curves it will be seen that to reduce this reading to the operating-day average it would have to be multiplied by substantially 0.5, while to reduce it to the 24-hour average value it would have to be multiplied by about one-third. Load-reduction curves of this sort should be prepared wherever a considerable number of readings are to be taken, after which the reduction of average readings for an hour or other relatively short time can be readily made to correspond to average all-day values. In a number of cities certain sections of the street railway system are supplied by one substation during certain periods of the day and by another substation at other times. Obviously under these conditions it is not possible to reduce observed readings to all-day average values by the use of a station-load curve. Even where there is but one source of current the load on a section of track may not vary with the station load. Thus, the peak conditions in the neighborhood of a ball park will be reached at the close of the game, while near a large factory the peak is controlled by its closing hour, which may or may not correspond to peak conditions in other sections of the city.

When recording instruments are available we would recommend that readings always be taken covering a period of at least one-half hour, and preferably one hour, if time permits. Where, however, only indicating instruments are available and a large number of readings must be taken, short-time readings may be necessary, in which case accuracy must be sacrificed to expedition.

(c) ALL-DAY AVERAGE BASIS

Where only a few readings are required so that sufficient time can be given to the work, it is best to take all important readings over a period of a full day. In most cases, however, in making a complete electrolysis survey this can not be done, and readings have to be taken for a shorter period and reduced to the all-day values by the method described above.

3. EFFECT OF REVERSALS OF POLARITY

Throughout a large portion of every grounded railway return system it will be found that the potential differences between pipes and track frequently reverse in direction, the pipes becoming alternately positive and negative to earth with periods varying from a few seconds to several minutes or even longer. Experiments have shown that under such conditions the corrosion is not proportional to the average of the current discharged by a structure. Special consideration must, therefore, be given to measurements in such places in order that even an approximate estimate of their significance can be made. In general, three different classes of reversing conditions have to be recognized in interpreting these measurements, as follows:

(a) POLARITY OF PIPES CHANGING WITH PERIODS OF SEVERAL HOURS

If the pipes at any point are continuously positive for a period of several hours, and then of opposite polarity for a succeeding period of some hours, a condition frequently existing in localities where a substation is operated during only a portion of the day, there will, in general, be little protective effect due to the period when the pipe is negative to earth, and the actual corrosion may be more nearly indicated by the arithmetical average value of the voltage during the hours in which the pipe is positive to earth, this average, of course, being reduced to the 24-hour average basis. Thus, if a given pipe is found to be 4 volts positive to the tracks or other neighboring structure, for a period of 12 hours, and either negative or at zero potential for the remaining 12 hours of the day, the actual amount of corrosion which would occur would undoubtedly be nearly equivalent to that which would result if the potential at the same point was maintained at 2 volts for the full 24 hours.

(b) POLARITY OF PIPES REVERSING WITH PERIODS OF ONLY A FEW MINUTES

Under these conditions it has been shown by extensive experiments that the corrosive process is, in large measure, reversible, and the actual amount of corrosion comes more nearly being proportional to the algebraic average of the applied potential than to the arithmetical average during the total time the pipe is positive.[11] In all cases, therefore, where the polarity of a pipe is continuously reversing and the period of reversal does not excede 5 or 10 minutes the algebraic average should be used as the criterion of the importance of the reading.

[11] B. S. Tech. Paper, No. 72.

current measurements, and the measurement of current discharge from pipes to earth. When we come to make an accurate quantitative determination of the significance of the various test data we are limited by the fact that the various classes of voltage readings, as well as the measurements of current flow on mains, have, in general, as has been repeatedly set forth above, only a qualitative significance, and can not be used to afford even an approximate measurement of the rate at which deterioration is in progress. The resistivity of the earth forming the leakage path, and the mutual influence of adjoining utilities which determine in large measure the location of the discharge, all combine to add to the uncertainty as to the quantitative significance of such data. Therefore, all such measurements should be regarded as affording no definite quantitative interpretation. They are, however, of value in connection with an electrolysis survey. They not only afford a good general idea of the electrical conditions of railway negative return, when properly interpreted, but also serve as a valuable guide for determining the more important locations in which measurements of earth currents are to be made for the purpose of giving more or less quantitative significance to the potential measurements.

