DEPARTMENT OF COMMERCE

TECHNOLOGIC PAPERS
OF THE
BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 26

EARTH RESISTANCE AND ITS RELATION TO ELECTROLYSIS OF UNDERGROUND STRUCTURES

BY

BURTON McCOLLUM, Electrical Engineer

and

K. H. LOGAN, Assistant Physicist

Bureau of Standards

[ISSUED DECEMBER 20, 1915]

WASHINGTON
GOVERNMENT PRINTING OFFICE
1915

ADDITIONAL COPIES

OF THIS PUBLICATION MAY BE PROCURED FROM

THE SUPERINTENDENT OF DOCUMENTS

GOVERNMENT PRINTING OFFICE

WASHINGTON, D. C.

AT

15 CENTS PER COPY

EARTH RESISTANCE AND ITS RELATION TO ELECTROLYSIS OF UNDERGROUND STRUCTURES

By Burton McCollum and K. H. Logan

CONTENTS

I. INTRODUCTION

For a number of years the Bureau of Standards has been studying the electrolysis of underground structures for the purpose of determining the conditions under which electrolysis takes place,

the factors controlling the distribution of stray currents, and the best methods of preventing damage to underground pipe and cable systems.

Among the important factors which influence the amount of current leaving a street railway track or other grounded conductor-carrying current is the resistance of the soil between the current-carrying conductor and other conductors within the earth.

It is the purpose of this paper to discuss the importance of the part played by the soil in the electrolysis problem, to describe some methods for determining the resistivity of soils, to give the results of some experiments on earth resistivity, to point out some factors influencing the electrical conductivity of the earth, and to suggest certain benefits to be derived from a proper application of a knowledge of soil conditions in protecting underground structures from stray currents.

The tendency of electric current to leave metallic conductors and flow through the earth is affected by three factors, namely, the resistances of the metallic circuit and of the earth, and the polarization at the surface of the metal. Because of the latter effect, the current distribution between the metallic conductor and the earth does not follow the ordinary law of divided circuits, unless we measure and include in the calculations the polarization voltages involved. Of the three factors affecting the leakage of current through the earth, the resistance of the earth near the metallic structures is generally the most important, and often the controlling influence. The specific resistance of soils is much higher than that of metals, but the cross section of the leakage path in the earth is so great that there is a considerable earth conductance, sometimes more than that of the tracks and return conductors provided for the current. As is indicated in the data which follow, the conductivity of the soil is almost entirely electrolytic; that is, it is due to the water which it contains and the salts and other materials dissolved in it. The resistivity of soils differs widely, therefore, in accordance with the various factors which influence the conductivity of electrolytes. Further variation is due to the distribution of the moisture in the soil, which determines to some extent the length and section of the path over which the return current travels.

As is indicated later, an investigation has been made to determine whether laboratory measurements of samples of soil taken from the field indicate the resistivity of the soil in situ. Besides measuring the specific resistance of a large number of soil samples representing a great variety of soils, studies have been made of the effects of the character of the soil, the moisture content, temperature, and pressure on soil resistance.

Supplementary tests have been made to determine the relation of the specific resistance of soil to the resistance between pipes and rails; that is, to determine what factors other than the electrical pressure and the resistance of the soil influence the amount of current passing from car tracks to pipe systems.

While a number of factors influence the amount of stray current escaping into the ground, the soil resistance is found to be one of the most important. It is evident that the current flowing in the rails and that returning to the power house by other paths are approximately proportional to the respective conductances of the two paths.

The conductance of the track depends upon the weight and composition of the rails and upon the character and condition of the bonds joining them. The conductance of the other path depends upon the roadbed upon which the track rests, the earth between the rails and underground conductors, the distance between the buried conductors and the rails, and the number, character, size, and distribution of the underground networks.

Of these various carriers of leakage current the earth has the highest specific resistance of any except the roadbed. If the rails rest on wooden ties which keep them free from the earth or if the roadbed is of crushed rock and is well drained, a considerable resistance may be interposed between the rails and the earth, and leakage currents are correspondingly reduced. If, on the other hand, the rails are in contact with moist soil or rest on a moist concrete foundation, there is a relatively low resistance from the rails to the soil, and the resistance of the latter is then one of the chief factors determining the leakage current.

Since, under most conditions, the current flowing between two electrodes in the earth is approximately proportional to the difference of potential between the points, and since in most cases

it is difficult and often impracticable to measure the current, it is customary to depend upon voltage measurements for an idea of the magnitude of the leakage current.

Since the leakage current is approximately proportional to the conductivity of the soil—that is, for a given current the potential difference between two points will depend upon the resistance of the soil between them—it is generally impracticable to obtain a reliable idea of the magnitude and distribution of the leakage currents, and hence of the danger from electrolysis, without a knowledge of soil resistivity. Of course it is the effective soil resistance rather than its specific resistance that is of importance, but the total resistance is necessarily a function of the specific resistance, and measurement of the latter will give an idea of the former if other conditions are sufficiently well known.

The safety of underground structures can not be determined by electrical measurements alone, but such measurements have to be interpreted in the light of local conditions and general experience. It is the purpose of this paper to point out the importance of soil resistance as one of the factors determining electrolytic conditions. High potential differences may mean high current or high resistance. The significance of potential differences can not be known unless the conditions as to resistance of the circuit are also known. These resistance conditions will depend upon the specific resistance of the soil, the character and drainage of the roadbed, the number and extent of the underground conductors, and their proximity to the track network.

II. SPECIFIC RESISTANCE OF SOILS

1. METHODS OF MEASUREMENT

(a) *Conditions of Measurement.*—The data recorded on another page indicate that the conductivity of the soil is very largely electrolytic. In measuring soil resistance, therefore, methods applicable to electrolytes must be employed; that is, it is necessary to prevent polarization due to current used in the test and to avoid any battery action due to the electrodes. This necessitates the use of alternating current and preferably also electrodes so nearly alike that the potential due to the difference in action of

the soil on the electrodes will be negligible compared with the electromotive force used in measuring the resistance. It is difficult to measure the resistance of a small sample of soil in situ. It is impossible to predict the nature and extent of the change in the resistance of the soil if the particles are disturbed, and so it would seem better to measure the soil resistance without disturbing it if possible. Further complication is introduced because of the nonhomogeneous character of the soil in many localities. On account of this any method of resistance measurement involving the assumption of a homogeneous soil throughout any considerable region may involve large errors.

Fortunately, it is not essential to make precise measurements of soil resistance, since the continual changes in temperature, moisture, and soluble content entail large changes in resistance. Moreover, the rapid change in the character of the soil either in a horizontal or vertical direction often renders it impracticable to determine the exact resistance between points any considerable distance apart from the specific resistance of soil samples. What is really of value is a general knowledge of the approximate resistivity of the soils of a given region, together with some information as to the effects of moisture and temperature on the resistivity. Since it is an average resistivity we desire, other things being equal, the larger the amount of earth involved in the measurement the better.

Two methods for measuring the resistance of earth in place were tried out and checked against each other, namely, a null method developed theoretically by Dr. F. Wenner and described in Scientific Paper No. 258 of the Bureau of Standards and the guard-ring method, which is described on page 19. A method employed for measuring the resistance of earth after it has been disturbed involves compressing it by means of a Riehle or other testing machine, and is described on page 12.

(b) *Wenner's Method.*—In making a measurement according to Dr. Wenner's method, which is referred to above, holes were bored in the earth with a 1½-inch auger to a depth approximately twice the distance apart of the holes. A small quantity of damp clay was then tamped in the bottom of each hole and a contact piece consisting of a bare sleeve 1¼ inches long and a plug screwed

to the end of a ½-inch pipe which had been painted and wrapped with insulating tape was thrust or driven firmly into the damp clay.

After the first set of data was taken the terminals were removed and some damp clay was packed in the holes and the measurements were repeated. The terminals were again removed, interchanged, and replaced, and the measurements again made. In this way 9 sets of observations were made to determine the effects of the contacts and the accuracy with which the measurements could be repeated. Table 1 gives the results of the 9 observations.

Trial showed that it was very difficult without a jig to bore a set of holes at equal distances apart and get them placed accurately enough to use the simplified equation given in Dr. Wenner's paper. In nearly all cases the error introduced was sufficient to necessitate working out the entire formula.

TABLE 1

Observations	Ohms per centimeter cube	Per cent of deviation from mean	Observations	Ohms per centimeter cube	Per cent of deviation from mean
1	7006	−5.6	7	7385	−0.5
2	7286	−1.8	8	7400	−0.3
3	7858	+5.9	9	7737	+4.3
4	7339	−1.1			
5	7534	+1.5	Average	7420	
6	7250	−2.3			

It will be seen that the results check within 6 per cent, a much higher degree of precision than is required for practical purposes.

Where an alternating current source is available and the soil is free from rock, measurements are not difficult, though the required transportation of the apparatus from place to place is an objection to the method.

After the measurements had been completed a number of samples of earth were taken in the immediate neighborhood and pressure-resistance curves run on them, using the testing machine, as is explained later. It is there shown that the resistivity obtained by Dr. Wenner's method corresponds to resistivity with

the compression method at pressures of from 30 to 75 pounds per square inch, depending on the soil.

(c) *Guard-Ring Method.*—This method, which likewise measures the resistance of soils in situ, has also been developed at the Bureau of Standards. In this method two parallel trenches large enough for a man to work in and a few inches apart are dug to any desired depth and the separating wall trimmed until the sides are smooth and parallel. Against one side of the wall is pressed a circular metal plate. Opposite this, against the other side of the

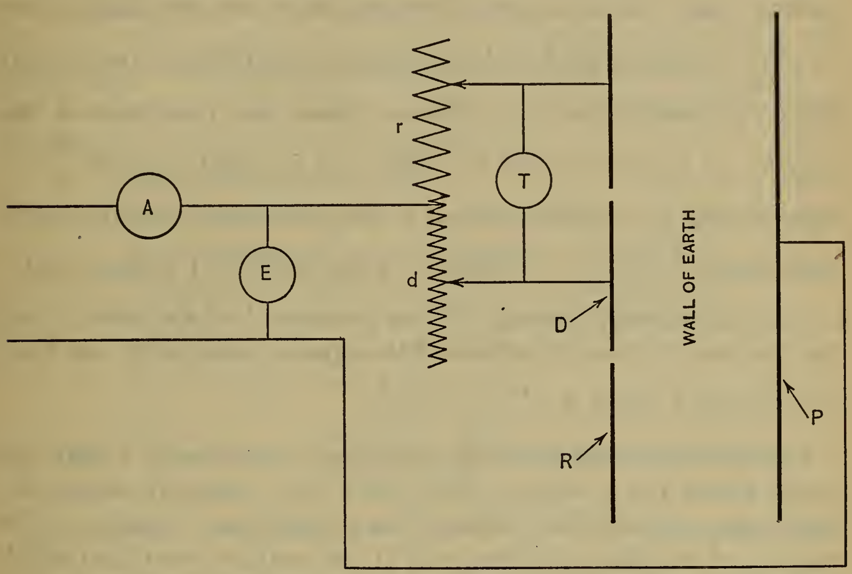

Fig. 1.—*Diagram of corrections and apparatus.*

D, disk; A, ammeter; R, guard ring; P, plate; E, voltmeter; r, resistance in series with guard ring; d, resistance in series with disk; and T, telephone receiver or vibration galvanometer.

wall, is pressed a disk of half the diameter of the first, surrounded by a wide ring of the same external diameter as that of the plate. The disk and ring are separated by a narrow insulating ring and held in position by being screwed to an insulating block of hard rubber or paraffined wood. The connections and apparatus are shown in Fig. 1. Contact was made to the earth wall by plastering on a thin coating of clay paste and the surface of each electrode pressed into the paste and held by clamps while the readings were being taken. In order to determine what portion of

the current indicated by ammeter (A) was being carried by the central circular plate, a noninductive resistance r was placed in series with the guard ring, and another resistance d in series with the disk D. The resistance r was variable, and with the current on the contact was moved back and forth until the vibration galvanometer T showed no deflection, or at least a well-defined minimum. The currents in the two paths would then be inversely proportional to the resistances, or $\frac{i}{I-i}=\frac{r}{d}$ where I is the total current and i is the current passing between the disks; then $i=\frac{Ir}{r+d}$. This method of determining the current in the central plate was devised by O. S. Peters. Now, the resistance of the cylinder of earth between the disk and the plate equals $\frac{E}{i}-d$. Substituting the above value of i, the resistance R of the earth then equals $\frac{E(d+r)}{Ir}-d$, where E is the impressed voltage and I is the total current flowing. From the area A of the disk D and the distance between the disks l the specific resistance can then be calculated, since $R=\rho\frac{l}{A}$, $\rho=\frac{RA}{l}$.

