Underground Corrosion

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UNITED STATES DEPARTMENT OF COMMERCE • Sinclair Weeks, *Secretary*
NATIONAL BUREAU OF STANDARDS • A. V. Astin, *Director*

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Melvin Romanoff

National Bureau of Standards Circular 579

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Preface

From the earth are obtained numerous raw materials that are processed into useful products. Conversely, any product placed in the earth ultimately tends to revert, by deterioration of nonmetals or corrosion of metals, to their original form as found in nature. As a result, the annual cost to the United States pipeline industry resulting from the protection and replacement of underground structures due directly to corrosion has been estimated to be in the order of 600 million dollars. In addition, a higher and undeterminable cost results indirectly from corrosion through the loss of products, the loss of life and property by fire and explosion, overdesign of structures, and shutdown of services.

This Circular supersedes the National Bureau of Standards Circular 450, issued in 1945, and is a condensed summary of the Bureau's investigations on the corrosion of metals in soils conducted over a period of 45 years. Included are many references to industrial investigations and field experiences related to the Bureau's underground corrosion studies. The aim is to provide a useful reference for the technician who is interested in the theoretical aspects of underground corrosion, and for the engineer who may be interested only in the practical aspects of the methods commonly used for the prevention of corrosion.

In interpreting the data reported in the Circular, it should be borne in mind that there are many diverse factors that affect the corrosion of underground structures and that the planning of adequate tests and the proper interpretation of the results are matters of considerable difficulty. Further, much of the subsequently determined phenomena about the causes of corrosion in soils was not generally understood during the organization of the investigations, and many of the early burial programs were exploratory in nature. Hence, for these reasons, experienced engineers frequently have different interpretations for the same corrosion data. Although a complete understanding of the phenomena of underground corrosion has not yet been attained, the results of the National Bureau of Standards investigations, have been a major contribution to a better understanding of the subject.

During the course of the investigations, the Bureau had the cooperation of many utilities, technical associations, and manufacturers who supplied materials for test, test sites, labor required for burial and removal of the specimens from the sites, and rendered valuable assistance in planning the tests.

Grateful acknowledgment is made to the many members of the Bureau's staff who were involved in the many phases of the underground-corrosion investigations and whose data are incorporated in the Circular. Acknowledgment is especially extended to the following individuals for critically reading either the entire manuscript or portions thereof and for their valuable contributions: G. A. Ellinger, J. G. Thompson, R. W. Buzzard, J. A. Bennett, M. R. Meyerson, W. J. Youden, and C. Eisenhart. Appreciation is also expressed to W. J. Schwerdtfeger, who, besides reading the portions of the manuscript on the electrical aspects of corrosion, assisted further by contributing additional data.

A. V. Astin, *Director.*

Contents

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The Circular is a final report on the studies of underground corrosion conducted by the National Bureau of Standards from 1910 to 1955.

Up to 1922, the studies were confined to corrosion due to stray-current electrolysis and its mitigation. After it became apparent that serious corrosion occurred in soils under conditions that precluded stray-currents as an explanation, a field burial program was initiated in order to obtain information pertaining to the effect of soil properties on the corrosion of metals. More than 36,500 specimens, representing 333 varieties of ferrous, nonferrous, and protective coating materials, were exposed in 128 test locations throughout the United States. During this time the electrical and electrochemical aspects of underground corrosion have been continuously studied in the laboratory. Results from both field and laboratory investigations are presented.

1. Introduction

The corrosion of metallic structures buried in soils or in contact with soils has long been a serious engineering and economic problem. There are in the United States about 988,000 miles of gas, water, and oil pipelines, 425,000 miles of railroad tracks, 167,000 miles of buried communication, signal, and power cable systems, as well as unknown numbers of tanks, both large and small, and many other structures [1].[1] The annual loss to the American pipeline industry alone, from actual destruction by corrosion and the cost of preventing corrosion, is estimated to be in the order of 600 million dollars [2]. To this figure, there should be added an additional and probably higher cost resulting indirectly from corrosion, namely, the loss of valuable fluids and the loss of life and property by fire and explosion, which may result from leakage due to corrosion. Because the corrosion rates are so often unknown, engineers often overdesign underground structures by specifying extra thickness of metal required to ensure adequate life and strength. This results in needless consumption of appreciable tonnages of critical metals.

"Stray-current electrolysis" is a term applied to accelerated corrosion of underground metallic structures caused by stray electric currents originating from external sources. Stray-current electrolysis was originally assumed to be responsible for all corrosion of metals buried in the soil. The seriousness of underground corrosion was recognized by Congress in 1910, when the National Bureau of Standards was authorized to make a study of corrosion caused by stray electric currents and of possible methods of its mitigation. Investigations, both in the field and in the laboratory over about a 10-year period, indicated that although very serious corrosion resulted from stray currents, equally serious corrosion also occured under circumstances that excluded stray currents as an explanation. The Bureau, therefore, undertook to determine the cause of this corrosion in underground pipe materials. It was determined that some soil environments were corrosive, and subsequent studies were made to determine the relation of the various properties of the soils to the corrosion of buried metals and to ascertain methods for reducing corrosion losses. A large number of manufacturers and users of materials for underground construction cooperated by furnishing materials and labor, and technical personnel actively participated in the test programs. The results and conclusions were published from time to time in the publications of the National Bureau of Standards and in technical and trade journals [3]. Most of these early publications are out of print, and although they may be on file in public, technical, and college libraries, the data are scattered through so many publications that the detailed results of the early investigations are not conveniently available. To consolidate the data and to make them more usable, the results of the underground-corrosion investigations up to that time were summarized in 1945 [4].

The present Circular is a revision of the 1945 publication to include additional data from 1945 to the conclusion of the field tests, and is a final report on the studies of underground corrosion conducted by the Bureau from 1910 to 1955. In addition to the results of the Bureau's investigations, there have been included results of the more important investigations made elsewhere, and a sufficient number of references have been given to enable the reader to familiarize himself with the details of these investigations, insofar as they have been published.

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[1] Figures in brackets indicate the literature references on page 195.

2. Investigations of Underground Corrosion

2.1. In the United States

The most extensive and long-continued study of underground corrosion is the investigation by the Bureau. The investigation of stray-current electrolysis was carried on actively for 10 years, and was reported in 17 Technologic Papers of the Bureau [5 to 21], which were abstracted in a Circular published in 1933 [22]. These papers discuss various phases of stray-current electrolysis, including surveys, track leakage, electrolysis in concrete, protective coatings, and the design of return feeder systems for street railways.

In 1921 the American Committee on Electrolysis, of which the National Bureau of Standards was a member, decided that the effect of soils on the corrosion of pipe in the absence of stray electric currents should be investigated, and the Bureau undertook the work in 1922. Thereafter the Committee became inactive and disbanded after publication of its final report [23].

The work of the Bureau on underground corrosion and means for combating this phenomenon was continued with the support and cooperation of a large number of manufacturers and users of underground pipe and pipe coatings, as listed in appendix 1. These organizations helped to bear the expense of the investigations, and their technical representatives assisted in planning the tests and in interpreting the results obtained, particularly in the early stages of the program. At various times, beginning with 1928, work at the Bureau under the Research Associate plan was supported by the Corrosion Committees of the American Gas Association, The American Petroleum Institute, and the Cast Iron Pipe Research Association.

In addition to the publications by the Bureau, by the cooperating organizations, and in the technical press, information resulting from the soil-corrosion work was disseminated through a series of Soil-Corrosion Conferences. The first Soil-Corrosion Conference was held at the National Bureau of Standards in 1928 for the purpose of bringing together delegates from various industries to discuss and exchange information relating to underground corrosion. The success of this meeting led to subsequent conferences in 1930, 1933, 1937, and 1943. Subjects discussed at these informal conferences usually were not published, but references to the discussions appeared in subsequent publications. These conference papers were the property of the organizations that the authors represented; the Bureau never had copies of the manuscripts available for distribution.

In addition to participation in the National Bureau of Standards program, most of the larger companies operating pipelines employ from one to a dozen or more men whose chief duty is to reduce pipeline corrosion by the practical application of available research data. Statistical studies of service pipelines have been made and many pipeline operators have experimented extensively in the laboratory and in the field with a large variety of protective coatings. The investigations conducted outside of the National Bureau of Standards have resulted in a large accumulation of data that as yet has not been adequately analyzed, although numerous papers based on portions of the data have been published. In many cases definite conclusions cannot be drawn from the corrosion records because the conditions under which the corrosion occurred are not described in sufficient detail. This is especially true with respect to data obtained by investigators who did not note accurate descriptions of soil conditions because of their unfamiliarity with the subject.

In addition to the investigations performed at the Bureau many technical and scientific organizations have formed committees to study problems related to the cause and mitigation of underground corrosion [24].

2.2. In Foreign Countries

Although the most extensive investigations of underground corrosion were carried out in the United States, there have been numerous contributions from other countries.

The Dutch Research Institute for Metals in 1931 set up a Central Corrosion Committee. This committee delegated its work to various subcommittees, some of which investigated the following topics: Corrosive effects of soils on pipes, corrosive effect of soils on cable sheaths, and protective coatings for steel construction. The subcommittee on the effect of soil on pipe inspected pipelines in various parts of Holland, made laboratory studies of soils, soil waters, and pipe materials. The data were correlated and a report issued [25] in 1935. A similar subcommittee on protective coatings issued a report [26], and subsequently, in 1937, a set of specifications [27] for the coating of pipes with asphalt. In addition to the reports of the committee, various members of the subcommittees published papers [28,29] resulting from their researches. Wichers [30,31] working on corrosion problems of the Municipal Water Works of Groningen, Holland, published several reports of the investigations paralleling the work of the subcommittees.

In Australia several organizations have conducted extensive investigations of underground corrosion and protective coatings, as well as of stray-current electrolysis, the results of which were presented in the technical press and at the 1937 and 1943 National Bureau of Standards Corrosion Conferences [32 to 39].

In England the Institution of Civil Engineers, the British Iron and Steel Institute, and the British Nonferrous Metals Association organized a Subcommittee on Soil Corrosion of Metals, which issued an interim report [40] in 1942. A detailed study of anaerobic corrosion [41] was conducted in England, the results of which were published in 1939. The Post Office Engineering Department [42] made studies of the corrosion of lead cable sheath, which were the subject of a detailed report in 1938. The British Board of Trade [23], as a result of an investigation of stray-current electrolysis, issued a set of regulations to govern tramway installations in 1912, which have been the subject of revision from time to time. Evans [43] correlated and summarized the results of extensive investigations conducted at the Chemical Research Laboratory of the Department of Scientific and Industrial Research, Teddington, and the Metallurgical Laboratories of Cambridge University relating to the electrochemical theory of corrosion. Recently the problem of underground corrosion in England has received considerable attention, partly because of recent interest by the Department of Ministry of Health, which provides about 50,000 miles of pipe throughout the country for water and other underground services [44]. As a result, research on underground corrosion was coordinated by the Subcommittee on the Corrosion of Buried Metals of the British Iron and Steel Research Association, and the results of recent research were made available in a symposium held in 1952 [45 to 50].

In Belguim, the seriousness of corrosion problems resulted in the organization of the Centre Belge d'Etude de la Corrosion in 1952 [51]. This body is under the cooperative sponsorship of the government and various industrial organizations, and is concerned with corrosion investigations in all environments, including soils.

The study of corrosion has been very extensive in Germany. Stray-current electrolysis has been regulated since 1910 by limiting the potential gradient between the rails and the earth and prohibiting electrical drainage to pipe systems [52] in order to reduce the hazard to other underground systems.

In Canada severe corrosion of cast-iron water mains in Winnipeg, Manitoba, led to an extended study of soil corrosion at the University of Manitoba [53 to 58].

3. Characteristics of Soils

Soils vary widely in physical and chemical characteristics and in their corrosivity toward metals. Consequently, a certain familiarity with pedology, the science of soils, is helpful to those concerned with corrosion. As much of this information is not readily available, this section will deal in detail with the characteristics and properties of soils. The relation of the properties of soils on corrosion will be discussed in subsequent sections.

3.1. Definition, Classification, and Mapping

a. Definition

In general, the term "soil" is applied to the first few feet of finely divided, modified rock material covering the level and moderately inclined portion of the earth. Crushed rock and unmodified rock on mountain tops are not soils, and, strictly speaking, earth removed from its original position is not soil if it has lost its structure.

Soil is the product of soil-forming processes acting on materials deposited or accumulated by geologic agencies. The characteristics of the soil at any given point are determined [59] by (1) the physical and minerological composition of the parent material, (2) the climate under which that material accumulated and has since existed, (3) the plant and animal life on and in the soil, (4) the topography of the land, and (5) the length of time the forces of soil development have acted on the soil material.

Climate and vegetation are the active factors of soil development changing the parent material from an inert mass to a body that has definite morphology. The effects of climate and vegetation are to varying degrees affected by drainage, aeration, the quantity of water that percolates through the soil, the rate of natural erosion, the vegetation, and exposure to sun and wind. Time, also is involved in the changes that take place, and geological age becomes a factor of soil development because it reflects the degree to which the soil has developed into a body that is in equilibrium with its environment.

The factors of soil genesis are so closely interrelated in their effects on the soil that few generalizations can be made regarding the influence of any one unless conditions are specified for all the others. The interrelations are so complex that many of the processes that may take place in the development of certain soils are unknown.

b. Classification

The classification of soils according to their characteristics is based on their physical and chemical properties rather than on their geologic origin or geographic location, although the soil characteristics may be influenced by both the origin and location.

Soils may be divided broadly into two classes: those in which lime accumulates in the subsoil (pedocals) and those in which it does not (pedalfers). In the United States the first class lies generally west of a line running from northwestern Minnesota to a point on the Gulf of Mexico, 100 miles north

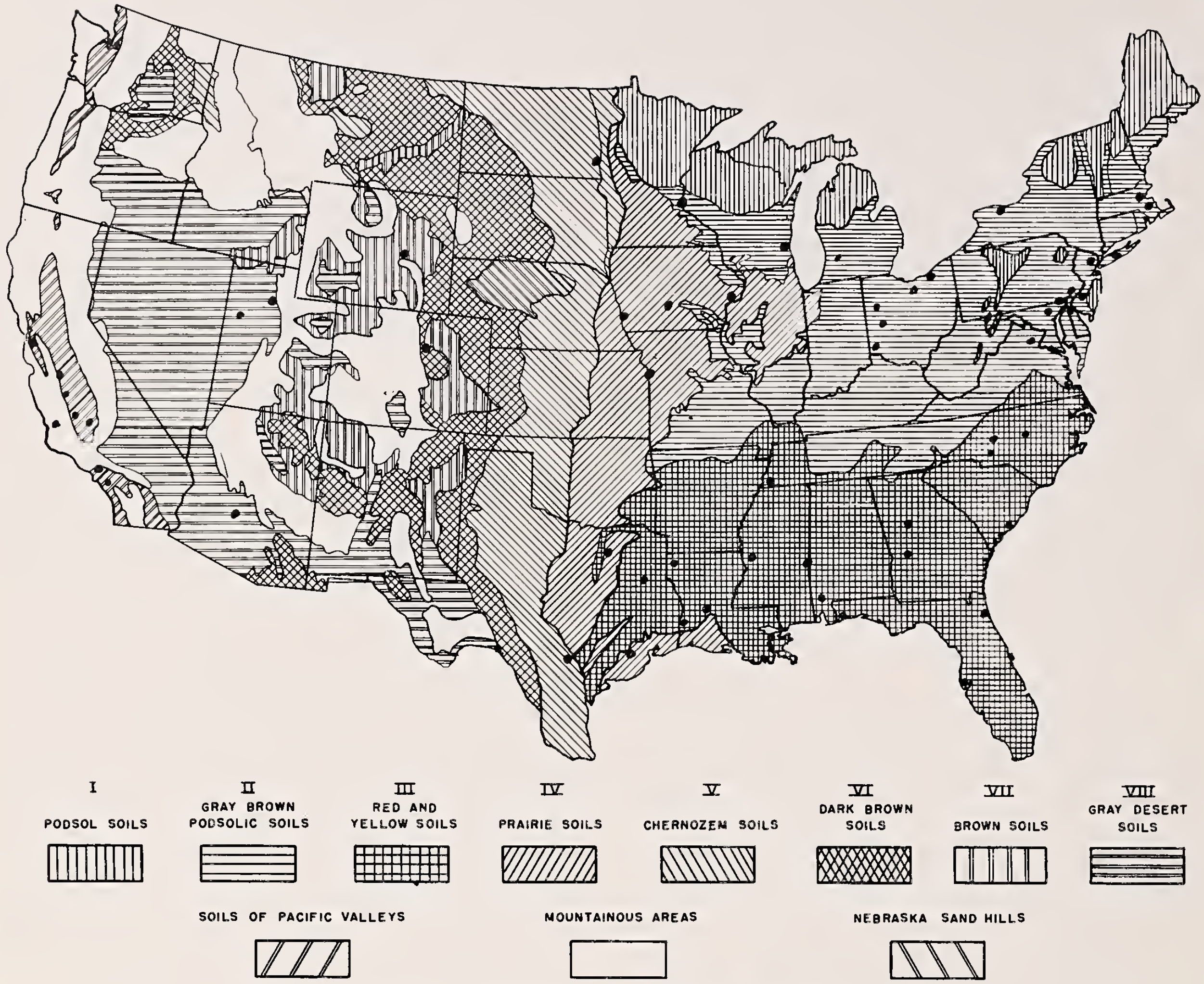

FIGURE 1. *Soil groups of the United States. Marbut [60].*
The dots show the location of the National Bureau of Standards test sites.

of the Mexican border. Marbut [60] in his authoritative treatise on the soils of this country classified the well-developed soils of the continental United States into eight great soil groups, to which he has added several groups of undeveloped soils, among which are muck, peat, rough stony land, sand, and others. Figure 1 shows the boundaries of the great soil groups, as defined by Marbut, as well as the location of National Bureau of Standards test sites. Baldwin, Kellogg, and Thorp [61] in general followed Marbut's groupings of soils but elaborated by supplementing his grouping with several additional groups.

The walls of a vertical hole dug in a soil usually contain a series of well-defined horizontal layers, or horizons, of varying thicknesses and differing in internal properties, such as color, texture, and structure. The sum of all of the horizons from the surface down to the parent material is called a soil profile.

The system of soil identification adopted by the U. S. Department of Agriculture [62,63] uses a letter symbol for each of the separate horizons of the soil profile. The surface layer in which life is most active and abundant is identified by the symbol A. The B horizon consists of the subsoil, and both the A and B horizons include the true soil. The C horizon is usually referred to as the parent material, which may be partly weathered. Figure 2, which has been reproduced from the U. S. Department of Agriculture Soil Survey Manual [63], shows the principal horizons of a hypothetical soil profile. In detailed studies the major horizons, A, B, and C, are further subdivided, the subhorizons being desig-

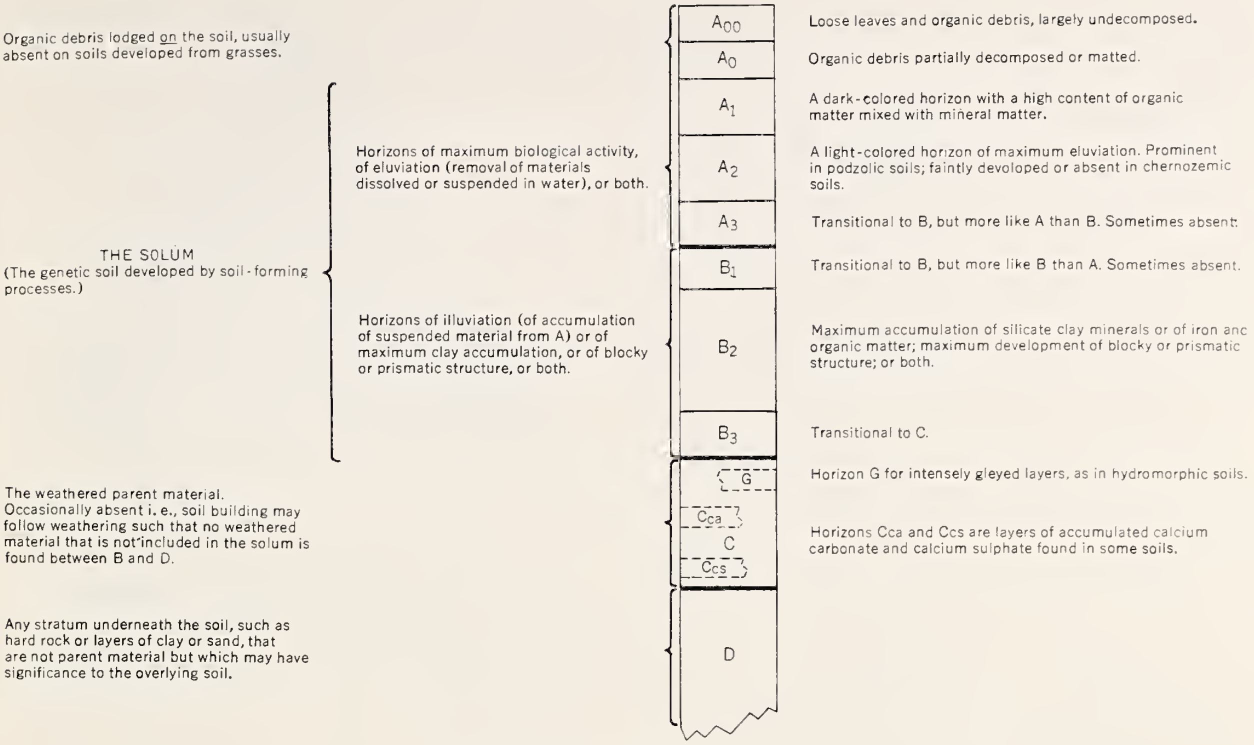

FIGURE 2. *A hypothetical soil profile having all the principal horizons.*

It will be noted that horizon B may or may not have an accumulation of clay. Horizons designated as C_{ca} usually appear between B_3 and C. The G may appear directly beneath the A. U. S. Department of Agriculture Soil Survey Manual [63].

nated by numerals, as A_1, A_2, or B_1, B_2, etc. Table 1 lists Marbut's great soil groups, briefly describes typical soil profiles, and gives some of the types represented in the National Bureau of Standards test sites.

The texture of a soil horizon refers to the relative amounts of clay, silt, and various grades of sand that compose the soil mass. It is determined by the percentages of the particles of various size groups. The particle size is subdivided into two main groups: (1) particles having diameters of 2 mm (0.079 in.) or more, which includes gravel, cobbles, and larger stone; and (2) a group of materials of smaller particle diameter subdivided as indicated in table 2.

Marbut [60] further, subdivided classes of soils according to texture as follows:

I. Sands include all soils containing 20 percent or less of silt and clay, the rest of the material being sand.
  1. Coarse sands contain 35 percent or more of fine gravel and coarse sand and less than 50 percent of other grades of sand.
  2. Medium sands contains 35 percent or more of fine gravel, coarse and medium sand, and less than 50 percent of other grades of sand.
  3. Very fine sands contain 50 percent or more of very fine sand.

II. Sandy loams contain from 20 to 50 percent of silt and clay. They are designated as coarse, medium, fine, and very fine sandy loams in accordance with the predominant sand class group present. There are also gravelly loams and stony loams.

III. Loams and clays contain 50 percent or more of silt and clay combined.
  1. Loams contain 20 percent or less of clay, from 30 to 50 percent of silt and from 30 to 50 percent of sand.
  2. Silt loams contain 20 percent or less of clay, 50 percent or more of silt, and 30 percent or less of other classes.
  3. Clay loams contain 30 percent or more of clay and 70 percent or less of other classes.

Table 1. *Description of typical profiles in great soil groups, and classification of soils in which the National Bureau of Standards test sites are located*

Class	Soil groups	Description of profile	Reaction of profile	Soil type
I	Podsol	A_0, a few inches of leaf mat A_1, very thin dark-gray A_2, whitish-gray, a few inches thick B_1, dark- or coffee-brown B_2, yellowish-brown	Strongly acid	None.
I	Brown podsolic	A_0, leaf mat and acid humus A_1, thin, dark-gray A_2, thin, gray-brown or yellowish-brown B, brown, only slightly heavier than surface soil	Acid	Gloucester sandy loam. Merrimac gravelly sandy loam.
II	Gray-brown podsolic	A_0, thin leaf litter and mild humus A_1, dark-colored, 2 to 4 inches thick A_2, grayish-brown, leached horizon extending to 8 to 10 inches B, yellowish-brown to light reddish-brown, definitely heavier in texture	do	Hagerstown loam. Chester loam. Sassafras silt loam. Miami clay loam. Lindley silt loam.
II	Yellow podsolic	A_0, thin, dark-colored organic covering A_1, pale yellowish-gray leached layer 6 inches to 3 feet thick. B, heavy, yellow C, red and gray mottled parent material (acid)	do	Kalmia fine sandy loam. Norfolk sandy loam. Ruston sandy loam.
III	Red podsolic	A_0, thin organic layer A_1, yellowish-brown or grayish-brown leached layer B, deep-red C, mottled, red, yellow, and gray	Acid	Cecil clay loam. Memphis silt loam. Susquehanna clay.
IV	Prairie	A, very dark brown or grayish-brown B, brown C, light-colored parent material at 2 to 5 feet	Slightly acid surface soil. Neutral to alkaline subsoil.	Marshall silt loam. Summit silt loam.
V	Chernozem	A, black or very dark grayish-brown friable soil to a depth ranging from 3 to 4 feet B, light-colored to whitish lime accumulation	Alkaline	Fargo clay loam.
VI	Dark brown soils	A, dark-brown or dark grayish-brown B, light-gray or white calcareous material at 1½ to 2 feet	do	
VII	Brown soils	A, brown B, light-gray or white calcareous layer at 1 to 2 feet	do	
VIII	Gray desert soils	A, light grayish-brown or gray, low in organic matter B, light in color, high in lime, often high in soluble salts	do	Mohave sandy loam. Panoche clay loam.
VIII	Soils of Pacific valleys	A, brown, reddish-brown or red, friable soil B, heavy, tough, more intense in color	Neutral to slightly alkaline	Ramona loam.
VIII	Rendzina (immature soils developed from marl)	A, dark-gray or black granular soil B, soft, light-gray calcareous material	Alkaline	Houston black clay loam.
VIII	Alluvial soils			Genesee silt loam. Miller clay. Sharkey clay. Wabash silt loam.
VIII	Saline soils	A, light-colored ashy material B, darker-colored heavy material of columnar structure	do	Docas clay. Fresno fine sandy loam.

Table 2. *Classification of soil particles as to size*

Class	Diameter *mm*
Gravel and stones	> 2
Fine gravel	1 to 2
Sand	0.05 to 1
Silt	0.002 to 0.05
Clay	< 0.002

A graphical method for presentation of the classification of soils as to texture was adopted by the U. S. Department of Agriculture [63], as shown in figure 3.

Not only are soils divided into classes according to texture, but, for the purposes of classification, are then subdivided into three categories known as series, type, and phase. Each of the great soil groups contain from 9 to 60 subgroups, known as series, which are further subdivided into soil types. Soils in a soil series have the same genetic horizons, are similar in important characteristics and arrangement in the soil profile, and have similar parent material. Thus, the series comprises soils having essentially the same characteristics of color, structure, and natural drainage. The texture of the upper part of the soil may vary within a series. The series are usually given geographic names related to the locality where the series was first identified. Examples of names of important soil series are Susquehanna, Norfolk, and Sassafras. More than 200 soil series have been identified in the United States.

There are one or more soil types within a series, defined according to the texture of the top layer or the A horizon. Thus, the complete name of the soil type is obtained by adding the class name of the texture to the soil series. Sassafras silt loam and Sassafras gravelly sandy loam are soil types within the Sassafras series. Except for the texture of the surface soil, these types have approximately the same characteristics.

