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ELECTROLYTIC MEASUREMENT OF THE CORROSIVENESS OF SOILS

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ABSTRACT

The electrolytic behavior of steel in contact with 47 soils of known corrosiveness was studied by means of a cell in which both electrodes were steel and the electrolyte was moist soil. By providing differential aeration of the electrodes the cell was enabled to develop its own electromotive force. Measurements were made of the voltage, current, and resistance of such cells. The relation between the current density and applied voltage was also studied. The losses in weight of the test specimens were related to the average current density over a certain range of applied voltage and to the total quantity of electricity produced in the corrosion process. The corrosion of the specimens in the laboratory tests was correlated with corrosion experienced in long-time field tests. The results of the tests may be applied practically in predicting the corrosiveness of soils toward iron and steel. However, they cannot be applied to the prediction of leaks or to the estimation of the useful life of a section of pipe line until the relations connected depth of pitting with exposed area and time can be established.

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I. INTRODUCTION

Corrosion of metals in soils is accompanied by a flow of current, which discharges into the soil at the anodic or corroding areas and returns to the metal surface at the cathodic areas. Since corrosion proceeds as a result of the action of electrolytic cells, the design of a suitable corrosion cell might be considered the first step in the study of soil corrosion in the laboratory by electrical methods. The cell should preferably be so designed that corrosion could proceed naturally; that is, by the cell developing its own electromotive force (emf). From measurements of voltage and current in such a cell it should be possible to determine what external voltage might be applied without materially altering the nature of the corrosion process occurring within the cell. The significance of the results obtained from such a study, particularly from the standpoint of corrosion testing, would depend largely upon the maintenance of those conditions of moisture and aeration that prevail in the natural soil, so far as these conditions can be reproduced in the laboratory and incorporated in a general corrosion test.

The primary purpose of this study was to determine whether the relative corrosiveness of soils toward steel could be predicted from measurements of the electrical properties of corrosion cells in which various soils constituted the electrolytes. A successful electrolytic test should render unnecessary the determination of separate factors in corrosion, such as hydrogen-ion concentration, total acidity, and concentration of soluble salts. The influence on the rate of corrosion of such factors should be manifested in the electrical properties of the corrosion cells. From measurements of current and potential of appropriate cells, either with an impressed emf or with only the internal emf associated with differences in aeration it should be possible to arrange soils in about the same order of their corrosiveness as is found from loss-of-weight tests conducted for short periods in the laboratory, and from long-time field tests.

II. PROPERTIES OF SOILS

The samples of soil used in this study were taken from the 47 original test sites selected by the National Bureau of Standards in its investigation of soil corrosion and described in its first report.[1] The soil samples were prepared by drying and crushing the aggregates in a mortar and passing them through a no. 20 sieve. Care was taken to avoid reducing the size of the soil aggregates below that necessary to pass the sieve, in order to preserve, as far as possible, their natural structure.

Water extracts of the soils were prepared as follows: A suspension of soil and water in the ratio of 1:5 was shaken mechanically at intervals for a total of 24 hours during a period of 72 hours. The extract was decanted into a 250-ml, tall-form beaker and was filtered through a Berkfeld filter (12 by 2.5 cm) into a pressure flask by suction. The extracts were analyzed by the methods described by Collins.[2]

Hydrogen-ion concentration was measured colorimetrically after 18 hours in a separate extract, using a 1:2 soil-water ratio. Portions of each indicator were adjusted isohydrically to the acid, midpoint, and alkaline ranges to avoid altering the pH value of the extract. Total acidity was determined by methods previously described by the writer.[3] The resistivity of each soil was determined by means of a wheatstone bridge, using 60-cycle, alternating current. The soil samples were saturated with water, mixed thoroughly, and allowed to stand several hours before being tested. The values of resistivity were corrected to 60° F (15.6° 3). The moisture equivalent was determined in the usual manner,[4] that is, by saturating a 30-g sample with water, subjecting it to a centrifugal force of 1,000 times gravity

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[1] K. H. Logan, S. P. Ewing, C. D. Yeomans. Tech. Pap. BS **22**, (1928) T368.

[2] W. D. Collins. Water Supply Paper 596–H, U. S. Geological Survey (1928).

[3] I. A. Denison. BS J. Research **10**, 413 (1933) RP539.

[4] L. J. Briggs and J. W. McLane. Am. Soc. Agron. **2**, 138 (1910).

for 40 minutes, and determining the residual water content by drying in an oven at 105° C. The moisture equivalent is a measure of the retentiveness of a soil for water and is an index of the texture of the soil. It has been shown to represent the condition in nature of a soil which after saturation has come into equilibrium with gravitational and capillary forces.[5,6] A significant feature of the moisture equivalent with respect to corrosion is that it represents the condition at which the finer pore spaces within a soil are filled with water, the larger spaces with air.

The determined properties of the soils are shown in table 1. The soils are grouped in two classes according to their reactions. Within each class the arrangement is in the order of increasing resistivity. The classification according to reaction is somewhat arbitrary since there are no criteria for the exact separation of soils on the basis of acidity or alkalinity. For instance, although soil 28 has a slightly acid reaction, it is an "alkali" if not an "alkaline" soil, in the terminology of soil investigators. Analyses of the water-soluble materials in most of the acid soils were not made because of the very low concentrations of soluble material in these soils.

Table 1 illustrates the remarkably wide range in the properties of the soils studied. In texture, the soils range from the coarsest sands to the heaviest clays; in pH, from the high acidity of pH 3.1 to marked alkalinity (pH 9.5); and in soluble material, from concentrations as high as several percent to very low concentrations. Special classes of soils such as peat, muck, and "tidal marsh" are also represented.

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[5] C. S. Schofield and C. W. Wright. J. Agr. Research **37**, (1928).

[6] W. W. Burr and J. C. Russell. Bien. Rep. Nebr. Dept. Pub. Works, p. 199 923-24).

TABLE 1.—*Properties of soils*

[mg-eq=milligram equivalent]

ALKALINE SOILS

Soil	Soil type	Location	Moisture equivalent	pH	Total acidity per 100 g of soil	Resistivity at 60° F	Composition of water extract per 100 g of soil						
							Na+K as Na	Ca	Mg	CO_3	HCO_3	Cl	SO_4
			%		mg-eq	ohm-cm	mg-eq	m -eq	mg-eq	mg-eq	mg-eq	mg-eq	mg-eq
45	Unidentified alkali	Casper, Wyo	14.8	7.4	(a)	263	8.15	3.70	0.70	0.00	0.24	0.18	11.98
23	Merced silt loam	Buttonwillow, Calif	24.7	9.4	(a)	278	8.38	.38	.22	.02	1.87	1.12	5.57
13	Hanford very fine sandy loam	Bakersfield, Calif	21.7	9.5	(a)	290	6.23	.09	.13	.00	1.12	1.64	3.76
8	Fargo clay loam	Fargo, N. Dak	37.0	7.6	(a)	350	1.42	1.72	2.55	.00	.71	.01	4.43
28	Montezuma clay adobe	San Diego, Calif	24.6	6.8	(b)	408	1.50	.06	.18	.00	.12	.99	.89
15	Houston black clay	San Antonio, Tex	51.4	7.5	5.0	489	2.18	.88	.20	.00	2.00	.13	.73
27	Miller clay	Bunkie, La	42.6	6.6	3.7	570	.53	1.86	1.12	.00	2.00	.08	1.54
2	Bell clay	Dallas, Tex	37.6	7.3	3.5	684	.28	1.09	.13	.00	1.18	.04	.18
30	Muscatine silt loam	Davenport, Iowa	29.4	7.0	2.6	1,300	.32	.65	.40	.00	.71	.09	.24
5	Dublin clay adobe	Oakland, Calif	28.8	7.0	6.5	1,346	.93	.48	.10	.00	.69	.03	.25
18	Knox silt loam	Omaha, Nebr	28.4	7.3	1.4	1,410	.27	.63	.20	.00	.94	.00	.25
46	Unidentified sandy loam	Denver, Colo	7.6	7.0	(b)	1,500	(b)	(b)	(b)	(b)	(b)	(b)	(b)
47	Unidentified silt loam	Salt Lake City, Utah	25.7	7.6	3.0	1,770	.67	.72	.39	.00	.88	.06	.48
25	Miami clay loam	Milwaukee, Wis	25.8	7.2	4.7	1,780	.23	.70	.41	.00	1.01	.03	.10
35	Ramona loam	Los Angeles, Calif	18.0	7.3	5.7	2,060	.68	.68	.49	.00	1.10	.06	.35
20	Mahoning silt loam	Cleveland, Ohio	22.4	7.5	1.5	2,870	.25	.48	.20	.00	.51	.00	.15
26	Miami silt loam	Springfield, Ohio	16.4	7.3	2.6	2,980	.27	.50	.31	.00	.70	.03	.12
12	Hanford fine sandy loam	Los Angeles, Calif	12.4	7.1	2.5	3,190	.39	.50	.16	.00	.40	.00	.14
32	Ontario silt loam	Rochester, N. Y	17.8	7.3	.5	5,700	.23	.70	.12	.00	.73	.01	.42