The contacts were generally good, but occasionally a bad one would throw the results off from what they evidently should be. The causes of these bad contacts are probably air bubbles on the surfaces of the plate and loose soil at the contact point into which the paste did not press properly. The thickness and resistance of the paste used did not greatly affect the results. Its total thickness was usually about 3 or 4 mm, and its resistance 2000 or 3000 ohms per centimeter cube. In measuring the length of the current path, about 2 mm were usually deducted from the total length to allow for the paste if the soil was of high resistance. No other correction was made. In calculating the area of the disk the mean diameter was taken; thus in one apparatus the diameter of the disk was 7.46 cm, while the internal diameter of the guard ring was 7.78 cm. The diameter used in calculating the area of disk A was 7.62 cm. Some moisture from the paste diffused into the soil, but as the resistance change came into the machine measurements too, it did not affect the check, although

the original resistance may have been reduced. To avoid adding moisture to the soil, a paste of an amalgam of solder and mercury may be used. In checking up on the testing machine, enough measurements were made to use all of the earth measured by the guard ring, and the average of all such measurements were taken in plotting the curve. No corrections for temperature effects were made until the last 12 measurements were made, which may account in some measure for the fact that in some cases the values obtained by the compression method were considerably less than the values obtained with the guard ring, as would be the case if the machine temperature was higher than that in the other test. The following example illustrates the application of this method and gives an idea of the order of magnitude of the quantities entering into the measurement:

Soil, disintegrated rock.
Electromotive force $=E=17.0$ volts.
Total current $=I=0.101$ amperes.
Resistance in series with disk $=d=206.6$ ohms.
Resistance in series with ring $=r=36.6$ ohms.
Thickness of earth wall $=l=8.1$ cm.
Area of disk $=A=49.3$ sq. cm.

$$R=\frac{E(d+r)}{Ir}-d=\frac{17.0(206.6-36.6)}{0.101\times 36.6}-36.6=910.7 \text{ ohms.}$$

The specific resistance $\rho=\frac{AR}{l}=\frac{910.7\times 49.3}{8.1}=5530$ ohms per centimeter cube. After the measurement had been completed the electrodes were removed and the experiment repeated. The results of four such measurements in the same place are given in Table 2.

TABLE 2

Number of trial	Specific resistance	Per cent variation
1	5542	+1.08
2	5400	−1.52
3	5530	+0.86
4	5460	−0.42
Average	5483	....

The guard-ring measurements having been made, that part of the soil tested may be examined for uniformity or other measurements may be easily taken by sliding the apparatus along the wall. With reasonable care the method will give consistent results, and it permits chemical analysis and determination of moisture content of the particular earth on which the resistance measurement was made. It also has the advantage over the first method of involving no question as to the condition of the soil tested. On the other hand, it requires somewhat more labor and can not readily be used for determining the average resistance of any considerable nonhomogeneous area.

(d) *Compression Method.*—Each of the two preceding methods requires considerable labor and apparatus and the use of an alternating current at the place where the soil is originally located, and this in many places would be difficult to obtain. The number of tests that can be made in this way is therefore quite limited, and it is very desirable to be able to use a method which can be applied to soil removed to a laboratory. Considerable work has consequently been done in developing a laboratory test and in determining the relation between laboratory and field results. The first step was to pack a sample of earth as tightly as possible in a heavy glass cylinder, cover the ends with a mercury-solder amalgam, place the cylinder between copper electrodes, and measure the resistance by the voltmeter-ammeter method, using a small alternating current. With a little practice one can duplicate results with a favorable soil within a few per cent. The results of different testers will differ more, and if the soil is a stiff clay, air pockets are difficult to remove and results vary more widely. To eliminate the personal equation and secure uniform conditions of test, as well as to determine the effect of variations in pressure, a glass cylinder was reinforced by an outside cylinder of iron held in position by cement and the earth slowly compressed in a testing machine.

In this way, with the application of sufficient pressure and careful preliminary packing, results were obtained which for most soils checked very well with the results obtained by the methods described above.

The electrical circuits employed in the compression method are shown in Fig. 2. The following example illustrates the method

of computing the results, the specimen being a soil of disintegrated rock taken 1 foot below the surface of the ground.

Resistance of ammeter $= r = 156.9$ ohms.
Reactance of ammeter at 60 cycles $= x = 187.9$ ohms.
Total pressure = 1000 pounds.
Depth of earth in cylinder $= l = 3.41$ cm.
Cross section of cylinder $= A = 20.28$ sq. cm.
Reading of voltmeter $= E = 41.5$ volts.
Reading of milliammeter $= I = 0.0475$ amperes.

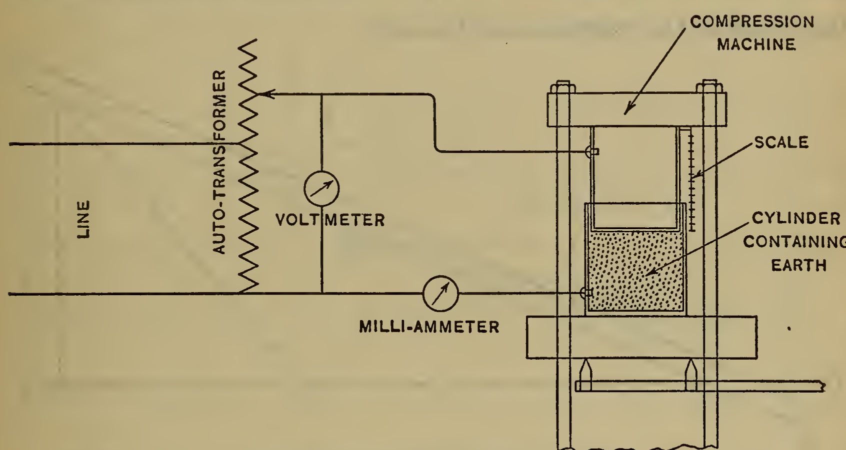

Fig. 2.—*Arrangement for measuring soil resistance by compression method*

Impedance $= \frac{E}{I} = [(R+r)^2 + x^2]^{1/2}$ where R is the resistance of the earth in the cylinder. Substituting the observed values given above $\frac{41.5}{0.0475} = [(R+156.9)^2 + 187.9^2)^{1/2}$. Solving, $R = 696.4$. The specific resistance of the soil is found from the equation $\rho = \frac{RA}{l}$, whence $\rho = \frac{396.4 \times 20.28}{3.41} = 4140$ ohms per centimeter cube.

If a large number of measurements are to be made, it is more convenient to compute R graphically. On a large sheet of finely subdivided cross-section paper lay off BA (Fig. 3) proportional to the reactance of the instrument and BO proportional to its resistance. Continue OB to C and mark the scale of ohms per

division along *OC* with the zero at *O*. Cut a strip from the top of the sheet and indicate a similar scale along one edge of the strip and place the zero on the point *A*. It is most convenient to fix the papers to a drafting board and to let the strip revolve about *A* as a center, using a pin through the zero point as an axis.

Determine $\frac{E}{I}$ and place the strip in such a position on the paper that the distance $AG=\frac{E}{I}$. *GO* will then be proportional to the value of the resistance of the soil.

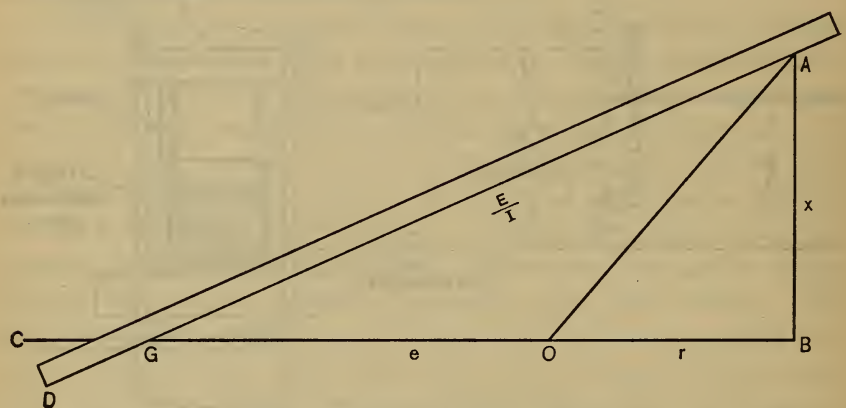

FIG. 3.—*Graphical determination of R*

With a little care the results so obtained will be as accurate as the data justify.

The results of three measurements of soil sampies from practically the same point are shown in Table 3, and indicate how nearly results can be duplicated.