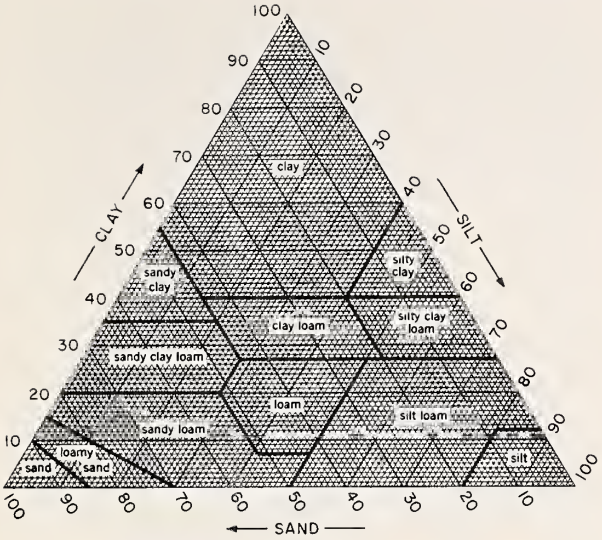

FIGURE 3. *Diagram showing the percentages of clay, silt, and sand by means of which the textural name of a soil may be determined from a mechanical analysis.*

U. S. Department of Agriculture Soil Survey Manual [63].

In using the diagram, the points corresponding to the percentages of silt and clay present in the soil under consideration are located on the silt and clay lines, respectively. Lines are then projected inward, parallel in the first case to the sand side of the triangle and in the second case parallel to the silt side. The name of the compartment in which the two lines intersect is the class name of the soil in question.

The A horizon is usually less than a foot in thickness and may differ in many ways from the horizon below it, in which pipes are commonly laid. Beneath the true soil may be one or more layers of unconsolidated material from which the soil is being slowly formed. As pipes usually do not lie in the A horizon, the name of the soil type does not always indicate the texture of the soil to which the pipe is exposed. However, as a soil with a given name is always substantially the same wherever it occurs, the name of the soil does disclose the character of the soil wherein it is found. Thus, the light-textured A horizon of Susquehanna sandy loam invariably is underlain by a heavy, impervious clay subsoil. The Norfolk sandy loam, on the other hand, always has a friable sandy clay subsoil. Consequently, by reading the soil descriptions that accompany soil maps, the pipeline engineer can determine whether a section of his line will be exposed to a poorly drained soil, where corrosion is likely to be severe, or to a well-drained soil, where little corrosion is to be anticipated.

When specified along with the soil series and type, a soil phase indicates variations in external features, such as form and steepness of slope, degree of stoniness, or differences in the degree of erosion. Such a variation may have some special practical significance but does not alter the major characteristics of the soil profile. Not all soils have sufficient variations in their external features to justify their subdivision into phases.

c. Soil Mapping

A soil map is designed to portray the distribution of soil types and phases, as well as other features of the earth's surface. Since 1899, the U. S. Department of Agriculture has been engaged in mapping the soils of the United States, and considerably more than two-thirds of the tillable soil of this country has been mapped [63,64]. Soil reports[2] are issued for single counties or specific areas consisting of all or parts of several counties. Each soil-survey report includes both the map and text, in which are described the area surveyed, the characteristics and capabilities for agricultural and engineering use of the soils, and the principal factors responsible for soil development. The reports do not discuss the corrosivity of the soils, but they are, nevertheless, very helpful to the pipeline engineer, who can obtain from them data pertaining to aeration, drainage, and other characteristics of the soil that affect corrosion along his right-of-way. Much of the desert and mountain lands, where oil and gas are frequently found, have not been mapped, but fortunately in these areas corrosion usually is not severe. The soils of the principal cities have been mapped, but soil surveys of cities are of little value to the corrosion engineer because of the disturbing effects of cuts, fills, pavements, and buildings.

3.2. Chemical Properties

A large number of chemical elements exist in soils, but most of them are combined in difficultly soluble compounds, which exert little direct chemical influence on corrosion. These inert compounds of soils are chiefly combinations of oxygen with silicon, aluminum, and iron. Iron in various degrees of oxidation is responsible for the color of many soils, and this color is an indicator of the degree of aeration of the soil For example, in well-aerated soils the iron compounds are oxidized to the ferric state. These soils are generally indicated by their red, yellow, or brown colors. In poorly aerated soils, due to the lack of sufficient oxygen, the soils are predominantly gray in color (sometimes mottled with yellow or brown), indicating the presence of reduced forms of iron. Accumulations of organic matter in humid areas favor the formation of darker-colored soils.

Chemical analyses of soils, for corrosion studies, are usually limited to determinations of the constituents that are soluble in water under standardized conditions. The elements usually determined are the base-forming elements, such as, sodium, potassium, calcium, and magnesium, and the acid-forming elements, such as, carbonate, bicarbonate, chloride, nitrate, and sulfate. The quantity of the water-soluble salts, as well as for the total acidity, are reported as milligram-equivalents per 100 of soil (mg-eq per 100 g of soil), the milligram-equivalent being the chemical equivalent or combining weight of the element or radical, expressed in milligrams. By this method of expression the comparison between the different ions is facilitated. In a typical analysis, if such values as 0.040 percent

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[2] Soil survey reports may be purchased from the Superintendent of Documents, Government Printing Office, Washington 25, D. C. The name of the County and State should be furnished.

of Ca, 0.024 percent of Mg, and 0.046 percent of Na are expressed in mg-eq per 100 g, it is obvious at once that the percentages all represent the same chemically equivalent amount of the different elements, since each corresponds to 2 mg-eq per 100g. The nature and amount of soluble salts, together with the moisture content of the soil, largely determine the ability of the soil to conduct an electric current. Extensive discussion of the chemistry of soils and methods of soil analyses are available in several texts [65,66,67].

The development of acidity in soils is a result of the natural processes of weathering under humid conditions. In regions of moderate rainfall, soluble salts do not accumulate except where soil waters seep to lower levels and collect in depressions. However, in regions of high rainfall, not only are soluble salts removed from the soil but the absorbed bases normally present in the colloidal materials of the soil are partially removed, and result in increased acidity. These processes eventually give rise to the condition known as soil acidity. The depths to which this leaching of the bases occurs varies with rainfall, drainage, type of vegetation, and nature of the material present. The fully developed soils of the prairie regions are acid to a considerable depth, whereas soils whose development has been retarded by poor drainage or other conditions are alkaline and may even contain appreciable quantities of salts. East of the prairies the well-developed soils are acid throughout the soil profile.

The degree or intensity of acidity or alkalinity of a soil is expressed as the pH, a value that represents the logarithm of the reciprocal of the hydrogen-ion concentration. A pH value of 7 indicates neutrality; lower values, acidity; and higher values, alkalinity. Terms used for soil reaction are defined in the Soil Survey Manual [63] as follows:

	pH
Extremely acid	Below 4.5
Very strongly acid	4.5 to 5.0
Strongly acid	5.1 to 5.5
Medium acid	5.6 to 6.0
Slightly acid	6.1 to 6.5
Neutral [3]	6.6 to 7.3
Mildly alkaline	7.4 to 7.8
Moderately alkaline	7.9 to 8.4
Strongly alkaline	8.5 to 9.0
Very strongly alkaline	9.1 and higher

Soils made alkaline by an abundance of calcium carbonate are called calcareous, and soils containing appreciable amounts of exchangeable sodium (or sodium plus potassium) are called alkali soils.

It should be emphasized that the pH value is a measure of the degree, or intensity, of the existing hydrogen-ion concentration, and not of the total quantity of ionizable hydrogen in the soil, which is referred to as the total soil acidity.[4] Because the pH and total acidity are influenced by the kind of clay, the kind and amount of organic matter, exchangeable bases present, and the soluble salts present in the soil, the relationship between pH and total acidity is not constant for all types of soils. Generally, soils rich in organic matter retain greater reserves of acidity and alkalinity than sandy soils or other soils low in organic matter. A soil with a high capacity or reserve, as indicated by the total acidity, is a well-buffered soil. Because buffered solutions resist a change in its hydrogen-ion concentration upon the addition of acid or alkali, the development of extremely low pH values are prevented in such soils. Usually the hydrogen-ion concentration, or the total acidity of the soil, or both, are determined.

The chemical properties of a soil may vary with time because of bacterial action. Certain types of bacteria are capable of "fixing" atmospheric nitrogen and of converting nitrogenous material in the soil to forms useful to plant life. Other bacteria convert sulfur and sulfides to sulfates, and still other bacteria accomplish the reverse reaction.

3.3. Physical Properties

The physical properties of soils that are of importance in corrosion are chiefly those that determine the permeability of the soil to oxygen or air and to water. The particle-size distribution of the soil is obviously an important factor with respect both to aeration and to moisture content. In soils of coarse texture, such as sands and gravels, where there is free circulation of air, corrosion approaches the atmospheric type. Soils that are free of clay and silt have low plasticity, low water-holding capacities, and are not much affected by changes in moisture content. These conditions, exemplified by coarse sandy soils, are favorable to good drainage and aeration.

Clayey and silty soils, in general, are characterized by fine texture, high water-holding capacity, and consequently, by poor aeration and poor drainage. The clay particles are highly plastic and become sticky and impervious when saturated with water. Such soils shrink and crack on drying, and swell on rewetting. Soils containing appreciable amounts of silt possess some plasticity and expand and contract considerably on wetting and drying, but to a much less degree than clay.

Terms that are used to define permeability and moisture retention in soils include air-pore space, apparent specific gravity, moisture equivalent, and shrinkage. The air-pore space is expressed as the percentage of the volume of soil at a definite moisture content that is occupied by air. It is therefore a relative measure of the permeability of the soils to air and to moisture, and, other things being equal, a high value of air-pore space indicates a relatively noncorrosive soil. The apparent specific gravity of the soils in their natural state was determined by measurements made on undisturbed lumps of soil from the test sites. The lumps were immersed in a dish filled with mercury, and the volume of the lump was determined by measuring the volume of mercury displaced. The weight per unit volume was calculated by dividing the weight of the soil by its actual volume. The apparent specific gravity is an index of the compactness of mineral soils because

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[3] Strict neutrality is pH 7.0, but in the field those soils between pH 6.6 and 7.3 are called neutral.

[4] Methods used for the determination of pH in the field and laboratory, and of total acidity in the laboratory are discussed in a later section.

the true specific gravity of the mineral particles in soils varies only within narrow limits. This value is influenced to a large extent by the amount of voids, or air-pore spaces, i.e., by the degree of packing. The amount of organic matter present may markedly influence the apparent specific gravity of a mineral soil. Therefore, the specific gravity of the A horizon is generally less than that of the lower horizons.

The moisture equivalent was determined by saturating a sample with water, subjecting it to a centrifugal force of 1,000 times gravity for 40 min and determining the residual water content by drying in an oven at 105°C until constant weight is obtained. The moisture equivalent is a measure of the retentiveness or water-holding capacity of the soil, i.e., the quantity of water retained by a soil in equilibrium with capillary and gravitational forces. 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 volume shrinkage was determined by measuring the volume of soil at the moisture equivalent and again in the oven-dried condition, the change in volume being expressed as percentage of volume at the moisture equivalent. It is an indication of the colloidal nature of the clay and loam particles in a soil and the tendency of the soil to crack on drying and to swell when wetted.

The physical properties of soils are described in detail in the Atlas of American Agriculture [60], and Soils and Men [62,65], by Lyon and Buckman [68], and by Keen [69].

4. Theory and Mechanism of Corrosion Underground

The ensuing discussion of the theory and mechanism of corrosion underground represents current opinion developed during the 30 odd years since the NBS exposure program was initiated.

4.1. Theory

Iron and many other metals used in underground constructions become coated with a thin film of oxide immediately upon being exposed to air. Such a film on iron may be merely of molecular thickness but, nevertheless, furnishes some degree of protection against further oxidation or corrosion. At sufficiently high temperatures oxygen can diffuse through, around, and under these films so that the film increases in thickness, forming scale that may flake off to expose fresh surfaces for the continuing reaction. At room temperature, however, the passive film of iron oxide furnishes considerable protection to the underlying metal and increases in thickness exceedingly slowly. Most of the corrosion of iron (and other metals) in underground service at normal or moderate temperatures is the result of an electrochemical reaction.

For electrochemical corrosion to occur, there must be a potential difference between two points that are electrically connected and immersed in an electrolyte. Whenever these conditions are fulfilled, a small current flows from the anode area through the electrolyte to the cathode area and then through the metal to complete the circuit. The anode area is the one that has the most negative potential, and is the area that becomes corroded through the loss of metal ions to the electrolyte. The cathode area, to which the current flows through the electrolyte, is protected from corrosion because of the deposition of hydrogen or other ions that carry the current.

The electrochemical theory of corrosion is simple, i.e., corrosion occurs through the loss of metal ions at anodic points or areas. However, correlation of this theory with actual or potential corrosion of metals underground is complicated and difficult because of the many factors that singly or in combination affect the course of the electrochemical reaction. These factors not only determine the the amount or rate at which corrosion occurs but also the kind of corrosion, whether it is uniformly distributed and therefore relatively ineffective or is localized as the pitting type of corrosion. The latter is much more dangerous because a few small perforations can greatly reduce the efficiency of a pipeline, even though there is only a very small or negligible loss in weight of the pipe as a whole.

Identification of the importance of various factors and the correlation of these data in terms of the electrochemical theory of corrosion have been discussed in many of the papers and books cited in in the list of references, particularly Evans [43], Burns and Schuh [70], Ewing [71], Gatty and Spooner [72], Hoar [73], Speller [74], and Uhlig [75]. It should be emphasized that, as a result of these corrosion studies there is better understanding of the role of individual factors than of the combined effect of a number of factors and conditions. In other words, underground corrosion that has occurred can be explained, but, even today, theory does not permit accurate prediction of the extent of corrosion to be expected to occur and is dangerous unless complete information is available regarding all of the factors present and their individual and interrelated effects.

4.2. Factors That Affect Corrosion Underground

These factors are grouped under four headings: (1) aeration, (2) electrolyte, (3) electrical factors, and (4) miscellaneous. In this discussion some repetition is unavoidable because the same phenomenon or factor may be operative in more than one grouping and the various factors frequently are interrelated. Much of the discussion refers specifically to iron and steel but applies in varying degrees to other metals. Also much of the discussion is based on results obtained from some of the early exposures of ferrous materials and the experimental evidence, on which this discussion is based, is described in detail in subsequent sections, e.g., section 8.6.

a. Aeration

Aeration factors are those factors that affect the access of oxygen and moisture to the metal and thereby affect the corrosion process. Oxygen, either from atmospheric sources or from oxidizing salts or compounds, stimulates corrosion by combining with metal ions to form oxides, hydroxides, or salts of metal. If these corrosion products are soluble or are otherwise removed from the anodic areas, corrosion proceeds but if the products accumulate they may serve either as a protective blanket to reduce corrosion, or to stimulate and localize corrosion because the products are more noble (cathodic) than the bare metal.

The aeration characteristics of a soil are dependent primarily upon physical characteristics such as the particle size, particle-size distribution, and apparent specific gravity, all of which are related to the size and continuity of the pore space. Local differences in the packing of the soil and in its moisture content may develop oxygen concentration cells, where the area with the least oxygen is anodic, in which corrosion may occur, to the areas to which oxygen is more readily accessible. This is in effect, a variation of the fact that a continuous oxide film on iron is more noble (less corrodible) than the iron but that, if the film is cracked or is not continuous, corrosion of the exposed iron is accelerated because it is less noble than the adjacent oxide. Such corrosion may be either general or localized, depending upon the relative size and distance between anodic and cathodic areas

Phenomena that affect aeration characteristics also have other effects. For example, most soils decrease in volume when they dry out and increase in volume when they are wet again. Particularly in the case of clay soils high in organic matter, the shrinkage in volume on drying produces cracks that provide effective channels for the oxygen of the air to reach the buried pipe. Other effects of this volume change that have been noted are mechanical effects, particularly on coated pipe. The shrinking soil tends to pull the coating off the pipe [76], whereas the coating may be deformed in compression when the soil expands. Figure 4 from an earlier NBS publication [4], illustrates cracking in a clay soil and deformation produced in a pipe coating.

b. Electrolyte

Factors included under this heading are (1) the electrolyte, (2) those that affect the flow of current through the electrolyte, and (3) the chemical reactions that occur within the electrolyte.

The principal function of soil moisture in underground corrosion is to furnish the electrolyte for carrying the current and thereby promoting the electrochemical corrosion process. The ions in the electrolyte may be hydrogen and hydroxyl ions from the water itself and a variety of cations and anions which depend upon the number and amount of soluble salts dissolved in the electrolyte. The presence of these ions determines the electrical conductivity, expressed as resistivity, of the electrolyte, as well as chemical properties, such as acidity or alkalinity, and the development of chemical reactions between the primary products of corrosion and the electrolyte. For example, iron is corroded by electrolytes that contain sulfates or chlorides from the soil because the corrosion products formed at the anode and the cathode are both soluble. On the other hand, the anodic corrosion of lead in the presence of sulfate ions ceases after a short time because of the deposition of insoluble lead sulfate on the anode surface. The principal cathodic reaction in the corrosion of iron is the combination of iron ions with hydroxyl ions in the vicinity of the cathode. However, cathodic deposits are not restricted to reactions involving ions from the metal anodes; if soluble calcium bicarbonate is present in the electrolyte, insoluble calcium carbonate may be precipitated in the cathodic areas because of the increase in alkalinity in those regions as a result of the flow of current.

A B

Figure 4. *Soil cracking and its effect on a pipe coating.*

A, Cracks in Lake Charles clay. The white spot below the junction of the cracks is a 50-cent coin; B, rag-felt-reinforced asphalt pipe coating wrinkled by soil pressure. Swelling of the soil forced the coating into the cracks. Note also cracks in the coating. Logan [4].

TABLE 3. *Relation of water soluble salts to some other properties and to corrosivity of certain soils*

Soil		Composition of water extract, mg-eq per 100 g of soil [1]							Acidity		Electrical resistivity at 60°F	Corrosivity
No.	Type	Na+K as Na	Ca	Mg	CO_3	HCO_3	Cl	SO_4	*p*H	Total acidity, mg-eq per 100 g of soil		Max. pit depth in Bessemer steel after 12 years
	LEAST CORROSIVE											
											Ohm-cm	*Mils*
47	Unidentified silt loam	0.67	0.72	0.39	0.00	0.88	0.06	0.48	7.6	3.0	1,770	29
17	Keyport loam	------	------	------	------	------	------	------	4.5	19.1	5,980	50
36	Ruston sandy loam	------	------	------	------	------	------	------	4.5	4.6	11,200	47
24	Merrimac gravelly sandy loam	------	------	------	------	------	------	------	4.5	12.6	11,400	31
26	Miami silt loam	.27	.50	.31	.00	.70	.03	.12	7.3	2.6	2,980	39
6	Everett gravelly sandy loam	------	------	------	------	------	------	------	5.9	12.8	45,000	40
31	Norfolk fine sand	------	------	------	------	------	------	------	4.7	1.8	20,500	45
	MOST CORROSIVE											
8	Fargo clay loam	1.42	1.72	2.55	0.00	0.71	0.01	4.43	7.6	(2)	350	119
45	Unidentified alkali soil	8.15	3.70	0.70	.00	.24	.18	11.98	7.4	(2)	263	137
29	Muck	2.15	1.92	1.55	.00	.00	1.69	2.30	4.2	28.1	1,270	146
33	Peat	1.52	7.30	4.06	.00	------	2.27	2.13	6.8	36.0	800	103
28	Montezuma clay adobe	1.50	0.06	0.18	.00	.12	0.99	0.89	6.8	(2)	408	153
23	Merced silt loam	8.38	.38	.22	.02	1.87	1.12	5.57	9.4	(2)	278	173

[1] Analyses by I. A. Denison; mg-eq = milligram equivalent.
[2] Alkaline.

The data in table 3 show the proportions of the principal elements that would be present either as ions or as molecular compounds in the electrolyte from several soils from early NBS test sites. The table also includes data on other properties of the soil and on the corrosive character of these soils as indicated by the maximum depth of pits developed in Bessemer steel after 12 years of exposure. The data show that the corrosive soils contain large amounts of soluble salts, which results in low resistivity values. The least corrosive soils as a group have high resistivities and such low soluble salt concentrations that it was not considered necessary to determine them for soils with resistivities above 3,000 ohm-cm. The relation between soluble salts and other properties of the electrolyte, or soil, is more definite for electrical resistivity than for *p*H, or total acidity. Specific values for total acidity are appreciably affected by factors other than the soluble salts, for example, by the buffering action of colloidal material.

c. Electrical Factors

Electrical factors define the size, number, and location of anodic areas and the amount of current that flows from the pipe to the soil. The effect of soluble salts on the electrical conductivity of the electrolyte is discussed in a preceding paragraph.

The principal electrical factor in the underground corrosion of metals is the variation in solution potential that exists at different points or areas on the surface of the metal. Whenever there is an appreciable difference in potential between two points or areas, a current will flow from the anode (more negative potential) through the electrolyte to the cathode (less negative potential) and then through the metal to the anode to complete the circuit. It is the anodic area that is corroded by loss of metal ions to the electrolyte.

Potential differences may develop because of contact between dissimilar metals or because of the presence of strains, inclusions, intermetallic compounds, separate constituents like graphite in cast iron, in fact, because of any departure from complete homogeneity of structure and composition of the metal. It has been mentioned previously that local variations in the supply of oxygen, because of differential aeration, can set up oxygen concentration cells in which the areas deficient in oxygen are anodic to the areas where oxygen is more plentiful. Potential differences as high as 0.9 v have been observed [77] in the laboratory when one portion of a soil in contact with a steel plate was kept moist and thereby was deficient in oxygen in comparison with an adjacent portion of soil that was drier and hence more permeable to oxygen. Practical examples of this phenomenon are encountered in pipelines where the water table is at or near the bottom of the pipe and where, consequently, the bottom areas of the pipe are more severely corroded than the top. Potential differences also may be caused by differences in oxygen accessibility to the metal because of surface phenomena such as breaks in a protective oxide film or local deposits of corrosion products. Because the potential difference involves both the metal and the electrolyte, it may be affected by local variations in either phase.

The potential difference that is effective in setting up a corrosion cell is the difference between the potentials of the anode and cathode areas. The amount of current that flows through the cell, as a result of this potential difference, is influenced by the electrical characteristics (conductivity or its reciprocal resistivity) of the electrolyte and by polarization at the metal surfaces. The conductivity of the metal itself, to complete the circuit back to the anode, is only a minor or negligible factor because the conductivity of metals in general is so much greater than that of soil electrolytes. The effective potential difference, and the resulting corrosive current, is not necessarily constant with time for any particular cell for the following reasons: (1) Accumulation of reaction products may blanket the anode or cathode and thereby increase the resistance of the cell; (2) the anode or cathode may become passivated through the discharge of enough hydrogen or hydroxyl ions to cover the surface with a film; and (3) chemical reactions within the electrolyte may create local deficiencies of ions to carry the current.

The relative size of the anode and cathode areas is a factor in determining the amount of corrosion damage. For a given potential difference, if the anode area is large (low anode current density) and the cathode area is small, the total current may be negligible because of passivity and other interfering affects at the cathode surface and the consequent small damage to the anode area is not important because it is distributed over an appreciable area. On the other hand, if the anode area is small (high anode current density) with respect to the cathode area, the corrosive action is localized and severe local damage may result.

In the matter of potential differences created by the contact of dissimilar metals, the relative positions of the two metals in the electrochemical series is not the sole determinant of the extent of corrosion. For example, it is common practice to screw brass corporation cocks into cast-iron water mains, and little or no corrosion has resulted. A possible explanation for this is that the anodic area (the iron pipe) is so large in comparison with the cathodic area (the brass cock) that either the corrosion is so widely distributed that it becomes unimportant or cathodic polarization reduces the corroding current to a negligible quantity. On the other hand, serious corrosion of iron parts of valves with brass seats exposed to moving sea water has occurred, and a number of cases of corrosion of steel pipe attached to copper pipe in domestic installations have been reported.

An unusual example of potential differences because of "dissimilar" metals in contact was reported by Logan, Rogers, and Putman [78]. When a new pipeline was laid parallel to an old one, as was sometimes done in the transportation of petroleum with the two lines interconnected at the pump station, it was found that the new line remained slightly anodic to the old one for several years. The resulting small currents did not damage the new pipe appreciably but may have protected and prolonged the life of the old pipe to some extent. This is in effect an application of cathodic protection in which reduction of corrosion of a metal surface is accomplished by making it cathodic.

Corrosion caused by stray currents, from grounded electric power sources or equipment, is an example of the combined effect of a relatively large potential difference or current plus the fact that the anode area, where the current leaves the pipe, is small. If the current flows from the pipe to the powerhouse, products of corrosion at the anode are carried away continuously and there is no chance for cathodic interferences to develop because the cathodic areas on the pipe are so far removed from the anodic area. Stray currents from electric generators and from electric railways having rails that are not well insulated from the soil have been, in the past, important sources of severe corrosion. However, with the development of methods of control this cause has diminished in importance and today is seldom encountered. It has been mentioned previously that, when the NBS investigation was started in 1910, stray currents were assumed to be the principal cause of all underground corrosion but that this assumption was soon found to be in error.

The so-called long-line currents frequently observed in cross-country pipelines are similar in effect to stray currents in creating potential differences in different sections or areas of a pipeline with possible resultant corrosive effects. These currents flow from an external anodic area through the earth over large distances and enter a cathodic area in an underground metallic structure, and return to the earth from some anodic point along this structure. If a sufficiently sensitive voltmeter is connected across a few feet of almost any pipeline, indications of a flow of current along the line will be obtained. These currents vary in different sections of the same pipe and usually represent a very small amperage. The origin of these long-line currents has been discussed by several authors; Gish [79] associated them with magnetic storms and Logan, Rogers, and Putnam [78] with static charges or potentials collected from the air by tanks and other structures connected to the pipeline or with local or regional differences in the nature and moisture content of the soil, which would affect the potentials of the same pipe in the different localities or areas. More attention was paid to establishing the existence of the potential differences or the current flowing within the pipe than to determining whether or where the current left the pipe. Consequently the conclusions of various authors [80,81,82,83,84] in regard to the relation of long-line currents to pipeline corrosion are somewhat contradictory but, in general, indicate that corrosion from this source is not serious.

d. Miscellaneous

There are several factors or phenomena that are difficult to classify because they are a combination of one or more of the previously mentioned causes of corrosion. For example, the variable corrosion of different sections of the same pipe caused by change of environment from contact with different horizons or areas of the same soil may result from variations in potentials, aeration, or chemical reactions, or combinations of all three. A variation of this effect, and an important source of difficulty in explaining or predicting corrosion in specific cases, is that, in backfilling the trench after the pipe is laid, the various soil horizons are not replaced in their original order nor original state of compactness.

Some pipeline operators attempt to minimize the the backfill effect by placing a layer of sand next to the pipe or by thorough wetting and tamping but the latter measures are used more to avoid subsequent settling of the backfill and consequent displacement of the pipeline. Occasionally, serious corrosion has been reported because of stones, sticks, or other foreign material that come in contact with the pipe when the trench was backfilled.

Logan [85] presented data from field tests and pipeline inspections to show what might be called a statistical factor, i.e., that the maximum pit depth observed will, in general, increase with increase in the area surveyed.

Bacterial action, another factor that influences underground corrosion is associated with aeration, the formation and presence of soluble salts. Bacteria are not only the simplest but also the most numerous forms of soil life. Certain forms, aerobes, thrive in the presence of air but other forms, anaerobes, function best in the absence or near absence of air. Each type of bacteria produce different chemical products. For example, Lyon and Buckman [68] described bacterial action whereby sulfur—containing proteins and other organic combinations were transformed to hydrogen sulfide or elemental sulfur, and these products were subsequently oxidized to the sulfite and sulfate conditions. However, the one that has received the most attention in studies of underground corrosion is the anaerobic bacteria spirovibrio desulfuricans, which extracts oxygen from the sulfate radical and thereby converts soluble sulfates to iron sulfide. It has been established that sulfate-reducing bacteria occur in practically all soils throughout the world when moisture, sulfates, and assimilable organic and mineral matter are present and oxygen is absent.