ACID SOILS

43	Tidal marsh	Elizabeth, N. J	55.4	3.1	36.8	60	45.10	5.17	9.45	0.00	0.00	43.30	37.00
33	Peat	Milwaukee, Wis	72.8	6.8	36.0	800	1.52	7.30	4.06	.00	(b)	2.27	2.13
40	Sharkey clay	New Orleans, La	33.0	6.0	9.4	970	.56	.58	.44	.00	.93	.07	.28
44	Wabash silt loam	Omaha, Nebr	31.2	5.8	8.8	1,000	1.05	1.08	.66	.00	1.97	.82	.41
1	Allis silt loam	Cleveland, Ohio	28.6	7.0	11.4	1,215	.72	.25	.43	.00	.09	.09	.83
29	Muck	New Orleans, La	34.5	4.2	28.1	1,270	2.15	1.92	1.55	.00	.00	1.69	2.30
41	Summit silt loam	Kansas City, Mo	33.1	5.5	11.0	1,320	.30	.54	.36	.00	.78	.04	.46
19	Lindley silt loam	Des Moines, Iowa	28.4	4.6	10.9	1,970	.38	.32	.41	.00	16	.03	.46
7	Unidentified silt loam [c]	Cincinnati, Ohio	34.3	4.4	29.8	2,120	------	------	------	------	------	------	------
21	Marshall silt loam	Kansas City, Mo	31.2	6.2	9.5	2,370	------	------	------	------	------	------	------
9	Genesee silt loam	Sidney, Ohio	24.8	6.8	7.2	2,820	------	------	------	------	------	------	------
14	Hempstead silt loam	St. Paul, Minn	17.2	6.2	5.6	3,520	------	------	------	------	------	------	------
34	Penn silt loam	Norristown, Pa	23.4	6.7	7.0	4,900	------	------	------	------	------	------	------
22	Memphis silt loam	Memphis, Tenn	28.4	4.9	9.7	5,150	------	------	------	------	------	------	------
17	Keyport loam	Alexandria, Va	30.8	4.5	19.1	5,980	------	------	------	------	------	------	------
4	Chester loam	Jenkintown, Pa	22.2	5.6	7.6	6,670	------	------	------	------	------	------	------
39	Sassafras silt loam	Wilmington, Del	24.2	5.6	6.6	7,440	------	------	------	------	------	------	------
10	Gloucester sandy loam	Middleboro, Mass	13.0	6.6	3.6	7,460	------	------	------	------	------	------	------
16	Kalmia fine sandy loam	Mobile, Ala	22.2	4.4	11.8	8,290	------	------	------	------	------	------	------
11	Hagerstown loam	Baltimore, Md	32.0	5.3	10.8	11,000	------	------	------	------	------	------	------
36	Ruston sandy loam	Meridian, Miss	13.8	4.5	4.6	11,200	------	------	------	------	------	------	------
37	St. Johns fine sand	Jacksonville, Fla	7.0	3.8	15.3	11,200	------	------	------	------	------	------	------
24	Merrimac gravelly sandy loam	Norwood, Mass	13.0	4.5	12.6	11,400	------	------	------	------	------	------	------
42	Susquehanna clay	Meridian, Miss	34.8	4.7	28.2	13,700	------	------	------	------	------	------	------
31	Norfolk sand	Jacksonville, Fla	2.8	4.7	1.8	20,500	------	------	------	------	------	------	------
3	Cecil clay loam	Atlanta, Ga	29.1	5.2	11.5	30,000	------	------	------	------	------	------	------
38	Sassafras gravelly sandy loam	Camden, N. J	3.0	4.5	1.7	38,600	------	------	------	------	------	------	------
6	Everett gravelly sandy loam	Seattle, Wash	12.2	5.9	12.8	45,100	------	------	------	------	------	------	------

[a] Alkaline.
[b] Not determined.
[c] Previously classified erroneously as Fairmount silt loam.

III. DESCRIPTION OF CORROSION CELL

The corrosion cell consisted essentially of two steel electrodes separated by a layer of moist soil as electrolyte, the whole being contained within a brass ring, which formed part of the external circuit. By aerating the electrodes differentially the cell was enabled to develop its own emf. This effect was accomplished by using as cathode a steel screen which was more readily accessible to air than the anode. In order that the accessibility of air to the cathode would be determined by the natural permeability of the soil, the cathode was covered by a layer of soil of definite thickness and with a definite moisture content.

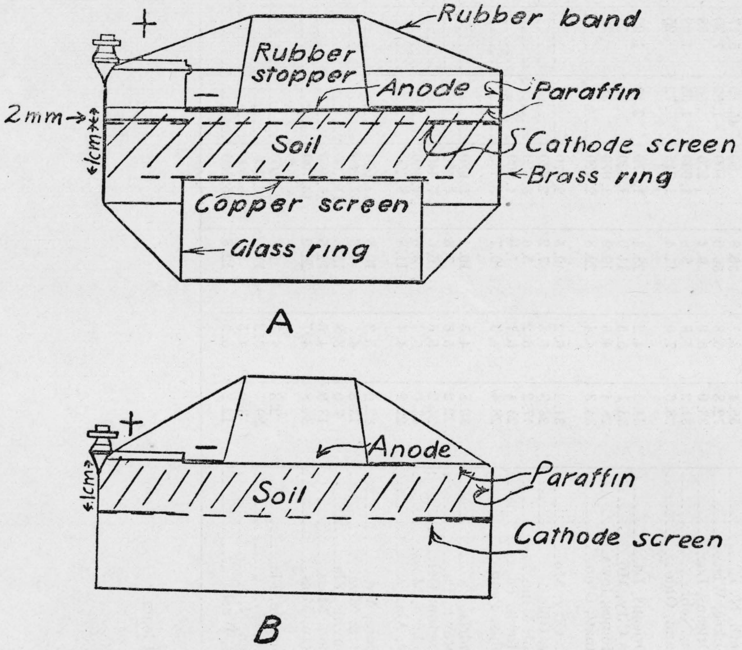

FIGURE 1.—*Corrosion cell.*

A. Cathode covered by soil; B. Cathode exposed to air.

Because of differential aeration the cathode attained a more positive potential. Consequently, when the circuit was closed, ferrous ions entered the soil at the anode, and at the cathode an equivalent quantity of hydrogen ions was discharged or otherwise consumed. The current flowed in the external circuit from the cathode through the brass ring to which it was connected by solder, completing the circuit to the anode through the binding post and the copper wire attached to the anode. Since the brass ring was insulated from the soil by a layer of paraffin, its function in the electrical circuit was merely as a conductor of current in the external circuit. The cell is shown diagrammatically in figure 1. The parts of the cell are shown in figure 2.

Both of the electrodes consisted of low-carbon steel. Since the cathode screen was not attacked, but simply served as the electrode upon which a reducing action took place, it was considered unneces-

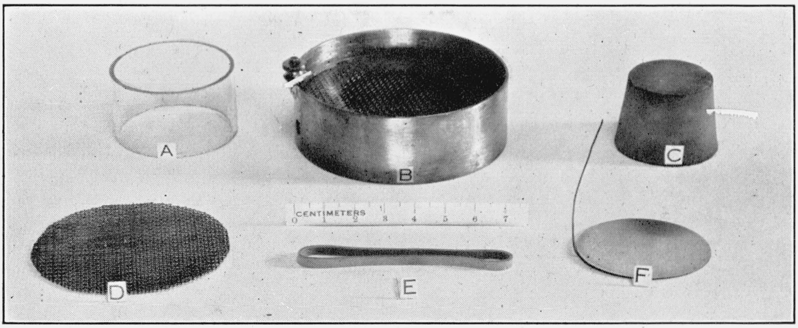

FIGURE 2.—*Parts of corrosion cell.*

A, Glass ring; B, cell; C, rubber stopper; D, copper screen; E, rubber band; and F, specimen.

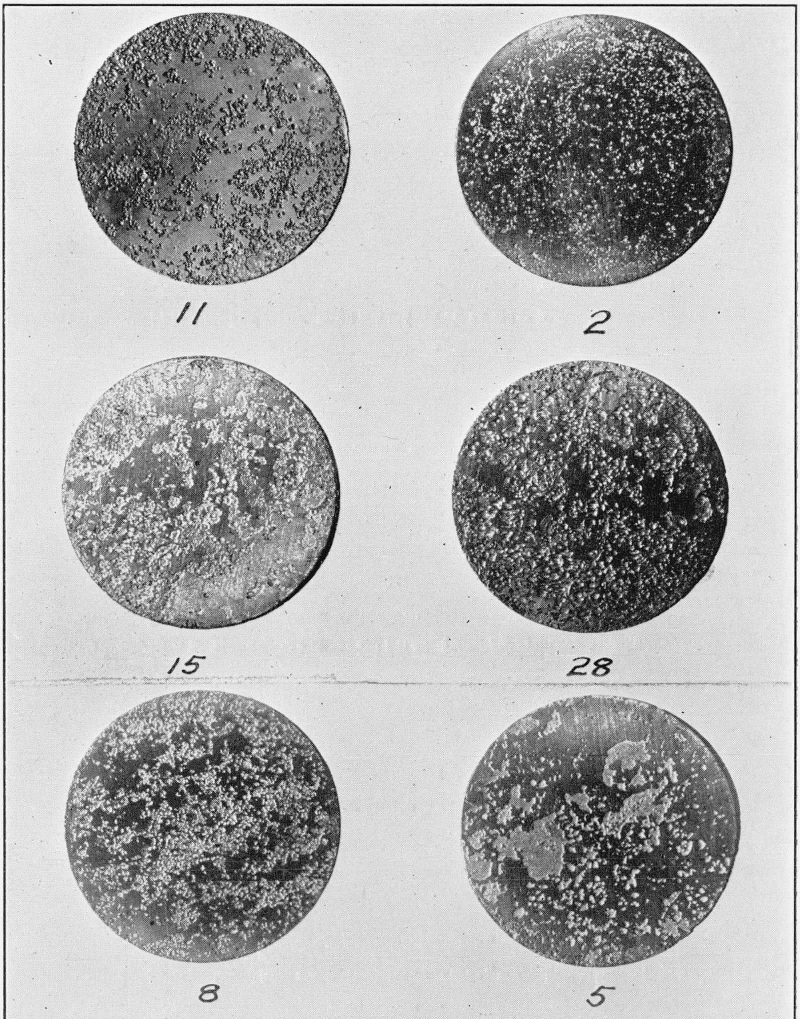

FIGURE 3.—*Appearance of corroded specimens after 14 days in laboratory corrosion test.*

Soil 11. Hagerstown loam, Baltimore, Md.
2. Bell clay, Dallas, Tex.
15. Houston black clay, San Antonio, Tex.
28. Montezuma clay adobe, San Diego, Calif.