TABLE 3

Sample No.	Pressure	Specific resistance	Per cent difference from average
	Pounds	Ohm/cm³	
1	1000	4140	+0.90
2	1000	4200	+2.36
3	1000	3970	−3.24
Average		4103	

2. MEASUREMENTS OF SPECIFIC RESISTANCE OF SOIL BY THREE METHODS

For the purpose of showing how nearly the different methods check, Table 4 has been prepared. Figs. 4 and 5 illustrate the relation between the results by the compression method, Wenner's method, and the guard-ring method, respectively. The varia-

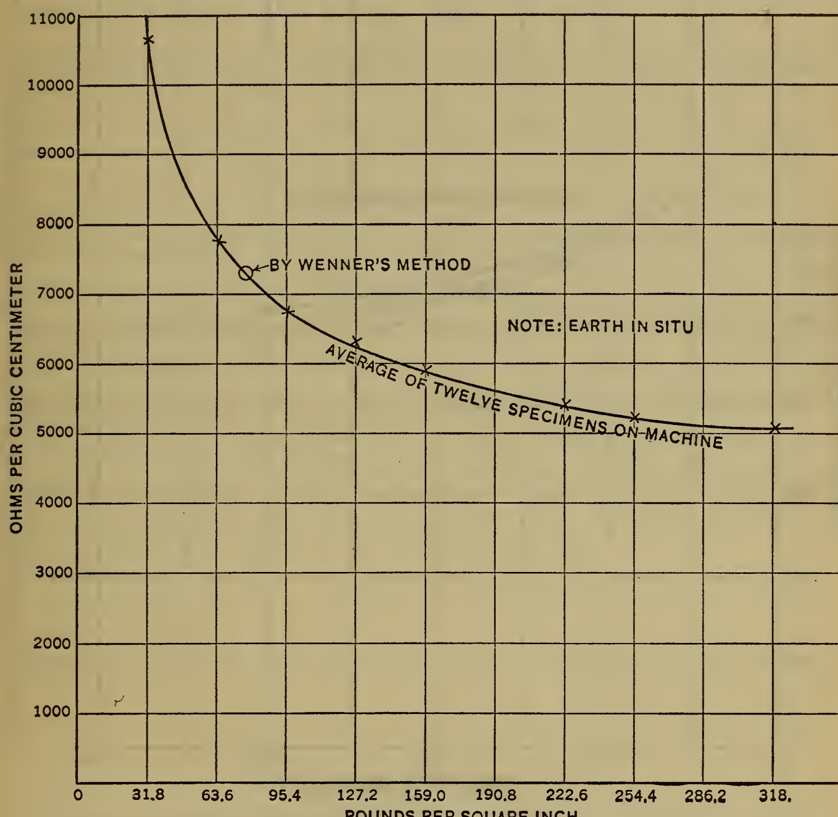

FIG. 4.—*Comparison of earth resistivities by Wenner's and compression methods*

tions in the results are more likely to be due to differences in soil than to errors in method, as the soil used was very heterogeneous, the color and texture sometimes changing very radically within a few feet.

Such variations in the character of the soil occur in many localities. As will be shown later, even the soil in any one locality

will change greatly in resistivity from time to time. It is not important, therefore, to obtain an accurate measurement of the soil resistivity at some particular time, but the approximate value of this resistivity will serve quite as well. This being true, any of the methods described will give satisfactory results and the

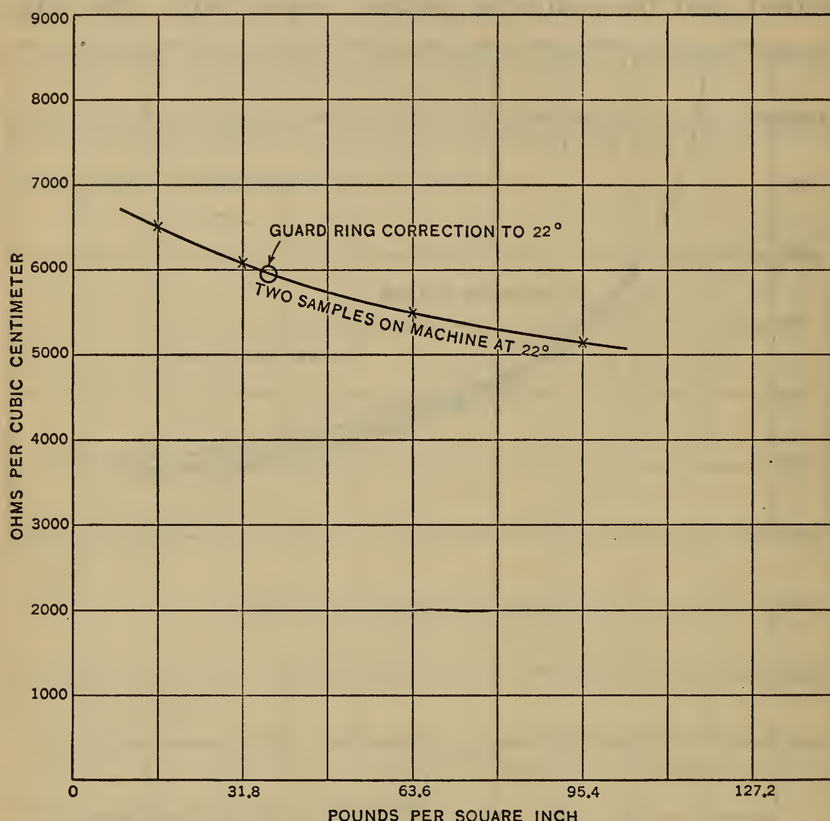

Fig. 5.—*Comparison of earth resistivities by guard ring and compression methods*

most convenient one may be chosen. For most purposes, where rapidity of working is important the compression method is preferable.

Table 5, taken from another publication of the Bureau of Standards,[1] contains the results of measurements of specific

[1] Burton McCollum and K. H. Logan, Electrolytic Corrosion of Iron in Soils, Technologic Paper No. 25, Bureau of Standards.

resistance of soil samples from various localities. These samples were for the most part taken from around gas or water mains or from ditches where new mains were being laid. Care was taken to obtain soil from the bottom of the excavation and that it should be free from any ususual contamination from the street. Where pipes were laid in made ground, the samples, of course, contained more or less foreign material; indeed, a great variety of materials has been identified in some of these samples. The samples were removed from the surrounding earth and transferred immediately to glass jars or tin cans and sealed at once to prevent loss of moisture. At least two samples of soil were taken at each place, and throughout the experiments care was taken to prevent contamination and loss or absorption of moisture. The measurement of specific resistance were made at ordinary room temperatures by the use of alternating current and a voltmeter and milliammeter. Care was taken not to allow the current to flow longer than necessary, so that there should be little heating due to the current. As has been said, the results could be duplicated only approximately. Their values serve very well, however, to show the range of soil resistances likely to be encountered in practice. For convenience, the moisture content of these soil samples is given in the same table.

9560°—15——3

TABLE 4

Comparison of Resistivities of Soils by Wenner's Method, the Guard-Ring Method, and the Compression Method

Specimen No.	Character of soil	Wenner's method	Guard-ring method	Compression method. Pressures in pounds per square inch [b]											
				16	32	64	96	128	160	192	224	256	320	384	640
1	Disintegrated rock, heterogeneous	7420			9670	7740	6800	6320	5900	5610	5400	5240	4960		
2	Red clay, soft	8250			8300	6870	6340	5890	5740						
3	Red clay	11 052			9720	8030	7296	6956							
4	Disintegrated rock, hard		2670					2555							2665
5			2047									1924			2096
6	Red clay		6618					7235						6460	
7	Disintegrated rock		5530		7180	6000	5250	4950			4150		4100		
8			5030		5500	4820		4320		4217		4115	4150		
9	Disintegrated rock, very solid		4630		5350	4690		4030		3750		3625	3520		
10	Disintegrated rock		5300		6730	5890		4900		4380		4130	4030		
11	.....do		6900		3660	3325		2865		2660		2690	2525		
12	Disintegrated rock (clearage plane)		8250		6920	6200	5640	5120							
13	Disintegrated rock		6160		7425	6200	5700	5150	4900						
14	Red clay		5000		3340	3025	2960	2880	2875						
15	Red clay, some stones		7900		8860	7820	7235	6865	6675						
16	Red clay, disintegrated rock		8700		10570	9170	7750	7250							
17	.....do		11 100		14 590	13 050	11 180	10 370							
18	.....do		13 900		15 100	12 450	11 050	10 200							
19	Sand with some loam		97 000	71 700	67 600	62 100	58 800	56 700							
20	.....do		92 000	89 830	85 700	76 100	71 830	68 200							
21	Loam and sand		61 600	63 400	59 860	57 100	54 800	52 300							
22	.....do		68 200	69 500	67 900	63 800	60 870	58 700							
23	Sand and loam, heterogeneous		50 000	37 900	36 500	36 200	35 500	35 400							
[a] 24			5950	6560	6000	5425	5185								
25			3250	3930	3750	3410	3399								
26			1795	1860	1815	1740	1720								

27			1450	1407	1370	1240	1280								
28			1750	1800	1740	1675	1630								
29			2030	2390	2270	2200	2150								
30			2000	2420	2270	2120	2085								
31			1560	1760	1630	1550	1500								
32			1670	2530	2370	2320	2230								
33			2128	2375	2380	2290	2220								
34			3460	3540	3460	3330	3290								
35			3660	3955	3900	3700	3630								

a The resistances of samples 24—35 by the guard-ring method have been reduced to resistance at the temperature at which the corresponding samples were measured in the testing machine by applying a temperature coefficient of 0.05 per degree F.

b For kilograms per square centimeter multiply by 0.0705.

TABLE 5

Specific Resistance of Soils

PHILADELPHIA SOILS

No.	Character	Moisture	Specific resistance
		Per cent	Ohms/cm [3]
1	Moist gray clay	11.7	651
2	Moist yellow clay	14.8	3850
3	Moist blue clay	16.1	3036
4	Near dry red sand	7.6	2700
5	Moist red clay	17.4	8820
6	Nearly dry mica schist	4.7	156 400
7	Nearly dry gray clay	16.2	5930
8	Nearly dry clay rock and cinders	17.9	595
9	Moist blue clay and gravel	13.1	2830
10	Moist blue clay	15.3	1605
11	Moist yellow clay	17.2	5340
12	Moist yellow clay and sand	13.4	6280
13	Wet gravel	11.0	24 550
14	Wet humus and clay	9.5	2600
15	Moist clay sand cinders	17.4	2060
16	Damp disintegrated schist	12.9	12 100
17	Wet clay cinders gravel	16.8	5000
18	Moist yellow clay	19.4	4825
19	.....do	17.3	3820
20	Moist red clay	19.3	21 200
21	Moist yellow clay	15.6	25 900
22	Moist red sand and clay	15.7	13 700
23	Moist clay cinders sand	13.7	1494
24	Moist clay and sand	20.0	821
25	.....do	18.7	1774
26	Damp clay and humus	16.7	2490
27	.....do	16.2	2585
28	Near dry disintegrated schist	0.3	610 000
29	Damp yellow clay	16.8	2250
30	Moist yellow clay	18.5	2455
31	Saturated clay and cinders	23.8	4410
32	Moist clay and sand	18.6	6260

PITTSBURGH SOILS

No.	Character	Moisture	Specific resistance
33	Damp sand	13.4	4506
34	Moist yellow clay	16.5	2819
35	Moist clay and humus	20.5	2300
36	Blue clay	26.5	14 025
37	Moist gray clay	26.3	619
38	Damp sand	13.0	1335
39	.....do	10.2	8709
40	Loam and cinders	21.8	1074
41	Near dry sand	12.3	2908