Anaerobic bacterial action has an effect on the corrosion of metals underground, principally because some of the products of bacterial action have been reported [28,88,89,90,91,92] to accelerate the normal corrosion processes, but the importance of sulfur-reducing bacteria appears to be greater in the corrosion of joints calked with sulfureous materials than in the corrosion of the metal pipe itself. Kuhr [28,93,94] in Holland was the first to report on anaerobic bacterial activity as a factor in underground corrosion. Hadley [86] reported that sulfate-reducing bacteria were most active in swamps and low lands when the *p*H of the soil water was between 6.2 and 7.8, and Romanoff [87] found that the *p*H of a poorly aerated sulfide-containing soil could be appreciably altered by oxidation of sulfur compounds during a laboratory drying process. Subsequent investigations were carried out by Bunker [41,95,96] in England, by Hadley [86,97,98,99] in the United States, and by others. Beckwith [88] reported that some aerobic bacteria may cause or accelerate corrosion and Deuber [100] summarized the results of most of these investigations.

5. Pitting Type of Corrosion

It has been pointed out in preceding sections that, in general, the most dangerous corrosion is that which occurs at anodes of limited area and results in the formation of deep pits within the metal and even complete perforations.

Denison and Darniele [101] developed an explanation of pitting of iron in soils from results obtained from a laboratory corrosion cell, in which the corrosion products and processes could be observed. In the initial stages iron ions migrate into the electrolyte from a small area that is anodic for any of the reasons previously discussed. At the same time, negatively charged hydroxyl ions and acid ions, such as chloride, sulfate, nitrate, carbonate, etc., migrate from the cathode area in the electrolyte toward the anode. This condition will continue as long as the two electrodes maintain their respective potentials and the electrolyte continues to supply ions for conducting the current, but the rate at which current flows or corrosion occurs may be affected by reactions that occur within the electrolyte. Figure 5, from a presentation by I. A. Denison to the 1948 convention of the American Gas Assn. [102], illustrates a case where the main surface of the metal is cathodic because of the presence of a

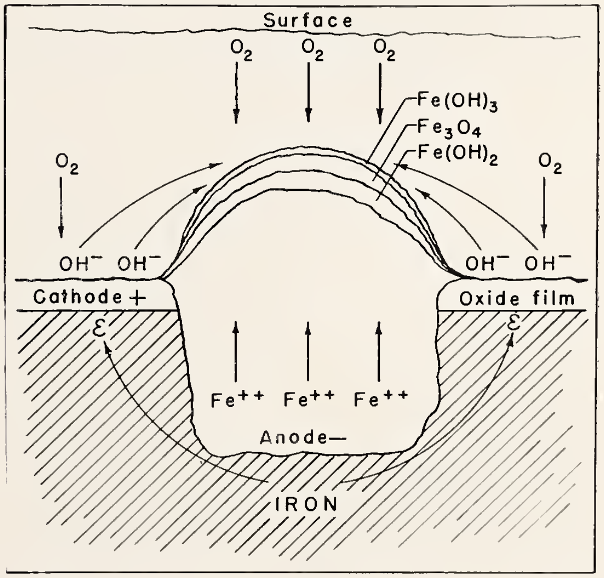

FIGURE 5. *Development of a pit in a ferrous material. Denison [102].*

continuous film of iron oxide, whereas a crack or other discontinuity in the oxide film produces a small anode area. As shown in the figure, corrosion has proceeded until the anode has receded below the surface and reactions between corrosion products have occurred. The first reaction product to form is ferrous hydroxide, $Fe(OH)_2$, formed by the union and neutralization of Fe^{++} and OH^- ions. This was first observed as a thin green precipitate over the anode area. As the reaction between Fe^{++} and OH^- ions continues, the film of ferrous hydroxide increases in thickness, and the outer layers are converted to ferric hydroxide by interaction with oxygen and hydroxyl ions of the electrolyte. The intermediate layer of magnetic oxide, Fe_3O_4, was postulated to be formed by interaction of the ferrous and ferric hydroxide films.

Corrosion continues after the tubercle of corrosion products forms over the anode area because the tubercle is permeable to some if not all of the ions involved in the corrosion process. Corrosion will continue within the pit, by migration of Fe^{++} ions from the anode, as long as the supply of chlorine, sulfate, and other anions is maintained and the soluble ferrous salts will be precipitated on or within the $Fe(OH)_2$ layer of the tubercle. However, if for any reason the solution within the pit becomes saturated with ferrous ions, the reaction will stop until the saturated condition is remedied by conversion of some of the ions to soluble compounds or to insoluble ferrous hydroxide.

Forest, Roetheli, and Brown [103] reported that the different oxides and hydroxides of iron had varying effects on the corrosion reactions, i.e., that the magnetic oxide was permeable to all ions and hence did not affect the corrosion processes, whereas films of ferric hydroxide excluded oxygen from the anodic areas and thereby influenced the anodic reactions.

Baylis [104] concluded that carbon dioxide absorbed in the water played an important role in the development of tubercles on the inner side of domestic water pipes that he investigated. Elaborating on Baylis data, it is evident that ferrous carbonate and calcium carbonate are insoluble compounds but that their solubility increases in the presence of bicarbonate ions, HCO^-_3. Precipitation of the insoluble ferrous and calcium carbonates may form tubercles, as did the iron hydroxides shown in figure 5, or may be deposited elsewhere.

Whether or not the corrosion process is accelerated by the formation of tubercles, instead of open pits, is a question. The soil conditions that promote the development of large tubercles have been listed as low permeability to air, high concentration of soluble salts and high acidity. The latter two factors are largely reciprocal in that the higher the concentration of soluble salts the lower is the acidity needed to induce corrosion. The tubercle does not always form immediately over the anode; tubercles were observed [101] to form at appreciable distances from the corroding surface, in definitely alkaline soils that were high in alkaline salts and in very acid soils that were deficient in soluble salts.

6. Correlation of Corrosion Theory With Practice

Several correlations of individual corrosion factors, or of interrelated factors, with corrosion of operating pipelines have been reported, in addition to the correlations previously mentioned in this Circular.

Denison and Ewing [105] showed that the degree of oxidation and aeration of certain Ohio soils, as indicated by the color and texture of the soils, bore a general relation to the corrosivity of the soil, as indicated by the percentage of the length of pipeline that had been repaired. Logan, Ewing, and Denison [106] established the relations, shown in figure 6, between aeration characteristics of a number of soils from NBS test sites and the rate of pit development in ferrous specimens during a 12-year exposure. Each plotted point represents the average depth of the deepest pits in 12 specimens. The slope of the lines shows that the pits increase in depth slowly in well-aerated soils and more rapidly in poorly aerated soils. Starkey and Wight [92] reported that a satisfactory correlation was obtained between the aeration characteristics (oxidation-reduction potentials) and the corrosion of operating pipelines.

The interrelation of hydrogen-ion concentration, soluble salts, total acidity, and electrical resistivity has been pointed out previously. Denison and Ewing [105] showed that the corrosion experienced in pipelines increased with higher total acidity values for a group of soils that had resistivities of 4,000 to 5,000 ohm-cm, and the correlation also showed increased corrosion with smaller resistivity values for another group of soils that all had total acidity values between 15- and 18-mg equivalents. Their results are shown in table 4. Denison and Hobbs [107] found a similar relation between total acidity and corrosiveness of soils, when other factors were nearly constant. However, these factors are interrelated, and it is difficult to control conditions so that there is only one variable. In the absence of such control, the correlation may be difficult or indefinite, as was the case for the acidity data shown in table 3.

These and other attempts at correlation emphasize again that underground corrosion is affected by a number of specific and interrelated factors, that the localized or pitting type of corrosion is much more serious than general corrosion and is harder to control, and that underground corrosion of any

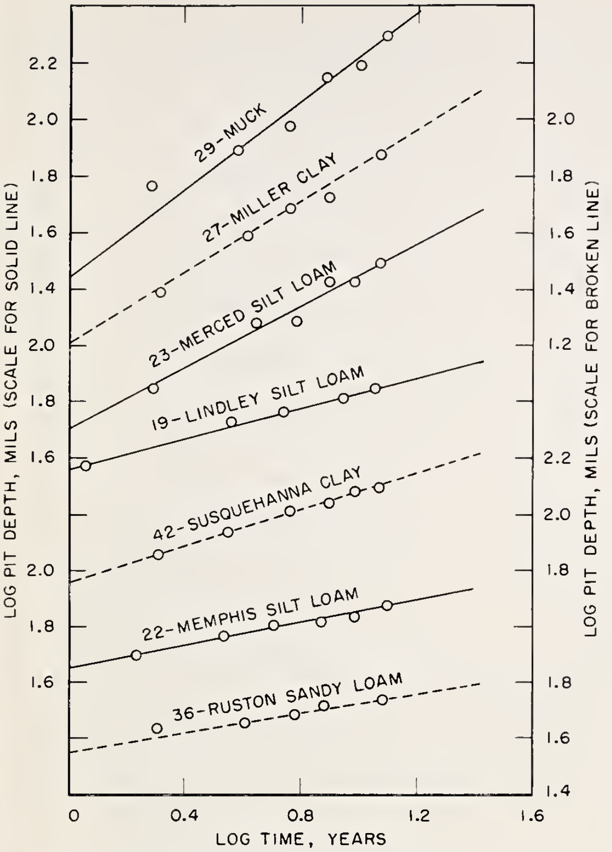

FIGURE 6. *Relation of slopes of pit-depth–time curves for ferrous metals to aeration of soil* [106].

Soil	Aeration	Soil	Aeration
29	Very poor	42	Fair
27	do	22	Good
23	Poor	36	Very good
19	Fair		

TABLE 4. *Corrosion of pipelines as affected by soil acidity and resistivity* [105]

Influence of Acidity—Soil Resistivity 4,000 to 5,000 ohm-cm

Soil type	Total acidity	Proportion of pipeline requiring repairs
	mg-eq[a]	*Percent*
Wauseon fine sandy loam	7.5	6.3
Caneadea silt loam	12.2	13.3
Miami silt loam	16.8	22.8
Mahoning silt loam	18.1	20.9
Trumball clay loam	21.1	20.0
Crosby silt loam	22.0	30.8

Influence of Resistivity—Total Acidity 15 to 18 mg-eq[a]

Soil type	Resistivity	Proportion of pipeline requiring repairs
	Ohm-cm	*Percent*
Lordstown fine sandy loam	11,450	3.3
Wooster loam	8,002	6.0
Volusia silt loam	5,473	13.6
Mahoning silt loam	4,903	20.9
Miami silt loam	3,982	22.8
Nappanee clay loam	1,009	57.0

[a] Milligram-equivalents of hydrogen ion per 100 g of soil.

kind seldom proceeds at a uniform rate throughout the exposure. Enough data are available to differentiate between very mildly corrosive and severely corrosive soils and soil environments. The lack of fundamental knowledge in this field is such that even when much more data is available than is normally reported for corrosion studies, it is sometimes difficult to explain and often difficult to predict results in corrosive soil environments. Such predictions are most reliable when they are based on a combination of laboratory and controlled field tests with actual experience in industrial pipes, all exposed to the same soil environment.

7. Investigations by the National Bureau of Standards

7.1. Scope and Methods

a. Field Burial Investigations

The Bureau's investigations, beginning in 1910, of stray-current electrolysis as the cause of underground corrosion, showed that this was not the sole cause. As a result of this work the Bureau initiated, in 1922, the study of the effect of soils free of stray-currents on commonly used pipe materials. It is important to remember this objective, as it was a prime factor in the design of the experimental procedures used in the investigation. The reader should also bear in mind that many of the subsequently determined phenomena related to the behavior of metals in soils were not generally understood at the time the tests were started.

At the beginning of the program a meeting of technical representatives of a number of manufacturers of cast and wrought ferrous pipe and of the National Bureau of Standards was held to determine the sizes and varieties of materials for the initial tests and the procedure of conducting the tests. The Bureau of Soils, now the Bureau of Plant Industry, Soils, and Agricultural Engineering, of the United States Department of Agriculture, acted as an adviser in the selection of the types of soils to which the specimens would be exposed and assisted in the selection of test sites that would represent definite soil types. However, in order to secure labor and keep expenses at a minimum, it was sometimes necessary to use sites that, in view of later work, might not have been considered suitable had the importance of very uniform soil conditions been fully realized.

Each time the specimens were to be removed, cooperating agencies were invited to have representatives present to observe conditions of the soil and specimens. Rough drafts of the progress reports were submitted to each manufacturer concerned, for comment prior to publication, and occasional conferences were held to discuss the whole program or portions thereof. In this way the Bureau obtained the advice and suggestions of a large number of experts in different phases of corrosion. Between 1922, when the field burial program started, and 1952, when the last of the specimens were removed from the test sites, more than 36,500 specimens, representing 333 varieties of materials, were exposed in 128 test sites throughout the United States. The scope of the National Bureau of Standards field burial investigation is shown in table 5.

TABLE 5. *Scope of the National Bureau of Standards corrosion tests*

Material	Number of varieties	Number of specimens buried
Ferrous:		
Plain and low-alloy wrought	40	8,662
High-alloy wrought	12	1,391
Plain and low-alloy cast	18	3,539
High-alloy cast	2	668
Nonferrous:		
Copper and copper alloy	24	3,828
Lead	8	1,242
Zinc	5	420
Aluminum	45	792
Nonmetallic:		
Asbestos-cement pipe	2	300
Protective coatings:		
Metallic—		
Lead	2	526
Zinc	17	1,639
Miscellaneous	3	254
Bituminous—		
NBS coatings	11	976
AGA coatings	42	2,352
API coatings	65	4,258
Nonbituminous-nonmetallic—	19	2,127
Miscellaneous:		
Nuts and bolts	9	788
Cable	1	246
Pipe fittings	8	2,496
Total	333	36,504

Number of test sites	128
Number of cooperating organizations:	
Manufacturers supplying materials	102
Companies supplying labor and test sites	103
Advisory organizations	13
Government Departments	3

Each of the cooperators, listed in appendix 1, has been listed only once, although many of them cooperated in several ways and in several tests. The widespread support of the soil-corrosion investigations by manufacturers and consumers alike is indicated by the large number of cooperating organizations, which, individually and jointly, contributed an appreciable portion of the total cost of the investigation, by supplying materials and labor at the test sites and in the support of research associates at the National Bureau of Standards.

Figures 7 and 8d, illustrate the ways in which the specimens were placed in the trenches at the test sites after careful tests has been made for the absence of stray electric currents. The depths at which the specimens were placed corresponded roughly to the depths at which pipes were generally laid in that region, and ranged from 18 in. in the southern locations to 6 ft in northern locations. Wherever possible, the specimens were buried in the same soil horizon. The specimens were placed in a definite order with respect to each other and from 6 in. to 1 ft apart to avoid one specimen affecting the corrosion of another by galvanic action and to facilitate the removal of selected specimens without disturbing the soil near the others. When the specimens were removed, the upper side or edge of each was marked with a center punch, to facilitate a study of the distribution of corrosion on each specimen with respect to its position in the trench.

As a rule, 10 or 12 specimens of each material were buried at each test site, and 2 specimens were removed at intervals of approximately 2 years. In later years the times between removals were modified in accordance with the apparent corrosiveness of the soil to which they were exposed. After 1924, precautions were taken to prevent internal corrosion of the metallic pipe specimens by coating the interiors of the specimens with a heavy grease and closing the ends with caps. The caps also served to prevent damage of the coated pipe specimens during shipment. A typical set of specimens, including ferrous, nonferrous and miscellaneous materials after removal from a test site in 1946, is shown in figure 9. After removal from the trench, the loose dirt was scraped off and the specimens were boxed and returned to the National Bureau of Standards. In the laboratory, each material was carefully cleaned and subjected to appropriate chemical and mechanical treatments, to remove the corrosion products with little loss in weight or mechanical injury to the base metal. The methods employed in cleaning the specimens are described in details in appendix 2, and the methods of obtaining, computing, and reporting the data are described in appendix 3. In general, the wrought specimens lost very little metal by the cleaning processes. Cast iron was much more difficult to clean as it corrodes along the boundaries between the graphite and the metal crystals and some uncorroded iron may have been removed with the corrosion products. On the other hand, there was some evidence that not quite all the corrosion products were removed in cleaning the cast-iron specimens.

In 1922, specimens of the most commonly used pipe materials were buried in 47 soils. Specimens were removed from these sites in 1924, 1926, 1928, 1930, 1932, and 1934 and the last set of specimens from the less corrosive sites in 1939. Results of exposures of 12 and 17 years are, therefore, available for these materials. At the time of the removal of the specimens in 1924, other materials were buried at the same sites, and in 1928 specimens were exposed to a new group of test sites.

It had become evident that the commonly used ferrous pipe materials corroded rapidly in some

Figure 7. *Arrangement of specimens buried in cinders at Milwaukee, Wis., in 1937.*

Figure 8. *Environmental conditions at several test sites.*

A, Site 56, Lake Charles clay at El Vista, Texas; B, site 70, Merced silt loam at Buttonwillow, Calif.; C, site 63, tidal marsh at Charleston, S. C.; D, site 55, Hagerstown loam at Loch Raven, Md.

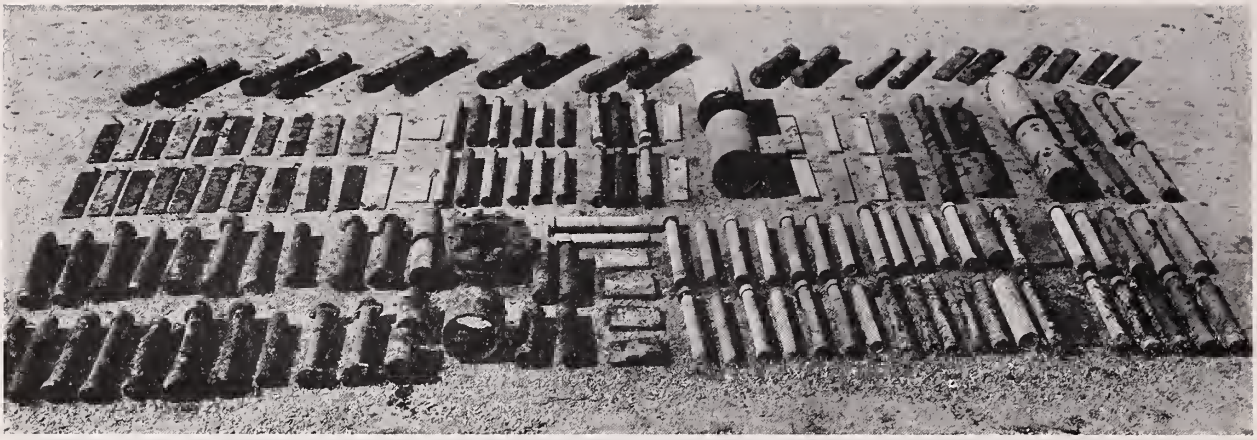

Figure 9. *Specimen removed from Hagerstown loam at Loch Raven, Md. in 1946.*

soils, and in 1932, a new series of tests was started to find materials suitable for use under the more corrosive conditions. For these tests in 15 sites, manufacturers were invited to submit materials they believed would be suitable for use. Specimens were removed from each of these sites in 1934, 1937, 1939, 1941, and 1946. At the time of the removal of the specimens in 1937, 1939, and 1941, additional materials were buried at the same sites and were removed in 1946, 1948, 1950 and 1952. Most of the data for the above-mentioned removals of the specimens have been published in progress reports [108 to 128].

b. Laboratory Investigations

Although the Bureau's extensive field investigation of the corrosion of metals underground is generally regarded as its major contribution to the field of soil corrosion, reference should be made to a lesser known aspect of the Bureau's activities in this field. From the early investigations of stray-current electrolysis to the present, and paralleling the development of the electrochemical theory of corrosion, electrical and electrochemical aspects of underground corrosion have been continuouly studied in the laboratory. It was hoped that the corrosion status of a metal in contact with the soil might be completely defined in terms of the standard electrical units, from measurements made on a continuously corroding surface. These laboratory researches with soil electrolytes are discussed in detail in subsequent sections of this circular [80,129 to 143].

7.2. Materials Tested

The 333 varieties of materials involved in the National Bureau of Standards program, have been summarized in table 5. The form, dimensions, composition, and the number of specimens of each material are given in tables in subsequent sections where the data for the particular materials or programs are presented.

It will be noted in the tables that the same identification letter has been used to designate different kinds of materials at different times in the 30-year program. Complete identification of a specimen or set of specimens involves an identifying letter, the name of the class of materials to which the specimen belongs, and the year in which the specimen was buried. The form and dimensions are also helpful for identifying the material.

7.3. Soils at the Test Sites

For a complete understanding of the results of the National Bureau of Standards tests, detailed information as to the conditions to which the materials were exposed is essential. Descriptions of the soil profiles of the test sites are therefore presented in appendix 4.

These descriptions were prepared in most instances by soil scientists of the U. S. Department of Agriculture, and in a few cases by the man who buried the specimens. Under the conditions of the tests it was impractical to secure test sites that were completely uniform throughout their lengths. Consequently, sets of specimens buried in one end of the trench might corrode at somewhat different rates than those in the other end, thus contributing to the dispersion of the data. However, the uniformity is greater than that encountered in pipelines. The lack of reproducibility of results is common to all corrosion tests, particularly to nonlaboratory tests. From a practical viewpoint it may be fortunate that completely uniform sites were not available, as such sites might have obscured an important feature of underground corrosion.

The 128 locations at which the National Bureau of Standards has conducted corrosion tests represent about 95 types of soils. Table 6 shows the locations and the chemical and physical properties of the soils in the Bureau's tests, and table 7 shows the mechanical analysis of some of these soils. The properties of the soils in which tests on bituminous coatings only were conducted are given in table 8.

TABLE 6. *Chemical and physical properties of the soils at the NBS test sites* [a]

Soil		Location	Internal drainage of test site [c]	Resistivity at 60°F	pH	Composition of water extract, mg-eq per 100 g of soil								Mean temperature [e]	Annual precipitation [e]	Moisture equivalent	Air-pore space	Apparent specific gravity	Volume shrinkage
No. [b]	Type					Total acidity [d]	Na+K as Na	Ca	Mg	CO_3	HCO_3	Cl	SO_4						
				Ohm-cm										*°F*	*Inches*	*Percent*	*Percent*		*Percent*
1	Allis silt loam	Cleveland, Ohio	P	1,215	7.0	11.4	0.72	0.25	0.43	0.00	0.09	0.09	0.83	49.2	33.8	28.6	1.1		6.6
2	Bell clay	Dallas, Tex.	P	684	7.3	3.5	.28	1.09	.13	.00	1.18	.04	.18	65.5	36.2	37.6	2.0	1.95	23.0
3	Cecil clay loam	Atlanta, Ga.	G	30,000	5.2	11.5								61.2	48.3	29.1	18.2	1.60	7.0
4	Chester loam	Jenkintown, Pa.	F	6,670	5.6	7.6								54	40	22.2	7.0	1.78	2.2
5	Dublin clay adobe	Oakland, Calif.	P	1,345	7.0	6.5	.93	.48	.10	.00	0.69	.03	.25	56.4	23.4	28.8	4.9	2.00	22.6
6	Everett gravelly sandy loam	Seattle, Wash.	G	45,100	5.9	12.8								51.0	34.0	12.2	40.6	1.50	0.1
7	Maddox silt loam	Cincinnati, Ohio	F	2,120	4.4	29.8								53.2	38.6	34.3	3.7	2.02	34.5
8	Fargo clay loam	Fargo, N. Dak.	P	350	7.6	A	1.42	1.72	2.55	.00	.71	.01	4.43	39	21	37.0	8.7	1.56	21.0
9	Genesee silt loam	Sidney, Ohio	P	2,820	6.8	7.2								51.2	39.0	24.8	15.8	1.74	5.6
10	Gloucester sandy loam	Middleboro, Mass.	F	7,460	6.6	3.6								50	41	13.0	27.8	1.58	0.2
11	Hagerstown loam	Loch Raven, Md.	G	11,000	5.3	10.8								55.4	42.6	32.0	15.5	1.49	8.6
12	Hanford fine sandy loam	Los Angeles, Calif.	F	3,190	7.1	2.5	0.39	0.50	0.16	.00	.40	.00	0.14	62.4	15.2	12.4	33.5		0
13	Hanford very fine sandy loam	Bakersfield, Calif.	F	290	9.5	A	6.23	.09	.13	.00	1.12	1.64	3.76	64.6	5.6	21.7	34.5		0
14	Hempstead silt loam	St. Paul, Minn.	F	3,520	6.2	5.6								44.2	27.2	17.2	14.4	1.76	1.0
15	Houston black clay	San Antonio, Tex.	P	489	7.5	5.0	2.18	.88	.20	.00	2.00	0.13	0.73	68.9	27.2	51.4	5.7	2.08	39.8
16	Kalmia fine sandy loam	Mobile, Ala.	F	8,290	4.4	11.8								67.3	61.6	22.2	12.0	1.65	0.6
17	Keyport loam	Alexandria, Va.	P	5,980	4.5	19.1								55.	42	30.8	4.4	1.72	5.4
18	Knox silt loam	Omaha, Nebr.	G	1,410	7.3	1.4	0.27	.63	.20	.00	0.94	.00	.25	50.6	27.8	28.4	16.6	1.26	1.3
19	Lindley silt loam	Des Moines, Iowa	G	1,970	4.6	10.9	.38	.32	.41	.00	.16	.03	.46	49.5	32.0	28.4	3.9	1.76	11.8
20	Mahoning silt loam	Cleveland, Ohio	P	2,870	7.5	1.5	.25	.48	.20	.00	.51	.00	.15	49.2	33.8	22.4	3.8	1.90	3.9
21	Marshall silt loam	Kansas City, Mo.	F	2,370	6.2	9.5								54.4	37.1	31.2	10.8	1.66	6.5
22	Memphis silt loam	Memphis, Tenn.	G	5,150	4.9	9.7								61.6	47.7	28.4	9.6	1.67	3.0
23	Merced silt loam	Buttonwillow, Calif.	F	278	9.4	A	8.38	.38	.22	.02	1.87	1.12	5.57	65	6	24.7	6.1	1.69	0.2
24	Merrimac gravelly sandy loam	Norwood, Mass.	G	11,400	4.5	12.6								50	41	13.0	31.7	1.4	0
25	Miami clay loam	Milwaukee, Wis.	F	1,780	7.2	4.7	0.23	.70	.41	.00	1.01	0.03	0.10	46.1	30.1	25.8	9.5	1.95	7.6
26	Miami silt loam	Springfield, Ohio	G	2,980	7.3	2.6	.27	.50	.31	.00	0.70	.03	.12	53	37	16.4	20.9	1.95	1.0
27	Miller clay	Bunkie, La.	P	570	6.6	3.7	.53	1.86	1.12	.00	2.00	.08	1.54	67	56	42.6	1.9	2.01	32.5
28	Montezuma clay adobe	San Diego, Calif.	P	408	6.8		1.50	0.06	0.18	.00	0.12	.99	0.89	61.0	10.3	24.6	2.5		5.9
29	Muck	New Orleans, La.	VP	1,270	4.2	28.1	2.15	1.92	1.55	.00	.00	1.69	2.30	69.3	57.4	34.5	26.6		5.8
30	Muscatine silt loam	Davenport, Iowa	P	1,300	7.0	2.6	0.32	0.65	0.40	.00	.71	0.09	0.24	49.9	32.1	29.4	7.2	1.81	7.5
31	Norfolk fine sand	Jacksonville, Fla.	G	20,500	4.7	1.8								69.3	47.4	2.8	38.1	1.55	0
32	Ontario loam	Rochester, N. Y.	G	5,700	7.3	0.5	.23	.70	.12	.00	.73	.01	.42	47.6	32.8	17.8	11.7	1.85	0.1
33	Peat	Milwaukee, Wis.	VP	800	6.8	36.0	1.52	7.30	4.06	.00		2.27	2.13	46.1	30.1	72.8	34.0		16.9
34	Penn silt loam	Norristown, Pa.	F	4,900	6.7	7.0								54	10	23.4	11.7	1.82	8.4
35	Romona loam	Los Angeles, Calif.	G	2,060	7.3	5.7	0.68	0.68	0.49	.00	1.10	0.06	0.35	62.4	15.2	18.0	10.9	1.89	3.1
36	Ruston sandy loam	Meridian, Miss.	G	11,200	4.5	4.6								64.0	53.0	13.8	16.0	1.62	0
37	St. John's fine sand	Jacksonville, Fla.	P	11,200	3.8	15.3								69.3	47.4	7.0			0
38	Sassafras gravelly sandy loam	Camden, N. J.	G	38,600	4.5	1.7								54	40	3.0	32.1	1.59	0
39	Sassafras silt loam	Wilmington, Del.	F	7,440	5.6	6.6								54	40	24.2	7.5	1.72	3.8
40	Sharkey clay	New Orleans, La.	P	970	6.0	9.4	.56	.58	.44	.00	0.93	.07	.28	69.3	57.4	33.0	2.3	1.78	16.4
41	Summit silt loam	Kansas City, Mo.	F	1,320	5.5	11.0	.30	.54	.36	.00	.78	.04	.46	54.4	37.1	33.1	6.9	1.61	14.6
42	Susquehanna clay	Meridian, Miss.	F	13,700	4.7	28.2								64.0	53.0	34.8	14.9	1.79	4.7
43	Tidal marsh	Elizabeth, N. J.	VP	60	3.1	36.8	45.10	5.17	9.45	.00	.00	43.30	37.00	52	43	55.4			
44	Wabash silt loam	Omaha, Nebr.	G	1,000	5.8	8.8	1.05	1.08	0.66	.00	1.97	0.82	0.41	50.6	27.8	31.2	7.2	1.55	6.0
45	Unidentified alkali soil	Casper, Wyo.	P	263	7.4	A	8.15	3.70	.70	.00	0.24	.18	11.98	47.2	15.3	14.8	18.7		0
46	Unidentified sandy loam	Denver, Colo.	G	1,500	7.0									50.0	14.1	7.6	23.2		0
47	Unidentified silt loam	Salt Lake City, Utah	P	1,770	7.6	3.0	0.67	0.72	.39	.00	.88	.06	0.48	51.6	16.1	25.7	2.6	1.72	3.7
51	Acadia clay	Spindletop, Tex.	P	190	6.2	13.2	10.27	15.55	5.03	.00	.56	5.75	22.00	69	49	47.1	1.4	2.07	37.9
52	Lake Charles clay loam	League City, Tex.	P	234	8.8	A	4.20	0.33	0.18	.52	1.36	1.33	1.26	69	47	54.8	3.7	1.97	33.9
53	Cecil clay loam	Atlanta, Ga.	G	17,790	4.8	5.1								61.2	48.3	33.7	18.2	1.60	7.0

See footnotes at end of table.