Soil 8. Fargo clay loam, Fargo, N. Dak.
5. Dublin clay adobe, Oakland, Calif.
23. Merced silt loam, Buttonwillow, Calif.
45. Unidentified alkali soil, Casper, Wyo.

sary to make it of steel identical with that of the anode. The latter was a disk 45 mm in diameter and 0.3 mm thick. The cathode, which was a 16-mesh screen (6 mesh/linear centimeter) having wires 0.46 mm in diameter, was soldered across the brass ring or container 1 cm from the top. The brass ring was 75 mm in diameter, 25 mm high, and 1 mm thick.

Electrical connection between the anode and cathode was made through a binding post on the brass ring by means of a copper wire soldered to the back of the anode. In order to restrict, as far as possible, the current flow to straight lines normal to the surface of the cathode, the apparent area of the latter was made equal to the area of the anode. This was accomplished by insulating the border of the screen and the inner surface of the ring with a layer of paraffin. The actual area of the screen, calculated from the length and diameter of the wires, was almost exactly twice the apparent area.

Each anode specimen was cleaned by means of alcohol and ether. The original surface of one face was then removed by rubbing with 1G French emery paper in opposite directions, rotating the disk through an angle of 90° and repeating the process. The copper wire was soldered to the back of the disk, and the prepared surface of the latter was recleaned by rubbing with filter paper moistened with distilled water. The disk was weighed to the nearest milligram and the reverse surface was covered with two coats of lacquer.

The procedure used in setting up the cell was as follows: The cell was inverted and the space of 1 cm above the cathode was filled with dry soil, which was compacted by means of a brass cylinder weighing about 500 g. The soil was prevented from running through the screen by placing a layer of muslin over the upper surface of the screen and moistening it with a few drops of water. Sufficient distilled water was added to the soil to bring it to the moisture equivalent. The soil layer was held in firm contact with the cathode by inserting a circular piece of copper gauze and a glass ring between the soil and a rubber band wrapped around the cell. With the cell resting on the glass ring, the section of the cell between the anode and cathode was filled with soil to a depth of 2 mm and moistened in the manner described, and the disk placed in position. The surface of the soil surrounding the disk was covered with a thin layer of melted paraffin. The disk was maintained in firm contact with the soil by inserting a rubber stopper between the disk and the rubber band, as shown in figure 1. The circuit was closed by attaching the copper wire to the binding post. The cell was placed in a 1-quart (0.95 l) friction-top can in which a small quantity of water was poured to provide a saturated atmosphere. After closing the lid the can was placed in a chamber and maintained at 30 ± 0.5° C for 14 days.

At the conclusion of the test period the disks were cleaned and the lacquer was removed by means of a wire brush. When necessary to remove rust, the disks were immersed for a few minutes in a warm 10-percent solution of ammonium citrate made alkaline with ammonia. Corrosion products not removed by this treatment were removed with the point of a knife blade. The disks were reweighed and the loss in weight was expressed as average penetration. All tests were run in duplicate, and tests for which the duplicates did not agree within 20 percent were repeated. Typical corroded specimens are shown in figure 3.

For the practical testing of soils certain modifications in the dimensions of the cell and in the procedure for setting up the cell may be suggested. The height of the cell should be so chosen that when the cell is filled with moist soil and the anode is placed in position, the electrodes be separated by a layer of soil 2 mm thick and the cathode well shielded from the atmosphere by a layer of soil 1 cm thick. The diameter of the cell should be so reduced that it would be only slightly greater than the diameter of the disk.

In order to avoid the necessity of determining in advance the proper quantity of water to apply to each soil, it would be preferable to presaturate the soil contained in the cell and to bring it approximately to the moisture equivalent by the application of suction. From a recent study [7] of soil moisture relations, based on energy considerations, it appears that the moisture equivalent can be attained by suction produced by means of a Buchner funnel and a water pump. The desired pressure is maintained by pouring a thin suspension of silt on the filter paper before the soil is applied. The silt layer allows water to pass readily through it but entirely prevents the flow of air. This method of producing the moisture equivalent could be readily adapted to the corrosion test.

IV. MEASUREMENTS WITH APPLIED EMF

1. METHOD

The method used for studying the current density-potential relation in soils was essentially that described by Blum and Rawdon.[8] According to this method the potentials applied to the cell are adjusted to produce certain desired current densities. The corresponding potential differences between the electrodes are measured after they have become steady, which was usually attained in from one to three hours. The current densities are then plotted against the cell potentials (corrected for IR drops if these are significant). The relative corrodibility of various metals in a given solution, or of the same metal in different solutions, is inferred from the relative positions and shapes of the current density-potential curves. This method with slight modifications was employed by Ewing in[9] testing the corrosiveness of a limited number of soils from the National Bureau of Standards test sites.

In the present study, current density-potential measurements were made after the cells had been on closed circuit from 24 to 36 hours. It was found that at least 24 hours' standing was necessary for the electrodes to become stabilized. The effect on the measurements of longer standing was not studied. The current density was increased by definite steps, and the voltages across the cell were corrected for IR drops. The current density at each step was maintained for 10 minutes, by which time the voltage had become steady. After each voltage reading, the resistance of the cell was quickly determined. This practice was made necessary by the marked increase in resistance with current density that was shown by many

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[7] R. K. Scofield. Trans. 3d Int., Cong. Soil Sci. **2**, 37 (1935).

[8] W. Blum and H. S. Rawdon. Trans. Am. Electrochem. Soc. **52**, 402 (1927).

[9] S. P. Ewing. Am. Gas Assn. Mo. **14**, 356 (1932).

of the cells. A steady current density was maintained despite an increasing resistance of the cell, by placing 10 000 ohms resistance in series with the cell and using 110 volts d–c, with a rheostat as a potential divider.

2. CURRENT DENSITY-POTENTIAL MEASUREMENTS

The relation between current density and the applied voltage is shown in figure 4 for typical soils. Because the cells develop their own emf, the curves do not usually pass through the origin. The curves indicate the departure of the potentials of the anode and cathode from their equilibrium potentials in the soils as the current densities on the electrodes are increased, and are therefore indicative of the total polarization of the cells at various current densities.

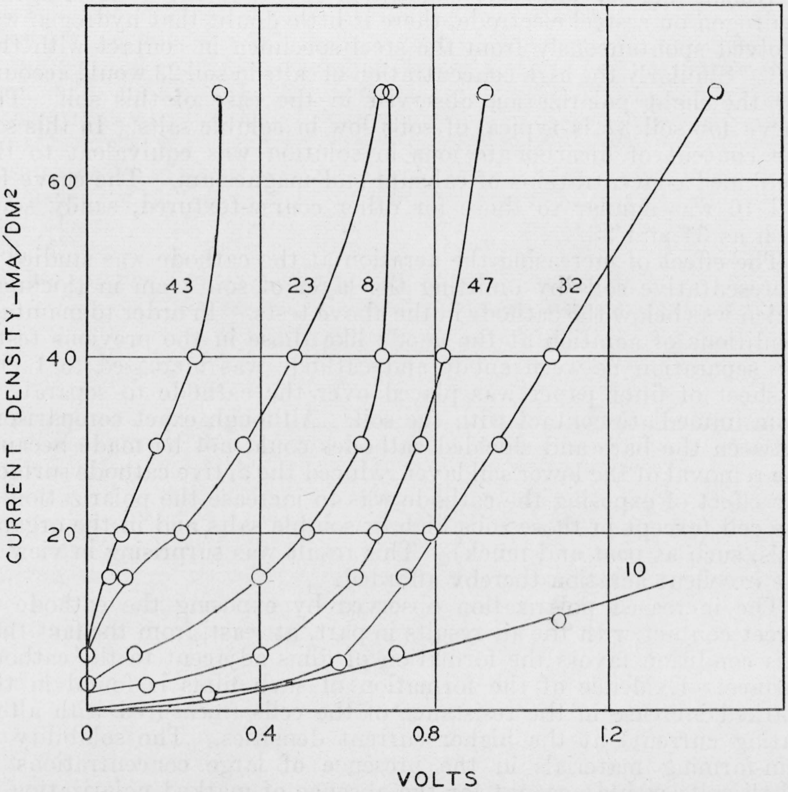

FIGURE 4.—*Current density-potential curves of typical soils when an external electromotive force is applied*

Soil numbers are designated on the curves

The relative positions of the curves would be expected to indicate the relative corrosiveness of the soils. Thus a small potential difference, such as 0.2 volt, which for any reason might develop on steel surfaces, would produce in contact with soil 10 a very slight current density and a corresponding low rate of corrosion, but with soil 43 a very high current density and rate of corrosion. From another point of view the potential required to produce a current density of say

20 ma/dm^2 would be only 0.1 volt in soil 43, but an impossibly high value in soil 10. As will be seen later, the relative corrosiveness of soils both with respect to field and laboratory tests can be predicted by comparison of their current density-potential curves.