For instance, if it is desired to determine to what extent one pipe network may be discharging current to, or drawing current from, a neighboring network, it will usually not be practicable to make excavations for earth-current measurements at more than a very small percentage of the places at which pipes come close together. On the other hand, voltage measurements can be very quickly and economically made throughout the entire network. The proper procedure in this case is to make a complete survey of the potential differences throughout the entire area under consideration and then make at selected points a few excavations for measurements with the earth-current meter. These should be made in places where the pipes come close together at parallels or crossings. Measurements both of the current intensity or discharge and of earth resistivity at these places should be made, and also potential-difference measurements between pipes. The earth-current measurements and the earth resistivity suffice here to give an indication of the importance of a particular value of voltage readings as found at this location, and wherever soil conditions are essentially similar so that the earth resistivity can be assumed to be substantially of the same order of magnitude, it may be assumed that with a fair degree of accuracy the leakage currents are proportional to voltage readings where spacings are substantially the same. This is usually the best that can be done where a very large number of observations are desired over a large area. If earth resistivities are found to vary greatly from point to point they can be checked approximately at each point of potential-difference measurement by boring a hole with a 2½ inch auger to a depth about equal to the depth of the pipes, and measuring the resistivity of the earth with a type B contactor and an earth-current meter. This measurement of resistivity can be made more quickly and cheaply than a complete earth-current measurement and can often be used to advantage for determining relative values only. If the degree of approximation thus obtained is not sufficient to meet the requirements, a greater number of earth-current measurements will have to be made.

A large amount of data has been accumulated in numerous cities with a view of determining the significance to be attached to earth-current measurements. Conditions vary much from place to place, but the data thus far available indicate that if the intensity of the leakage current, as measured by the earth-current meter, does not exceed about one-half to 1 milliampere per square foot, the pipes may be regarded as safe. The lower figure would, in general, apply to steel, wrought iron, or lead pipe and the higher one to cast-iron pipe. If the current intensity ranges around 1 milliampere per square foot, the condition is one that will probably call for some slight improvements, although the urgency of the case is not to be regarded as very great. These figures are tentative and may be changed somewhat by further experience. Where values larger than this are found, remedial measures become more and more urgent in proportion to the magnitude of the readings observed. Experience generally indicates that where the current intensity of discharge amounts to a few milliamperes per square foot, serious corrosion may be expected. In cases where the pipes have been eaten out within six months or a year after being laid, earth-current measurements as high as 20 to 40 milliamperes per square foot have been observed.

VII. SELECTION OF INSTRUMENTS

In general, in making electrolysis surveys both indicating and recording instruments are required, the former being useful for taking very short-time readings of a preliminary nature, which often assist materially in laying out a detailed plan for a comprehensive survey. Such instruments are also useful at times in certain kinds of measurements, such as measurements of current flow in large pipes, where, because of the low value of the potential drop, recording instruments can not readily be obtained with sufficient sensitivity to record the values. Wherever it is practicable to use recording instruments, however, it is desirable to do so, since in this way readings can be taken over a greater length of time without unduly increasing the cost of the survey; and, moreover, a permanent record is obtained in which the personal element is eliminated.

On account of the variable and more or less irregular character of the readings, high accuracy in the measuring instruments is not required, but all instruments should be sufficiently rugged to yield moderate accuracy even under the severe handling which such instruments must inevitably receive in field service.

An indicating instrument, which often must be read quickly, owing to the highly variable character of the load, should have a scale so graduated that fractions of numbered divisions can be quickly estimated without probability of error. This can be best, most easily, and accurately done if the subdivisions are tenths of the numbered divisions. Since readings reverse frequently, zero-center instruments are usually desirable both in indicating and recording types. In many cases, especially in indicating instruments, it may be more convenient to have the zero a little to one side of the center so as to give a scale, such as −5, 0, and +10 volts, or other ranges in the same proportion. This is desirable, because readings usually tend more strongly in one direction than in another, and in a scale of this kind a wider effective range of the instrument is secured. For all purposes an instrument of very long period is desirable, since with rapidly fluctuating loads such an instrument can be more easily and accurately read, and it is the average values rather than momentary peaks that we desire to secure. When two instruments are to be read simultaneously, it is important that they have identical periods, as otherwise phase displacements of the pointers may give rise to large errors. A long period is especially desirable in the case of recording instruments, where, unless the period of the pointer be comparatively long, the record will, on a rapidly fluctuating load, be so obscured that it will be practically impossible to determine the true average of the reading over any desired period of time.