TABLE 5—Continued

ERIE SOILS

No.	Character	Moisture	Specific resistance
42	Moist clay and gravel	6.0	18 080
43	Clay coal gravel	16.7	1796
44	Wet blue clay	19.3	3779
45	Moist blue clay and sand	11.9	3080
46	Moist gravel	5.7	14 025
47	Wet blue clay and sand	19.6	2462
	ST. LOUIS SOILS		
50	Wet clay	20.4	600
51	Blue clay	21.1	700
52	Moist virgin soil	20.8	1500
53	Moist yellow clay	21.5	1250
54	Yellow clay	19.0	1800
55	.....do	....	1600
56	.....do	21.1	1800
57	.....do	22.8	1400
58	.....do	21.3	1400
59	Virgin black soil	21.2	1700
60	Yellow clay	16.0	1800
61	.....do	23.4	990
62	.....do	18.4	700
63	.....do	21.9	950
64	Sand and humus	17.8	925
65	.....do	20.0	900
66	Blue clay	22.0	470
67	Virgin yellow clay	19.1	1450
68	.....do	22.5	484
69	Yellow clay	22.0	700
70	Virgin yellow clay	20.0	1700
71	Virgin soil	22.9	840
72	Yellow clay	23.3	900
73	Blue clay	26.1	400
74	.....do	19.1	600
75	.....do	24.2	830
76	Moist blue clay	23.1	500
77	Near dry yellow clay	16.4	1100
78	Blue clay	17.1	650
79	Yellow and blue clay	26.9	600
80	.....do	19.7	820
81	Blue clay	20.0	750
82	Clay and loam	19.2	1450
83	Sandy clay	19.5	1600
84	Yellow clay	22.6	1200

TABLE 5—Continued

APOLLO, PA., SOIL

No.	Character	Moisture	Specific resistance
48	....	30.5	1796

ALBUQUERQUE, N. MEX., SOILS

No.	Character	Moisture	Specific resistance
85	....	15.3	43 960
86	....	11.1	59 475
87	....	11.9	41 908

WASHINGTON, D. C., SOILS

No.	Character	Moisture	Specific resistance
88	Air-dry red clay..................................	4+	2 340 000
89	Near dry..................................	10	14 660
90	Moist loam..................................	20	8729
91	Wet yellow clay and sand..................................	30	41 490
92	Wet humus, clay, and sand..................................	30	24 060

Two samples of soil from 20 to 50 grams each were removed from the jars of earth, placed in evaporating dishes and weighed, and then transferred to an oven maintained at about 105° C. From time to time the samples were reweighed until they showed no further loss of water. The per cent of moisture was then computed in terms of the original weight of the soil. The significance of the moisture content of the soil is discussed in a later paragraph.

III. FACTORS AFFECTING THE SPECIFIC RESISTANCE OF SOILS

The wide range of resistances shown in Table 5 at once raises the question of the cause of these differences. A number of experiments have been tried to determine the causes of the differences in specific resistance and to determine the effect of each.

1. EFFECT OF PRESSURE

It will be seen from Figs. 4, 5, and 6, showing the specific resistance of soil at different pressures, that the resistance of the soil decreases as pressure is applied until about 100 pounds per

square inch is reached. Beyond this point there is but a slight change in resistance with pressure. Fortunately, the results of outdoor measurements check fairly close with this limiting value. It seems, therefore, that a satisfactory idea of soil resistance may be obtained without taking apparatus into the field.

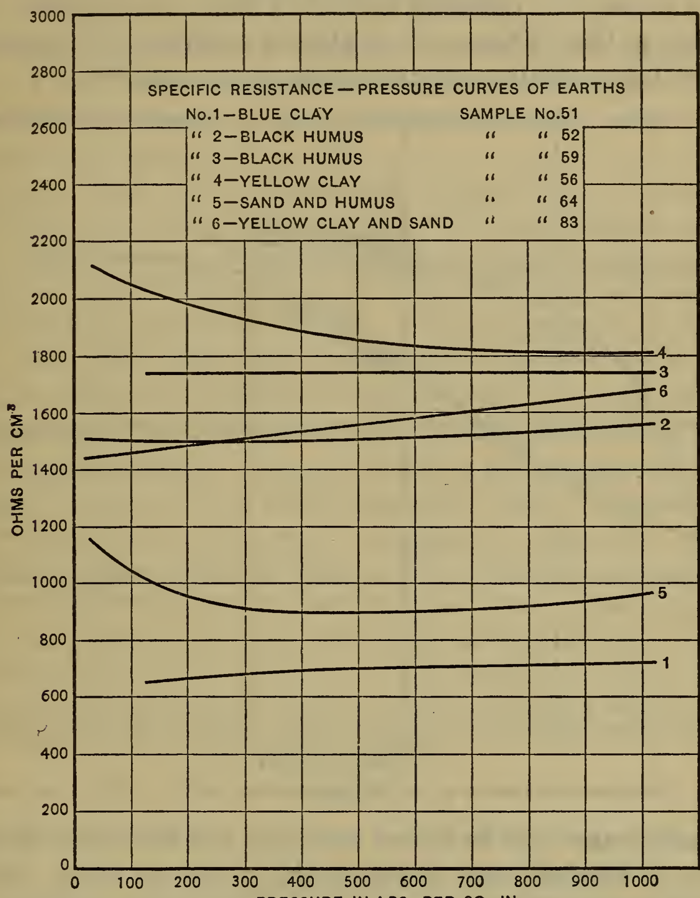

FIG. 6.—*Specific resistance of soil at different pressures*

Certain precautions must be observed, however, chief among which is to apply the pressure slowly enough to permit the earth to adjust itself to the pressure applied before readings are taken. The time required for this adjustment will range from a few minutes to several hours, according to the change in pressure and

the character of the soil. Fig. 7 shows this change of resistivity with time for two samples of soil. It will be noted that the total change in resistivity even after standing from one to two hours amounts to only about 5 per cent, so that for ordinary purposes it is not necessary to wait long before taking the measurement. As will be seen by reference to Figs. 4 and 5, a resistivity corresponding to that of the earth in place is obtained by bringing the pressure up to about 50 to 75 pounds per square inch.

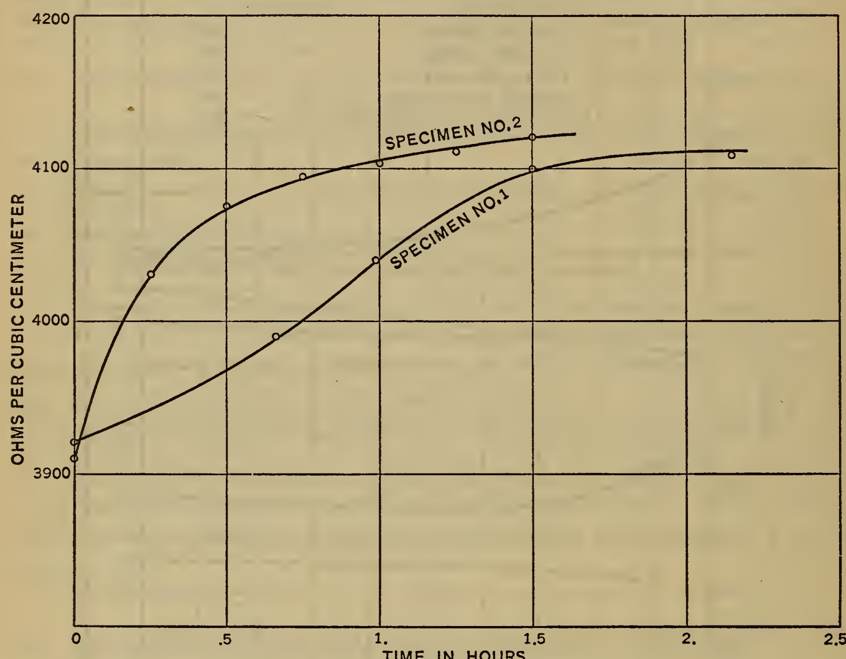

FIG. 7.—*Resistance-time curves of wet red clay standing under a load of 1,600 pounds*

Usually water will be forced from the soil before the limiting pressure is reached, and of course this excess of water must be carefully removed to prevent leakage of the testing current. On account of the loss of water mentioned above the moisture content of the soil tested in the machine is not the same as that of the soil in the field, with which it is compared as to resistivity. What is obtained, therefore, is not identity of condition but an equivalent resistivity. The earth in the machine will evidently

be saturated, since it has given off excess water, while the earth in the field may be far from saturation. The temperature coefficient of soil is high, and care must be taken not to heat the soil by the current used in measuring its resistance.

2. EFFECT OF MOISTURE

As was stated in the introduction to this paper, the conductivity of the soil is electrolytic, and the passage of a current through it is by means of the soil moisture and the salts or other materials in solution.

Table 6, taken from Technologic Paper No. 25 (Bureau of Standards), gives the results of an experiment illustrating this fact. It consists of a series of resistivity measurements taken on samples of a red clay soil. A quantity of this soil was dried at 105° until it ceased to lose weight. Various quantities of distilled water were then thoroughly mixed with samples of the dried earth to obtain the desired moisture contents. At the close of the experiment the moisture content was also determined by the loss of weight method. From the table it will be seen that when the earth is nearly dry its resistivity is very high. The resistivity falls rapidly as the per cent of moisture is reached. Further addition of water has little effect. The slight rise in resistivity when the moisture content became more than 50 per cent may be due to a dilution of the conducting solution due to a lack of soluble material in the soil, but it is difficult to work with soil containing so much water, and the apparent small rise in resistivity may be due to these difficulties.

TABLE 6

Relation Between the Amount of Moisture in the Soil and its Specific Resistance

Per cent moisture (in terms of dry earth)	Specific resistance (ohms per centimeter cube)	Per cent moisture (in terms of dry earth)	Specific resistance (ohms per centimeter cube)
5.0	2 340 000	44.5	4725
11.1	237 400	55.6	4870
16.7	13 880	56.7	5197
22.2	6835	77.8	5045
33.3	5400		

While a similar set of data may be obtained with any soil, the point at which the resistivity reaches a nearly constant value will of course depend upon the sample measured. We may think of each particle of soil as surrounded by a film of water of greater or less thickness and held in place by capillarity or by adhesion between soil and water. When the soil is saturated all the spaces between the earth particles are filled with water, and current flowing across the soil has its shortest and widest path. As the soil becomes dryer the layer of water surrounding each soil particle becomes thinner, and the current which must pass through the soil by way of the water has, therefore, a narrower and more circuitous route. The soil resistivity consequently becomes greater as this water film decreases in thickness and as the length of the path over the surface of particles between points of contact increases. Probably it is this conducting moisture film that explains the effect of pressure noted above. The contact between the soil particles as they are first placed in the testing cylinder is poor, and the resistivity is consequently high. With the increase of pressure larger areas come into contact with each other, and moisture is forced from those regions where the pressure is greatest and fills voids, thus further reducing the resistivity. More pressure may cause a loss of water, but if gradually applied it is accompanied by a corresponding decrease in the length of the earth cylinder which remains saturated, and therefore the change in resistance will be approximately proportional to this change in length of the cylinder, which would be very small.

3. CHARACTER OF SOIL

The experiments on the effect of pressure and of moisture show that while moisture is a determining factor in soil resistivity the amount of water (the number of grams of water per kilogram of earth) is not a definite criterion of the conductivity of the soil, if its condition as to compactness is unknown. A given quantity of water in a hard-packed road will produce much greater conductivity than the same amount in a soil recently loosened by freezing and thawing.

It is evident, too, that the character of the soil will largely determine the effect of a given quantity of water. If the soil, due to its location or composition, contains large quantities of soluble salts, absorption of moisture will greatly decrease its resistivity; while if practically all soluble material is absent, the water absorbed will remain nearly pure, and consequently a poor conductor.