The positions of the curves for the soils tested can be explained in a general way on the basis of the properties of the soils, as given in table 1. Thus very little polarization would be expected in soil 43, owing to the fact that it has a pH of 3.1, a total acidity of 36.8 me-eq per 100 g of soil, and a specific resistance of but 60 ohm-cm. Since increasing acidity and salt concentration lower the overvoltage of hydrogen on a steel electrode, there is little doubt that hydrogen was evolved spontaneously from the steel specimen in contact with this soil. Similarly the high concentration of salts in soil 23 would account for the slight polarization observed in the case of this soil. The curve for soil 32 is typical of soils low in soluble salts. In this soil the content of bicarbonate ions in solution was equivalent to the combined concentrations of calcium and magnesium. The curve for soil 10 was similar to those for other coarse-textured, sandy soils, such as 31 and 38.

The effect of increasing the aeration at the cathode was studied in representative soils by omitting the layer of soil 1 cm in thickness which was below the cathode in the above tests. In order to maintain conditions of aeration at the anode like those in the previous tests, the separation between anode and cathode was increased to 1 cm. A sheet of filter paper was placed over the cathode to separate it from immediate contact with the soil. Although exact comparisons between the bare and shielded cathodes could not be made because the removal of the lower soil layer reduced the active cathode surface, the effect of exposing the cathode was to increase the polarization of the cell (except in those soils high in soluble salts and in the organic soils, such as peat and muck). This result was surprising in view of the excellent aeration thereby afforded.

The increased polarization observed by exposing the cathode to direct contact with the air results in part, at least, from the fact that this condition favors the formation of films adjacent to the cathode surface. Evidence of the formation of such films is found in the marked increase in the resistance of the cells (measured with alternating current) at the higher current densities. The solubility of film-forming materials in the presence of large concentrations of alkali salts would account for the absence of marked polarization in soils 23, 28, and 45 on exposing the cathode to the air. Marked reduction in polarization in exposing the cathode was observed in the case of muck (soil 29), peat (soil 33), and soil 37, which was a mixture of quartz sand and organic matter. The effect of covering the cathode by a layer of organic matter is to increase polarization, because the oxygen present in the pore spaces is largely consumed in oxidizing the organic matter instead of acting as a depolarizer at the cathode.

V. MEASUREMENTS WITHOUT APPLIED EMF

The voltage developed by the corrosion cells is due to differences in the concentration of oxygen at the surface of the electrodes. On the addition of water to soil contained in a test cell, ferrous ions initially enter the soil from both electrodes, and the hydrogen deposited on each electrode tends to be removed by combination with oxygen. On closing the circuit, current flows from the disk to the screen through the soil, because the greater concentration of oxygen in contact with the screen produces a more positive potential, the screen thereby becoming cathodic. From a somewhat different point of view, the flow of current from disk to screen may be considered to result from the lower concentration of hydrogen on the latter, since current necessarily flows toward that surface on which the concentration of hydrogen is less.

In view of the fact that the surfaces of ordinary ferrous metals show a certain degree of air passivity and are naturally covered by a thin oxide film, the maximum voltage of a corrosion cell will probably not be developed until breakdown of the oxide film has occurred. However, as Britton and Evans[10] have pointed out, there is, in addition to the primary distribution of corroded areas, a secondary distribution which is dictated largely by differential aeration and the disposition of the corrosion products. It would seem, therefore, that the distribution of corroded areas, and hence the potential of the disk, would be affected by the aeration of the soil. With an excess of oxygen at certain parts of the disk, as is the case in a porous, well-aerated soil, precipitation of an adherent film of ferric hydroxide in immediate contact with the metal at certain points of incipient breakdown will result in repair of the film and the maintenance of a low (i. e., more noble) potential.

Since the potential of the disk at any time would be the average potential of the attacked and protected areas, the maximum voltage of the cell would depend largely upon the nature of the soil contained in the cell. As corrosion continues, the accumulation of ferrous and ferric ions at the anode along with other electrode changes would tend to diminish the voltage of the cell by polarization.

The current flowing through the corrosion cell is, of course, related directly to the rate of corrosion. If the cell should function ideally, all of the current generated in the corrosion process would pass through the soil between anode and cathode, and the total quantity of electricity flowing over the period of the test would be an exact measure of the quantity of steel corroded. Since, however, local circuits on the anode are usually active in corrosion, at least in soils of high resistivity, an exact correspondence between corrosion and quantity of electricity is not to be expected.

The relation between current and voltage in these cells depends on the resistance and polarization of the cells. The cell resistance is in turn dependent on the active area of the electrodes and the resistance of the soil, which may be modified by the deposition of corrosion products on the electrodes and in the soil mass. The active areas of the electrodes do not correspond to the actual areas because corrosion does not proceed uniformly over the surface of the anode, but from small breaks or pinholes in the slightly protective oxide film. Initially the resistance of the circuits is relatively great because the anodic areas are small, but as these areas extend and become more numerous the resistance tends to decrease, unless it is increased by deposition of corrosion products. The effect of polarization has been previously shown in connection with the study of the current-density potential relation with applied voltage.

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[10] S. C. Britton and U. R. Evans. Trans. Electrochem. Soc. **61**, 441 (1932).

1. METHODS

Measurement of the electrical properties of the corrosion cells with no applied emf were made at frequent intervals on the cells previously used for the current density-potential measurements. The latter measurements were made 18 hours after the cells were set up. For the first few days measurements were made daily, after which they were made on alternate days. After 2 weeks the cells were taken down and the losses in weight of the disks were determined.

The voltages of cells of low internal resistance, i. e., below 100 ohms, were measured by means of a voltmeter having a resistance of 10 000 ohms. For cells of higher resistance a voltmeter having a resistance of 1 000 000 ohms per volt was used. When the external resistance of the circuit is very high the terminal voltage of the cell is substantially the same as the emf and corrections are unnecessary. The current was measured with a milliammeter, and the resistance with a wheatstone bridge and a 60-cycle, alternating-current galvanometer. The current was read first and the voltage and resistance immediately afterward.

2. MEASUREMENTS WITH THE CATHODE COVERED BY A LAYER OF MOIST SOIL

The average voltage of each cell was between 20 and 150 mv with an average for all cells of about 100 mv. The maximum voltage during the test period, usually 150 to 200 mv, was reached within 18 hours, and the voltage then declined to as low as 10 mv at the expiration of the test. In some soils the polarity of the cell did not become established for several days, after which there was a slow increase instead of a decrease in voltage. The cells containing the organic soils 29, 33, and 37 did not acquire a definite polarity during the test period. In view of the tendency for the organic matter in these soils to absorb oxygen, it is probable that insufficient oxygen reached the gauze to produce a significant difference in potential between it and the disk. Typical current-time curves for various soils are shown in figure 5.

The marked differences in the curves in figure 5 are to be attributed primarily to differences in the solubility of the corrosion products in various soils. Because of the greater solubility of hydroxides of iron in acid soils and in soils containing chlorides and sulfates, the corrosion products readily diffuse away from the anode. This diffusion prevents the formation of protective films and allows corrosion to continue. The curve for soil 28 is typical of soils such as 23 and 45, in which the soluble material is chiefly alkali chlorides and sulfates. The curve for soil 17 is typical of strongly acid soils, such as 7 and 43. Since at the same pH the solubility of ferric hydroxide is much less than that of ferrous hydroxide, the current in a well aerated soil would be expected to be less than in a poorly aerated soil. The small current associated with soil 3, which at the moisture equivalent is well aerated, was caused by the precipitation of ferric hydroxide in the vicinity of the points of attack, and the resultant increase in the resistance of the cell. The precipitation of corrosion products directly over the points of attack in well-aerated soils such as sands, in contrast to the diffusion of the products of corrosion in poorly drained soils, accounts in part for the great difference in corrosiveness shown by these two classes of soils.