The volt sensitivity required of instruments is dependent on the range desired for each measurement, but it is often very important that the instrument require a relatively small current for full-scale deflection. High resistance is readily obtained in the better classes of instruments and should be sufficient to overshadow or permit an accurate correction for external resistance, such as long leads or soil-contact resistance.

For an indicating instrument, the Bureau of Standards has frequently used a special voltmeter, with a resistance of 2,900 ohms per volt; and ranges of 5, 25, 50, and 100 volts have been found convenient and suitable for most voltage surveys in which an indicating instrument is needed. For recording instruments having a resistance of from 2 to 4 ohms in the lowest range, multipliers have been provided giving ranges of 0.005, 0.025, 0.1, 0.5, 2, 10, 50, and 150 volts. These ranges give a practically universal recording instrument for voltage and current survey work. The lower ranges are used chiefly for current measurements by measuring the millivolt drop on a pipe or cable, the resistance of which is determined by calculation or from tables; or the millivoltmeter may be used on a standard shunt. Recording instruments for electrolysis work should always be of the dotting type, in order that they may have sufficient sensitivity and should have a high resistance to eliminate, as far as practicable, the necessity of correcting for the resistance of leads or contacts. Where necessary data are available the resistance of the circuit can be directly calculated, or in some cases it may be measured.

The Bureau of Standards has used, in its survey work, a roll chart dotting-type graphic recording voltmeter, and also the dotting-type smoke-chart recording voltmeter. Both of these instruments have been found very satisfactory for most purposes. The roll-chart instrument has an advantage, in certain cases, especially where readings are to be taken over a long period of time, because the ribbon-type record makes it practicable to run the chart at high speed, and thus get greater detail over a long period without changing charts. Where records are to be taken over periods of 1 hour to 24 hours the smoked-chart instrument has some advantages. With this instrument running on the one-hour speed, sufficient detail can be obtained for practically all purposes and the record at each point can be taken on a separate chart, which greatly facilitates classification and filing of the records. The smoke-chart records have to be handled carefully until after the record is taken and fixed, and this is in some cases a disadvantage. Figure 25 shows typical roll and smoke chart records.

For indicating instruments a zero-center multiple-range voltmeter with ranges of from 5 millivolts to 50 volts has been found very satisfactory. For preliminary testing a multiple-range pocket voltmeter with ranges of 1.5, 15, and 150 volts, has proven convenient. For measuring currents in pipes by the drop-of-potential method, an instrument with a full-scale deflection for 1 millivolt has been frequently used. This instrument is rather fragile and must be used with care.

The earth-current meter is manufactured by a well-known firm of instrument makers.

For general electrolysis work, it is recommended that one or more of all of the above-mentioned instruments be available, and where much work is to be done a considerable number of recording voltmeters will be found desirable, both for reasons of economy and for expediting tests.