TABLE 6. *Chemical and physical properties of the soils at the NBS test sites* [a]—Continued

Soil		Location	Internal drainage of test site [c]	Resistivity at 60°F	pH	Composition of water extract, mg-eq per 100 g of soil								Mean temperature [e]	Annual precipitation [e]	Moisture equivalent	Air-pore space	Apparent specific gravity	Volume shrinkage
No. [b]	Type					Total acidity [d]	Na+K as Na	Ca	Mg	CO_3	HCO_3	Cl	SO_4						
														°F	*Inches*	*Percent*	*Percent*		*Percent*
54	Fairmount silt loam	Cincinnati, Ohio	P	886	7.0	3.5	0.59	10.10	.59	.00	0.70	0.08	9.05	53.2	38.6	26.1	4.7	1.96	6.1
55	Hagerstown loam	Loch Raven, Md.	G	5,210	5.8	10.9	----	----	----	----	----	----	----	55.4	42.6	32.0	15.5	1.49	8.6
56	Lake Charles clay	El Vista, Tex.	VP	406	7.1	5.1	3.12	0.69	.47	.00	.80	1.59	3.04	69	49	28.7	5.0	2.03	30.1
57	Merced clay adobe	Tranquillity, Calif.	P	128	7.7	A	23.40	13.50	4.51	.00	.34	1.15	37.50	63	8	40.9	5.1	1.89	29.5
58	Muck	New Orleans, La.	VP	712	4.8	15.0	2.03	2.23	1.29	.00	.00	0.47	2.54	69.3	57.4	57.8	22.4	1.43	36.9
59	Carlisle muck	Kalamazoo, Mich.	VP	1,660	5.6	12.6	1.03	3.08	2.70	.00	.00	3.47	1.04	49	31	43.6	----	----	----
60	Rifle peat	Plymouth, Ohio	P	218	2.6	297.4	2.91	10.95	2.86	.00	.00	0.00	56.70	49	37	43.4	33.2	1.28	9.1
61	Sharkey clay	New Orleans, La.	P	943	6.8	4.9	0.73	0.68	0.33	.00	.71	.10	0.91	69.3	57.4	30.8	2.3	1.78	16.4
62	Susquehanna clay	Meridian, Miss.	F	6,920	4.5	12.0	----	----	----	----	----	----	----	64.0	53.0	34.6	14.9	1.79	4.7
63	Tidal marsh	Charleston, S. C.	VP	84	6.9	14.6	33.60	6.85	4.0	.00	.00	12.70	36.60	66.0	45.2	46.7	19.5	1.47	18.8
64	Docas clay	Cholame, Calif.	F	62	7.5	A	28.10	2.29	0.76	0.00	0.89	28.80	0.26	58	16	41.1	4.7	1.88	27.7
65	Chino silt loam	Wilmington, Calif.	G	148	8.0	A	7.65	12.40	2.20	.00	1.30	6.05	16.90	62.4	15.2	26.4	15.8	1.41	5.7
66	Mohave fine gravelly loam	Phoenix, Ariz.	F	232	8.0	A	6.55	0.51	0.18	.00	0.73	2.77	2.97	69.7	7.8	16.5	20.1	1.79	2.7
67	Cinders	Milwaukee, Wis.	VP	455	7.6	A	0.77	3.03	.53	.00	.55	0.08	2.89	46.1	30.1	11.1	----	----	----
68	Gila clay	Phoenix, Ariz.	F	----	----	----	----	----	----	----	----	----	----	69.7	7.8	----	----	----	----
70	Merced silt loam	Buttonwillow, Calif.	F	278	9.4	A	8.38	0.38	.22	.02	1.87	1.12	5.57	65	6	24.7	6.1	1.69	0.2
71	Mahoning silt loam	West Austintown, Ohio	F	2,582	7.1	4	0.22	.37	.28	----	0.33	0.03	0.27	----	----	----	----	----	----
72	Papakating silty clay loam	Deerfield, Ohio	VP	762	7.2	17	3.11	7.49	.95	----	----	----	11.58	----	----	----	----	----	----
73	Wabash silty clay loam	East St. Louis, Ill.	VP	521	6.8	6	0.44	2.80	.68	----	1.75	.02	1.99	----	----	----	----	----	----
74	Otero clay loam	Rocky Ford, Colo.	F	436	7.3	5	4.72	18.42	4.24	----	0.77	.38	26.22	----	----	----	----	----	----
75	Unidentified silt loam	Albuquerque, N. Mex.	F	379	8.4	A	5.80	0.87	0.16	----	.56	.70	5.58	----	----	----	----	----	----
76	Chino silt loam	Los Angeles, Calif.	G	2,650	9.2	A	1.54	.065	----	.16	1.23	.07	0.15	----	----	----	----	----	----
77	Susquehanna clay	Louisville, Miss.	F	9,390	4.3	42	0.39	.14	----	----	----	.40	.05	----	----	----	----	----	----
78	Caddo fine sandy loam	Latex, Tex.	P	821	4.5	24	1.06	.18	.31	----	----	.82	.74	----	----	----	----	----	----
101	Billings silt loam (low alkali)	Grand Junction, Colo.	F	261	7.3	A	5.21	19.24	1.43	.00	0.66	1.56	22.48	52.0	8.8	30.0	----	----	----
102	Billings silt loam (mod. alkali)	Grand Junction, Colo.	F	103	7.3	A	22.63	16.56	3.85	.00	.56	4.67	36.82	52.0	8.8	20.4	----	----	----
103	Billings silt loam (high alkali)	do	F	81	7.3	A	22.01	13.32	2.00	.00	.18	11.09	25.70	52.0	8.8	30.6	----	----	----
104	Cecil clay	Charlotte, N. C.	G	8,500	4.6	11.0	----	----	----	----	----	----	----	60.2	46.1	34.1	----	----	----
105	Cecil clay loam	Macon, Ga.	G	28,000	4.8	12.9	----	----	----	----	----	----	----	64.2	44.5	34.2	----	----	----
106	do	Salisbury, N. C.	G	25,000	4.8	12.8	----	----	----	----	----	----	----	60	46	38.8	----	----	----
107	Cecil fine sandy loam	Raleigh, N. C.	G	54,400	4.8	11.8	----	----	----	----	----	----	----	60.1	46.3	29.6	----	----	----
108	Cecil gravelly loam	Atlanta, Ga.	G	44,400	4.9	11.2	----	----	----	----	----	----	----	61.2	48.3	34.3	----	----	----
109	Fresno fine sandy loam (low alkali)	Fresno, Calif.	P	497	8.4	A	2.62	0.07	0.10	.31	.59	1.56	0.48	63	9	18.6	----	----	----
110	Fresno fine sandy loam (mod. alkali)	do	P	531	10.2	A	3.53	.07	.12	1.49	1.07	0.79	.25	63	9	18.4	----	----	----
111	Fresno fine sandy loam (high alkali)	Kernell, Calif.	P	51	7.3	A	41.55	16.21	.44	0.00	0.58	34.58	23.41	63	9	22.1	----	----	----
112	Imperial clay (mod. alkali)	Niland, Calif.	P	149	7.4	A	22.18	14.09	1.29	.00	.36	10.94	25.98	71	2	34.6	----	----	----
113	Imperial clay (high alkali)	do	F	102	7.4	A	9.56	0.84	.51	.00	.63	6.26	4.06	71	2	30.2	----	----	----
114	Lake Charles clay	El Vista, Tex.	VP	320	7.1	----	2.65	.68	.26	.00	.77	1.84	0.93	69	49	35.8	----	----	----
115	Memphis silt loam	Vicksburg, Miss.	G	3,450	6.9	4.7	----	----	----	----	----	----	----	65.6	51.9	25.7	----	----	----
116	Merced clay	Los Banos, Calif.	F	320	9.2	A	9.30	.33	.18	4.60	2.10	1.17	1.57	63.4	8.1	39.7	----	----	----
117	Merced clay loam adobe	Tranquillity, Calif.	P	106	8.5	A	36.19	14.66	.83	0.00	1.55	2.89	46.53	63	8	51.8	----	----	----
118	Niland gravelly sand (low alkali)	Niland, Calif.	F	273	7.3	A	4.30	1.03	.64	.00	0.20	5.01	0.86	71	2	6.1	----	----	----
119	Norfolk sandy loam	Macon, Ga.	G	10,800	4.7	9.7	----	----	----	----	----	----	----	64.2	44.5	24.1	----	----	----
120	Norfolk sand	Pensacola, Fla.	G	34,400	5.7	1.3	----	----	----	----	----	----	----	67.7	57.9	4.4	----	----	----
121	do	Tampa, Fla.	G	16,400	4.8	1.2	----	----	----	----	----	----	----	71.8	49.4	3.0	----	----	----
122	Panoche clay loam	Mendota, Calif.	F	552	7.4	A	2.32	0.05	.26	.00	.70	0.07	1.40	63	6.4	30.0	----	----	----
123	Susquehanna clay	Shreveport, La.	P	6,840	4.1	21.9	----	----	----	----	----	----	----	65.8	43.4	37.6	----	----	----
124	do	Troup, Tex.	P	1,160	4.4	28.1	----	----	----	----	----	----	----	66.0	42.7	36.0	----	----	----
125	Susquehanna fine sandy loam	Shreveport, La.	P	5,770	3.9	28.3	----	----	----	----	----	----	----	65.8	43.4	37.2	----	----	----

[a] Measurements and determinations by I. A. Denison, R. B. Hobbs, and M. Romanoff. [b] Different numbers for soils that appear to be identical indicate either different sites in the same locality or that different classes of materials were buried at different times at the same site. [c] Internal drainage: G, good; F, fair; P, poor; VP, very poor. [d] A, alkaline reaction. [e] Data for mean temperature and annual precipitation furnished by United States Weather Bureau. Values with no figures to the right of the decimal point are for some nearby city.

TABLE 7. *Mechanical analysis*[a] *of soils at National Bureau of Standards test sites*

Soil [b]	Depth	Mechanical analysis			Soil [b]	Depth	Mechanical analysis		
		Sand	Silt	Clay			Sand	Silt	Clay
	Inches	*Percent*	*Percent*	*Percent*		*Inches*	*Percent*	*Percent*	*Percent*
1	90	9.8	37.7	52.5	25	36	21.0	43.0	36.0
2	40	17.2	37.9	44.9	27	30	1.4	10.8	87.8
3	32	29.0	24.9	46.1	30	36	2.1	65.5	32.4
4	36	29.3	53.0	17.7	31	24	97.3	2.1	0.6
5	30	25.6	38.6	35.8	32	48	42.1	42.1	15.8
6	36	69.0	23.8	7.2	35	36	35.9	37.3	26.0
7	40	10.3	26.1	63.6	36	36	60.6	21.8	17.6
8	48	2.2	27.7	70.1	37	30	90.6	4.9	4.5
10	30	64.0	29.4	6.6	39	36	42.1	42.6	15.3
11	60	25.8	21.1	53.1	40	30	2.5	50.4	47.1
14	60	56.6	29.5	13.9	41	36	3.0	56.7	40.3
15	36	4.4	25.2	70.4	42	30	30.1	24.1	45.8
16	30	50.4	23.1	26.5	44	30	2.4	66.4	31.2
17	36	9.6	38.6	51.7	47	36	9.0	44.9	46.1
18	48	1.3	78.4	20.3					
19	36	15.7	50.1	34.2					
20	50	19.6	44.1	36.3					
21	36	3.2	65.9	30.9					
22	33	1.2	76.5	22.3					
24	33	72.0	22.4	5.6					

[a] Measurements and determinations by I. A. Denison and R. B. Hobbs.
[b] See table 6 for names and locations of soils.

TABLE 8. *Properties of the soils in the American Petroleum Institute and American Gas Association coating tests*

Aeration: G, good; F, fair; P, poor; VP, very poor. Total acidity: A, alkaline reaction.

Soil		Location	Mean temperature[b]	Annual precipitation[b]	Moisture equivalent	Air-pore space	Apparent specific gravity	Internal drainage	pH	Total acidity (mg-eq per 100 g of soil)	Resistivity at 60°F
No.[a]	Type										
AMERICAN PETROLEUM INSTITUTE SITES											
			°F	*Inches*	*Percent*	*Percent*					*Ohm-cm*
201	Bell clay	Temple, Tex.			31.6	5.1	2.00	P	8.4	A	947
202	Oswego silt loam	Arkansas City, Kans.			20.7	19.2	1.76	G	7.0		1,295
203(56)	Lake Charles clay	Beaumont, Tex.	69	49	40.7	2.6	2.00	VP	7.1	5.1	495
204(52)	Lake Charles loam	League City, Tex.	69	47	21.1	5.1	1.93	VP	7.2		1,485
205	Miami silt loam	Preble, Ind.			21.5	6.9	1.87	P	6.3		2,200
206	Unidentified	Council Hill, Okla.			25.4	5.5	1.78	P	5.5		5,180
207	Oswego silt loam	Caney, Kans.			20.6	13.8	2.04	P	5.4		3,510
208(51)	Acadia clay	Spindletop Gully, Tex.	69	49	47.6	2.9	2.04	VP	5.4		259
209	Hanford fine sandy loam	Long Beach, Calif.			9.8	29.9	1.47	G	8.9	A	353
210	Muscatine silt loam	Mt. Auburn, Ill.						P	6.1		
211	Unidentified	Skiatook, Okla.			15.7	16.6	1.65	P	5.2		440
212(117)	Merced clay loam	Mendota (Tranquillity) Cal.	63	6.4	36.8	7.2	1.84	P	8.9	A	61
213(27)	Miller clay	Bunkie, La.	67	56	38.0	2.5	2.01	VP	7.9	A	674
214	Hagerstown loam	Chambersburg, Pa.			21.3	8.3	1.46	G	6.4		5,090
215(64)	Docas clay	Cholame, Calif.	58	16	36.8	3.8	1.88	F	8.4	A	155
AMERICAN GAS ASSOCIATION SITES											
301	Cinders	Pittsburgh, Pa.						G	5.5		730
302(67)	do	Milwaukee, Wis.	46.1	30.1	11.1			VP	8.0	A	380
303	Tidal marsh	Brockton, Mass.						VP	3.6	42.5	44
304	do	Atlantic City, N. J.						VP	3.0	38.0	32
305	Muck	W. Palm Beach, Fla.			15.0			VP	4.3	75.8	1,180
306	do	Miami, Fla.						VP	5.7	22.2	1,650
307(3)	Cecil clay loam	Atlanta, Ga.	61.2	48.3	40.4	29.1	1.60	G	5.8	13.3	43,800
308	do	Raleigh, N. C.	60.1	46.3	38.8			F	6.9	6.3	16,000
309(123)	Susquehanna clay	Shreveport, La.	65.8	43.4	35.5			P	4.6	15.7	6,840
310	Miller clay	do	65.8	43.4	37.2			P	7.4	1.1	870
311	do	Bryan, Tex.			49.9			P	7.2	0	1,000
312	White alkali soil	Los Angeles, Calif.	62.4	15.2	45.0			G	7.3	A	93
313	Black alkali soil	do	62.4	15.2	14.0			G	9.2	A	1,700
314	Marshall silt loam	Kansas City, Mo.	54.4	37.1	41.0			G	6.5	12.8	3,150

[a] The soil number in parentheses is the number assigned to the same site in the NBS tests on uncoated specimens.
[b] Data furnished by United States Weather Bureau. Values with no figures to the right of the decimal point are for a nearby city.

The chemical and physical properties of the soils represent a wide range of environmental conditions. The hydrogen-ion concentration ranges from that of high acidity, pH 2.6 to high alkalinity, pH 10.2 and the resistivity from 51 ohm-cm, approximately that of sea water to 54,400 typical of a very well drained and aerated sandy soil. The soils also represent a wide range of components and soluble salt contents. For example, in the extremely acid Rifle peat (soil 60) the soluble material consists almost entirely of sulfates, whereas in Docas clay (soil 64) the soluble materials are in the form of chlorides. Wide differences in aeration are exhibited, ranging from very poorly drained soils to well-drained soils. Certain of the environments are highly oxidizing (well aerated), whereas others are definitely reducing (poorly aerated soils). Table 9 shows, for many of the soils, the combined effect

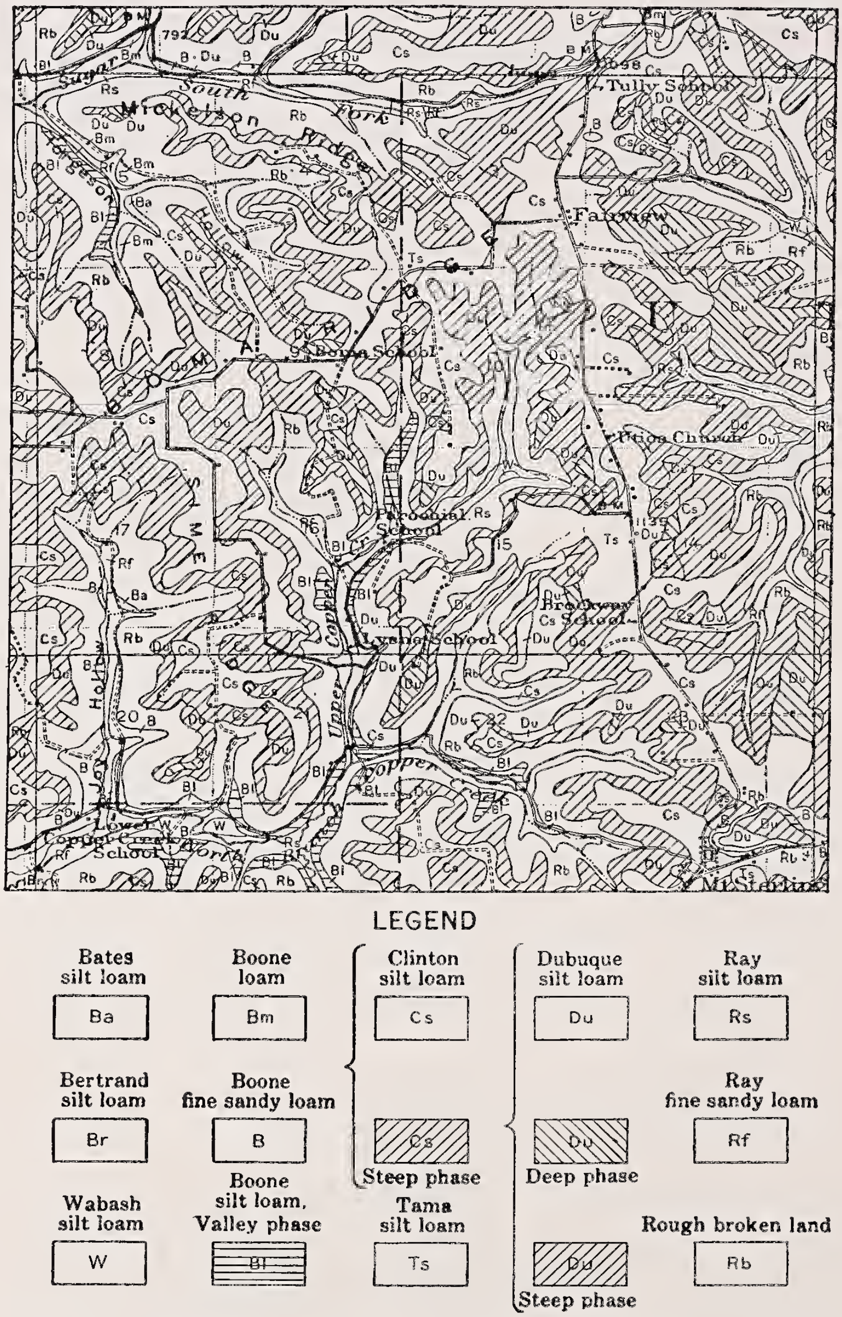

FIGURE 10. *Reproduction of a portion of a published soil map in Crawford County, Wis. [144] illustrating the soil series in a 4⅜- by 5-mile area.*
Reproduced from Soils and Men [64].

Table 9. *Classification of soils by number*

Inorganic soils				Organic soils, reducing, acid
Oxidizing		Reducing		
Acid	Alkaline	Acid	Alkaline	
3, 4, 6, 10, 11, 12, 16, 19, 22, 24, 25, 26, 31, 32, 35, 36, 38, 41, 42, 46, 53, 55, 62	13, 65, 66	1, 2, 5, 7, 9, 14, 17, 27, 28, 30, 37, 40, 44, 51, 61	8, 15, 20, 23, 45, 47, 56. 64, 70	29, 33, 43, 58, 59, 60, 63

of composition, structure, and the environmental conditions of particular test sites. Environmental conditions at several of the test sites are illustrated in figure 8. The soils are placed in two groups, depending on whether they are organic (peat, marsh) or inorganic (sandy soils). The inorganic soils are further divided into two subgroups according to their oxidizing or reducing nature. Finally, the soils were classified according to acid or alkaline reaction. For the classification of these soils according to the great soil groups, see table 1.

The selection of the early test sites was governed to a large extent by the distribution of pipelines and pipe networks, that is, by the importance of the soil with respect to underground construction. Each test site represented an important soil condition, but, as within an area of a few square miles several quite different soils usually exist, they are not necessarily representative of the soil conditions prevailing in the general region of the site. This is illustrated by figure 10, which shows the soil series in a 4⅜- by 5-mile area in Crawford County, Wisc. [144].

It should be obvious that a test of materials in any one locality may not duplicate the behavior of the same materials in a different soil which may be found within a short distance from the test site. Moreover, as the soil horizons of a single soil may differ widely in physical and chemical properties, degree of aeration, and moisture content, a test of a material in one soil horizon may yield results different from those of a test of the same material exposed to another horizon of the same soil type. For example, the averages of the two deepest pits in five ferrous materials buried for 5 years in Rifle peat near Plymouth, Ohio, were 38, 37, 21, 24, and 67 mils, respectively, whereas the corresponding values for the pit depths on the same materials exposed for 7 years at the same site were 30, 34, 16, 17, and 62 mils, respectively. An examination of the site showed that the two sets of specimen were placed in parallel trenches only a few feet apart. The depths of the trenches were approximately the same, but the 5-year-old specimens were laid in the peat horizon, whereas the 7-year-old specimens were placed in the clay subsoil just below the peat. The surface of the ground was level and the depths of the trenches were the same, but the thickness of the peat layer varied.

8. Field Tests of Ferrous Materials

Both losses in weight and maximum pit depths furnish bases for comparison of materials and corrosivities of soils, but in a somewhat different manner. The loss in weight and the average penetration, as calculated from the loss in weight (see appendix 3), indicate the general trend of corrosion, whereas the maximum penetration, as measured on the corroded specimens, indicates the trend of the material toward local perforation. Each of these measurements is important, but in a different way. For example, in pipelines or other liquid or gas carrying materials, the maximum pit depth after a given exposure period is of major importance because this will indicate the tendency toward local perforation and subsequent loss of the transported commodity. On the other hand, for underground structures that are primarily load bearing, such as piling, the maximum penetration is of less interest than the overall weight loss or average penetration.

8.1. Description of the Materials

a. Wrought Materials

The compositions of the wrought ferrous materials buried at the various test sites are given in table 10. Where there is a possibility of confusion in referring to specimens that have been assigned the same letter symbol, the symbol has been followed in the table by the year of burial. The plain wrought materials represented in the tests are open-hearth iron, hand-puddled and mechanically puddled wrought iron (Roe process), open-hearth steel and Bessemer steel.

The development of low-alloy steels of high strength made available a large number of materials some of which might be selected for service underground if their resistance to corrosion in soils could be established. In 1932, specimens of low-alloy steels containing copper and molybdenum, copper and nickel, and chromium were buried at 15 test sites selected to represent different soil conditions and degrees of corrosiveness. In 1937, 1939 and 1941, additional specimens of the newly developed low-alloy materials were buried at these sites.

The high resistance to corrosion by high-chromium alloy steels, with and without nickel and molybdenum, results from the capacity of these materials to assume and maintain the passive state in many corrosive environments. Specimens of these materials were buried in 1932 and 1939 (table 10).