A second factor which tends to diminish the flow of current in the cells is the deposition of protective films near the cathode. In alkaline soils these films are formed by the concentration at the cathode of calcium and magnesium ions and of hydroxyl ions (produced by reduction of oxygen). Carbon dioxide, which is produced in the soil by bacterial activity, leads to the formation of films of calcium and magnesium carbonate. The carbonate films reduce the current flow

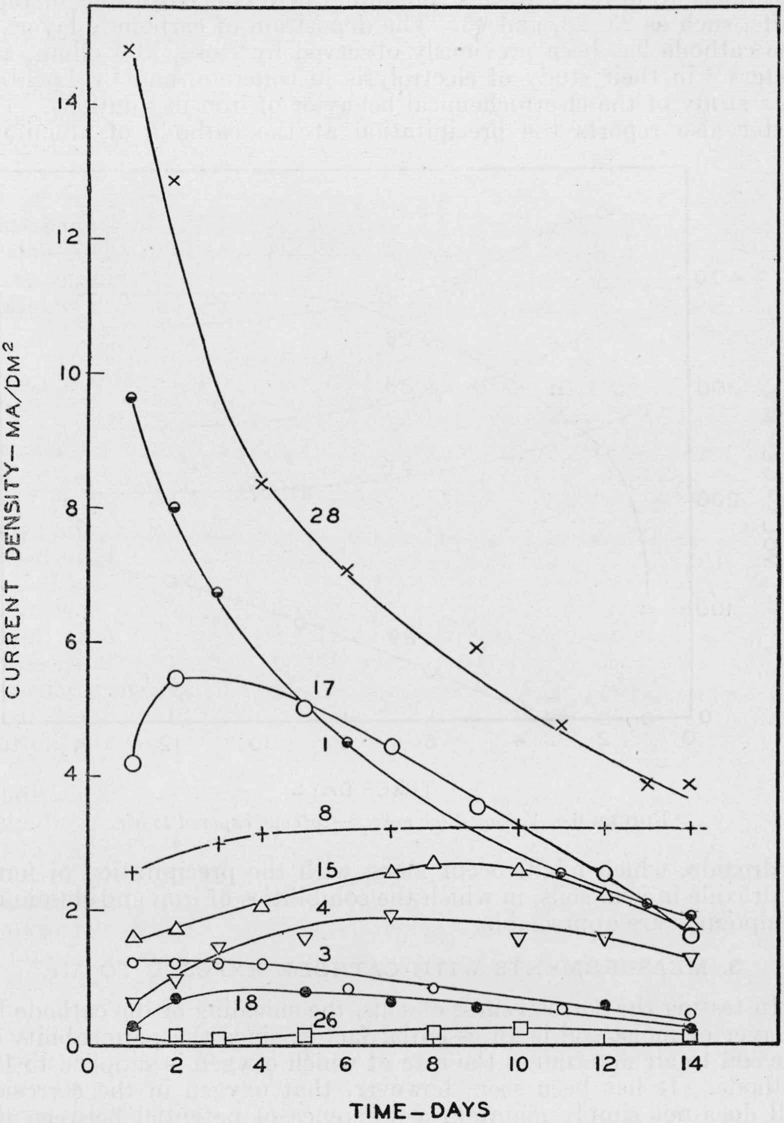

FIGURE 5.—*Current density-time curves—cathode covered with moist soil.*

by reducing the accessibility of oxygen to the cathode, that is, by polarization; and by increasing the resistance of the corrosion circuits. Since as shown by Baylis,[11] the solubility of calcium carbonate is much greater at a given pH in solutions of sodium chloride and sodium sulfate than in pure water, protective carbonate deposits are not likely to develop in soils containing high concentrations of these salts, such as 23, 28, and 45. The deposition of carbonate layers at the cathode has been previously observed by Rosa, McCollum, and Peters [12] in their study of electrolysis in concrete, and by Lochte [13] in a study of the electrochemical behavior of iron in solutions. The latter also reports the precipitation at the cathode of aluminum hydroxide, which might occur along with the precipitation of ferric hydroxide in acid soils, in which the solubilities of iron and aluminum compounds are appreciable.

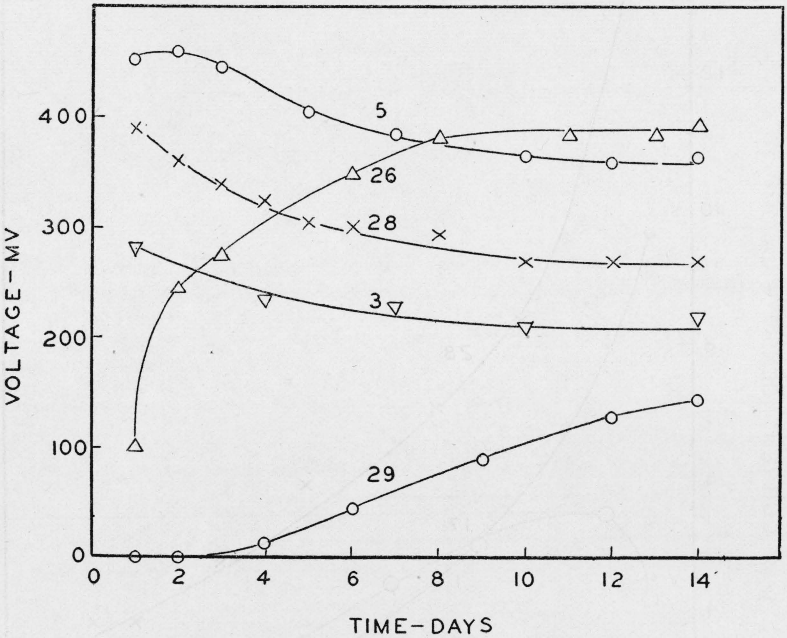

FIGURE 6.—*Voltage-time curves—cathode exposed to air.*

3. MEASUREMENTS WITH CATHODE EXPOSED TO AIR

In testing the corrosiveness of soils, the shielding of the cathode by a layer of moist soil is an essential factor, since the permeability of the soil to air determines the rate at which oxygen is supplied to the cathode. It has been seen, however, that oxygen in the corrosion cell does not simply maintain a difference of potential between the electrodes, but it also affects the formation and deposition of protective films of corrosion products. To obtain additional information on the effect of the degree of aeration on the behavior of the

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[11] J. R. Baylis. J. Am. Water Works Assn. **12**, 211 (1924). F. N. Speller. Corrosion—Causes and Prevention (McGraw-Hill Book Co., New York, 1926).
[12] E. B. Rosa, Burton McCollum, and O. S. Peters. Tech. Pap. BS **2**, (1913) T18.
[13] H. L. Lochte. Trans. Electrochem. Soc. **64**, 173 (1933).

cell, cells were set up in which the cathodes were exposed directly to the atmosphere. From measurements on such cells, in which the tendency toward film formation at the cathode would be intensified, the effects of aeration could be more readily studied. In order not to affect the aeration of the anode, the distance between cathode and anode was increased to 1 cm.

As predicted, the voltages of the cells were almost invariably greater with the cathode bare than shielded. Curves for representative soils are shown in figure 6. Except in organic soils, such as 29, and in especially well-aerated soils, the voltages of the cells were above 200 mv, while in several cases the voltage exceeded 450 mv.

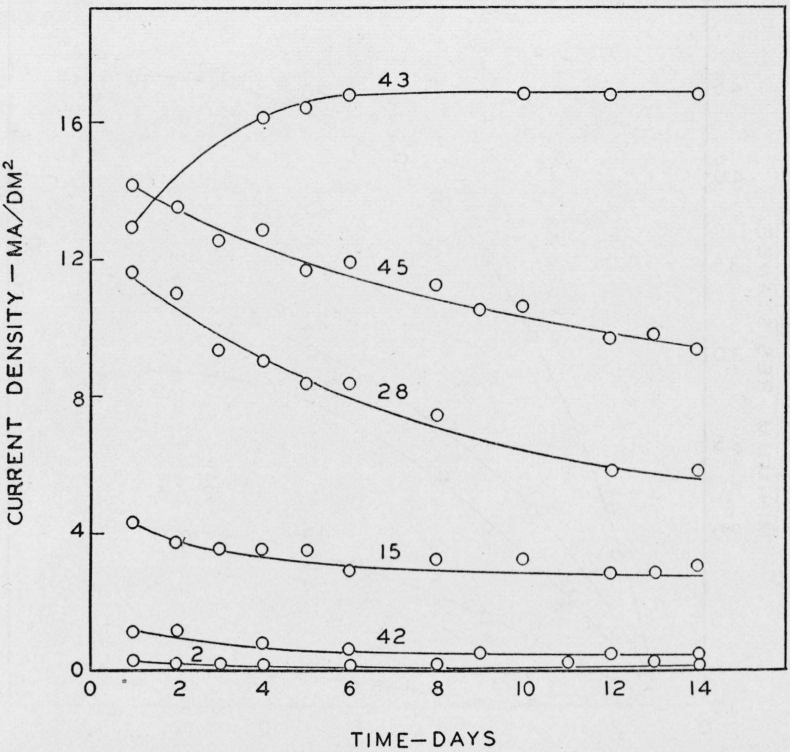

FIGURE 7.—*Current density-time curves—cathode exposed to air.*

A decrease in the current associated with corrosion can generally be accounted for by an increase in polarization, as shown by current density-potential measurements, or by an increase in cell resistance. Thus, the cells containing soils 43, 45, and 28, in which the current flow was large (fig. 7), showed very little polarization at high current densities, and relatively little change in cell resistance. The reverse was true for cells in which small currents were measured.