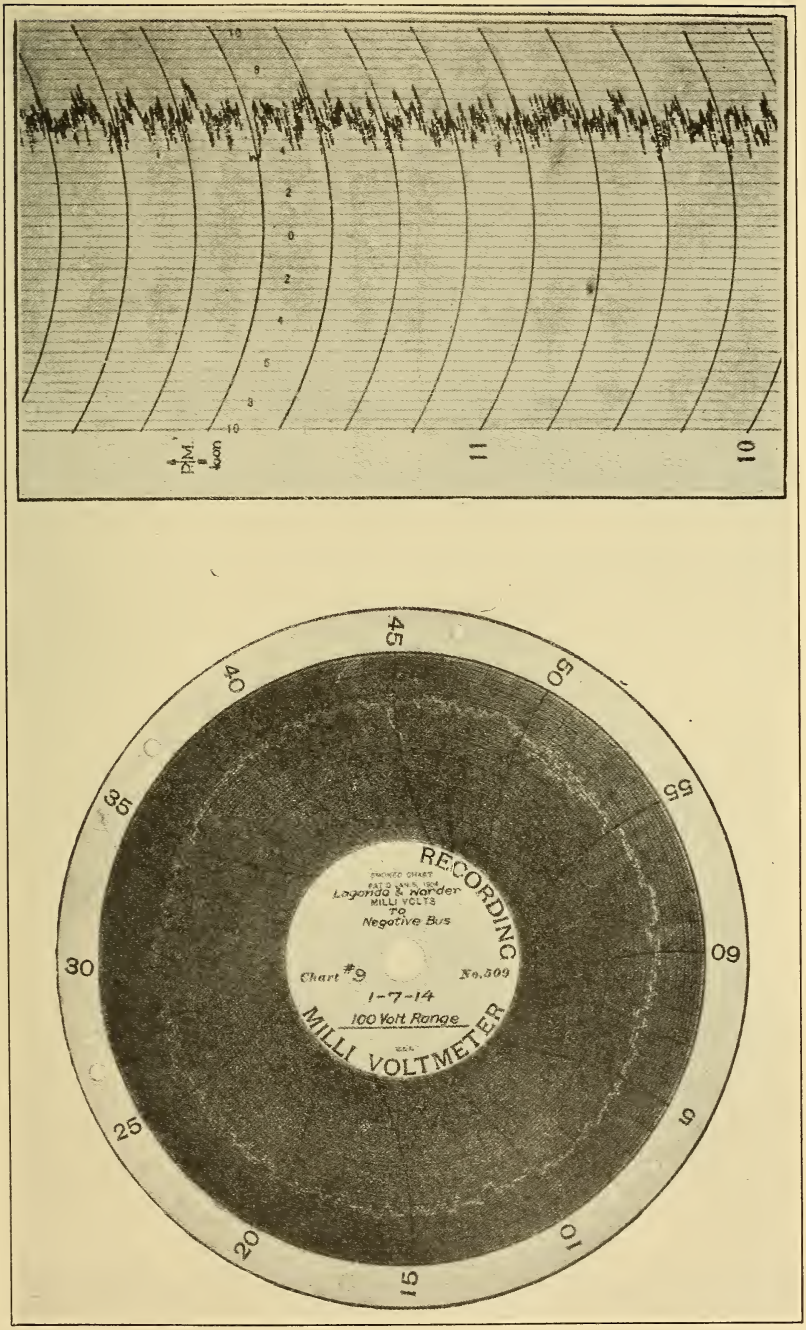

Fig. 25.—*Typical roll and smoke charts*

VIII. NEED FOR SUPERVISION OF ELECTROLYSIS SURVEYS

It is well to emphasize here the desirability of having electrolysis surveys carried on under the direct supervision of a competent engineer thoroughly familiar with the subject of electrolysis from stray currents. The very great value of the properties generally exposed to possible danger from electrolysis is such as make this question one of great importance. Further, the subject is a very complicated one, and not only are the sources of error in measurements and interpretation of results very great but also many of the measurements, unless studied and interpreted by one thoroughly familiar with the subject, may be so misleading as to destroy, in large measure, the value of the investigation.

While almost anyone familiar with the use of electrical-measuring instruments can carry out the details of the work, this should always be done under the supervision of an engineer who has had considerable experience in work of this kind, and where no local engineer is available for supervising this work a competent consulting engineer should be employed. Such experienced supervision is of special importance when the earth-current meter is used.

Wherever possible an electrolysis survey should be made on a cooperative basis by as many of the interests concerned as can be induced to join in the work. This can best be done by forming a joint committee representing all of the interests and the actual survey should preferably be carried on by an experienced electrolysis engineer under the administrative direction of the joint committee.

We can not too strongly urge upon the owners of underground utilities and railway companies the importance of considering this matter of electrolysis investigations as a serious engineering problem, and one which should not be dealt with by the more or less empirical and unscientific methods which have too often been followed in the past. It must be said, however, that there has in recent years been a marked tendency toward giving more careful and scientific study to this subject, and this has led to a marked betterment of electrolysis conditions in general throughout the country.

WASHINGTON, April 27, 1927.