TABLE 10. *Composition of wrought ferrous materials*

Material	Identification		Number of specimens buried	Form	Nominal width or diameter	Length	Thickness	C	Si	Mn	S	P	Cr	Ni	Cu	Mo	Other elements
	Symbol	Year buried															
					Inches	*Inches*	*Inches*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Commonly used iron and steels:																	
Wrought iron, hand puddled	b,d	1922	564	Pipe	1.5	6	0.145	0.03	0.15	Trace	0.023	0.145	------	------	0.02	------	------
Do	B,D	1922–28	742	do	3	6	.216	.02	.15	0.033	.022	.195	------	------	.03	------	
Do	A	1932	150	do	1.5	12	.145	.016	.10	.029	.018	.160	------		------	------	Oxide +slag, 2.56
Wrought iron, mechanically puddled	B	1932	150	do	1.5	12	.145	.017	.125	.041	.018	.106	------			------	Oxide +slag, 2.68
Wrought iron, surface machined	D	1926	18	do	2	17	.185	------	------	------	------	------	------	------	------	------	------
Wrought iron, surface unfinished	K	1926	18	do	2	17	.185	------	------	------	------	------	------	------	------	------	------
Pure open-hearth iron	A	1924	40	Sheet	2.0	6	.125	------	------	------	------	------	------	------	------	------	Fe, 99.9
Open-hearth iron	a	1922	568	Pipe	1.5	6	.145	.02	.09	Trace	.05	.01	------	------	.014	------	------
Do	A	1928	174	do	3	6	.216	.02	.09	do	.05	.01	------	------	------	------	------
Open-hearth steel	K	1922	568	do	3	6	.216	.12	------	0.41	.036	.043	------	------	------	------	------
Do	A	1937	150	Plate	2.5	12	.188	.033	.002	.029	.017	.006	0.049	0.034	.052	------	------
Bessemer steel	e	1922	568	Pipe	1.5	6	.145	.09	------	.39	.040	.088	------	------	------	------	------
Do	y	1922	568	do	1.5	6	.145	------	------	.38	.050	.092	------	------	------	------	------
Do	M,N	1922–28	888	do	3	6	.216	.08	------	.40	.038	.098	------	------	------	------	------
Bessemer steel, surface machined	M	1926	18	do	2	17	.140	------	------	------	------	------	------	------	------	------	------
Bessemer steel, unfinished	P	1926	18	do	2	17	.185	------	------	------	------	------	------	------	------	------	------
Carbon steel	N	1932	150	do	2	10	.154	.15	------	.49	.030	.013	------	------	------	------	------
Do	S	1937	150	do	1.5	14	.145	.13	------	.45	.06	.09	------	------	------	------	------
Low-alloy irons and steels:																	
Copper-bearing steel	Y	1922	568	do	3	6	.216	.07	------	.24	.032	.008	------	------	.22	------	------
Do	S	1924	40	Sheet	2.0	6	.062	------	------	------	------	------	------	------	------	------	------
Do	C	1926	20	Pipe	2	17	.185	------	------	------	------	------	------	------	1.5	------	------
Copper-molybdenum open-hearth iron	MM	1939	150	Plate	2.5	12	.25	.04	------	.16	.027	.008	.04	.14	0.51	0.07	Sn, 0.002
Do	O	1937	150	do	2.5	12	.25	.03	.003	.16	.032	.007	.02	.15	.45	.07	------
Do	N	1937	150	do	2.5	12	.25	.06	.001	.098	.029	.069	.02	.14	.54	.13	------
Do	H	1932	150	Pipe	1.5	12	.145	.04	.05	.32	.027	.016	------	------	.52	.15	------
Do	H	1941	150	do	1.5	13	.145	.036	.005	.16	.025	.008	------	------	.47	.08	------
Copper-nickel steel	J	1937	150	Plate	2.5	12	.265	.06	.047	.49	.025	.095	------	.52	.95	------	------
Nickel-copper steel	B	1937	150	do	2.5	12	.248	.07	.14	.44	.022	.010	------	1.96	1.01	------	------
Do	Y	1941	150	Pipe	2.0	8.5	.154	.12	.12	.58	.025	.07	------	1.95	1.04	------	------
Do	D	1932	150	do	1.5	12	.145	.14	.19	.21	------	------	------	2.47	1.08	------	------
Composite steel [a]	P	1941	150	Plate	2.5	14	.172	------	------	------	------	------	------	------	------	------	------
Carbon steel layers	------	------	------	------	------	------	.036	.16	.21	.78	.030	.018	------	------	0.04	------	------
Nickel-copper layer	------	------	------	------	------	------	.100	.14	.16	.48	.009	.021	.04	1.86	.98	------	------
Chromium-silicon-copper-phosphorus steel	C	1937	150	do	2.5	12	.188	.075	.84	.20	.018	.124	1.02	0.22	.428	------	------
2 percent chromium steel with molybdenum	NN	1939	150	Pipe	1.5	14.5	.145	.09	.25	.46	.010	.015	1.96	------	------	.49	------
Do	KK	1937	150	Plate	2.5	12	.175	.082	.51	.46	.015	.017	2.01	.07	.004	.57	------
4 to 6 percent chromium steel	P	1932	150	Pipe	2	10	.154	.13	------	.46	.025	.012	5.05	------	------	------	------
Do	D	1937	150	Plate	2.5	12	.245	.077	.43	.37	.005	.015	5.02	.09	.008	------	------
4 to 6 percent chromium steel with molybdenum	E	1937	150	do	2.5	12	.188	.074	.41	.32	.006	.013	4.67	.09	.004	.51	Al, 0.030; Ti, 0.022
Do	H	1937	150	do	2.5	12	.203	.060	.39	.40	.014	.021	5.76	.17	.004	.43	Al, 0.27
High-chromium steels:																	
12 percent chromium steel	U	1932	175	Sheet	4	6	.063	.065	.28	.38	.017	.011	11.95	.482	.025	------	------
18 percent chromium steel	V	1932	175	do	4	6	.063	.070	.34	.36	.015	.014	17.08	.092	.021	------	------
Do	X	1932	60	Pipe	1.5	12	.145	.12	.277	.42	.017	.016	17.72	.287	------	------	------
26 percent chromium steel	C	1926	66	do	1	6	.250	------	------	------	------	------	26.	------	------	------	------
High-chromium-nickel and manganese steels:																	
18 percent chromium with nickel	K	1932	150	Sheet	2.5	11	.025	.08	.33	.44	.022	.015	17.20	8.95	------	------	------
Do	R	1932	60	Pipe	1.5	12	.145	.05	.28	.46	.011	.015	17.52	8.85	------	------	------
Do	W	1932	175	Sheet	4	6	.063	.093	.42	.36	.017	.008	18.69	9.18	.016	------	------
18 percent chromium steel with nickel and manganese	T	1932	25	do	6	10	.063	.06	.40	6.09	------	------	17.76	3.83	.95	------	------
18 percent chromium steel with manganese	S	1932	30	do	6	10	.063	.07	.48	9.44	------	------	17.78	------	.74	------	------
18 percent chromium steel with nickel, manganese, and molybdenum	CM	1939	150	Plate	2	12.5	.25	.07	.40	1.24	.008	.016	17.78	10.96	------	2.63	------
20 percent chromium steel with nickel, manganese, and molybdenum	DT	1939	150	do	2.5	12	.25	.07	.91	1.99	.012	.014	19.27	22.12	1.07	3.52	------
22 percent chromium steel with nickel and manganese	Y	1932	175	Sheet	4	6	.063	.144	.59	1.80	.011	.015	22.68	12.94	0.021	------	------

[a] Specimens composed of 3 layers: outer layers—plain carbon steel, 0.036 in. thick; intermediate layer—2% nickel, 1% copper steel, 0.100 in. thick.

TABLE 11. *Composition of cast ferrous materials*

Material	Identification		Number of specimens buried	Form	Nominal width or diameter	Length	Thickness	C			Si	Mn	S	P	Cr	Ni	Cu
	Symbol	Year buried						Free	Combined	Total							
					Inches	*Inches*	*Inches*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
deLavaud cast iron	C	1922–24	639	Pipe	6.0	6.0	0.44	--------	--------	3.56	2.34	0.73	0.083	0.77	--------	--------	--------
Sand mold cast iron (northern ore)	L	1922	370	do	6.0	6.0	.44	--------	--------	3.45	1.55	.56	.075	.55	--------	--------	--------
Sand mold cast iron (southern ore)	Z	1922	280	do	6.0	6.0	.44	--------	--------	3.40	1.61	.43	.083	.84	--------	--------	--------
Southern cast iron	A	1928	140	do	6.0	6.0	.44	2.90	0.70	3.60	1.70	.40	--------	.80	--------	--------	--------
Monocast iron	I	1928	160	do	6.0	6.0	.25	2.65	.75	3.40	1.50	.50	--------	.70	--------	--------	--------
Charcoal cast iron [a]	CB	1939	150	Plate	3.5	12.0	.375	--------	--------	2.40	0.95	.95	.065	.17	--------	--------	1.00
deLavaud cast iron [a] [b]	CC	1939	150	do	3.5	12.0	.50	--------	3.70	--------	1.51	.38	.071	.78	--------	--------	--------
Rattled cast iron [c]	G	1932	150	Pipe	1.25	13.5	.250	2.94	0.64	3.58	1.64	.48	.074	.79	--------	--------	--------
Sand-coated cast iron	F	1932	150	do	1.25	13.5	.250	2.94	.64	3.58	1.64	.48	.074	.70	--------	--------	--------
Plain cast iron	A	1941	150	do	1.5	13.0	.250	--------	--------	3.22	2.19	.91	.12	--------	--------	--------	--------
High-silicon cast iron	D	1922	568	do	3.0	6.0	--------	--------	--------	0.72	13.44	.26	.123	.11	--------	--------	--------
Low-alloy cast iron	I	1932	150	do	1.25	12.0	.350	--------	--------	2.53	1.43	.28	.077	.128	--------	--------	.51
Do	J	1932	150	do	1.25	12.0	.350	--------	--------	2.90	2.04	.83	.060	.248	--------	--------	.62
Do	C	1932	150	do	1.5	12.0	.250	3.00	.50	3.50	2.50	.70	.050	.400	0.30	0.15	--------
Do	B	1941	150	do	1.5	13.0	.250	--------	--------	3.28	2.09	.83	.12	--------	--------	1.27	.32
Do	C	1941	150	do	1.5	13.0	.250	--------	--------	3.24	2.08	.80	.12	--------	--------	1.71	.98
Do	NC	1941	150	Plate	2.5	14.0	.5	--------	--------	2.80	2.03	--------	--------	--------	--------	2.08	1.10
Do	N	1941	150	do	2.5	14.0	.5	--------	--------	2.75	2.00	--------	--------	--------	--------	3.10	--------
Do	D	1941	150	Pipe	1.5	13.0	.250	--------	--------	3.21	2.11	.72	.12	--------	--------	3.32	--------
High-alloy cast iron	E	1932	150	do	1.5	10.0	.250	--------	--------	2.98	2.13	1.00	--------	--------	2.61	15.00	6.58

[a] The deLavaud and charcoal cast-iron plates were connected together by means of a charcoal cast-iron bolt and a steel bolt.

[b] Curved plate cut from 12-in. class 150 super deLavaud pipe.

[c] Ordinary iron horizontally cast in green-sand molds and rattled to remove sand.

b. Cast Materials

The original field tests included sand cast-iron pipe, (materials L and Z, 1922, table 11) de Lavaud centrifugal cast pipe, (material C, 1922) and high-silicon cast-iron pipe (material D, 1922). Subsequent exposures included some alloy cast irons, which had become available. Improvement in the structure of cast iron brought about by alloy additions or by modifications in the manufacturing process apparently has the effect of reducing graphitic corrosion, which results from electrolytic action between ferrite and graphite, the former constituting the anode and the latter the cathode of galvanic cells within the corroding iron. Graphitization may decrease or accelerate the normal rate of corrosion depending upon the tendency of corrosion products to deposit within the pores of the castings as determined by the nature of the environment [145].

Although a large variety of special cast irons are now available, relatively few were available for inclusion in the field tests. Cast irons of compositions other than those given in table 11 are now in use for types of service that suggest that these irons might be successfully employed for underground service. For example, Dieffenbach [146] reported that a copper-molybdenum cast iron showed no noticeable corrosion in more than 2 years of service as lock gate valves under conditions where protective coatings could not be used. Cast irons containing small percentages of nickel, chromium, and molybdenum also are understood to be used for similar purposes.

c. Miscellaneous Ferrous Materials

Miscellaneous ferrous materials buried at the test sites include nuts, bolts, elbows, nipples, and similar fittings listed in table 12.

TABLE 12. *Miscellaneous ferrous specimens included in the NBS tests*

Symbol	Material	Year buried	Number of specimens buried
A	Malleable-iron nuts and bolts, decarburized	1932	48
B	Malleable-iron nuts and bolts, not decarburized	1932	48
C	Malleable-iron nuts and bolts, high strength	1932	48
D	Steel nuts and bolts	1932	48
CD	Charcoal cast-iron nuts and bolts	1939	150
CE	Steel nuts and bolts	1939	150
E	Sheradized nuts and bolts	1924	100
—	Lead-coated nuts and bolts	1924	96
—	Black wrought iron nuts and bolts	1924	100
E	2-in. cast steel elbows	1924	56
I	4-in. machined cast iron nipple	1924	24
V	2-in. semisteel nipples	1924	48
S	2-in. malleable-iron bends	1924	48
—	1½-in. coupling attached to threaded pipe	1922	192

8.2. Results on Wrought Materials

a. Plain Irons and Steels

The loss in weight and the maximum penetration of the 1½-in. and 3-in. wrought black pipe for all removals of the specimens buried in 1922 in the original 47 NBS test sites are given in table 13. In some of the soils it was necessary to discontinue the

TABLE 13. *Loss in weight and maximum penetration of wrought black ferrous pipe buried in 1922*[a, b]

(Average of two specimens)

Soil			Loss in weight (oz/ft²)								Maximum penetration (mils)							
			1½-in. pipe				3-in. pipe				1½-in. pipe				3-in. pipe			
No.[c]	Type	Duration of exposure	Open-hearth iron	Wrought iron	Bessemer steel	Bessemer steel (scale-free)	Wrought iron	Open-hearth steel	Bessemer steel	Open-hearth steel with 0.22 percent Cu	Open-hearth iron	Wrought iron	Bessemer steel	Bessemer steel (scale-free)	Wrought iron	Open-hearth steel	Bessemer steel	Open-hearth steel with 0.22 percent Cu
	Material		a	b	e	y	B	K	M	Y	a	b	e	y	B	K	M	Y
		Years																
1	Allis silt loam	1.0	1.1	1.2	1.1	1.1	1.2	1.4	1.3	1.2	<10	<10	<10	<10	<10	<10	<10	<10
		3.6	3.3	4.0	3.9	3.9	4.2	4.2	4.3	3.8	46	33	40	40	42	36	45	50
		5.5	4.4	5.5	5.5	4.7	5.4	5.4	5.1	4.6	55	45	38	55	58	55	50	49
		7.7	5.0	6.8	6.8	6.6	6.6	5.6	7.4	6.6	44	74	52	51	53	54	62	45
		9.6	8.1	9.4	9.7	8.8	9.4	10.1	8.9	9.1	64	73	86	91	96	94	90	98
		11.6	8.9	8.8	7.0	9.3	9.5	9.5	[d]11.6	8.8	92	72	84	68	76	94	[d]101	125
2	Bell clay	2.1	1.9	2.0	1.8	2.4	1.9	2.2	2.2	1.8	<10	<10	<10	<10	<10	<10	<10	<10
		4.0	2.9	3.0	3.0	3.0	3.5	2.7	3.1	2.5	55	41	38	47	49	45	44	47
		5.9	3.8	4.2	3.9	3.4	3.6	4.0	4.2	4.2	42	40	46	41	37	43	42	60
		7.9	3.8	3.7	3.7	3.6	3.7	3.1	3.9	2.3	48	36	41	50	46	45	50	48
		12.0	[d]6.0	7.1	[d]5.8	5.9	6.3	5.4	[d]6.6	5.9	[d]56	48	[d]55	80	56	54	[d]49	67
		17.6	7.8	8.4	7.8	8.1	8.1	7.7	7.1	7.4	71	60	56	64	47	70	58	67
3 (53)	Cecil clay loam	2.0	1.5	1.8	1.7	2.0	1.6	2.0	2.1	1.7	62	46	44	56	55	53	50	60
		4.1	2.9	3.2	3.3	3.5	3.6	3.3	3.6	3.9	74	66	78	64	63	53	73	90
		6.0	3.2	4.2	3.7	3.5	3.8	3.6	3.6	4.2	69	60	70	72	72	82	70	65
		8.0	3.7	4.4	4.2	3.9	3.7	4.1	4.5	3.8	62	58	70	74	62	68	66	68
		10.1	4.2	4.6	4.3	4.1	3.2	3.6	3.8	4.0	[e]118+	70	72	75	74	62	84	80
		12.1	3.7	4.9	4.7	5.1	4.6	4.2	4.3	4.5	89	80	62	55	76	68	72	84
4	Chester loam	1.4	1.5	1.2	1.5	1.4	1.4	1.4	1.4	1.5	<10	<10	<10	<10	<10	<10	<10	<10
		4.0	3.7	3.5	3.5	3.5	3.7	3.7	3.5	3.7	33	27	26	24	26	32	30	42
		6.1	4.5	4.4	4.4	4.6	4.7	4.6	4.4	4.9	82	47	44	47	50	56	46	90
		8.0	5.2	5.4	5.4	5.3	5.5	5.5	5.4	5.8	60	36	34	44	38	58	41	76
		12.0	7.0	6.6	7.0	6.2	7.1	7.0	6.9	7.5	145+	78	79	82	87	108	84	152
5	Dublin clay adobe	1.9	1.1	0.9	1.3	1.4	1.0	1.0	0.9	1.0	<10	<10	<10	<10	<10	<10	<10	<10
		4.1	[d]1.5	2.2	2.5	2.4	2.2	2.1	2.2	2.1	[d]29	22	36	32	28	31	30	32
		6.2	4.9	5.0	4.5	4.8	4.9	3.9	4.8	4.4	44	35	50	34	40	62	62	38
		8.1	5.9	6.9	5.0	5.2	5.2	5.7	5.8	5.4	36	54	44	38	38	52	58	45
		12.1	6.5	7.6	7.0	5.4	6.4	7.3	7.3	7.1	33	50	42	37	44	48	46	49
		17.5	7.2	9.5	[d]7.1	8.3	9.4	11.1	8.6	9.2	76	45	[d]51	42	66	91	62	71
6	Everett gravelly sandy loam	1.9	0.2	0.2	0.1	0.2	0.1	0.2	0.2	0.2	14	26	26	20	22	18	19	21
		4.1	.7	.7	.9	.8	.5	.7	.5	.5	22	22	21	20	16	22	23	16
		6.2	.6	.6	.8	.7	.6	.8	.9	.8	22	14	16	21	23	25	22	18
		8.1	.8	.9	1.0	.8	.9	.8	.9	.9	17	20	12	17	20	22	18	19
		12.1	1.0	1.2	1.4	.9	1.1	1.1	1.5	1.3	23	20	18	18	30	16	26	32
		17.5	2.2	1.6	2.0	1.5	1.9	1.9	1.9	2.0	27	30	18	20	32	30	20	26
7	Maddox silt loam	1.0	0.5	0.7	0.6	0.6	0.6	0.5	0.7	0.6	<10	<10	<10	<10	<10	<10	<10	<10
		3.5	2.4	2.5	2.4	2.4	2.7	2.9	2.5	2.5	29	<20	22	16	18	32	20	19
		7.7	4.0	4.3	4.4	3.7	4.2	3.9	4.2	4.2	23	34	25	25	36	44	39	22
		11.5	5.0	5.1	4.9	[d]4.3	4.8	4.9	5.6	5.6	52	40	50	[d]29	47	44	48	48
		16.9	7.6	5.5	5.8	6.4	5.6	5.7	5.1	5.1	48	36	50	61	74	67	48	56
8	Fargo clay loam	1.1	0.7	0.7	0.7	0.8	0.7	0.6	0.8	0.7	44	30	38	30	38	43	47	62
		3.8	1.9	1.9	2.0	2.0	1.7	1.7	1.9	1.8	46	36	44	37	38	51	48	57
		5.8	3.2	3.2	2.9	2.6	2.9	3.1	3.3	3.3	62	52	52	54	68	77	56	70
		7.7	3.3	3.3	3.2	3.2	4.1	3.5	4.2	4.3	62	52	66	52	62	86	75	94
		9.9	5.1	5.1	4.6	4.6	5.2	5.3	5.6	5.6	74	66	61	67	63	93	72	75
		11.8	8.4	6.9	7.7	6.5	8.7	7.9	8.3	8.8	100	76	74	58	83	92	110	127

		Years																
9	Genesee silt loam	1.0	0.6	1.2	0.7	0.9	0.6	0.6	0.6	0.5	45	30	24	22	30	32	29	34
		3.5	1.7	2.3	2.3	2.0	1.9	1.2	1.9	1.7	46	50	54	54	54	58	68	64
		5.5	2.2	2.3	2.4	2.3	2.6	2.7	2.7	2.6	18	31	28	27	32	45	36	32
		7.7	3.2	3.4	3.2	3.0	3.5	3.4	3.2	3.1	36	46	38	32	43	48	46	40
		11.5	4.7	4.8	5.2	5.0	4.9	5.0	4.6	4.7	42	42	32	52	40	48	49	96
		16.9	5.4	6.0	5.8	5.4	5.5	5.4	5.1	5.2	69	51	64	65	68	56	62	109
10	Gloucester sandy loam	1.3	1.4	1.2	1.2	1.3	1.1	1.0	1.4	1.2	26	15	18	16	29	20	22	25
		4.0	1.4	[d]2.1	2.7	[d]1.2	1.7	1.2	2.6	1.6	<20	[d]20	<20	[d] <20	16	<20	15	<20
		6.1	3.4	3.4	3.5	3.4	3.4	3.7	3.4	3.4	46	38	39	42	48	38	41	50
		7.9	4.4	4.3	4.5	4.5	4.7	4.6	4.6	4.6	48	32	38	37	48	56	40	42
		12.0	4.3	5.4	4.9	4.4	4.8	4.4	4.9	5.1	50	52	40	38	45	52	54	66
11 (55)	Hagerstown loam	1.4	0.3	0.5	0.4	0.5	0.4	0.4	0.4	0.4	49	38	32	28	38	33	38	42
		4.0	1.4	1.1	1.1	1.2	1.0	.9	1.0	.9	62	67	50	61	68	54	78	62
		6.0	1.1	1.4	1.4	1.3	1.3	1.4	1.3	1.5	68	71	61	70	62	61	92	73
		7.8	1.0	2.2	1.9	1.5	1.5	1.4	1.6	1.4	64	64	56	46	66	58	72	62
		10.0	1.4	1.7	2.0	2.0	1.7	1.8	1.6	1.5	75	60	76	70	90	66	66	71
		11.9	1.7	[d]2.7	2.1	1.9	2.0	2.0	1.7	2.2	99	[d]75	71	58	82	70	80	88
12	Hanford fine sandy loam	1.9	[d]0.2	0.2	[d]0.4	0.3	[d]0.2	[d]0.2	[d]0.3	[d]0.2	[d] <10	<10	[d] <10	<10	[d] <10	[d] <10	[d] <10	[d] <10
		4.1	1.4	1.9	1.6	2.0	1.5	1.5	1.3	1.6	44	43	44	42	46	40	42	65
		6.2	3.2	2.3	3.4	3.0	3.3	2.8	2.7	2.9	54	60	65	56	68	54	63	60
		8.0	1.0	1.4	0.9	[d]1.0	0.9	0.8	0.8	1.1	26	17	26	[d]20	24	18	18	25
		12.1	3.4	[d]4.4	4.1	[d]3.9	4.0	3.6	3.6	[d]3.3	60	[d]58	55	[d]59	74	52	65	[d]85
		17.5	7.2	5.6	6.0	[d]5.6	5.4	4.8	5.3	5.9	70	48	72	[d]64	76	56	86	69
13	Hanford very fine sandy loam	1.9	2.5	3.0	3.7	3.4	3.9	4.5	3.3	4.1	36	32	48	36	47	65	63	71
		4.2	2.7	7.0	3.9	3.3	3.0	2.3	4.4	4.7	27	55	47	37	38	58	62	64
		5.9	6.5	8.3	6.7	7.4	5.5	6.1	7.8	8.6	49	97	67	85	59	67	75	55
14	Hempstead silt loam	1.1	0.3	0.4	0.4	0.5	0.4	0.5	0.4	0.4	34	38	26	28	32	32	40	65
		3.8	2.0	2.5	2.6	2.4	2.3	2.2	2.2	2.0	54	60	52	53	63	56	64	74
		5.8	2.4	3.7	3.6	3.1	3.4	3.2	3.1	2.9	87	82	84	79	98	90	94	153
		7.7	2.0	3.7	2.5	2.2	1.9	1.7	3.3	2.3	82	86	107	103	89	77	135	161
		9.9	3.8	6.4	4.5	5.3	5.0	4.0	4.6	3.6	120	106	130	131	97	97	114	142
		11.8	4.1	4.5	5.2	4.5	[d]4.8	4.3	4.6	4.7	101	109	80	84	[d]127	83	94	112
15	Houston black clay	2.0	2.4	2.1	2.3	2.1	2.2	2.3	2.7	2.7	30	34	40	35	40	34	44	44
		4.0	3.6	3.0	3.0	3.2	3.1	3.4	3.8	3.1	56	26	35	28	30	34	43	48
		5.9	6.2	6.1	5.6	5.4	6.2	5.7	5.2	6.4	65	59	54	53	64	64	64	58
		8.0	5.0	4.7	5.4	5.5	5.8	5.7	5.1	5.0	59	66	62	38	65	45	44	52
		12.0	8.1	8.5	7.7	7.8	8.3	8.2	8.1	9.1	78	50	56	54	63	82	72	62
		17.6	12.3	12.4	10.9	10.4	12.5	16.0	11.2	7.6	63	57	57	58	61	66	52	62
16	Kalmia fine sandy loam	2.0	1.9	2.5	2.7	2.1	2.2	2.3	2.6	2.1	43	36	38	40	42	35	39	45
		4.0	2.9	3.9	3.5	3.0	2.9	3.0	3.3	3.5	46	46	54	47	46	46	72	70
		6.0	5.2	4.9	4.4	4.3	5.6	4.5	5.0	5.0	92	84	94	120	84	62	96	90
		7.9	5.1	5.0	4.6	4.5	4.6	4.6	4.5	5.1	59	84	68	67	69	84	69	74
		10.0	6.7	6.6	6.8	6.2	5.8	6.2	6.9	6.2	69	61	64	56	74	70	66	71
		12.0	8.3	8.2	8.0	7.3	7.7	7.6	7.5	7.6	82	61	58	62	56	86	70	84
17	Keyport loam	1.2	1.5	1.5	1.4	1.4	1.6	1.5	1.6	1.5	<10	<10	<10	<10	<10	<10	<10	<10
		3.8	3.3	3.2	3.4	3.2	3.7	3.4	3.6	3.6	22	16	22	20	23	24	32	21
		5.9	5.2	5.9	5.6	5.2	6.1	6.1	6.0	6.2	32	26	26	32	32	32	31	35
		7.7	6.4	7.1	6.4	6.6	7.4	7.0	7.4	7.4	32	36	36	30	40	39	36	38
		11.8	9.4	8.6	8.3	9.0	10.6	10.2	9.6	10.0	41	38	42	39	42	47	48	42
		17.0	7.9	8.8	9.5	8.2	9.5	9.4	9.5	8.9	42	38	41	34	43	50	48	57
18	Knox silt loam	1.2	0.4	0.7	0.4	0.6	0.4	0.3	0.5	0.5	27	20	19	14	24	28	16	28
		3.8	1.2	1.8	1.9	1.6	1.3	1.2	1.2	1.7	40	40	18	34	34	52	43	37
		5.8	2.3	4.0	3.2	2.6	2.9	2.7	3.2	2.6	71	72	71	67	64	66	62	80
		7.7	1.8	3.3	2.9	2.0	2.2	1.9	2.3	2.1	55	37	40	42	56	57	42	50
		9.8	2.8	3.5	3.2	3.3	3.0	3.4	3.1	2.9	46	46	51	57	54	64	50	46
		11.7	3.0	2.7	3.1	2.6	2.0	2.7	2.4	3.9	52	42	41	38	41	70	44	44
19	Lindley silt loam	1.1	0.6	0.8	0.7	0.7	0.6	0.7	0.8	0.8	38	24	26	24	28	25	32	38
		3.7	2.0	1.5	2.2	2.2	2.3	2.3	1.8	2.0	38	45	50	38	36	46	59	50
		5.7	2.2	3.0	2.2	2.3	2.3	2.3	2.0	2.1	46	50	48	48	58	59	58	50
		7.6	2.5	3.0	2.7	2.8	2.4	2.4	3.0	2.5	44	40	46	40	56	58	56	66
		9.7	3.0	3.2	3.2	2.9	3.1	2.9	3.1	3.0	62	51	61	55	56	78	65	68
		11.6	2.9	3.5	3.8	3.4	3.2	3.4	3.3	3.5	56	62	71	66	66	85	60	63

See footnotes at end of table.