Figure 8 illustrates the change in resistance of cells containing representative soils. The marked change in resistance of alkaline soils, such as 20, is produced by the precipitation of carbonates of calcium and magnesium on the cathode and in the pores of the filter paper in contact with the cathode. Evidence of the formation of carbonate films is found in the active effervescence of the soil on the cathode and filter paper on treatment with acid. The detection of such films in soils which do not naturally contain carbonates is, of course, proof of their formation at the cathode by the electrolytic action of the cell.

The chemical compositions of the extracts of the alkaline soils (table 1) are generally consistent with the values for current and resistance. Thus, in soils 28 and 45, illustrated in figures 7 and 8, the excess of alkali chlorides and sulfates would be expected to prevent the formation of carbonate films; whereas in soil 2 the quantity of such salts is insignificant. The excess of alkali salts over the alkaline earths in soil 15 indicates the probability of partial protection, such as is illustrated by the curve for this soil in figure 7.

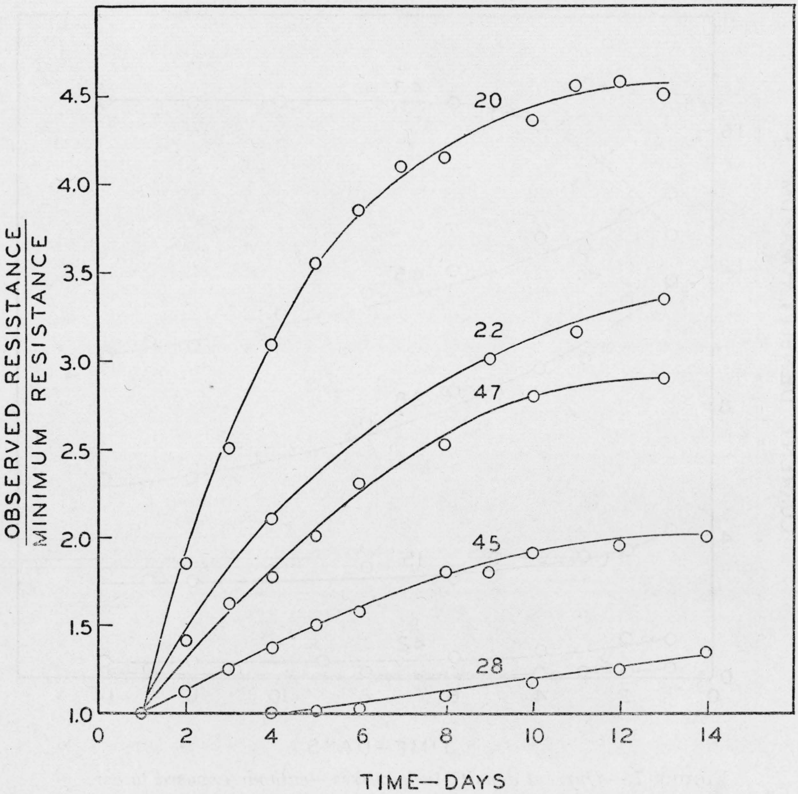

FIGURE 8.—*Resistance-time curves—cathode exposed to air.*

The very small current associated with soil 42 (fig. 7) and the marked change in resistance shown in figure 8 for soil 22, indicate that film formation at the cathode may have occurred, even in these acid soils, for example, by concentration of ions of iron and aluminum at the cathode and their precipitation as hydroxides.

The effect of aeration of alkaline soils (2 and 23) upon the formation of protective films at the cathode was studied by setting up cells with the moisture content at saturation instead of at the moisture equivalent. The results are shown in figure 9.

The curves for soil 2 are typical of the alkaline soils with relatively low resistivity, in which the soluble material consists chiefly of calcium, magnesium and bicarbonate ions. The curves for soil 23 are typical of the alkali soils, in which the soluble material is chiefly sulfates and chlorides of the alkali metals. The difference in current for soil 23 at moisture equivalent and at saturation is not great but for soil 2 this difference is enormous, and very little current flows in the cell at the lower moisture content. The reason for such marked differences is seen when the change in resistance with time for the two soils is compared. In soil 23, with the soil at moisture equivalent, very little change in resistance took place until after 1 week, whereas in soil 2 a fivefold increase in resistance occurred within 3 days.

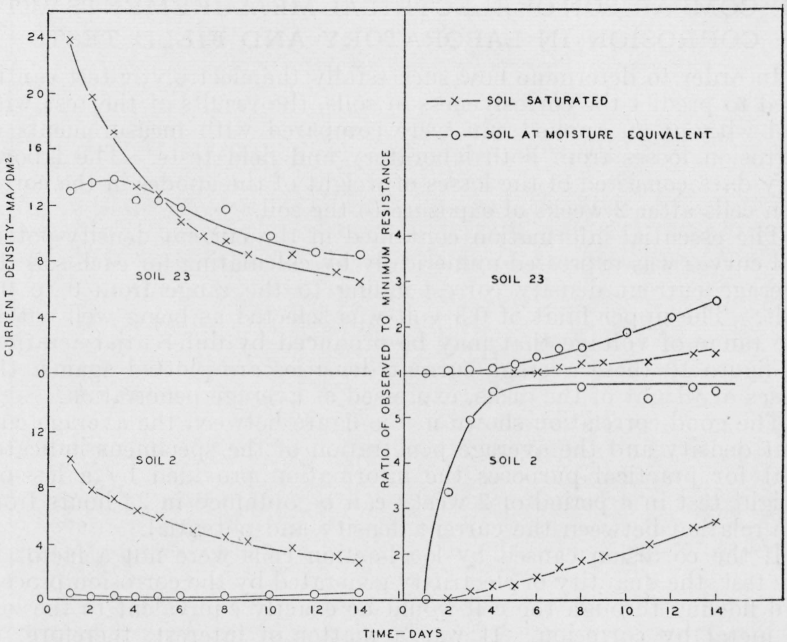

FIGURE 9.—*Effect of moisture content on current density and resistance.*

The explanation for this marked difference in behavior of the two soils is to be found in the formation of a protective carbonate layer in soil 2 at the moisture equivalent. With the soil in the well aerated condition that exists at the moisture equivalent, production of carbon dioxide by bacterial activity proceeds rapidly. The reaction between dissolved carbon dioxide and the calcium and magnesium ions concentrated at the cathode under the influence of the current, in the presence of the hydroxyl ions produced at the cathode, causes the formation of a difficultly soluble protective layer. The increased resistance of this layer produces the marked diminution in current shown in the figure. No such deposit was possible in soil 23, in which ions capable of forming protective deposits are practically absent.

This explanation was confirmed by an experiment in which cells containing these and similar soils in a saturated condition were exposed to an atmosphere containing 15 percent of carbon dioxide.

Marked reductions in current were noticed within 24 hours in soil 2 and similar soils, but not in soils such as 23.

From the results of the studies just described it is reasonable to infer that, in the absence of large concentrations of soluble salts, the action of calcium and magnesium carbonates in inhibiting corrosion would depend largely on the aeration of the soil. The carbonates of the alkaline earths are probably important factors in limiting the rate of corrosion in porous, well-drained soils, where the production of carbonate films is favored. On the other hand, in heavy, poorly drained soils, where the rate of production of carbon dioxide is necessarily limited, there is little tendency for films to be formed and no reduction in the rate of corrosion is to be expected.

VI. COMPARISON OF ELECTRICAL MEASUREMENTS WITH CORROSION IN LABORATORY AND FIELD TESTS

In order to determine how successfully the electrolytic test can be used to predict the corrosiveness of soils, the results of the test with and without an applied emf were compared with measurements of corrosion losses from both laboratory and field tests. The laboratory data consisted of the losses of weight of the anodes in the corrosion cells after 2 weeks of exposure to the soil.

The essential information contained in the current density-potential curves was expressed numerically by calculating for each soil the average current density corresponding to the range from 0 to 0.3 volt. The upper limit of 0.3 volt was selected as being well within the range of voltage that may be produced by differential aeration. In figure 10 these average current densities are plotted against the losses of weight of the disks, expressed as average penetration.

The good correlation shown in the figure between the average current density and the average penetration of the specimens indicates that for practical purposes the information provided by a loss-of-weight test in a period of 2 weeks can be obtained in 24 hours from the relation between the current density and potential.

If the corrosion caused by local-action cells were not a factor in the test, the quantity of electricity generated by the corrosion process and flowing through the cell would be exactly equivalent to the loss of metal by corrosion. It was a matter of interest, therefore, to compare the average penetration of the specimens with the estimated quantity of electricity produced by the cell over the period of test (fig. 11).

The departure of the relation shown in figure 11 from the theoretical linear relation is to be ascribed to local corrosion at the lower current densities. It is seen that the rate of increase of average penetration per unit of electricity decreases until the quantity of electricity reaches about 0.2 ampere-hour, after which the average penetration is roughly proportional to the quantity of electricity. This relation simply means that at the lower current densities,[14] the current flowing through the cells is but a fractional part of the total current associated with corrosion. It follows, therefore, that at the lower current densities much of the nominal anode surface actually acts as a cathode, and the corrosion circuits are confined largely to the disk. As the current density increases an increasingly larger fraction of the disk becomes anodic until at some relatively high current density, prac-

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[14] Since the time and size of specimen is the same for all soils current density may be considered as proportional to quantity of electricity.