Likewise the physical character of the soil has a great influence. If the particles are fine, it will require a much larger quantity of water to cover their surfaces with a conducting film than if the soil is composed chiefly of large grains of sand, since in the latter case the ratio of surface to mass will be much smaller, the volume increasing as the cube and the surface as the square of the dimensions of the particles. Thus saturated sand may show a much higher resistivity than unsaturated clay, because the sand may contain less soluble material to make the water a conductor and because the amount of water may actually be less.

Often the soil beneath the pavements of the streets receives much organic matter in solution due to traffic. In some alleys and streets this is augmented by refuse thrown upon them and the overflow of or absorption from drains and sewers. The conductivity of such soil is usually high.

In many cities large areas consist of made land, the material of which is composed largely of refuse of many kinds, both organic and inorganic. The conductivity of such land is usually especially high, due partly to the amount of soluble material it contains and partly to the fact that it is usually lower than the neighboring regions, and consequently contains more moisture. Often it not only receives the drainage of the higher land, but seepage water from the river or bay from which it has been reclaimed. Salt marshes and moist alkali soils in general may be expected to exhibit very low resistivity.

In such regions we may expect not only a maximum damage from any stray current which may be discharged from buried pipes, but also a maximum natural corrosion due to chemical action.

4. EFFECT OF TEMPERATURE ON SOIL RESISTANCE

Since the conductivity of soil is electrolytic, we would expect soil samples to show a temperature coefficient similar to that of other electrolytes. This temperature effect is described in Technologic Paper No. 25 (Bureau of Standards). To obtain data on the subject a fairly moist soil was packed in a glass vessel and the resistance measured between a metal cylinder on the outside of the soil and a hollow cylindrical electrode in the center. The soil was placed in a chamber which was surrounded by salt and ice and allowed to remain until a steady temperature of −19° C was reached, the resistance being measured by means of the electrodes with an alternating current and the temperature being observed by means of a mercury thermometer in the hollow central electrode.

The change in temperature was quite gradual and the diameter of the cylinder about 3 inches, so there was probably no large difference of temperature between the outer and the inner electrode. The data are given in Table 7 and plotted in Fig. 8.

TABLE 7

Effect of Temperature on Resistance of Soil

[Soil No. 32; moisture, 18.6 per cent; specific resistance at 20°, 6260 ohms/cm³]

Temperature	Resistance	Temperature	Resistance
°C	Ohms	°C	Ohms
18.0	224	− 3.0	1185
13.0	286	− 5.5	4340
8.5	398	−12.0	21 700
1.5	458	−13.0	24 600
1.0	462	−15.0	36 200
0.0	542	−18.0	45 000
−2.0	940	−19.0	48 900

An interesting phenomenon occurs when the electrolyte is cooled below the freezing point of water. Here the data indicate a very rapid rise in resistance. The increase may be attributed to the freezing of the solution and the consequent deposition of particles of ice of high resistance throughout the mass.

While the change is very rapid just after the freezing point of water is reached, the continued rise in resistance as well as the

rate of change in resistance with time indicate that the solution has no definite freezing point, but that, due to the salts in solution, the freezing is gradual, and the proportion of frozen material

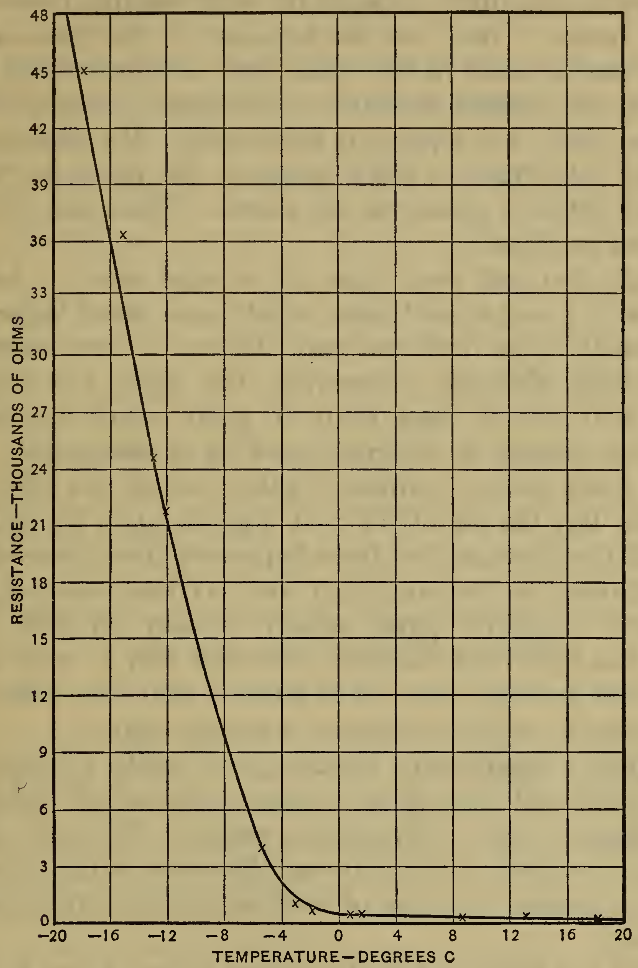

FIG. 8.—*Effect of temperature on earth resistance*

is a function of temperature. A number of tests of which data recorded are typical have been made on different soils with similar results, although the specific resistance of the different earths at a given temperature varied greatly.

5. RESISTANCE LAYERS BETWEEN PIPES OR RAILS AND SOIL

While the specific resistance determines the conductivity of the soil itself, the soil resistance is only one of the factors which determine the quantity of electricity which escapes from a street railway system. That the conductance of the track and the relative conductances of the track and underground structures, as well as the roadbed resistance and distance between the track and pipes, affect the leakage is self-evident. We may now consider still other factors which influence the resistance between pipes and rails to a greater or less extent. These may be termed interposed resistances.

Wrought-iron and steel pipes are covered more or less completely with a coat of mill scale, which has a much higher resistance than the pipe itself and may also act to some extent as a noncorrodible electrode. Moreover, the pipes are frequently covered with one or more coats of paint, which also tends to reduce the amount of current picked up or discharged. There is little doubt that a continuous paint coating will offer a high resistance, but the life of the coat depends upon the soil, moisture, and the electromotive force impressed upon it as well as on the constituents of the paint itself, and has been shown to be very uncertain.[2] Cast-iron pipes usually contain on their surface more or less sand from the mold, and there may be some alloying of the sand and the iron. It is possible that this surface layer might either be of high resistance or noncorrodible.

Preliminary experiments, however, with similar cast-iron pipes, half of which had the original surface machined off, fail to show any resistance, due to the surface coating. We may also add that we have failed to find material differences in the rate of electrolytic or natural corrosion of surfaced and unsurfaced cast-iron specimens.

If pipes are buried when the ground is dry, there is a possibility that when the ditch is first filled there will be a poor contact between earth and pipes in certain localities. We would expect, however, that as water found its way down to the pipes

[2] Burton McCollum and O. S. Peters, Surface Insulation of Pipes as a Means of Preventing Electrolysis, Technologic Paper No. 15, Bureau of Standards.

the joint action of the moisture and pressure of the earth above would pack the earth firmly against the pipe in a short time.

No experiments have been made in the field to date to determine either the magnitude or the duration of resistance due to poor contact between earth and rails or pipes.

The following laboratory experiment, however, indicates that with fairly homogeneous moist soil the contact resistance between a pipe and the soil will be small.

A box of paraffined wood 4 inches square and 14 inches long inside was filled with a rather dry clay collected from the side of a hill. Sheet-iron electrodes 4 inches square were placed in the

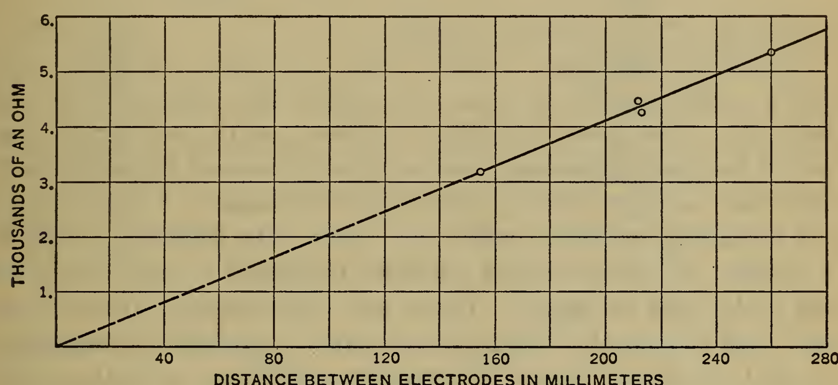

FIG. 9.—*Relation of earth resistance to distance between electrodes*

box 12 inches apart, the earth tamped thoroughly and the resistance measured with a voltmeter and milliammeter using alternating current. One electrode was then removed, a few inches of the earth shaved away, the electrode replaced, and the earth tamped in behind it. The tamping of the earth between the electrodes was thus maintained constant. The box was kept covered during measurements to conserve the moisture in the soil.

The results of a series of these measurements are given in Table 8 and plotted in Fig. 9. A continuation of the curve passes through the origin of coordinates and indicates that there was no appreciable contact resistance between the earth and the electrodes. The curve also indicates a linear relation between the resistance and the distance between the plates. The deviation

of two points from the curve may be due to variations of temperature in the soil or to errors in determining the distance between the plates since it was difficult to get them exactly parallel.

TABLE 8

Soil Resistance—Distance Data

Distance between electrodes	Resistance of soil
Millimeters	Ohms
155	3210
213	4430, 4265
260	5370
305	6320, 6640

While the resistance between two conductors buried in the earth would usually be much less than that measured in the laboratory, the area of contact between earth and conductors would be much larger, and the relation of contact to earth resistance may be expected to remain about the same. A soil containing insulating materials might, of course, give different results if a number of the insulating particles happened to come between the metal and the earth. Dryer soil might make a poorer contact with the metal, but the soil resistance would also be increased, so that we would expect the relative resistance of contact and soil to remain about the same.

6. POLARIZATION AND SURFACE FILMS

Polarization voltage is *the change in voltage between an electrolyte and an electrode immersed therein* due to the flow of electric current to or from the electrode. When a potential difference exists between two electrodes in an electrolyte the positive ions migrate toward the negative electrode and the negative ions toward the positive electrode. Thus, with aqueous electrolytes hydrogen and oxygen may be liberated at the electrodes, and where no chemical reaction with the electrolyte occurs these gases collect on the electrodes, forming films of high resistance. Hence it happens that if one attempts to measure the resistance of a soil sample by means of direct current, the apparent resistance is found to be a function of the time and the amount of current employed.