TABLE 13. *Loss in weight and maximum penetration of wrought black ferrous pipe buried in 1922* [a, b]—Continued

(Average of two specimens)

Soil			Loss in weight (oz/ft^2)								Maximum penetration (mils)							
			1½-in. pipe				3-in. pipe				1½-in. pipe				3-in. pipe			
No.[c]	Type	Duration of exposure	Open-hearth iron	Wrought iron	Bessemer steel	Bessemer steel (scale-free)	Wrought iron	Open-hearth steel	Bessemer steel	Open-hearth steel with 0.22 percent Cu	Open-hearth iron	Wrought iron	Bessemer steel	Bessemer steel (scale-free)	Wrought iron	Open-hearth steel	Bessemer steel	Open-hearth steel with 0.22 percent Cu
	Material		a	b	e	y	B	K	M	Y	a	b	e	y	B	K	M	Y
		Years																
20	Mahoning silt loam	1.0	0.9	0.8	1.1	1.0	0.9	1.0	0.9	0.9	<10	<10	<10	<10	<10	<10	<10	<10
		3.6	2.2	2.4	1.8	2.3	2.2	2.2	2.1	2.0	<20	<20	<20	<20	<20	<20	<20	<20
		5.5	2.4	2.7	2.4	2.1	2.3	2.3	2.8	2.2	<20	26	22	32	29	24	34	28
		7.7	2.7	3.4	2.7	2.5	3.2	2.9	3.5	2.8	28	38	40	42	32	35	42	65
		9.6	3.9	4.8	4.6	4.1	5.1	4.6	4.8	4.2	32	52	38	22	44	36	42	36
		11.6	6.6	6.5	6.1	6.0	5.6	6.1	6.0	5.6	67	48	72	64	45	80	56	62
21	Marshall silt loam	1.5	2.0	2.1	2.1	2.1	2.2	2.0	2.0	2.1	<10	<10	<10	<10	<10	<10	<10	<10
		4.0	2.5	2.6	2.9	2.4	2.8	2.9	2.9	2.5	61	40	50	63	60	39	48	44
		6.0	4.2	4.4	5.0	4.7	4.8	5.1	4.6	4.6	71	52	60	58	60	59	66	60
22	Memphis silt loam	1.7	1.4	1.6	2.0	1.9	1.4	1.5	1.4	1.8	44	35	44	44	38	39	52	47
		3.7	3.2	3.9	3.4	3.7	3.6	3.7	3.5	3.5	45	46	51	44	58	60	54	50
		5.6	5.3	5.4	4.6	5.4	4.6	4.6	4.5	3.6	68	55	58	54	62	62	62	60
		7.6	5.7	6.2	7.4	5.8	6.4	6.2	7.8	7.5	43	56	63	52	56	58	66	69
		9.6	6.7	7.0	7.5	6.4	7.2	6.8	7.5	6.5	65	62	54	57	68	65	63	68
		11.6	7.0	7.6	7.5	7.1	7.9	6.9	7.8	7.0	72	66	66	78	60	56	65	71
23 (70)	Merced silt loam	1.9	5.4	7.6	7.7	7.8	5.8	6.5	6.7	7.8	53	48	48	50	48	86	52	67
		4.3	11.2	13.3	13.7	10.5	12.0	11.9	12.0	9.7	94	103	114	83	98	134	108	97
		6.2	13.7	15.7	12.2	15.7	12.9	14.5	13.8	17.4	145+	124	90	100	91	109	100	130
		8.0	18.2	20.5	15.5	18.6	18.6	21.1	19.2	23.8	145+	145+	145+	128+	158	159	134	216+
		10.2	19.5	21.6	19.3	18.9	19.7	19.7	21.7	20.2	145+	145+	145+	145+	136	151	136	163
		12.1	20.1	21.1	19.8	20.4	20.7	19.6	19.6	[d]24.3	145+	145+	145+	145+	150	150	163	[d]177
24	Merrimac gravelly sandy loam	1.3	0.2	0.3	0.3	0.3	0.2	0.3	0.3	0.2	<10	<10	<10	<10	<10	<10	<10	<10
		4.0	.4	.6	.5	.4	.4	.4	.4	.3	<20	<20	<20	<20	<20	<20	<20	<20
		6.1	.9	1.2	1.3	.8	1.1	1.1	1.1	1.0	<20	<20	<20	<20	21	20	20	28
		7.9	.9	1.0	1.0	.8	1.0	0.9	1.0	0.8	22	<20	<20	<20	19	25	<20	31
		12.0	1.3	1.4	1.5	1.4	1.2	1.4	1.4	1.2	28	23	21	25	28	28	30	31
		17.2	1.3	1.9	1.8	1.4	1.4	1.3	1.6	1.2	26	24	16	26	30	27	36	28
25	Miami clay loam	1.0	0.4	0.6	0.4	0.4	0.3	0.4	0.4	0.4	24	19	18	25	22	27	28	25
		3.7	.6	1.4	1.1	1.1	.7	.9	1.4	1.4	34	30	27	30	31	29	38	34
		5.7	1.7	1.7	1.9	1.9	1.8	1.7	1.7	1.5	48	41	39	36	47	48	58	52
		7.6	1.8	2.3	2.0	2.0	1.9	1.8	1.8	1.7	42	35	36	34	52	38	47	42
		11.7	3.4	[d]4.0	3.4	2.9	2.8	3.6	3.3	2.8	52	[d]43	48	32	48	46	57	52
		17.0	3.0	4.2	3.8	3.1	2.8	3.2	2.7	2.7	75	50	42	42	54	62	56	57
26	Miami silt loam	1.0	0.8	0.9	0.8	0.8	0.8	0.8	0.9	0.9	<10	<10	<10	<10	<10	<10	<10	<10
		3.5	1.6	2.2	1.8	1.8	1.9	1.9	2.2	1.9	39	45	42	46	36	45	66	48
		5.5	1.5	2.1	1.7	1.5	1.2	1.2	1.4	1.4	70	66	67	64	72	66	78	80
		7.7	1.3	2.1	2.0	1.6	1.5	1.5	1.6	1.7	39	47	38	44	47	48	48	58
		11.5	3.5	4.2	3.6	3.5	4.0	3.7	3.8	3.4	38	47	44	35	44	46	38	43
		16.9	4.0	5.1	4.3	4.1	4.7	4.1	4.8	4.3	43	42	42	36	42	60	58	53
27	Miller clay	2.0	0.4	0.6	0.5	0.5	0.6	0.6	0.6	0.5	<10	<10	<10	<10	<10	<10	<10	<10
		4.0	3.2	3.1	3.9	3.6	3.5	3.5	3.3	2.7	20	22	31	33	36	38	27	42
		6.0	3.0	3.8	4.1	3.0	3.1	3.1	3.0	3.2	21	28	32	40	30	56	35	46
		8.0	4.6	4.3	4.2	5.4	4.3	4.9	3.9	4.4	31	34	26	36	41	72	46	42
		12.0	7.1	8.5	8.8	7.6	8.3	7.0	8.2	8.1	42	48	60	60	55	80	82	74
		17.6	9.3	11.4	10.1	9.3	9.7	8.5	8.9	8.4	39	58	69	54	74	92	84	78

		Years																
28	Montezuma clay adobe	1.6	3.4	2.7	3.6	3.0	2.1	3.2	2.9	3.5	20	26	34	26	29	40	35	36
		5.6	10.3	9.3	9.5	10.6	8.9	10.7	10.5	10.7	50	69	60	55	56	76	56	75
		7.7	11.6	12.8	14.5	15.1	15.3	16.4	13.2	18.3	137	124	117	106	132	161	117	153
		9.6	15.7	15.4	16.4	16.8	16.8	16.2	15.5	17.7	145+	132+	137+	145+	167	183+	152	216+
29 (58)	Muck	2.0	4.0	3.3	3.8	4.4	3.5	4.2	4.1	4.2	48	37	54	56	42	68	43	37
		4.1	7.2	7.7	7.3	6.8	7.2	7.3	6.9	7.9	65	47	60	68	72	78	60	90
		6.0	10.0	8.9	9.4	9.9	9.2	9.6	8.9	9.3	104	78	92	83	56	80	90	81
		8.0	14.3	13.0	[d]13.7	14.0	10.9	16.4	11.0	15.7	104+	68	[d]90	90	98	90	128	178
		10.0	16.2	13.4	13.8	14.0	14.9	15.3	14.8	15.6	145+	97	74	92	84	120	100	178
		12.0	21.5	16.2	19.2	19.4	15.6	17.9	14.8	20.1	145+	90	136+	145+	134	216+	119	216+
30	Muscatine silt loam	1.1	0.9	0.9	1.1	0.9	0.9	1.1	1.1	1.0	24	<10	12	10	12	16	16	18
		3.6	1.1	1.2	1.2	1.2	1.4	1.3	1.4	1.2	<20	<20	<20	<20	<20	<20	<20	<20
		5.7	1.8	2.3	2.6	2.0	2.5	2.7	2.5	2.4	<20	<20	24	16	28	28	27	28
		8.2	4.1	4.7	4.1	4.2	4.7	4.0	4.4	3.8	46	36	33	34	62	35	48	31
		11.6	5.2	5.6	4.8	5.3	6.3	5.8	5.6	5.2	54	51	58	51	53	54	63	66
		17.0	6.1	5.9	5.7	5.4	6.0	6.0	6.9	6.4	50	44	52	42	53	64	76	65
31	Norfolk fine sand	2.0	0.7	1.3	1.2	1.5	0.8	1.2	1.3	1.1	30	33	67	39	37	48	52	54
		4.1	2.0	1.7	2.1	2.2	2.1	2.5	2.1	2.3	24	26	25	25	30	47	28	34
		6.0	1.6	1.8	1.9	1.9	1.5	1.9	2.3	2.3	28	26	30	53	29	56	32	46
		8.0	1.8	2.2	2.4	2.8	2.1	2.2	2.3	2.6	36	44	37	38	42	45	64	36
		12.0	2.9	3.0	2.8	2.7	2.8	2.8	2.8	3.4	34	29	34	30	41	41	40	36
		17.7	4.9	4.2	3.7	4.4	6.3	4.5	4.1	4.6	50	42	43	52	41	90	66	49
32	Ontario loam	1.0	0.2	0.5	0.4	0.4	0.3	0.4	0.4	0.3	40	26	21	22	30	23	27	26
		3.7	1.2	1.8	1.6	1.4	1.4	1.3	1.3	1.4	44	40	30	27	40	34	36	41
		5.8	1.8	2.1	2.3	1.8	2.3	2.2	2.6	2.5	37	32	30	36	38	39	37	42
		7.6	2.0	2.8	2.7	2.3	2.5	2.6	2.3	2.7	32	42	42	39	38	48	44	46
		9.6	2.1	3.2	3.1	2.5	3.0	2.4	2.8	2.6	43	55	46	44	52	49	54	94
		11.7	3.1	3.5	3.3	3.7	3.6	3.6	4.2	3.2	58	42	46	50	59	86	62	93
33	Peat	1.0	0.4	0.4	0.4	0.5	0.4	0.4	0.4	0.4	<10	<10	<10	<10	<10	<10	<10	<10
		3.7	3.5	3.3	3.4	3.5	3.7	3.5	3.6	3.8	38	<20	<20	25	32	30	40	38
		5.8	4.7	4.6	4.6	5.6	4.3	5.6	4.8	3.0	46	36	<20	51	36	54	33	28
		7.6	8.4	9.2	9.2	8.8	8.5	8.8	8.9	7.8	130+	60	66	97	100	117	96	94
		9.7	11.1	12.4	11.4	9.8	10.1	9.9	11.4	10.5	114	82	92	74	112	102	115	111
		11.7	14.1	14.0	14.3	14.2	14.3	11.6	12.8	14.0	112	98	90	104	104	108	96	84
34	Penn silt loam	1.4	1.3	1.3	1.2	1.1	1.4	1.4	1.4	1.2	20	21	20	18	22	27	22	29
		4.0	1.6	1.8	1.8	1.9	1.8	1.9	1.8	1.8	23	21	<20	18	16	18	16	17
		6.1	3.1	2.8	2.8	2.7	2.8	3.1	2.8	2.9	48	28	16	32	36	38	29	48
		8.0	3.0	3.3	3.4	3.5	3.5	3.2	3.3	3.2	42	46	45	52	43	67	40	68
		9.9	4.2	4.8	4.6	4.1	4.5	3.9	4.3	4.4	82	48	84	94	71	73	77	104
		12.0	3.8	4.8	4.0	3.2	5.9	4.3	5.3	4.8	58	36	41	32	55	36	50	74
35	Ramona loam	1.9	0.8	0.9	0.7	0.7	0.8	0.9	1.1	0.9	<10	17	<10	<10	<10	<10	17	18
		4.1	1.7	[d]2.0	1.8	1.4	2.1	2.0	1.9	1.8	16	[d]20	<20	<20	20	17	22	24
		6.2	1.2	1.2	1.5	1.0	0.9	0.7	1.0	1.4	<20	<20	40	<20	22	<20	18	21
		8.0	2.4	2.1	1.7	1.7	2.1	2.1	2.1	2.3	32	24	23	<20	18	38	28	97
		12.1	1.6	2.7	2.2	[d]1.1	1.8	1.7	2.5	1.9	10	24	18	[d]<20	36	22	69	27
		17.5	1.5	4.1	1.5	0.9	1.2	0.9	3.2	3.3	12	54	9	17	32	34	36	64
36	Ruston sandy loam	2.0	1.2	1.2	1.4	1.1	0.8	0.8	1.0	0.9	28	37	34	38	37	48	43	37
		4.1	1.4	2.0	2.2	2.1	1.7	1.7	1.6	1.5	37	38	30	31	39	50	46	42
		6.0	1.3	1.7	1.7	1.8	1.4	1.8	1.4	1.6	47	48	37	41	41	52	48	42
		8.0	2.0	3.0	2.5	2.4	1.8	2.0	2.1	2.1	48	54	35	38	48	58	50	50
		12.0	2.5	3.3	3.2	2.9	2.3	2.8	2.4	2.5	56	46	48	48	47	60	45	44
		17.7	3.3	4.1	4.1	3.7	2.5	3.0	2.6	3.1	51	50	55	45	50	60	49	57
37	St. John's fine sand	2.0	2.3	2.3	2.4	2.4	2.4	2.4	2.5	2.4	38	35	48	48	42	43	53	90
		4.1	4.2	4.4	4.4	4.2	4.5	4.4	4.5	5.0	46	42	62	66	59	58	55	92
		6.0	4.2	4.6	3.6	4.6	3.8	4.2	4.1	3.8	46	51	38	73	38	48	56	59
		8.0	5.8	6.1	5.2	5.2	6.3	6.1	5.8	6.5	58	49	52	54	64	68	67	96
		10.1	9.1	8.6	8.0	7.7	8.2	8.7	8.5	10.0	69	71	89	74	75	72	84	114
		12.0	8.3	9.0	7.7	6.8	8.2	8.4	9.0	10.4	76	64	78	68	80	63	95	127
38	Sassafras gravelly sandy loam	1.4	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	<10	<10	<10	<10	<10	<10	<10	<10
		4.0	.5	.7	.7	.6	.5	.4	.6	.5	<20	28	<20	<20	<20	<20	<20	<20
		6.1	.9	.8	1.2	.8	1.1	1.3	1.2	1.2	40	26	20	20	37	17	24	35
		8.0	2.0	2.0	2.1	1.8	2.0	2.0	2.2	2.1	52	28	20	24	34	26	29	24
		12.0	2.1	2.4	2.8	2.6	2.4	2.5	2.2	2.7	35	34	26	20	28	22	42	26
		17.2	2.7	3.4	2.3	2.6	2.3	2.8	2.8	2.5	40	33	28	36	34	38	34	33
39	Sassafras silt loam	1.4	1.0	1.2	1.2	1.3	1.2	1.3	1.2	2.1	<10	<10	<10	<10	<10	<10	<10	<10
		4.0	3.1	2.8	2.9	[d]2.7	3.2	3.0	3.2	2.9	42	24	38	[d]25	16	24	32	46
		6.1	2.3	3.2	2.6	2.7	3.2	3.1	3.2	3.2	31	44	38	50	48	38	44	50
		8.0	4.1	4.5	4.6	3.6	4.9	4.8	4.9	5.1	48	50	46	42	66	72	52	77
		9.9	4.6	5.2	4.9	4.5	5.3	5.0	4.7	4.8	68	42	42	51	53	68	52	88
		12.0	4.8	5.5	6.1	5.2	6.3	5.6	6.4	5.0	77	56	50	60	69	69	94	106

See footnotes at end of table.

TABLE 13. *Loss in weight and maximum penetration of wrought black ferrous pipe buried in 1922*[a, b]—Continued

(Average of two specimens)

Soil		Duration of exposure	Loss in weight (oz/ft²)								Maximum penetration (mils)							
			1½-in. pipe				3-in. pipe				1½-in. pipe				3-in. pipe			
No.[c]	Type		Open-hearth iron	Wrought iron	Bessemer steel	Bessemer steel (scale-free)	Wrought iron	Open-hearth steel	Bessemer steel	Open-hearth steel with 0.22 percent Cu	Open-hearth iron	Wrought iron	Bessemer steel	Bessemer steel (scale-free)	Wrought iron	Open-hearth steel	Bessemer steel	Open-hearth steel with 0.22 percent Cu
	Material		a	b	e	y	B	K	M	Y	a	b	e	y	B	K	M	Y
		Years																
40 (61)	Sharkey clay	2.0	2.1	2.1	2.1	2.0	2.3	2.5	2.2	2.8	46	28	38	31	28	41	32	42
		4.1	4.0	4.3	3.9	3.7	4.2	4.3	4.6	4.2	61	52	43	35	41	46	44	46
		6.0	5.4	5.5	5.0	5.3	6.1	6.6	6.1	5.6	61	69	70	60	65	88	74	84
		8.0	6.4	6.5	6.5	5.5	7.0	7.1	8.2	7.7	86	101	64	74	70	99	96	92
		10.0	6.9	7.2	7.3	6.0	8.1	7.2	9.3	7.5	75	62	87	62	65	72	64	86
		12.0	6.9	7.9	7.2	6.7	8.6	8.6	7.0	8.3	139	68	69	82	69	91	78	75
41	Summit silt loam	1.5	0.8	0.5	0.5	1.0	0.6	0.6	0.4	0.4	19	39	33	40	44	30	42	32
		4.0	2.7	3.6	3.0	3.0	2.7	2.9	2.4	2.5	34	36	40	45	47	38	43	46
		6.0	4.6	4.7	4.5	4.2	3.2	3.6	4.1	3.9	53	50	48	60	55	52	67	52
		7.9	4.8	5.4	5.0	4.7	4.2	4.2	4.6	4.4	61	65	55	60	58	58	62	56
		12.0	6.0	6.2	6.3	5.3	6.5	6.3	6.0	6.0	101	94	79	91	86	72	85	80
		17.4	5.9	7.4	6.9	7.0	5.5	5.5	7.0	7.0	122	94	92	101	86	67	101	78
42 (62)	Susquehanna clay	2.0	3.0	3.6	3.3	3.1	2.9	2.4	2.9	1.9	53	58	59	50	54	62	78	55
		4.1	4.5	7.3	5.7	5.9	4.8	3.4	5.1	3.4	64	74	73	76	79	85	82	74
		6.0	7.0	8.0	7.7	7.3	5.7	6.9	6.2	6.6	77	92	84	74	78	86	95	81
		8.0	5.9	7.7	8.2	9.3	6.4	6.8	6.7	5.6	76	89	113+	111+	80	93	88	90
		10.1	11.5	10.6	12.1	12.5	8.8	11.1	9.3	9.2	84	84	104	92	96	129	103	104
		12.0	10.6	17.1	12.5	17.4	8.9	11.2	11.0	13.4	94	89	111	86	88	125	92	116
[f]43 (63)	Tidal marsh	1.3	1.4	1.7	1.9	2.8	2.0	2.2	2.3	2.4	18	36	24	28	44	45	66	47
		4.1	3.6	7.2	4.6	4.8	4.7	5.2	6.9	6.4	39	44	35	46	101	79	83	59
		6.2	5.8	8.0	9.7	7.4	7.2	6.2	7.7	8.3	88	82	67	76	104	132	119	53
		8.0	9.1	15.3	10.3	11.4	10.1	10.8	9.0	14.4	84+	102+	76	70	116	136	78	90
		9.9	11.6	11.4	10.5	17.0	10.4	11.2	9.8	12.0	94	76	70	73	136	100	116	155
		12.0	15.5	16.6	19.5	17.6	14.1	12.7	13.1	16.3	90	80	100	105	138	78	74	72
44	Wabash silt loam	1.1	0.3	0.6	0.4	0.5	0.4	0.3	0.4	0.4	38	36	28	32	26	39	32	38
		3.6	1.4	1.8	2.0	1.8	1.4	1.4	1.2	1.3	78	43	54	55	46	44	44	50
		5.7	2.3	2.2	2.3	2.4	2.1	2.2	2.0	2.0	70	52	51	66	56	72	60	68
		7.6	1.7	2.3	2.2	2.0	1.9	2.1	2.0	2.1	72	49	62	50	56	50	62	88
		11.6	2.9	4.1	4.7	3.5	3.4	2.8	3.4	3.2	87	56	63	69	65	58	82	74
45	Unidentified alkali soil	1.2	1.2	1.4	1.4	1.3	1.1	1.0	1.7	1.4	<10	20	15	13	<10	17	30	28
		3.8	3.6	3.0	2.9	3.3	2.9	3.2	2.8	3.3	36	28	24	24	32	36	31	49
		5.8	2.9	3.2	2.3	3.1	3.3	3.1	3.2	3.0	45	43	40	34	47	36	48	52
		7.7	3.5	[d]5.6	4.2	3.8	4.1	3.9	3.8	4.2	50	[d]46	60	45	56	60	60	66
		9.8	13.7	11.9	11.9	12.1	12.5	13.1	12.3	13.5	143	114	138	117	118	138	128	158
		11.7	9.7	9.0	9.7	9.3	10.6	11.3	9.3	11.2	82	78	84	82	85	112	98	124
46	Unidentified sandy loam	1.5	0.8	1.3	1.2	0.9	1.0	1.1	1.2	1.2	57	54	55	54	50	40	56	79
		4.0	2.7	3.2	2.9	2.6	2.4	2.6	2.7	3.2	80	64	79	82	66	58	106	110
		5.1	2.9	2.8	3.1	3.0	2.8	3.0	2.6	3.2	68	65	66	54	68	46	96	96
		8.0	5.6	6.2	5.2	5.7	5.7	5.9	5.8	6.7	60	80	108+	118+	69	68	136	134
		10.2	4.0	4.7	4.8	4.1	4.4	3.6	4.3	3.9	74	95	68	83	82	66	84	80
		12.0	4.0	5.1	4.5	4.4	4.7	4.3	4.8	4.8	48	62	64	104	77	62	114	80
47	Unidentified silt loam	1.5	[d]0.5	0.5	0.5	0.4	0.4	0.6	0.5	0.4	[d]<10	<10	<10	<10	<10	<10	<10	<10
		4.1	1.3	1.9	1.7	1.3	1.3	1.3	1.6	2.0	<20	<20	<20	<20	<20	<20	<20	<20
		6.1	1.2	1.5	1.6	1.2	1.9	1.6	2.2	1.5	<20	<20	<20	<20	<20	<20	<20	<20
		8.0	2.2	2.1	1.7	1.8	2.1	2.1	2.0	1.6	<20	<20	<20	<20	<20	<20	<20	<20
		12.1	2.3	3.9	3.0	2.8	3.2	3.0	2.8	3.1	16	46	26	31	34	24	27	26
		17.4	5.8	6.4	7.9	8.4	6.1	6.5	5.4	5.1	42	53	37	57	51	40	48	46

[a] See table 10 for composition of materials. [b] See table 6 for properties of soils. [c] The soil number in parentheses is the number assigned to the same soil in a later series of tests. See table 15. [d] Data for 1 specimen only. [e] The plus sign indicates that 1 or both specimens contained holes because of corrosion. [f] Site 43 is not identical with site 63 geographically, but the soil environment, tidal marsh, is the same.

tests in less than 12 years because the sites were no longer available. However, approximately half of the exposures were continued for 12 years and in 19 of the less corrosive soils, exposure was continued for approximately 17 years. In 1928, samples of some of the 3-in. pipes were exposed to 28 additional soils, and in later years (1932 and 1937) samples of 1½-in. pipes and a plate were exposed to 15 soils. These results are given in tables 14 and 15.

For similar periods of exposure the relative corrosion rate of a material in two soils may not be the same, as the initial rate of loss in weight or pitting may be maintained in one soil, whereas in another the rates may decrease because of the effect of the corrosion products and properties of the soil. Differences of this nature are illustrated in figure 11, which shows the relation of maximum pit depth of wrought iron and steel to the length of exposure in five different soils. Because of these changes in the rates of corrosion with time, the data for all periods of exposure should be taken into account before attempting to estimate the behavior of a material in a soil or the corrosiveness of that soil.

The depth of the deepest pit is a function of the area from which it is chosen. For a given material, the maximum pit depth resulting from a particular exposure has been found to vary with the exposed area, i.e., the greater the exposed area the greater the chance of finding one or more unusually deep pits [110]. Table 16 presents the maximum and weighted maximum pit depths of the wrought pipe specimens during the maximum exposure period. The weighted values have been adjusted to give comparable data based on their area for the specimens of different sizes, that is, the single deepest pit on each 1½-in. pipe and the two deepest pits on each of the two 3-in. pipes. Therefore, the data in the last 4 columns for the 3-in. pipe may be compared with data for similar materials of the 1½-in. pipe in columns 3 to 6. As a check on this procedure, the pit depths of the corresponding 1½-in. and 3-in. wrought iron and Bessemer steel specimens (table 16) may be compared. In each case the same manufacturer furnished both sizes of the same materials. There are 19 soils in which the weighted pit depths are of the same magnitude and 16 soils in which the weighted pit depths are greater for the larger specimens compared with 12 soils in which the pit depths are less.

Effect of Composition. Although the principal purpose of the original soil-corrosion investigation was to determine the effect of soils, a comparison of the different materials could not be avoided because of their varying compositions.

A comparison of the behavior of the more commonly used irons and steels was made in Research Paper 883 [113], which reported the average depths of the deepest pits, over an interval of 12 years, of all the ferrous specimens buried in 1922. The difference in the soils was so great that average rates for all soils had little value, except that they permitted a comparison of different materials exposed to the same conditions. The pit depths were adjusted to take into account the areas of the specimens.

Although table 16 indicates that there may be a small difference between open-hearth iron specimens and the other 1½-in. wrought specimens, this difference is not considered to be significant. Similarly, the 3-in. open-hearth steel, containing 0.2 percent of copper, may corrode at a greater rate than copper-free steel. In both cases the reason for the differences may be due to the character of the surfaces or the different surface finishes of the specimens employed. In the case of the open-hearth iron, the surfaces of the specimens may have been covered by an almost continuous thin oxide film that broke down in a relatively few places, thus concentrating the galvanic action. A basis for this suggestion is the low loss in weight of the specimens of this material (table 13).

The copper-bearing steel specimens, on the other hand, carried heavy local patches of mill scale that had not been removed after fabrication. It is possible that galvanic action between this mill scale and the remainder of the surface of the pipe accelerated the corrosion, or that after a period of exposure the mill scale became loosened and galvanic action between the unprotected spots and the oxidized areas caused additional corrosion.

The loss in weight is smallest for the wrought-iron specimens, but the difference between the average maximum rates of penetration for wrought-iron and Bessemer steel is not sufficient to show positively a difference in the rates of corrosion of these materials for either the 1½-in. or the 3-in. specimens.