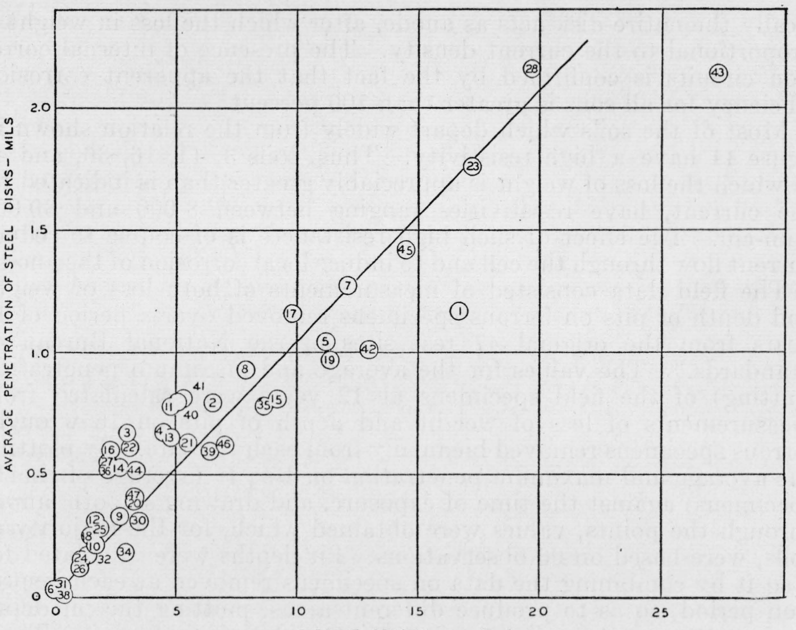

Figure 10.—*Relation between average current density from current density potential curves with applied electromotive force and the average penetration of test specimens.*

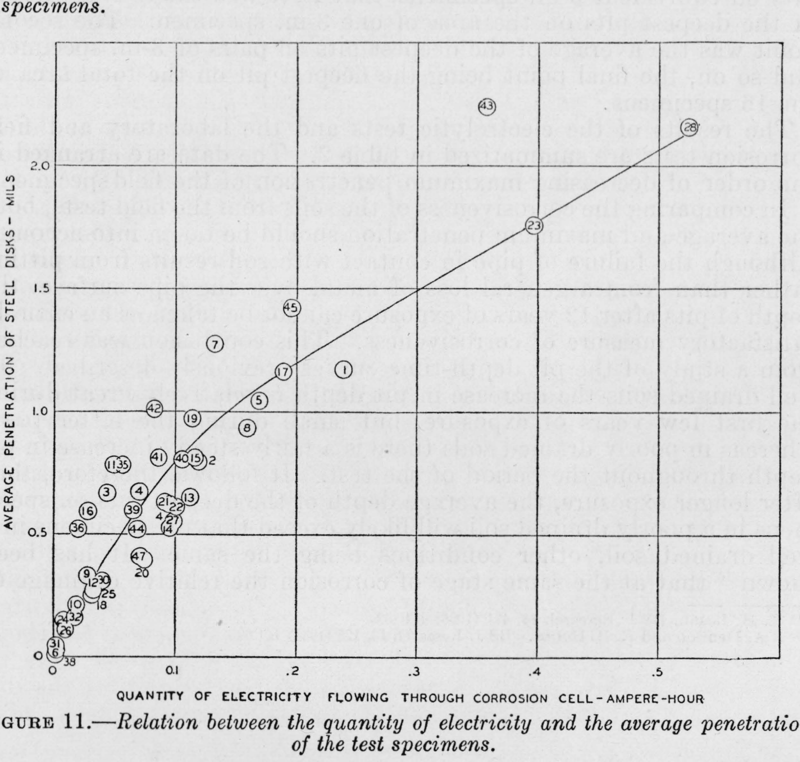

Figure 11.—*Relation between the quantity of electricity and the average penetration of the test specimens.*

tically the entire disk acts as anode, after which the loss in weight is proportional to the current density. The presence of internal corrosion circuits is confirmed by the fact that the apparent corrosion efficiency for all soils is greater than 100 percent.

Most of the soils which depart widely from the relation shown in figure 11 have a high resistivity. Thus, soils 3, 11, 16, 36, and 42 in which the loss of weight is appreciably greater than is indicated by the current, have resistivities ranging between 8 000 and 30 000 ohm-cm. The effect of such high resistances is of course to reduce current flow through the cell and to induce local corrosion of the anode.

The field data consisted of measurements of both loss of weight and depth of pits on ferrous specimens removed over a period of 12 years from the original 47 test sites of the National Bureau of Standards.[15] The values for the average and maximum penetration (pitting) of the field specimens at 12 years were calculated from measurements of loss of weight and depth of pits on 16 wrought ferrous specimens removed biennially from each test site. By plotting the average and maximum penetration on 1 sq ft (average of the 16 specimens) against the time of exposure, and drawing smooth curves through the points, values were obtained which, for the majority of soils, were based on 96 observations. Pit depths were calculated for 1 sq ft by combining the data on specimens removed at each inspection period, so as to produce different areas, plotting the pit depth against the corresponding area and interpolating to 1 sq ft. Thus, the first point on the curve was obtained by averaging the deepest pits on equivalent 3-in. specimens, that is, it was the average depth of the deepest pits on the area of one 3-in. specimen. The second point was the average of the deepest pits on pairs of 3-in. specimens and so on, the final point being the deepest pit on the total area of the 16 specimens.

The results of the electrolytic tests and the laboratory and field corrosion tests are summarized in table 2. The data are arranged in the order of decreasing maximum penetration of the field specimens.

In comparing the corrosiveness of the soils from the field tests, both the average and maximum penetration should be taken into account. Although the failure of pipe in contact with soil results from pitting rather than from a general loss of metal over the pipe surface, the depth of pits after 12 years of exposure cannot be taken as an entirely satisfactory measure of corrosiveness. This conclusion was reached from a study of the pit depth-time curves previously described. In well drained soils the increase in pit depth is relatively great during the first few years of exposure, but small during the latter part; whereas in poorly drained soils there is a fairly steady increase in pit depth throughout the period of the test. It follows, therefore, that after longer exposure, the average depth of the deepest pits on specimens in a poorly drained soil will likely exceed that on specimens in a well drained soil, other conditions being the same. It has been shown [16] that at the same stage of corrosion the relative drainage or

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[15] K. H. Logan, BS J. Research **16**, 431 (1936) RP883.

[16] I. A. Denison and R. B. Hobbs. BS J. Research **13**, 125 (1934) RP696.

TABLE 2.—*Comparison of results of electrical tests with corrosion data from laboratory and field tests*

Soil	Electrical test results		Corrosion test results			
			Laboratory	Field		
	With applied emf. Average current density between 0 and 0.3 v	Without applied emf. Quantity of electricity	Average penetration in 2 wk	Average penetration in 12 yr	Estimated average maximum penetration in 12 yr on 1 sq ft	Pitting factor at 12 yr $\frac{\text{max penetration}}{\text{avg penetration}}$
	ma/dm²	ma-hr	mils	mils	mils	
28	19.7	525	2.16	29.6	229	7.7
29	(c) 21.0	(a)	(a)	27.0	195	7.2
23	17.2	397	1.76	32.8	191	5.8
45	14.5	197	1.42	(b) 19.5	167	8.6
14	4.4	88	.53	7.4	138	18.7
43	27.3	358	2.24	24.5	132	5.4
42	13.0	83	1.01	18.4	120	6.5
33	(c) 20.2	(a)	(a)	20.7	119	5.8
8	7.9	160	.93	8.0	105	13.1
40	5.1	106	.80	11.8	105	8.9
37	19.2	(a)	(a)	14.0	100	7.1
46	7.1	86	.62	7.1	100	14.0
1	16.7	240	1.17	15.2	98	6.4
11	4.8	49	.78	3.1	93	30.0
4	9.5	70	.67	10.6	90	8.5
16	3.4	28	.60	11.7	87	7.4
41	5.3	87	.81	9.2	85	9.2
3	3.0	43	.67	6.9	85	12.3
44	3.4	69	.52	3.8	84	22.1
39	6.4	65	.60	8.6	83	9.7
15	9.2	117	.81	12.6	78	6.2
19	11.4	115	.97	5.2	78	15.0
22	4.2	101	.61	11.5	76	6.6
12	1.7	33	.31	5.7	76	13.3
5	11.2	171	1.05	10.6	75	7.1
27	2.2	99	.55	11.5	73	6.4
2	6.6	120	.80	9.4	72	7.7
20	3.3	75	.39	9.2	71	7.7
34	3.0	(a)	(a)	6.9	66	9.6
10	1.7	19	.21	7.4	64	8.7
9	2.7	28	.33	7.4	60	8.1
18	1.5	31	.25	4.9	59	12.0
36	2.2	20	.52	4.1	56	13.7
25	1.9	33	.27	5.1	55	10.8
32	1.3	17	.16	5.5	55	10.0
7	12.1	133	1.28	7.8	54	6.9
30	3.5	40	.31	8.8	54	6.2
26	1.1	9	.12	6.0	54	9.0
35	8.7	57	.78	3.2	53	16.6
17	9.8	190	1.16	14.8	49	3.3
31	.3	2	.04	4.2	45	10.7
47	3.3	71	.41	4.9	39	8.0
38	.4	1	.01	3.8	39	10.3
24	1.1	8	.15	2.1	26	12.4
6	.0	2	.03	1.8	25	13.9

[a] Cell had no definite polarity.
[b] Average penetration in 10 years.
[c] Cathode bare.

permeability of a soil is indicated by the pitting factor, which is the ratio of maximum penetration to average penetration. A low pitting factor is indicative of poor drainage, whereas a high factor is indicative of good drainage conditions. Consequently, a given depth of pit associated with a low average penetration (low pitting factor) should be given greater weight than when the same pit depth is associated with high average penetration (high pitting factor).