The same phenomenon occurs when current flows between two buried conductors. The following experiments illustrate the character and magnitude of this effect. Two current electrodes 5 cm square were set vertically about 10 cm apart in a stone jar of earth. Just back of each electrode, and insulated from it by a

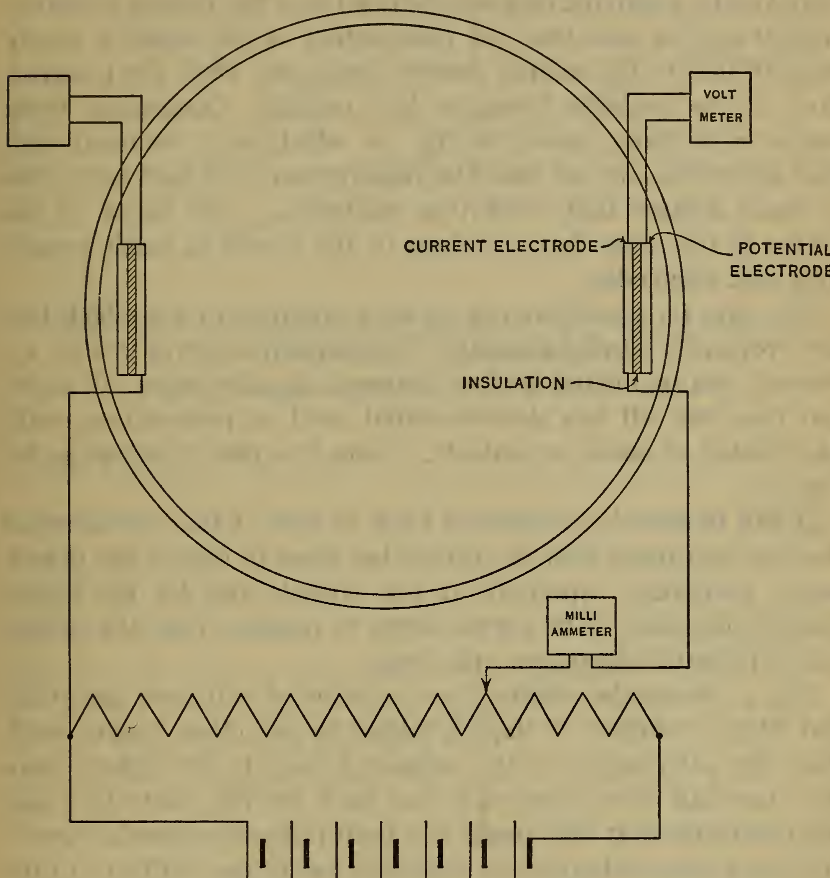

FIG. 10.—*Apparatus for determining polarization potentials*

layer of pitch, similar potential electrodes were placed. Current was passed between the inner electrodes, and the potential difference between each electrode and the adjacent potential electrode was measured by means of a high-sensibility voltmeter, which required very little current. Fig. 10 represents the arrangement of the apparatus.

The current density at the electrodes was varied and the polarization potentials at each electrode read when a steady value was obtained.

Figs. 11, 12, 13, 14, 15, and 16 show the results of these observations. From Fig. 11, which shows the results with iron electrodes and a virgin red clay soil obtained near the Bureau of Standards, it will be seen that the polarization at the anode is nearly proportional to the current density employed, while the polarization at the cathode increases less rapidly. Comparing these curves with those shown in Fig. 12, which were obtained with lead electrodes, we see that the polarization with lead electrodes is much greater than with iron electrodes. The shape of the curves is the same, but the slope of the curves is much greater with lead electrodes.

The data for the above curves were obtained in soil which had not previously carried current. To obtain the curves in Fig. 13, current was permitted to flow between the electrodes all night, and then the cell was short-circuited until no polarization could be detected at anode or cathode. Data was then obtained as for Fig. 12.

It will be seen by comparing Figs. 12 and 13 that the effect of the long continued flow of current has been to reduce the polarization potentials, especially at the cathode and for the higher current densities. The curves seem to indicate that the polarization potential decreases with time.

Fig. 14 shows the results of an experiment with iron electrodes and with a solution of Na_2CO_3 added to fine clean quartz sand. Here the polarization at the cathode is seen to be slightly more than one-half that when clay was used for the electrolyte and the polarization at the anode has been reduced somewhat more. It is not evident whether the change is due to the $NaCO_3$ or to the substitution of sand for the clay. However, since the sand was considerably more porous than the clay, it would allow any gases to escape more readily, and this would tend to reduce the polarization potential. Fig. 15 shows the results of a similar experiment with lead electrodes and a solution of Na_2NO_3 in sand. The cathode curve is similar to that in Fig. 14. The anode curve is very peculiar, showing a critical value at a current density of

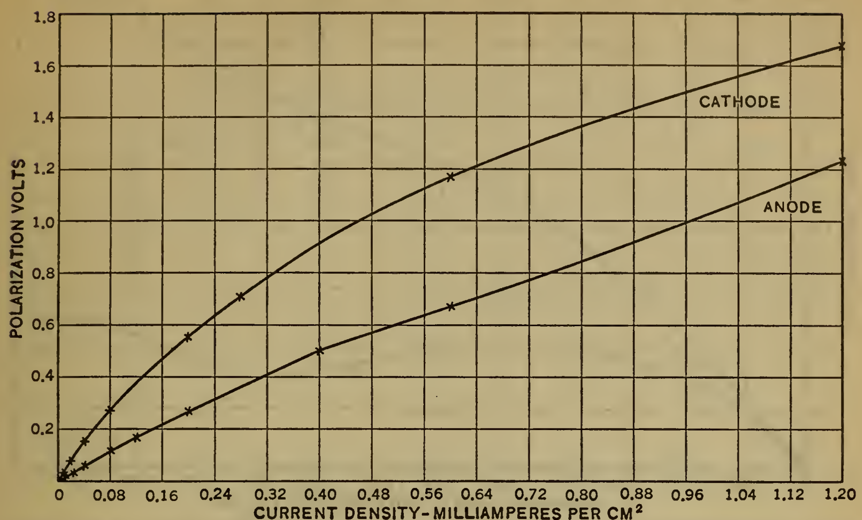

FIG. 11.—*Polarization voltage—Iron electrodes in natural soil*

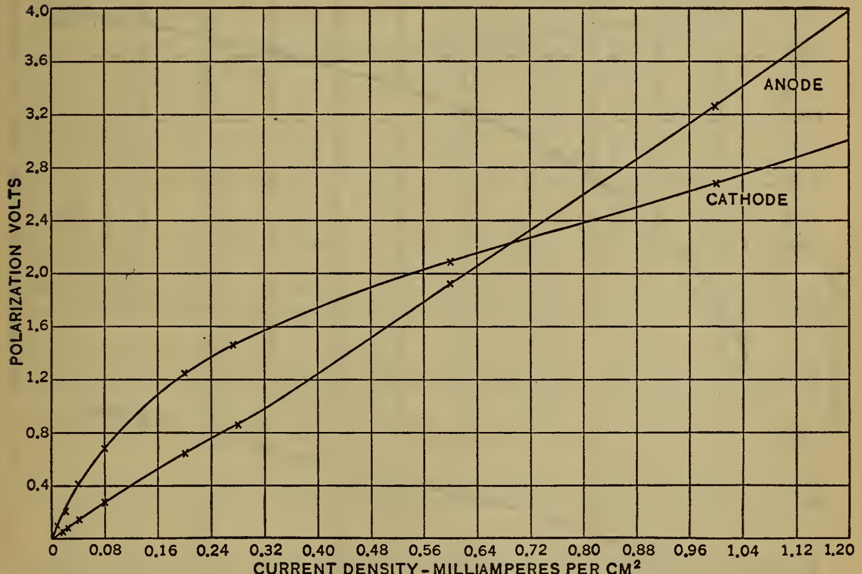

FIG. 12.—*Polarization voltage—Lead electrodes in natural soil*

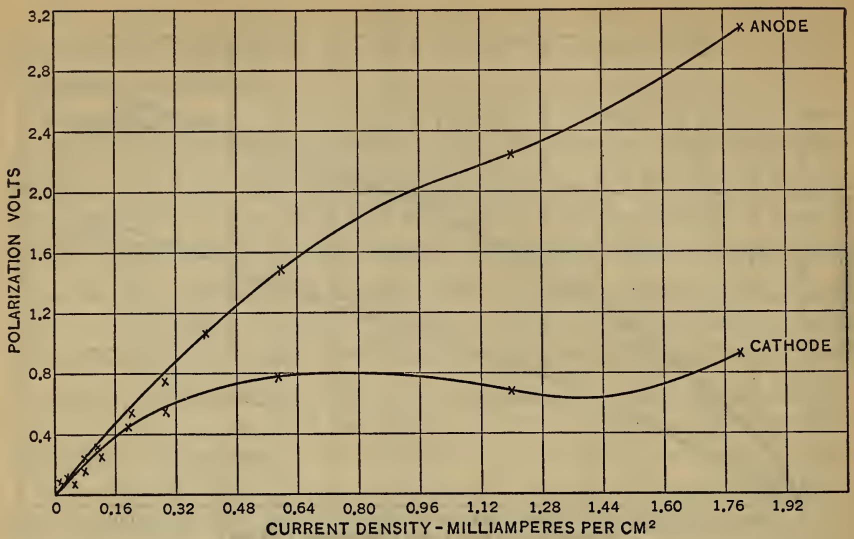

FIG. 13.—*Polarization voltage—Lead electrodes in natural soil—Current on all night before observations*