The averages of the data for all soils for any material in table 16 indicate that the maximum pit depth is generally greater on the 3-in. than on the 1½-in. specimens. However, the data for individual soils show that this is not always the case. This is the "area effect" previously mentioned in the description of the weighting procedure.

Because each of these test sites was examined carefully and no location accepted where there was a possibility of stray currents in the earth, the corrosion observed in the specimens could not have been caused by stray currents. Moreover, an examination of the distribution of the corrosion with respect to the position of the specimens in the trench confirmed this statement. It is evident in tables 13 through 15 for the wrought ferrous materials, that as a rule all the specimens in the same trench corroded similarly with respect to losses in weight and depths of deepest pits. Further examination of the specimens showed that the distribution of the corroded areas of individual specimens in the same trench was also similar. From this it follows that the cause of corrosion did not lie within the specimens because they differed in composition and were furnished by several independent pipe mills. Differences in composition of the plain irons and steels were thus eliminated as primary causes of underground

Table 14. *Loss in weight and maximum penetration of 3-inch wrought black ferrous pipe buried in 1928*

(Average of two specimens)

Soil		Duration of exposure	Loss in weight			Maximum penetration		
No.	Type		Open-hearth iron	Wrought iron	Bessemer steel	Open-hearth iron	Wrought iron	Bessemer steel
	Material		A	B	M	A	B	M
		Years	oz/ft^2	oz/ft^2	oz/ft^2	*Mils*	*Mils*	*Mils*
52	Lake Charles clay loam	2.0	3.1	3.4	2.7	66	62	40
		5.4	14.7	14.6	13.5	116	123	118
		7.5	19.0	19.0	16.9	116	176	163
54	Fairmount silt loam	1.9	1.0	1.0	0.7	14	16	6
		5.2	1.5	1.3	1.2	14	21	11
		7.3	3.4	2.5	3.5	54	36	40
68	Gila clay	1.7	3.2	3.6	2.9	42	50	37
		5.1	3.7	4.3	3.7	43	43	38
		7.2	4.8	4.9	4.4	48	48	45
101	Billings silt loam (low alkali)	1.9	3.9	5.2	3.9	70	66	60
		4.1	7.5	8.8	7.2	116	94	94
		9.3	10.5	9.4	9.1	131	95	86
102	Billings silt loam (moderate alkali)	1.9	3.9	5.1	4.3	42	37	26
		4.1	9.4	10.2	9.3	102	80	72
		9.3	18.3	16.1	17.6	124	93	95
103	Billings silt loam (high alkali)	1.9	3.7	5.0	3.6	63	48	37
		4.1	11.2	10.4	10.1	88	86	66
		9.3	18.8	21.3	17.8	190	136	192
104	Cecil clay	1.9	2.9	3.0	2.5	71	70	88
		4.1	4.8	4.3	3.7	84	86	93
		11.7	7.1	7.2	7.6	88	94	114
105	Cecil clay loam	2.0	3.2	3.6	3.4	50	45	58
		4.0	3.6	3.8	4.2	48	48	46
		11.7	4.8	3.7	4.9	58	51	54
106	do	1.9	2.6	2.5	2.0	62	46	48
		4.1	3.4	4.0	3.6	64	64	56
		11.7	7.3	8.6	9.0	93	70	75
107	Cecil fine sandy loam	1.9	2.0	2.3	2.4	57	66	64
		4.1	2.9	3.2	3.1	73	72	66
		11.7	5.4	5.5	5.6	97	90	129
108	Cecil gravelly loam	1.9	2.8	3.3	3.4	67	38	53
		4.0	3.1	3.6	3.4	86	50	62
		11.7	4.7	4.5	5.9	85	70	95
109	Fresno fine sandy loam (low alkali)	1.9	4.7	5.9	5.2	70	70	74
		4.0	7.9	7.6	6.3	74	82	63
		9.2	11.6	11.8	11.3	121	100	108
110	Fresno fine sandy loam (moderate alkali)	1.9	3.9	4.5	4.1	74	60	42
		4.0	7.6	7.1	7.4	84	85	73
		9.2	18.6	15.8	20.2	155	126	155
111	Fresno fine sandy loam (high alkali)	1.6	4.4	4.5	5.2	54	48	38
		3.7	8.7	7.8	8.7	104	78	80
		8.9	17.6	18.8	19.4	162+	165	119
112	Imperial clay (moderate alkali)	1.9	7.1	7.3	7.3	76	58	68
		4.0	14.5	13.6	14.0	188+	128	132
		5.9	19.8	16.9	18.8	250+	177+	232+
113	Imperial clay (high alkali)	1.9	8.2	8.1	8.2	92	54	54
		4.0	19.0	16.0	18.5	216+	157+	216+
		5.9	25.8	21.8	23.6	224+	178+	231+
114	Lake Charles clay	0.9	1.5	1.3	1.3	32	15	14
		3.0	4.8	6.0	5.0	99	72	67
		10.5	14.3	14.6	14.1	159	90	106
115	Memphis silt loam	2.0	1.8	1.9	1.7	32	34	32
		4.1	2.4	2.8	2.7	75	64	64
		11.7	3.3	3.5	3.9	89	48	64
116	Merced clay	1.9	6.1	6.6	5.8	46	51	36
		4.0	13.0	11.8	11.5	96	97	90
		9.3	21.6	19.1	19.4	121	173	88
117	Merced clay loam adobe	1.9	7.6	7.9	8.0	118	92	86
		4.0	9.6	9.9	9.4	135	112	101
		9.3	21.0	19.8	20.5	185	127	141
118	Niland gravelly sand (low alkali)	1.9	5.4	5.0	5.5	108	72	60
		4.0	12.2	10.9	13.1	151+	124	122+
		5.9	16.0	15.4	14.9	240+	153	158
119	Norfolk sandy loam	2.0	0.7	0.6	0.5	<10	<10	<10
		4.0	3.9	4.3	4.6	86	52	68
		11.7	8.2	8.7	8.9	98	67	77

Table 14. *Loss in weight and maximum penetration of 3-inch wrought black ferrous pipe buried in 1928*—Continued

(Average of two specimens)

Soil		Duration of exposure	Loss in weight			Maximum penetration		
No.	Type		Open-hearth iron	Wrought iron	Bessemer steel	Open-hearth iron	Wrought iron	Bessemer steel
	Material		A	B	M	A	B	M
		Years	*oz/ft²*	*oz/ft²*	*oz/ft²*	*Mils*	*Mils*	*Mils*
120	Norfolk sand	2.0	2.4	2.6	2.6	72	46	49
		4.0	0.9	0.9	0.8	22	20	20
		11.6	1.8	1.8	2.1	36	28	26
121	do	2.0	1.1	0.9	0.8	22	19	20
		4.0	1.0	.9	.7	26	20	20
		11.7	1.4	1.4	1.5	28	25	21
122	Panoche clay loam	1.9	1.9	2.2	1.9	46	32	25
		4.0	2.8	3.2	3.6	48	60	38
		9.3	5.0	4.5	7.1	58	49	48
123	Susquehanna clay	2.0	3.0	3.2	3.2	32	30	32
		4.1	5.5	6.4	5.4	46	38	44
		11.7	10.4	10.9	10.9	44	60	62
124	Susquehanna silt loam	0.9	2.4	2.6	2.7	47	48	47
		2.7	4.5	5.0	5.2	54	54	55
		10.5	8.1	8.5	8.5	84	80	80
125	Susquehanna fine sandy loam	2.0	3.4	3.9	3.6	42	46	40
		4.1	4.9	4.5	4.6	56	44	47
		11.8	7.0	7.9	8.5	68	74	78

Table 15. *Loss in weight and maximum penetration of wrought black ferrous pipe (1½ inch) and plate buried in 1932 and 1937*

(Average of two specimens)

Soil		Exposure		Loss in weight					Maximum penetration				
No.	Type	For pipe A, B, and N	For pipe S and plate A	Wrought iron pipe, hand puddled	Wrought iron pipe, mechanically puddled	Carbon steel pipe	Carbon steel pipe	Open-hearth steel plate	Wrought iron pipe, hand puddled	Wrought iron pipe, mechanically puddled	Carbon steel pipe	Carbon steel pipe	Open-hearth steel plate
	Material			A	B	N	S	A	A	B	N	S	A
		Years	*Years*	*oz/ft²*	*oz/ft²*	*oz/ft²*	*oz/ft²*	*oz/ft²*	*Mils*	*Mils*	*Mils*	*Mils*	*Mils*
51	Acadia clay	2.0	2.1	11.7	8.2	7.4	7.5	11.6	50	60	82	52	54
		5.4	------	12.6	13.6	12.7	------	------	144	[a]129+	154+	------	------
		7.5	[b]9.0	15.1	15.3	11.5	17.4	19.1	122+	145+	135+	128+	138+
		[c]14.3	------	23.9	26.7	21.0	------	------	135+	131+	146+	------	------
53	Cecil clay loam	2.0	2.1	3.5	3.4	2.7	1.8	1.8	34	30	37	42	40
		5.5	4.0	2.6	3.0	3.0	2.9	3.2	64	71	50	98	76
		7.6	8.9	3.3	3.4	4.2	3.4	3.9	77	76	54	74	57
		9.5	11.2	3.7	3.7	4.1	3.4	3.4	50	73	59	78	72
		14.3	12.7	4.9	4.8	4.4	3.9	4.0	72	66	84	68	78
55	Hagerstown loam	1.9	1.9	2.8	2.9	2.4	1.8	2.0	40	42	41	33	42
		5.2	3.9	2.3	2.4	2.2	2.6	2.6	79	84	57	50	54
		7.1	9.0	3.5	3.4	3.2	4.1	3.8	70	60	57	92	90
		9.1	11.0	3.7	3.8	3.8	3.9	3.3	60	84	59	84	77
		14.2	12.6	3.4	3.7	3.1	3.4	4.0	76	88	65	73	66
56	Lake Charles clay	2.0	2.1	3.5	4.4	4.0	13.8	14.4	22	24	20	77	80
		5.4	4.0	10.8	7.6	13.9	16.0	18.3	66	65	71	104	100
		7.5	8.9	17.2	14.7	21.0	27.8	28.0	90	106+	125+	145+	126+
		9.4	11.1	[d]22.8	19.5	28.8	[e]D	48.1	[d]96	106	154+	145+	188+
		14.4	12.7	26.6	26.5	35.2	D	D	145+	145+	135+	145+	188+
58	Muck	2.0	2.1	3.5	3.2	3.2	5.1	5.7	20	18	18	29	31
		5.5	4.0	9.8	10.4	11.2	8.8	9.9	68	64	103	46	61
		7.6	8.9	11.9	11.6	14.1	17.3	16.9	84	110	110	98	89
		9.5	11.2	12.6	12.7	16.2	16.3	17.2	118	116	110	110	161+
		14.4	12.7	19.6	17.4	25.5	17.6	18.1	96	78	154+	124	188+
59	Carlisle muck	------	2.1	------	------	------	1.5	1.5	------	------	------	12	6
		5.1	4.0	1.8	1.6	2.4	3.3	4.2	25	18	20	20	22
		7.2	9.1	2.0	1.8	3.0	7.5	9.9	18	15	30	101	98
		9.1	11.1	2.4	2.3	4.7	9.6	9.5	32	28	40	76	96
		[c]14.2	12.7	4.3	4.2	3.9	9.6	11.1	37	32	34	72	90
60	Rifle peat	1.9	2.1	5.7	5.0	6.2	4.0	6.3	24	24	37	15	30
		5.2	4.0	6.3	6.8	11.0	8.1	9.5	38	37	24	38	40
		7.3	9.1	5.1	5.4	7.6	17.6	22.0	30	34	17	58	56
		9.2	11.1	14.3	[f]16.5	16.7	19.6	15.8	[f]55	[f]64	[f]27	89	63
		14.3	12.7	25.1	28.8	28.8	21.0	21.7	78	78	82	118	60

See footnotes at end of table.

TABLE 15. *Loss in weight and maximum penetration of wrought black ferrous pipe (1½ inch) and plate buried in 1932 and 1937*—Continued

(Average of two specimens)

Soil		Exposure		Loss in weight					Maximum penetration				
No.	Type	For pipe A, B, and N	For pipe S and plate A	Wrought iron pipe, hand puddled	Wrought iron pipe, mechanically puddled	Carbon steel pipe	Carbon steel pipe	Open-hearth steel plate	Wrought iron pipe, hand puddled	Wrought iron pipe, mechanically puddled	Carbon steel pipe	Carbon steel pipe	Open-hearth steel plate
	Material			A	B	N	S	A	A	B	N	S	A
		Years	*Years*	oz/ft^2	oz/ft^2	oz/ft^2	oz/ft^2	oz/ft^2	*Mils*	*Mils*	*Mils*	*Mils*	*Mils*
61	Sharkey clay	1.0	2.1	1.3	1.2	0.8	2.2	2.6	17	10	10	40	34
		5.5	4.0	5.6	4.9	4.0	5.0	5.4	41	37	[f]54	45	50
		7.6	8.9	6.3	6.4	5.6	4.2	4.3	44	50	63	48	90
		9.5	11.2	6.4	5.7	5.8	6.9	7.3	61	[f]86	[f]96	58	103
		14.4	12.7	10.2	11.9	10.0	7.5	8.1	84	82	88	64	85
62	Susquehanna clay	1.9	2.1	3.0	4.0	4.1	3.2	2.8	49	70	62	40	34
		5.5	4.0	4.0	4.0	4.7	4.3	3.7	54	56	66	56	47
		7.6	8.9	6.0	6.0	5.3	5.3	4.2	69	78	71	68	59
		9.5	11.2	7.8	9.4	6.6	6.0	5.0	[f]72	[f]101	[f]87	72	77
		14.3	12.7	8.3	7.1	7.9	6.8	5.9	74	65	101	79	84
63	Tidal marsh	2.0	2.1	3.0	2.6	3.8	2.7	3.6	28	16	15	24	18
		5.6	4.0	3.1	2.4	4.5	9.2	[d]6.2	22	37	36	38	[d]26
		7.7	8.9	3.4	3.5	7.1	10.7	[d]8.9	64	39	70	80	[d]36
		9.6	11.2	8.5	4.2	[f]9.0	12.2	16.9	100	[f]55	54	94	48
		14.4	12.6	[f]10.1	[f]6.8	9.6	18.5	16.5	74	80	61	126	44
64	Docas clay	1.9	2.1	11.4	13.3	12.6	8.7	7.1	102	118	130	80	44
		5.2	4.0	22.1	23.1	25.3	6.0	7.4	129	110	154+	67	78
		7.3	9.0	34.4	35.4	35.6	4.7	7.5	144+	145+	154+	80	87
		9.2	11.2	[g]16.0+	[g]18.4+	D	12.4	[f]19.0	120+	145+	154+	118	156+
		14.2	12.8	[g]38.3+	[g]18.4+	D	[f]17.2	18.6	145+	145+	154+	122	188+
65	Chino silt loam	1.9	2.1	8.0	6.2	7.4	4.3	4.6	54	66	40	50	47
		5.3	4.0	7.4	7.2	10.3	4.6	5.3	91	87	74	59	51
		7.3	9.0	9.0	8.8	13.7	7.0	7.2	110+	106	83	65	75
		9.2	11.2	13.6	11.4	12.9	6.2	6.1	102	110	112	84	79
		14.2	12.7	10.4	9.2	13.0	7.2	8.2	98	98	86	98	91
66	Mohave fine gravelly loam	1.9	2.1	8.6	7.8	7.7	9.2	8.3	88	82	66	145+	86
		5.3	4.0	10.2	11.3	15.1	12.3	16.8	85	106	154+	145+	188+
		7.4	9.0	11.6	11.1	14.3	[f]8.1	4.6	110	140+	154+	78	66
		9.2	11.2	[d]5.8	10.0	18.6	16.3	[f]17.7	[d]88	130+	154+	145+	188+
		14.2	12.7	20.3	[g]17.2+	D	[f]20.3	19.9	142+	145+	154+	145+	188+
67	Cinders	2.0	2.1	8.6	11.4	21.5	40.0	12.0	100	98	154+	145+	46
		5.3	4.0	31.8	24.9	34.6	37.0	34.3	145+	145+	119+	145+	132+
		7.3	9.0	29.7	27.0	23.5	31.7	D	145+	145+	127+	145+	188+
		9.2	11.1	[g]15.2+	D	[g]58.4+	D	37.8	145+	145+	154+	145+	188+
		14.3	12.7	D	D	D	D	D	145+	145+	154+	145+	188+
70	Mereed silt loam	-------	2.1	-------	-------	-------	4.9	5.0	-------	-------	-------	50	86
		-------	4.0	-------	-------	-------	[f]9.7	10.6	-------	-------	-------	118+	188+
		-------	9.0	-------	-------	-------	13.4	17.9	-------	-------	-------	122	66
		-------	11.2	-------	-------	-------	24.5	24.0	-------	-------	-------	145+	188+
		-------	12.8	-------	-------	-------	21.3	25.7	-------	-------	-------	145+	188+

[a] +, one or more specimens contained holes because of corrosion.

[b] Data for 8 specimens.

[c] Data for 4 specimens.

[d] Data for 1 specimen. The other specimen was missing.

[e] D, both specimens destroyed by corrosion.

[f] Data for the individual specimens differed from the average by more than 50 percent.

[g] Data for 1 specimen. The other specimen was destroyed by corrosion.

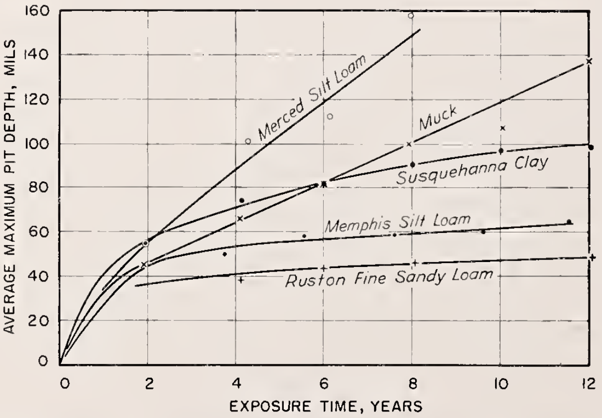

FIGURE 11. *Pit-depth–time curves for wrought ferrous pipe.*

TABLE 16. *Maximum pit depth and weighted maximum penetration of 1½-inch and 3-inch wrought black pipe specimens (buried in 1922) during the maximum exposure period*

(Average of two specimens, in mils)

Soil	Maximum exposure	Maximum penetration								Weighted maximum penetration [a]			
		1½-inch pipe				3-inch pipe				3-inch pipe			
		Open-hearth iron	Wrought iron	Bessemer steel	Bessemer steel (scale free)	Wrought iron	Open-hearth steel	Bessemer steel	Open-hearth steel with Cu	Wrought iron	Open-hearth steel	Bessemer steel	Open-hearth steel with Cu
	Material	a	b	e	y	B	K	M	Y	B	K	M	Y
	Years												
1	11.6	92	74	86	91	96	94	101	125	90	91	95	120
2	17.6	71	60	56	80	56	70	58	67	54	62	56	64
3	12.1	[b]118+	80	78	75	76	82	84	90	64	74	79	77
4	12.0	145+	78	79	82	87	108	84	152	74	103	71	146
5	17.5	76	54	51	42	66	91	62	71	62	82	58	68
6	17.5	27	30	26	21	32	30	23	32	30	27	20	29
7	16.9	52	40	50	61	74	67	48	56	57	55	47	51
8	11.8	100	76	74	67	83	93	110	127	80	86	68	109
9	16.9	69	51	64	65	68	58	68	109	58	52	66	95
10	12.0	50	52	40	42	48	56	54	66	45	47	48	53
11	11.9	99	75	76	70	90	70	92	88	84	66	80	74
12	17.5	70	60	72	64	76	56	86	85	70	54	83	81
13	5.9	49	97	67	85	59	67	75	71	56	70	70	64
14	11.8	120	109	130	131	127	97	135	161	117	90	129	154
15	17.6	78	66	62	58	65	82	72	62	60	69	66	60
16	12.0	92	84	94	120	84	86	96	90	80	76	94	88
17	17.0	42	38	42	39	43	50	48	57	41	46	44	51
18	11.7	71	72	71	67	64	70	62	80	60	61	60	76
19	11.6	62	71	71	66	66	85	65	68	62	78	64	68
20	11.6	67	52	72	64	45	80	56	65	44	72	55	57
21	6.0	71	52	60	63	60	59	66	60	56	54	60	55
22	11.6	72	66	66	78	68	65	66	71	66	63	63	65
23	12.1	145+	145+	145+	145+	158	159	163	216+	157	158	145	216+
24	17.2	28	24	21	26	30	28	36	28	31	26	30	30
25	17.0	75	50	48	42	54	62	57	57	51	54	53	54
26	16.9	70	66	67	64	72	66	78	80	69	64	77	75
27	17.6	42	58	69	60	74	92	84	78	68	84	78	59
28	9.6	145+	132+	137+	145+	167	183+	152	216+	160	180	142	216+
29	12.0	145+	97	136+	145+	134	216+	128	216+	117	194+	101	171+
30	17.0	54	51	58	51	62	64	76	66	60	63	72	63
31	17.7	50	44	43	53	42	90	66	49	40	83	64	47
32	11.7	58	55	46	50	59	86	62	94	58	81	58	90
33	11.7	130+	98	92	104	112	117	115	111	103	113	102	106
34	12.0	82	48	84	94	71	73	77	104	66	68	73	101
35	17.5	32	54	40	17	36	38	69	97	31	24	57	54
36	17.7	56	54	55	48	50	60	50	57	50	59	48	53
37	12.0	76	71	89	74	80	72	95	127	73	69	91	120
38	17.2	52	34	28	36	37	38	42	35	34	33	36	31
39	12.0	77	56	50	60	69	72	94	106	60	67	81	98
40	12.0	139	101	87	82	70	99	96	92	67	95	87	88
41	17.4	122	94	92	101	86	72	101	80	81	71	94	77
42	12.0	94	92	113+	111+	96	129	103	116	94	122	98	106
43	12.0	94	102+	100	105	138	136	119	155+	131	126	102	135+
44	11.6	87	56	63	69	65	72	82	88	62	54	77	79
45	11.7	143	114	138	117	118	138	128	158	111	135	126	150
46	12.0	80	95	108+	118+	82	68	136	134	77	60	115	127
47	17.4	42	53	37	57	51	40	48	46	48	38	47	44
	Average	81	70	73	75	75	83	82	95	70	78	75	87

[a] The maximum penetration and the weighted maximum penetration for the 1½-inch pipe have the same value.

[b] A plus (+) indicates that 1 or both specimens were punctured by corrosion.

corrosion. Furthermore, it is observed (tables 13, 14, and 15) that in some soils all materials corroded much more seriously than in other soils. It is evident, therefore, that the chief causes of corrosion of the commonly used wrought materials are associated with soils or soil conditions. The similar corrosion of specimens of different wrought materials exposed to the same soil is shown in figure 12, and figure 13 illustrates the variation in the corrosiveness of different soils with respect to the same material.

Effect of Environment. It was observed in inspecting underground pipelines and specimens from the NBS tests, that corrosion may take widely different forms, from the production of sharp isolated pits to a uniform attack of the metal surface as illustrated in figure 13. It will be observed that in specimen 1 there is very little pitting, although practically the entire surface has been attacked, whereas in the specimens in the lower row, pitting is especially pronounced and the corroded areas are relatively small.

The variation in the type of corrosion on the same steel that may occur in soils is exhibited in figure 14, which illustrates corrosion patterns on Bessemer steel specimens, ranging from a uniform attack of the metal surface without pitting (14–1) to a highly localized attack in the form of deep,

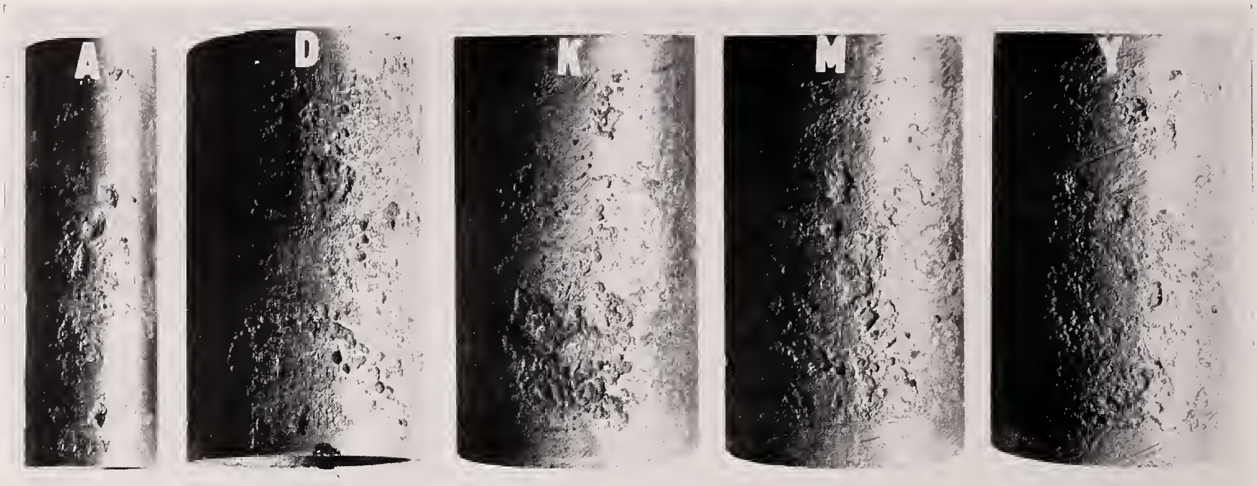

Figure 12. *Different wrought materials exposed to Hempstead silt loam for approximately 12 years.*

Note similarity of corrosion patterns of the different metals. A, Open-hearth iron; D, wrought iron; K, open-hearth steel; M, Bessemer steel; Y, open-hearth steel with 0.2 percent of copper.

Figure 13. *Open-hearth steel exposed for approximately 12 years to different soils.*

1, A poorly drained silt loam; 2, Ontario loam; 3, Susquehanna clay; 4, tidal marsh; 5, muck; 6, Allis silt loam; 7, Montezuma clay adobe; 8, Merced silt loam containing alkali. Note the differences in the effects of the different soils on the same material.