The foregoing discussion of certain features of underground corrosion helps to explain several of the inconsistencies between the field and laboratory data shown in table 2. For example, the maximum depth of pit on the specimens from soil 17 is but 49 mils, although according to the laboratory tests this soil would be classed as definitely corrosive. However, the high average penetration of 14.8 mils is consistent with the results of the laboratory tests. As indicated by the low pitting factor of 3.3, this soil is poorly drained, which is a condition favorable to deterioration of ferrous metals. The corrosiveness of the soil is further supported by its extreme acidity, the pH value being 4.5 and the total acidity 19.1 mg-eq. On the other hand, soils 11 and 44 are probably less corrosive than would be indicated by the pit depths of 93 and 84 mils, respectively. The low average penetration of 3.1 and 3.8 mils and the high pitting factors of 30.0 and 22.2, are consistent with the fact that these test sites are well drained and that the pits are not likely to deepen greatly with time.

Soil 7 is a very acid soil which, for some reason peculiar to the test site, does not appear from the field test to be corrosive. In view of its extreme acidity (pH 4.4 and total acidity 29.8 mg-eq) it is probable that, under slightly different conditions of aeration or drainage, serious corrosion might be experienced in this soil. The slight corrosiveness of soil 35 in the field tests is probably due to the low rainfall and consequent dryness of the soil. The average annual precipitation at this site in Los Angeles was but 11.75 in. during the 10-year period of the test. The marked depth of pitting of specimens in soil 14 is probably due to some peculiar condition of the test site rather than to the soil in contact with the specimens.

If the results of the laboratory and field tests shown in table 2 are compared with the properties of the soils given in table 1, certain effects of chemical composition on the rate of corrosion may be noted. Thus the most corrosive soils are with few exceptions either very acid soils or soils which contain large quantities of salts, chiefly of sodium and potassium. The moderately corrosive soils, which produce a maximum penetration between 75 and 105 mils, are either moderately acid or contain appreciable concentrations of soluble material. Soils 8, 15, 2, and 27 are of interest because they are only moderately corrosive, although they contain fairly high concentrations of soluble material. However, it will be noted from the analyses that the equivalents of calcium and magnesium ions in these soils either exceed those of sodium and potassium or at least form a relatively large part of the total bases. The moderate corrosivenes of soil 8 suggests that fairly high concentrations of calcium and magnesium ions, when present largely as sulfates, are not necessarily corrosive in the presence of solid calcium carbonate under conditions of reasonably good drainage. With regard to the following alkaline soils, 27, 47, 20, 30, 25, 18, 32, and 26, it should be noted that not only is the soluble material low in amount but that the ions of calcium and magnesium predominate over the alkalies.

In figure 12 the data from the laboratory corrosion test (column 5, table 2) are shown plotted against the average depth of the maximum pit on the field specimens after 12 years (column 7). The scattering of the points should be attributed largely to the fact that the pit-depth-time curves do not all have the same shape, but show a marked tendency to intersect after long periods. As previously stated, the tendency for the rate of pitting to decrease with time is greatest in well drained soils and least in poorly drained soils. The points which deviate widely from the trend line, such as those for soils 1, 7, 17, 43, and 47 are all more or less poorly drained. After greater periods of time it is reasonable to predict that these points will be nearer the curve than they are after 12 years.

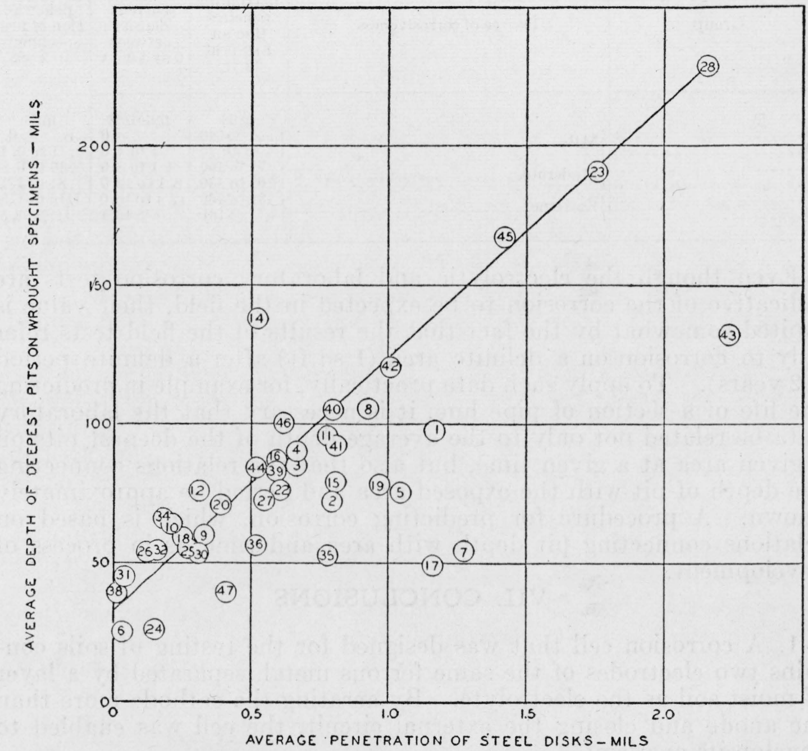

FIGURE 12.—*Relation between the maximum penetration of field specimens at 12 years and the average penetration of test specimens.*

In order to facilitate the practical application of the corrosion test it is desirable to set limits of current density and average penetration which will indicate the range of pit depth to be expected in practice in soils of unknown corrosiveness. Table 3 has been prepared by arbitrarily dividing the soils tested into groups and selecting for each group limiting values of (1) pit depth on 1 sq. ft. at 12 years; (2) average current density corresponding to the range of 0 to 0.3 volt;

and (3) average penetration of the test specimens. Since the relative corrosiveness of the different groups may not be readily appreciated from the measurements of pit depth on 1 sq ft, qualitative terms characterizing the degree of corrosiveness of the groups are included in the table.

TABLE 3.—*Classification of soils on basis of corrosiveness as indicated by field and laboratory tests*

Group	Degree of corrosiveness	Estimated maximum penetration on 1 sq ft at 12 yr	Average current density between 0 and 0.3 v	Average penetration of test specimens in 2 wk
		mils	ma/dm²	mils
I	Mild	<40	0	>0.1
II		41 to 70	.1 to 4.0	.11 to 0.45
III	Moderate	71 to 100	4.1 to 8.0	.46 to 0.80
IV		101 to 130	8.1 to 12.0	.81 to 1.15
V	Extreme	131 to 160	12.1 to 16.0	1.16 to 1.50
VI		>161	>16.1	>.1.50

Even though the electrolytic and laboratory corrosion tests are indicative of the corrosion to be expected in the field, their value is limited somewhat by the fact that the results of the field tests refer only to corrosion on a definite area (1 sq ft) after a definite period (12 years). To apply such data practically, for example in predicting the life of a section of pipe line, it is necessary that the laboratory data be related not only to the average depth of the deepest pits on a given area at a given time, but also that the relations connecting the depth of pit with the exposed area and period be approximately known. A procedure for predicting corrosion, which is based on relations connecting pit depth with area and time, is in process of development.

VII. CONCLUSIONS

1. A corrosion cell that was designed for the testing of soils contains two electrodes of the same ferrous metal, separated by a layer of moist soil as the electrolyte. By aerating the cathode more than the anode and closing the external circuit, the cell was enabled to develop its own emf.

2. The quantity of electricity developed by the cell over a 2-weeks' period is approximately proportional to the loss of weight of the anode and to corrosion losses in field tests.

3. The corrosion test may be accelerated by the use of an external emf. From the relation between current density and the voltage impressed across the cell, corrected for IR drop, the relative corrosiveness of soils can be predicted.

4. The time curves of voltage, current and resistance of corrosion cells that operated with only the emf associated with corrosion, were influenced by the physical and chemical properties of soils.

5. The chief factors that induce corrosion in soils are high concentrations of soluble salts, especially those of the alkali metals; and high acidity. Both factors tend to increase the solubility of the hydroxides of iron and to prevent the formation of protective layers of corrosion products.

6. Corrosion is relatively slight, except under conditions of poor drainage, in soils in which the content of bicarbonate in a water extract of the soil is equivalent to the sum of the calcium and magnesium ions. Well aerated soils, in which the hydroxides of iron are precipitated in immediate contact with the corroding surface, are usually noncorrosive.

7. The results of a laboratory test on a soil were correlated with the loss in weight and the depth of the deepest pit on 1 sq ft of ferrous materials exposed to that soil for 12 years.

8. A laboratory test of corrosiveness of soils, such as that described in this paper, is an essential part of any rational procedure for calculating the life of pipe in a given soil or the number of leaks likely to develop on a section of pipe line in any period.

WASHINGTON, June 22, 1936.