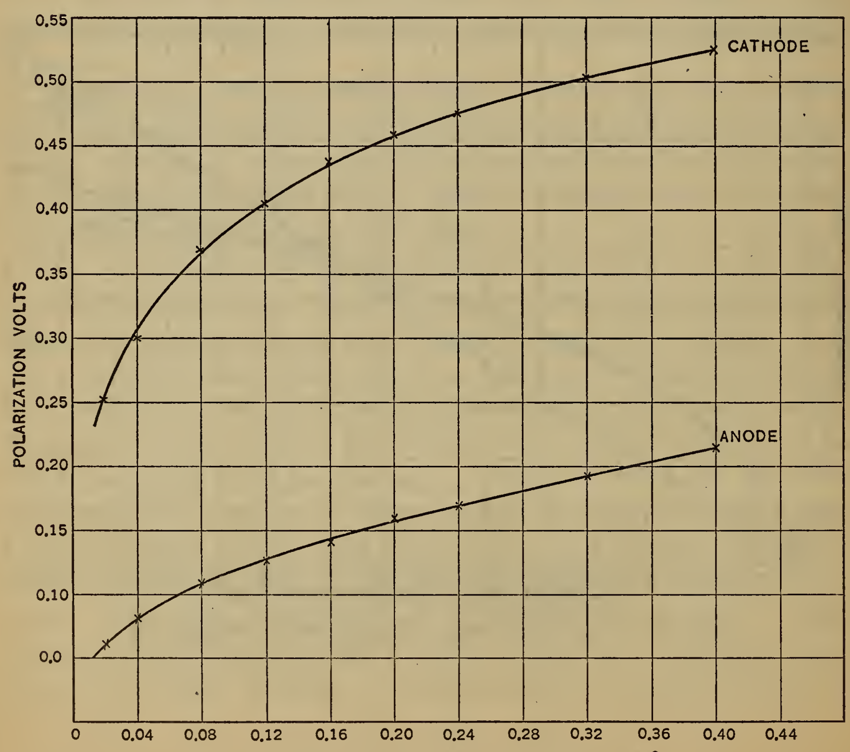

FIG. 14.—*Polarization voltage iron electrodes—2 per cent Na^2CO^3 in fine sand*

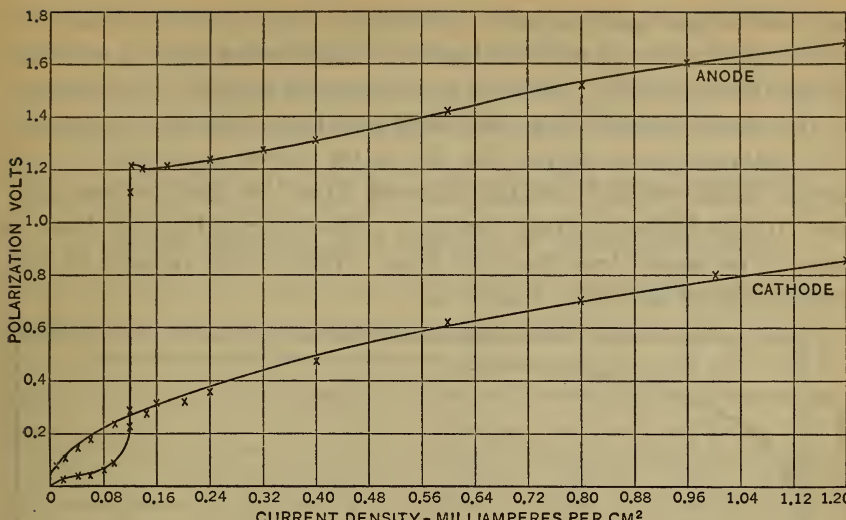

FIG. 15.—*Polarization voltage—Lead electrodes 2 per cent $NaCO^3$ in fine sand*

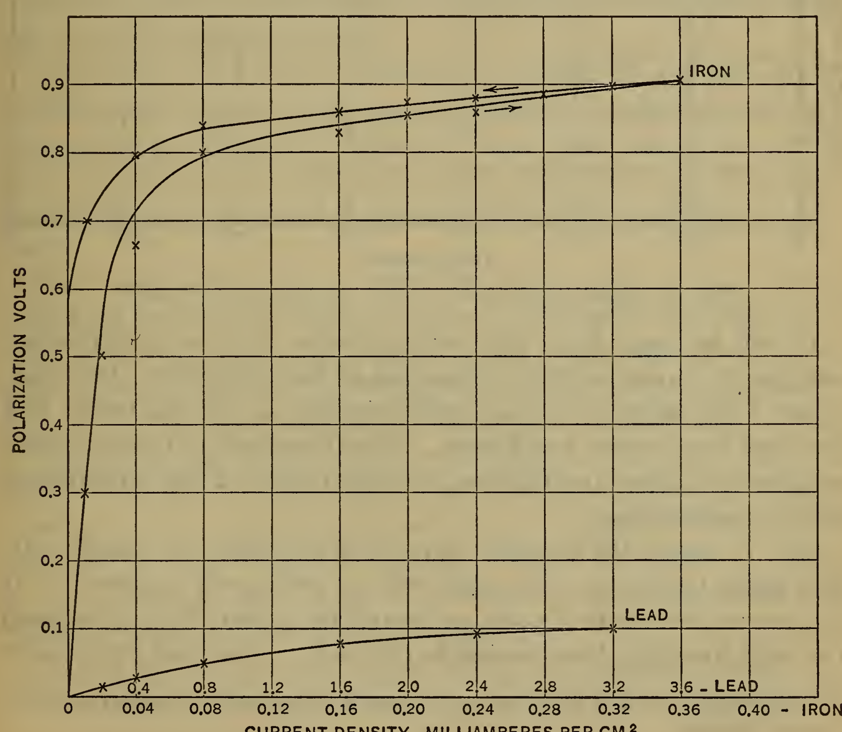

FIG. 16.—*Polarization voltage iron and lead electrodes NaOH in fine sand*

0.12 milliampere per square centimeter. Fig. 16 shows the anode polarization voltage with lead and iron electrodes when a solution of NaOH was used. With the iron electrode a curve was obtained as the current density was increased and then as it was decreased. The polarization is higher for the latter curve, as would be expected if the cell did not fully recover from the effect of polarization at the higher current density. The polarization for lead is seen to be much less than for iron. This is the reverse of the results shown in Figs. 11 and 12.

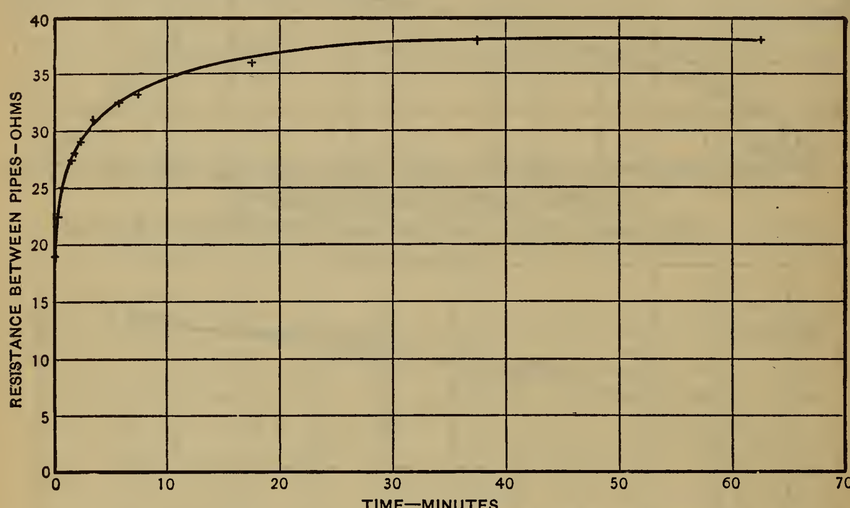

FIG. 17.—*Effect of polarization on resistance between buried pipes*

It will be seen from the curves shown that the polarization voltage at an electrode is a function of the electrolyte, the character of the electrode, the current density at the electrode, and the time the current has flowed. The phenomena of polarization voltage are under investigation, and the results of the experiments will be reported later.

Fig. 17 shows the decrease in current between two 4-inch cast-iron pipes buried in a wet clay soil, as previously reported.[3] It represents the effects of polarization on the current flowing between two cast-iron pipe lines buried in clay soil. The lines were about

[3] Burton McCollum and K. H. Logan, Electrolytic Corrosion of Iron in Soils, Technologic Paper No. 25, Bureau of Standards.

50 feet long and the soil very wet. The resistance of the earth between the pipes was about 18 ohms at the beginning of the experiment. As will be seen from the figure, the apparent resistance of the circuit was practically doubled in half an hour.

IV. RELATION OF SOIL RESISTANCE TO ELECTROLYSIS

1. TRACK LEAKAGE AS A SOURCE OF STRAY CURRENTS

From the data given above it will be seen that the specific resistance of soils varies through a very wide range, and that this resistivity depends on a number of factors which are difficult or impossible of accurate determination with respect to soils between buried conductors. When one attempts to deal with the total resistance between a portion of a track network and a neighboring pipe line, the problem is of course much more complicated. It is important, however, to make a thorough study of resistance conditions and to determine as accurately as practicable their effect on the leakage current.

(a) *Bonding and Track Network.*—It should be pointed out in the first place that in so far as practicable the return currents of street railways should be confined to the tracks and return feeders. To this end the conductivity of the grounded return system should be as good as can be procured for the permissible investment.

This means, first of all, that the bonding of the rail joints should be kept in the best condition by frequent thorough tests of all bonds and the prompt repair of any found defective. Pressure wires for measuring potential drops in the earth return will also be of great service in determining track conditions. Under service conditions track resistance is found to vary between wide limits, according to the weight of rail and the effectiveness of the bonding. For a well-bonded track of 100-pound rails the resistance will be approximately 0.0045 ohm per 1000 feet of single track. Owing to bad bonding, however, actual track resistance will often reach several times this figure.

A more neglected factor is the number of tracks returning current directly to the power house. Frequently a substation is

located with not more than a single track passing near it when shifting the location of the substation a few blocks would afford a return path of two or even four tracks. Since a 90-pound rail has approximately the conductivity of 1 000 000 circular mils of copper, the advantage of the larger number of tracks becomes apparent as soon as an attempt is made to limit the current density in the return portion of the circuit.

(b) *Roadbed.*—Another factor so far as the railway system is concerned is the conductivity of the roadbed. In so far as the roadbed is given a high resistance leakage current is of course prevented.

For interurban roads wood ties and good rock ballast, well drained, will do much toward preventing electrolysis. In city streets the same degree of insulation is more difficult to attain. We may point out, however, the fact that stone has a much higher resistance than moist concrete. In fact, moist concrete has a specific resistance but little higher than clean earth, ranging from about 4000 ohms per cubic centimeter up, depending upon the character of the concrete and the amount of moisture it contains. The specific resistance of dry rock is very high, and many kinds of rock absorb much less water than concrete. The conductivity of a rock-ballast roadbed is due, therefore, largely to the conductivity of the films of moisture and dirt on the surfaces of the stones.

While only a little data is at hand relative to the resistances of different kinds of roadbeds, such data as is available show that the resistance of a rock ballast is higher than a bed of concrete or cinders, moisture conditions being equal. A number of measurements made on several different kinds of roadbed in actual service show that the leakage resistance varies between wide limits, but for the most part will be found to range between 0.2 and 12.0 ohms per 1000 feet of single track, the values for double track being approximately 70 per cent of those for single track.

The practice in many cities of frequently flushing the rails to prevent the formation of a high-resistance scale on the head of the rail due to dirt from the street must add considerably to the leakage currents, since this flushing is most necessary with dirt roads, a condition frequently, though not necessarily, coupled with

poor roadbed and loose rail joints. The situation presents an excellent opportunity for cooperation between the city and railway company in diminishing electrolysis damage as well as in improving conditions generally. It not infrequently happens that the street railway company delays relaying an old track on an unpaved street because the street is to be paved within a few years, at which time extensive changes in the tracks would probably be necessary. When the city is in a position to do so, it may be advisable for the city to pave the street somewhat sooner than was planned that the railway company be put to no unnecessary expense. This is especially true if the railway company is required to bear a share of paving expense.

2. EFFECT OF DISTRIBUTION OF UNDERGROUND STRUCTURES

After the consideration of track conditions comes the question of the number of underground conductors in the street, their size, and their location with respect to the rails. In most cases, perhaps, these things must be fixed without regard to electrolysis conditions, but in some cases the danger from stray currents may be minimized by a careful study of local conditions. It is our experience that in the majority of cases gas lines pick up less current than water mains of the same size, probably because of the greater depth of burial, lighter material used, and the introduction of high resistances, such as cement joints or expansion joints with rubber gaskets. Usually, too, the distributing pipes for a gas system are smaller than the water pipes serving the same neighborhood. It would seem advisable, then, that if the two systems of pipes must be on the same side of the street that the water mains be placed nearer the curb.

Lead-sheath cables of all kinds may well go between the rails and the gas mains, both on account of the insulating properties of the ducts through which they run, although this resistance is not very high, and because the lead sheaths can be relieved of current more easily than the pipes.

It must be said in this connection, however, that lead is much more easily destroyed by electrolysis than iron and that a judicious draining of the lead sheaths is in most cases necessary for their protection.

In cities where the density of population warrants the expense, gas and water mains may be run along both sides of streets occupied by street railways. While the conductivity of the pipe network is thus somewhat increased, the necessity of running service pipes beneath the rails is avoided. When service pipes run under the tracks, the highest gradient is usually between the rails and these services, and in areas where the pipes are positive to the tracks corrosion is concentrated on these small pipes.

While, of course, a leaky service is not so expensive to replace as a leaky main, the thinner material in the former case and the fact that the pipes run at right angles to the rails causes a concentration of corrosion and a very rapid destruction of the pipe. The damage to the street is practically the same whether a main or a service is replaced. A great deal of inconvenience and probably a considerable expense for renewals is therefore avoided by the double-main system.

Our measurements of current in gas and water mains have convinced us that the cement joint frequently used in gas mains, even when installed with no attempt to keep the pipe ends apart, very materially reduces the current collected by these mains. The subject of the proper use and the effectiveness of insulating joints in preventing electrolysis is considered in another paper.[4] In locating a new car track or a new supply main it may in some cases be possible to prevent electrolysis trouble by shifting the location somewhat to avoid paralleling an important main or heavily loaded track.

3. SOIL CHARACTERISTICS AND ELECTROLYSIS

Just what portion of the total resistance of the leakage circuit the earth forms depends, of course, upon a number of factors, and while no such variations in the total resistance are to be expected as are found in the table of specific resistances, nevertheless the soil resistance and the factors influencing it are doubtless very important.

(a) *Soil Resistivity and Electrolysis.*—The table of specific resistances referred to above serves to call our attention to the

[4] E. B. Rosa and Burton McCollum, Electrolysis and its Mitigation, Technologic Paper No. 52, Bureau of Standards.

wide range of resistivities which have been found to occur in actual field work. Certain kinds of soil, especially those containing a large percentage of sand or gravel, are almost invariably of high resistivity and of low moisture content.

A study of the samples of clay soils shows a wide variation in resistivity which can not be closely connected with the physical appearance or the amount of moisture and which is due no doubt to its chemical properties. We might add here that the appearance of soil as to moisture, while indicating roughly its relation to the saturated condition, is not an indication of the amount of moisture present. A sand which feels quite moist will actually contain less moisture than a clay or loam much drier in appearance. It would seem unnecessary to point out the fact that samples of soil taken for resistivity measurements must be so treated as to prevent any change in this moisture content, but we have experienced considerable difficulty in impressing the importance of this upon some who have collected soil samples for us. It is, of course, absolutely essential that the moisture content shall not change if the sample is to indicate the resistivity of the soil from which it was taken.

On account of the wide variation in soil resistivity it is important to include measurements of soil resistivity in any study of electrolysis conditions. Samples of soil should be obtained in the immediate neighborhood of the power house and along the tracks throughout the positive and negative areas. For this purpose a 1½-inch soil auger is convenient. If at any point three or four holes are bored and samples taken at, say, 2, 4, and 6 feet below the surface of the earth and all of the samples well mixed, a single measurement of the specific resistance of a part of the mixture should afford a fair idea of the conductance of the soil in that region.

How many such measurements should be made will, of course, depend on the extent of the track network and the diversity of the soils within the city. An idea of the latter can often be obtained from the officials of the local gas or water company, as well as by surface indications along the tracks.

(b) *Effect of Pressure.*—The experimental data show that little variation in soil resistance is to be expected, due to the hardness

with which the soil is packed, except in so far as this influences the moisture content. We would not, therefore, expect any material change in electrolysis conditions due to the packing of the earth by traffic over the road in which the pipes are buried.

(c) *Effect of Soil Moisture.*—The importance of soil moisture can scarcely be overestimated and every effort should be made by street railways and by pipe owners to keep the earth in the neighborhood of their conductors as dry as possible. Well-drained tracks in the suburbs and well-ballasted tracks in the cities, drained streets with good pavements, and tight joints in water mains will do much toward reducing leakage currents.

The influence of moisture in the soil must be kept in mind in interpreting the results of electrolysis surveys. Readings taken after a prolonged season of wet weather will undoubtedly show lower over-all potentials and greater currents on pipes than those taken under dry conditions. On account of the excellent conductivity of salt water or water containing quantities of vegetable matter the location of power houses along water fronts is to be avoided in so far as consistent with other operating conditions, and if it seems desirable to choose such a location on account of the coal or water supply it is only fair that the increased expense of track feeders and track insulation due to the high conductivity of the soil in such localities should be charged against the advantages of the situation.

Especial precautions must also be taken that the insulation of the track be as high as practicable when interurban roads cross marshy land.

(d) *Effect of Temperature and Freezing.*—Two important phenomena occur with respect to the effect of temperature on soil resistance, as is indicated in Fig. 8. The temperature coefficient of the soil is negative and relatively high. This and the positive temperature coefficient of the rails produce a shifting of the relative amounts of current carried at different seasons of the year.

It will be observed that at even a few degrees below zero the resistance of the soil is largely increased, and we may expect, therefore, that if the ground is frozen only to a depth of a few inches the leakage current from tracks will be materially dimin-

ished, due to the increased resistance, and the danger from electrolysis proportionally reduced. In the cities in the northern half of the United States the time during which the frost is in the ground is sufficient to make this phenomenon of some importance.

The direct determination of the effect of temperature on leakage currents by tests of current on water pipes is made difficult by the changes in conditions of pipe lines, tracks, and station outputs which are almost sure to take place between two sets of readings taken six months or more apart. Some data have, however, been obtained on the relative currents in underground pipes in a number of places during the winter and summer months, all of which show that such pipes generally carry more current in proportion to the railway load in summer than in winter. The data obtained in the neighborhood of the Ann Avenue substation in St. Louis, Mo., given in Table 9, will serve to illustrate this effect. These figures represent currents reduced to the average summer-load conditions.

TABLE 9

Currents on Water Pipes in the Neighborhood of Ann Avenue Substation, St. Louis, in Summer and Winter

Location	Amperes	
	Summer	Winter
Mississippi and Ann Avenues	3.06	0.85
Mississippi and Russell Avenues	19.30	4.57
Mississippi and Allen Avenues	1.70	0.76
Eighteenth Street and Russell Avenue	1.63	1.19
Eighteenth Street and Ann Avenue	1.86	1.04
Total	27.55	8.41 [a]

[a] Winter current is 30 per cent of the summer current.

The temperature of the earth when the last readings were taken was about 32° F, but there had been several weeks of cold weather previously and the frost was not entirely out of the ground. Indeed there was snow on the ground in many places though the weather for the previous two days had been quite warm for winter. The condition of the ground at the base of the rails and

below is, therefore, somewhat in doubt, and the increase in earth resistance is probably less than it might have been had the readings been taken a few days earlier. On the other hand, we can not be sure just what changes had occurred in track and pipe conditions or that the assumed corrections for the time of day or the increase of the winter load are exactly correct. The table is therefore not an exact index of the magnitude of the change, but these data, as well as a considerable amount of similar data obtained elsewhere, leaves no doubt as to the character of the change and to temperature variations, although some of the changes found have been less marked.

It will be seen that the current in moderately cold weather has been reduced to approximately one-third of its value during the fall months, when the earlier measurements were taken. No doubt if fall measurements had been taken immediately after a period of wet weather the difference would have been much larger.

These changes must, of course, be taken into account in considering electrolysis surveys made during cold weather.

(e) *Effects of the Flow of Current on the Resistance of the Leakage Path.*—We have seen that as a unidirectional current flows through the earth there is an increase of resistance due to polarization and the collecting of gas about the electrodes. The polarization depends partly upon the difference of potential and partly upon the character of the medium surrounding the electrodes. In cinders the polarization electromotive force is high and persists for a long time.

The amount of gas collected about the electrodes will depend somewhat on the porosity of the soil.

Another possible effect of the passage of current is an increase in the resistance of the soil due to the decrease in the soluble salts or to chemical changes taking place in connection with the migration of the ions. With large currents there may be some drying of the soil due to the electrolysis of the water and to the heating effect of the current. Under most circumstances, however, it seems probable that the supply of soluble materials will be renewed by diffusion and from the surface of the ground, and that no protection can be expected from these phenomena.

(f) *Other Possible Sources of Resistance.*—While it is possible that there are a number of other causes which may increase the resistance between rails and buried pipes, we have so far been unable to determine them. Our experiments show that in some cases at least there is no appreciable resistance due either to a poor contact between soil and pipes or to the slag on the surface of cast-iron pipes. Although the paint applied to pipes while in good condition often offers a considerable resistance to the passage of a current, the experiments of the Bureau on insulating paints [5] indicate that the period of time that a paint film will withstand even a low potential when exposed to moisture is comparatively short, and that the failure of the coating in spots concentrates corrosion, causing the life of the pipe to be less than it would have been if the paint had not been used. It seems better, therefore, not to make any allowance for the resistance of paint films in estimating resistances between pipes and rails, since though the resistance of the leakage path is increased the danger of damage by the escaping current is also increased.

V. SUMMARY

In the foregoing sections the resistivity of the soil in which metallic structures are buried is shown to be of much importance with respect to electrolysis of these structures. Three methods of measuring the specific resistance of the soil, two of which do not require the removal of the soil from its original position, are described. Results of soil-resistivity measurements by each method are compared, and it is shown that any of the described methods is satisfactory for practical purposes, although each has advantages over the others under certain conditions.

The results of a large number of measurements of resistivity of soil samples from widely separated points in the United States have been tabulated. These data show great variations in soil resistivity, and indicate the desirability of a study of local soil conditions in connection with any complete electrolysis survey. The majority of soils tested show resistivities of between 1000 and 5000 ohms per centimeter cube.

[5] Burton McCollum and O. S. Peters, Surface Insulation of Pipes as a Means of Preventing Electrolysis, Technologic Paper No. 15, Bureau of Standards.

A number of factors have been found to influence the resistivity of the soil. Increasing the pressure on a sample of soil under test tends to increase the conductance of the sample slightly, especially if the original pressure is low. Increase in moisture increases the conductance of the soil if it is not saturated with water. The amount and kind of soluble material in the soil affects its resistivity. The resistivity of soil is found to increase as its temperature falls, especially when the freezing point of water is reached. The flow of current through the soil has been found to produce an apparent temporary increase in soil resistivity in the neighborhood of the electrodes.

The relation of soil resistivity to electrolysis is considered from the standpoint of leakage from street railway lines using the track as a return current. The importance of good rail bonding and of well-drained roadbed is pointed out.

The relations of the various factors affecting leakage resistance, namely, character of the soil, pressure, moisture, freezing, and polarization, and surface films to the electrolysis problem are described, and it is shown that a knowledge of the resistivity of the soil is of importance in estimating the danger indicated by potential difference and potential gradient measurements. It is also shown that the moisture and temperature of the soil materially affect the amount of current escaping from a grounded track used as a return circuit, and that these factors must be given due consideration in the interpretation of data obtained during an electrolysis survey.

In conclusion the authors wish to express their appreciation of the assistance of their colleague, O. S. Peters, who did a large amount of work in connection with the development of the guard ring and compression methods of soil-resistance measurements, and rendered valuable assistance in connection with the measurement of the resistivity, of earth samples.

WASHINGTON, September 9, 1915.