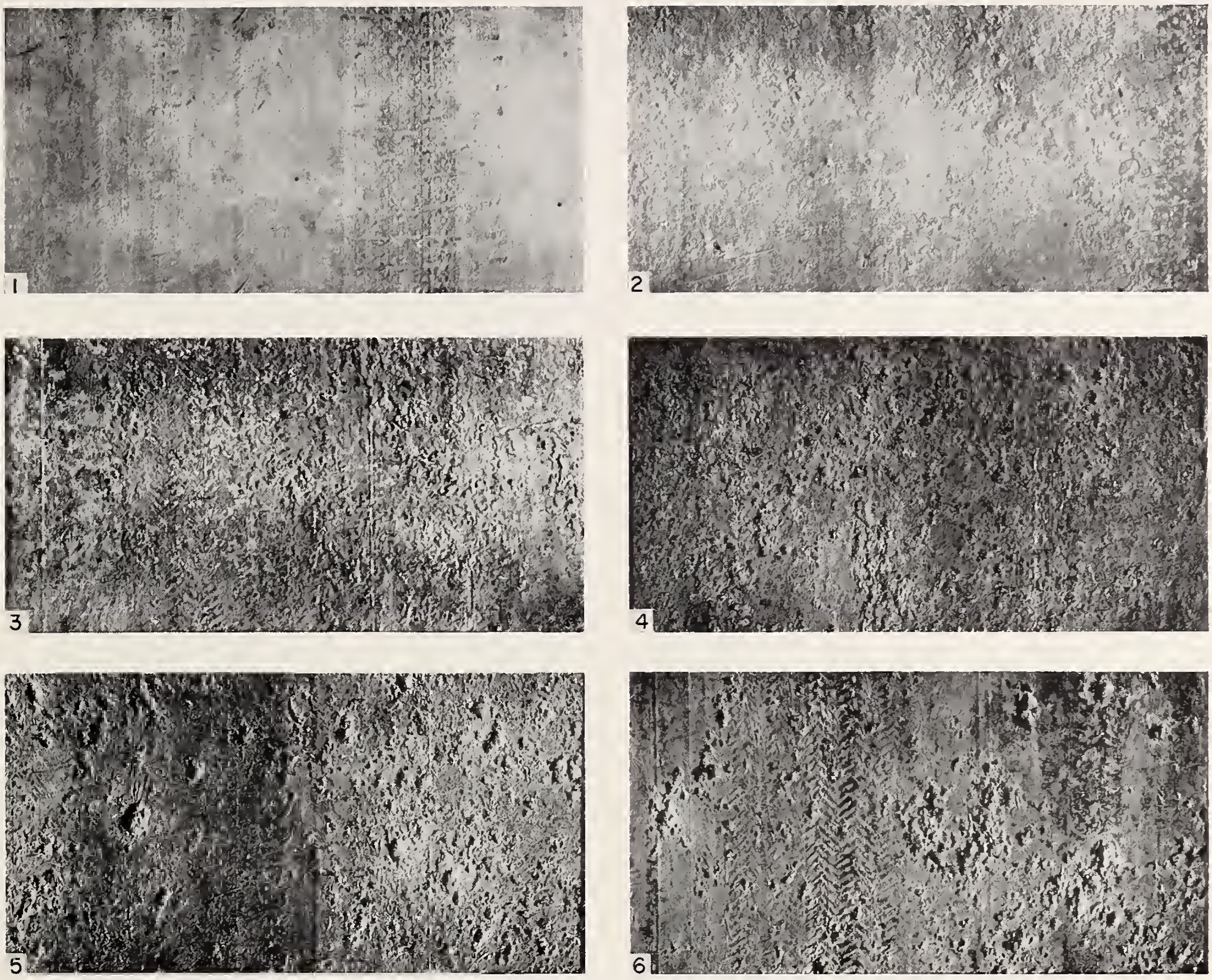

FIGURE 14. *Types of corrosion shown by the same Bessemer steel specimens in various soils.*
See table 17 for identification of soils and corrosion data.

well-marked pits (14–6). It will especially be noted from table 17, which contains the essential data relative to figure 14, that the maximum depths of pits range from 3 to 107 mils, even though the weight of metal lost is about the same for each specimen. Accordingly, the pitting factor, defined as the ratio of the maximum depth of pit to the average penetration, varies from 1 to 25.5.[5]

The fact that the plain ferrous specimens removed from any one soil exhibit essentially the same corrosion pattern, regardless of the nature of the material, further suggests that the physical or chemical properties of the soil control the character of corrosion of these materials.

The relation of other soil characteristics to the pitting factor was discussed by Denison and Hobbs [107], who observed that the pitting factors are roughly proportional to the ratio of the uncorroded to the corroded areas of a pipe. They also observed that the pitting factors of wrought materials in typical acid soils tended to become less with increased exposure and became approximately constant after about 8 years of exposure, i.e., the ratio of the rates of average to maximum penetration remained the same.

An empirical equation based upon the pit-depth measurements of the wrought ferrous specimens given in table 13 afforded a means for defining the corrosiveness of soils [106,147]. By plotting the logarithm of the average maximum pit depth of

TABLE 17. *Variation of maximum pit depth and pitting factor after similar periods of exposure*

Identification (fig. 14)	Soil		Loss in weight	Average penetration	Depth of maximum penetration [a]	Pitting factor [a]
	No.	Type				
			oz/ft²	*Mils*	*Mils*	
1	47	Unidentified silt loam	2.1	3.2	3	1
2	27	Miller clay	3.7	5.7	36	6.3
3	20	Mahoning silt loam	3.0	4.6	34	7.4
4	16	Kalmia fine sandy loam	4.2	6.5	60	9.3
5	3	Cecil clay loam	3.4	5.3	63	11.8
6	14	Hempstead silt loam	2.9	4.4	107	24.5

[a] See appendix 3 for methods of calculating the average penetration and pitting factor.

---

[5] See appendix 3 for definitions and methods of computing the average penetration and pitting factor.

equivalent 3-in. specimens (fig. 6) against the logarithm of the time, approximately linear relationships were obtained, that is, they conformed in general to the equation

$$P = kT^n, \qquad (1)$$

where P = depth of the deepest pit at the time, T, and k and n are constants. Taking logarithms of both sides,

$$\log P = \log k + n \log T. \qquad (2)$$

Hence n is the slope of the line, and $\log k$ the intercept on the $\log P$ axis.

The values n and k were calculated by averaging the pit-depth measurements for all the materials shown in table 13, taking the 1½-in. specimens in pairs to obtain equivalent areas. Thus for each site and for each exposure period, the average represented the best value of the deepest pit on an area of 0.4 ft^2. These values were analyzed by least squares to find the best relation between log pit depth and log time, in accordance with eq (2). It may be shown that the minimum percentage error in k is obtained if this is calculated for the mean of the exposure times, 5.3 years. Calculation of the value of $k_{5.3}$ rather than the value of k, necessitates modification of the equation connecting pit depth with time to read as follows:

$$P = k_{5.3}\left(\frac{T}{5.3}\right)^n. \qquad (3)$$

The standard error of estimate (standard deviation of the mean) of the values for n and $k_{5.3}$ were calculated according to the method of Ezekiel [148]. The values of $k_{5.3}$ and n for the individual soils are given in table 18.

Except for soils 12, 13, 26, and 30, in which the standard deviations are so large that the constants have little or no significance, the values of the constants, $k_{5.3}$ and n, can be fixed with fair precision. The magnitude of the standard deviations is in general due to the failure of one or two points on the pit-depth–time curves to conform to the tendency shown by the other points.

TABLE 18. *Mean values of constants a, k, and n and their standard errors*

Soil		Number of removals	$k_{5.3}$ mils on 0.4 ft^2 at 5.3 yr	$\sigma_{k_{5.3}}$	n	σ_n
No.	Type					
1	Allis silt loam	6	58.5	2.7	0.49	0.06
2	Bell clay	5	45.4	2.2	.34	.08
3	Cecil clay loam	6	68.8	2.3	.17	.05
4	Chester loam	5	51.6	6.4	.59	.17
5	Dublin clay adobe	5	37.0	3.0	.47	.13
6	Everett gravelly sandy loam	5	21.7	1.1	0	.05
7	Maddox silt loam	4	31.1	2.0	.46	.07
8	Fargo clay loam	6	64.4	0.9	.32	.07
9	Genesee silt loam	5	44.0	5.4	.16	.15
10	Gloucester sandy loam	5	37.2	3.2	.42	.13
11	Hagerstown loam	6	63.2	2.4	.05	.05
12	Hanford fine sandy loam	4	51.2	14.0	.13	.73
13	Hanford very fine sandy loam	3	63.7	7.8	.18	.20
14	Hempstead silt loam	6	85.5	4.5	.48	.07
15	Houston black clay	5	51.4	3.6	.32	.11
16	Kalmia fine sandy loam	6	66.0	3.7	.32	.13
17	Keyport loam	5	33.1	1.9	.19	.07
18	Knox silt loam	6	46.0	5.8	.18	.12
19	Lindley silt loam	6	51.5	2.6	.36	.06
20	Mahoning silt loam	6	34.4	2.7	.42	.09
21	Marshall silt loam	3	55.7	3.1	.60	.07
22	Memphis silt loam	6	57.7	1.1	.21	.03
23	Merced silt loam	[a] 5	107.3	2.9	.51	.04
24	Merrimac gravelly sandy loam	5	22.7	1.6	.11	.09
25	Miami clay loam	5	40.8	2.0	.29	.06
26	Miami silt loam	5	45.7	7.1	.41	.22
27	Miller clay	5	38.1	1.6	.65	.08
28	Montezuma clay adobe.	[a] 4	86.0	13.2	.92	.22
29	Muck	[a] 6	92.0	2.0	.60	.03
30	Muscatine silt loam	5	32.1	7.0	.53	.26
31	Norfolk fine sand	5	40.4	2.0	[b] −.13 (0)	.08
32	Ontario loam	6	44.8	2.6	.33	.07
33	Peat	6	56.4	7.1	.74	.16
34	Penn silt loam	6	41.4	5.0	.55	.17
35	Ramona loam	5	26.5	1.3	.25	.08
36	Ruston sandy loam	5	45.4	0.9	.14	.03
37	St. John's fine sand	6	64.8	3.7	.30	.09
38	Sassafras gravelly sandy loam	5	27.5	0.4	.23	.02
39	Sassafras silt loam	6	47.4	2.4	.51	.07
40	Sharkey clay	6	60.9	3.9	.50	.10
41	Summit silt loam	5	52.3	2.8	.32	.06
42	Susquehanna clay	[a] 6	84.7	0.4	.30	.006
43	Tidal marsh	[a] 6	83.2	4.0	.47	.06
44	Wabash silt loam	5	58.5	0.4	.30	.009
45	Unidentified alkali soil	6	54.3	8.6	.78	.16
46	Unidentified sandy loam	6	77.8	5.2	.17	.09
47	Unidentified silt loam	5	20.1	1.2	.32	.08

[a] In these cases, because the pipe was penetrated, the pipe wall thickness was used in calculating k and n so that the value of n as given is slightly less than the correct value.

[b] Since a negative slope on a log pit depth-log time curve has no physical significance, the value for n in parenthesis is preferred.

In order to test the possible relation between the slope of the line in the log pit-depth–log time equation and the aeration of the soil, the soils at the test sites were arranged in four groups according to the degree of aeration for comparison with the values of n. Aeration depends largely on drainage, which is indicated by topographic features, average height of the water table, texture of the soil, degree of mottling, the depth at which mottling appears, and the depth at which the specimens were placed. The essential difference in classfying soils according to drainage rather than aeration is that the latter allows the degree of rainfall and surface run-off to be considered. Thus, because of deficiency of rainfall in arid and semiarid regions, soils that are usually poorly drained might in such regions be well aerated. Similarly, in regions of higher rainfall a soil occupying a slope would absorb less moisture and consequently be better aerated than a soil of the same physical properties but situated in a level area. In table 19 the soils at the test sites are arranged in four groups according to the degree of aeration. The values of n and its standard error (σ_n) for the individual soils and as averages of the four groups are also shown.

Before considering the values of the constant, n, as affected by aeration, certain properties of the soils in the four groups should be noted. The soils classified as having good aeration (group I) include the following classes: (1) Coarse sands or sandy loams, such as soils 6, 12, 24, 31 and 36; (2) light-textured silt loams, such as soils 18, 22, 32, and 35; (3) porous loams or clay loams which are thoroughly oxidized to great depths, soils 3 and 11. No mottling is to be observed throughout the soil profile and the water table is very low. The soils

Table 19. *Classification of soils according to aeration and values of the time constant, n*

Good aeration			Fair aeration			Poor aeration			Very poor aeration		
Soil	n	σ_n	Soil	n	σ_n	Soil	n	σ_n	Soil	n	σ_n
3	0.17	0.05	9	0.16	0.15	1	0.49	0.06	28	0.92	0.22
6	0	.05	10	.42	.13	2	.34	.08	29	.60	.03
11	.35	.05	14	.48	.07	4	.59	.17	33	.74	.16
12	[a].13	.73	16	.32	.13	5	.47	.13	43	.47	.06
13	[a].18	.20	19	.36	.06	7	.46	.07	----	----	----
18	.18	.12	23	.51	.04	8	.32	.07	----	----	----
22	.21	.03	25	.29	.06	15	.32	.11	----	----	----
24	.11	.09	26	[a].41	.22	17	.19	.07	----	----	----
31	0	.08	37	.30	.09	20	.42	.09	----	----	----
32	.33	.07	41	.32	.06	21	.60	.07	----	----	----
35	.25	.08	42	.30	.006	27	.65	.08	----	----	----
36	.14	.03	----	----	----	30	.53	.26	----	----	----
38	.23	.02	----	----	----	34	.55	.17	----	----	----
44	.30	.01	----	----	----	39	.51	.07	----	----	----
46	.17	.09	----	----	----	40	.50	.10	----	----	----
						45	.78	.16	----	----	----
						47	.32	.08	----	----	----
Number of observations		13		10			17			4	
Mean $\overline{X}$		0.19		0.35			0.47			0.68	
Standard error		0.03		0.03			0.04			0.10	

[a] Value of n not included in average.

of fair aeration might be considered well-drained soils in an agricultural sense, that is, no artificial drainage would be required. These soils are generally silt loams or sandy loams usually characterized by slight mottling in the lower part of the profile and a low-water table. The poorly aerated soils are, as a class, soils of heavy texture (clay loams and clays), which would require artificial drainage if used for growing crops. The soils generally occupy flat areas, mottling occurs close to the surface, and the water table is at about the depth at which the specimens were placed. The very poorly aerated group includes those soils in which the water table is either at the surface, soils 29, 33, and 43, or which, by reason of the nature of the colloidal material they contain, are extremely impermeable, soil 28.

It is seen from table 19 that the values of the time constant, *n*, are determined largely by the aeration of the soil, the better the aeration of the soil, the smaller is the value of *n*. Thus the period of exposure has a much greater effect on the depth of pits in poorly aerated soils than in soils of good aeration, in fact, in a few well-aerated soils, such as 6 and 31, in which the slope is nearly zero, the maximum depth of pit is reached during the initial period of exposure.

Because the change in pit depth with time may vary from complete cessation of pitting after the initial period of exposure to a rate that is proportional to time, it would not be possible to predict the life of an underground steel structure from measurements of depths of pits made after some short period of exposure, such as 1 or 2 years. This is illustrated by data in table 20 for steel specimens exposed to a well-aerated soil, 11, and to a very poorly aerated soil, 33. Up to the 6-year exposure the depth of the deepest pit in a well-aerated soil is greater than that in a very poorly aerated soil, but at greater periods of exposure the deepest pit increases only slightly in the well-aerated soil, whereas in the poorly aerated soil the increase is roughly proportional to time.

Table 20. *Progress of corrosion of Bessemer steel in a well-aerated and in a poorly aerated soil*

Period of exposure	Depth of deepest pit	Average penetration
Soil 11, good aeration, $n=0.35$		
Years	*Mils*	*Mils*
1.4	40	0.7
4.0	53	1.8
6.0	54	2.4
7.8	52	2.1
10.0	59	2.4
11.9	68	3.2
Soil 33, very poor aeration, $n=0.74$		
1.0	22	0.7
3.7	33	5.1
5.8	45	8.0
7.6	86	14.0
9.7	102	14.4
11.7	135	19.6

Comparison of the values for *k* and *n* (table 18) shows that there is an inverse relationship between these two constants, which indicates that the higher the initial pitting the more rapidly does the rate decrease with time. A necessary corollary of this conclusion is that the measurements of the initial rate of pitting of wrought ferrous materials in soils cannot be used for predicting corrosion over a long period.

The effect of aeration on the shape of the pit-depth–time curve can be explained on the basis of the mechanism of corrosion. In well-aerated soils the rate of pitting, although initially great, falls off rapidly with time because in the presence of an abundant supply of oxygen, oxidation and precipitation of iron as ferric hydroxide occur close to the metal surface, and the protective membrane formed in this manner tends to decrease the rate of pitting with time. On the other hand, in poorly aerated soils, the initial rate of pitting decreases slowly, if at all, with time. Under such conditions the products of corrosion, remaining in the deoxidized state, tend to diffuse outward into the soil, offering little or no protection to the corroding metal. The slope of the pit-depth–time curve may also be affected by the corrosiveness of the soil. Thus, even in a well-aerated soil an excessive concentration of soluble salt would prevent the precipitation of protective layers of corrosion products and the rate of corrosion would not be decreased with time.

b. Low-Alloy Irons and Steels

The losses in weight and depths of maximum penetration, respectively, for the low-alloy wrought materials buried since 1932 for periods up to 14 years at 15 test sites are recorded in tables 21 and 22. Some specimens were in the form of pipe, others as plate, but in each case the exposed area of each specimen was approximately 0.3 ft.^{2} The condition of the low-alloy plate materials in typical soils is illustrated in figures 15 and 16. Each of the four environmental conditions based on aeration is

TABLE 21. *Loss of weight of low-alloy irons and steels in different soils*

(Average of two specimens, in ounces per square foot)

Identification		Material	Form	Average exposure	Aeration, test site number, and soil type														
Symbol	Year buried				Good aeration				Fair aeration			Poor aeration			Very poor aeration				
					Cecil clay loam	Hagerstown loam	Susquehanna clay	Chino silt loam	Docas clay	Mohave fine gravelly loam	Merced silt loam	Muck	Rifle peat	Sharkey clay	Acadia clay	Lake Charles clay	Carlisle muck	Tidal marsh	Cinders
				Soil---	53	55	62	65	64	66	70	58	60	61	51	56	59	63	67
				Years															
H	1932	Open-hearth iron; 0.52 Cu, 0.15 Mo----	Pipe---	2.0	2.8	2.0	3.7	7.5	16.1	8.8	------	2.9	4.9	[a] 0.9	6.2	2.3	------	2.5	7.8
				5.4	2.8	1.8	4.1	11.2	23.4	14.4	------	10.4	5.8	4.1	11.6	8.8	1.7	3.0	25.0
				7.4	3.9	3.4	5.0	14.7	34.6	14.3	------	12.2	4.5	4.9	11.6	13.0	2.6	4.8	13.8
				9.3	4.0	3.2	7.0	15.0	[f] D	14.6	------	14.5	13.7	5.6	------	[c] 18.9	2.4	6.3	D
				14.3	4.2	3.2	5.9	14.9	31.5	D	------	17.3	25.5	9.8	[d] 21.9	23.0	[d] 4.3	[c] 8.0	D
O	1937	Open-hearth iron; 0.45 Cu, 0.07 Mo----	Plate--	2.1	2.1	2.0	3.0	5.0	8.0	9.1	5.4	5.8	4.1	3.0	7.5	12.4	1.3	2.5	33.8
				4.0	2.9	2.8	3.6	5.0	8.0	11.6	11.0	9.9	7.4	5.6	------	13.8	2.9	4.7	33.2
				9.0	3.4	4.7	4.6	6.4	6.4	5.9	13.6	17.3	16.4	4.8	[g] 19.0	28.4	7.8	7.1	25.1
				11.1	3.7	3.7	5.0	5.3	13.3	16.4	22.9	17.0	21.1	7.9	------	48.2	8.3	11.6	29.3
				12.7	3.7	3.3	5.2	8.9	18.5	15.2	21.8	17.5	17.9	8.6	------	D	10.1	15.9	30.5
N	1937	Open-hearth iron, 0.54 Cu, 0.13 Mo----	---do---	2.1	2.0	1.9	3.0	4.6	8.0	7.4	4.8	5.5	4.8	2.7	7.2	13.0	1.4	3.0	20.9
				4.0	3.0	2.7	3.7	5.0	6.6	12.0	[e] 10.2	9.4	8.2	5.6	------	17.4	2.9	4.7	27.7
				9.0	3.3	4.6	4.7	6.7	5.8	[e] 6.9	15.0	17.0	14.5	4.6	[g] 18.8	33.7	7.6	7.2	21.9
				11.1	3.5	3.5	5.2	5.5	14.7	[e] 20.5	20.3	17.1	20.0	7.5	------	45.2	7.9	9.1	27.5
				12.7	3.8	3.4	5.3	8.1	18.0	15.1	20.0	17.0	20.8	8.6	------	D	7.4	11.7	29.5
MM	1939	Open-hearth iron; 0.51 Cu, 0.07 Mo----	---do---	1.9	[c] 2.3	.9	3.0	[c] 3.1	4.1	6.6	10.1	4.7	3.4	2.3	------	11.2	[c] 2.2	2.1	26.0
				6.9	3.6	1.8	5.2	4.9	[c] 20.2	12.4	11.0	12.7	8.4	6.4	[h] 24.1	45.8	4.6	6.7	27.9
				9.0	4.2	2.0	4.2	5.6	12.7	14.1	18.3	12.0	10.3	4.1	------	14.1	6.7	8.6	43.9
				10.6	4.2	2.1	6.4	6.1	10.3	15.6	D	12.6	14.0	7.8	------	17.8	7.6	10.4	52.3
				12.1	4.0	2.8	6.1	8.6	18.3	17.1	D	16.8	18.4	9.1	------	D	7.9	12.4	D
H	1941	Open-hearth iron; 0.47 Cu, 0.08 Mo----	---do---	5.0	3.7	2.0	3.4	5.7	20.4	17.5	6.0	5.0	5.3	3.0	------	6.3	5.5	3.5	D
				[j] 7.2	3.2	2.3	3.4	3.8	17.2	21.3	13.7	6.2	11.9	2.8	------	9.8	4.2	3.2	D
				8.7	3.6	2.8	4.6	4.2	22.8	13.0	14.3	6.1	12.2	2.7	------	8.3	6.2	2.3	D
				[j] 11.0	3.8	3.1	5.4	8.4	28.5	22.4	21.9	10.4	18.9	7.2	------	D	7.7	5.7	D
J [i]	1937	Copper-nickel steel; 0.95 Cu, 0.52 Ni---	---do---	2.1	.8	1.2	2.4	3.4	9.0	7.3	4.2	5.2	5.3	2.3	7.0	14.0	1.6	[c] 2.5	20.3
				4.0	1.3	1.8	3.3	5.0	6.0	10.4	[e] 7.6	10.6	8.6	4.8	------	19.2	2.6	3.5	35.1
				9.0	2.4	3.5	4.0	6.2	4.7	8.2	17.3	16.0	18.8	3.9	[g] 18.1	34.6	5.5	7.0	30.4
				11.1	2.8	2.6	5.4	4.7	17.7	17.8	22.7	17.6	20.1	6.7	------	49.5	8.2	7.8	28.2
				12.7	3.0	2.6	5.5	8.8	23.2	25.5	20.0	18.7	14.3	7.9	------	53.9	8.5	9.3	[c] 17.4
B [i]	1937	Nickel-copper steel; 1.96 Ni, 1.01 Cu----	---do---	2.1	.6	.8	2.1	4.9	6.6	8.9	3.9	6.2	6.4	2.0	7.4	13.0	1.4	2.3	23.0
				4.0	1.1	1.2	2.9	5.0	4.9	11.4	7.8	11.0	9.6	3.9	------	19.5	2.4	3.4	44.3
				9.0	2.8	2.6	2.9	7.6	7.1	3.1	18.4	17.7	24.1	3.2	[g] 20.2	31.2	7.2	8.9	D
				11.1	2.4	2.4	5.1	5.4	[e] 21.2	17.4	26.8	18.8	17.0	6.8	------	45.9	7.8	7.3	31.9
				12.7	3.2	3.1	8.2	10.8	14.4	19.8	29.6	20.8	21.0	7.6	------	D	9.4	11.7	39.0
D	1932	Nickel-copper steel; 2.47 Ni, 1.08 Cu----	Pipe---	2.0	2.2	1.7	2.7	5.0	6.5	5.1	------	3.5	4.9	1.2	4.7	3.3	------	1.6	16.4
				5.4	2.2	1.4	2.3	4.2	23.6	8.4	------	7.7	7.8	2.6	8.3	5.1	1.7	2.3	23.5
				7.4	2.6	2.2	3.7	6.1	37.6	9.2	------	9.7	3.8	3.8	9.6	9.7	2.9	4.1	27.5
				9.3	2.5	2.0	5.4	6.0	[c] 24.8	[e] 7.5	------	6.6	[e] 10.3	3.4	------	16.7	2.6	7.6	D
				14.3	3.4	2.4	3.6	6.9	25.5	14.6	------	13.1	17.4	6.2	[d] 15.9	14.5	[d] 3.7	10.4	D
Y	1941	Nickel-copper steel; 1.95 Ni, 1.04 Cu----	---do---	5.0	3.6	2.0	3.5	3.9	20.4	15.8	6.9	3.4	3.3	2.6	------	.6	4.6	1.2	D
				[j] 7.2	3.2	2.4	3.6	2.3	10.4	16.3	22.8	5.4	8.0	2.8	------	12.7	4.5	3.6	D
				8.7	3.8	2.8	4.6	2.8	15.4	28.5	21.0	6.8	8.2	3.2	------	13.3	6.8	1.8	27.6
				[j] 11.0	3.7	2.7	5.0	4.3	19.6	D	D	11.1	16.1	6.5	------	17.3	6.3	5.8	D
P	1941	Composite steel [k]------------------	Plate--	5.0	4.6	4.1	------	5.7	13.0	11.3	6.2	6.2	5.7	3.9	------	------	5.6	[c] 5.9	------
				[j] 7.2	3.2	3.9	3.5	4.1	11.0	12.6	18.2	7.3	12.1	3.3	------	------	5.8	5.0	D
				8.7	4.2	2.7	4.4	6.1	22.2	12.8	18.6	7.3	12.0	4.0	------	------	8.4	5.4	D
				[j] 11.0	5.1	4.3	4.8	7.2	D	16.4	D	13.4	15.1	4.6	------	------	9.1	6.2	D

C	1937	Cr-Si-Cu-P steel; 1.02 Cr, 0.42 Cu	do	2.0	1.5	1.3	1.9	4.4	4.9	6.9	5.4	4.4	5.8	2.4	9.2	12.5	1.1	2.4	17.7
				4.0	2.4	2.3	3.0	5.4	5.1	13.6	9.8	9.0	10.2	4.6	-------	20.8	2.5	4.1	13.9
				9.0	3.3	3.0	3.8	11.0	5.7	3.9	15.8	16.7	24.9	3.6	[g]19.6	28.1	7.8	[c]5.8	26.3
				11.1	2.9	2.7	4.7	9.9	10.6	[e]12.3	28.1	18.0	18.5	7.1	-------	44.0	7.5	7.9	25.2
				12.7	3.6	3.3	5.5	11.4	7.6	17.6	D	18.7	18.0	7.1	-------	D	8.5	7.8	D
NN	1939	2 percent chromium steel with Mo	Pipe	1.9	2.0	.9	2.6	3.9	3.9	9.0	12.8	5.9	4.1	2.0	-------	13.8	1.9	1.8	17.8
				6.9	[c]2.9	-------	[c]4.4	7.2	15.8	18.0	12.1	15.6	9.8	5.8	[h]27.1	46.0	4.0	5.0	23.5
				9.0	3.9	2.1	3.8	9.7	9.2	14.8	24.7	10.7	15.8	3.0	-------	14.2	5.0	7.5	25.8
				10.6	4.0	2.1	5.2	8.6	8.9	15.9	34.8	13.1	16.2	7.5	-------	19.3	6.0	6.2	29.6
				12.1	3.9	2.4	5.8	9.7	10.2	17.1	D	16.2	19.1	7.4	-------	D	6.6	7.1	D
KK	1937	2.01 percent chromium steel with 0.57 Mo	Plate	2.1	1.6	1.6	2.4	4.2	4.9	7.2	5.4	3.3	3.8	2.4	7.9	9.0	1.2	1.8	[e]18.1
				4.0	2.2	2.4	3.0	4.5	5.4	12.3	9.7	8.4	6.0	4.7	-------	14.5	2.5	3.1	16.4
				9.0	2.9	4.7	4.3	7.7	4.6	[e]6.0	13.5	12.9	13.8	4.1	[g]17.9	28.9	4.8	4.9	15.0
				11.1	3.0	2.8	3.8	7.3	8.5	[e]18.9	26.2	13.6	18.5	6.4	-------	34.3	7.9	5.3	20.4
				12.7	3.5	2.5	4.7	9.1	8.8	14.0	20.6	14.0	15.3	6.6	-------	34.2	7.3	6.7	13.7
P	1932	5.05 percent chromium steel	Pipe	2.0	1.4	1.2	2.4	7.2	14.0	7.7	-------	1.8	4.3	[a].8	6.4	2.5	-------	1.3	7.4
				5.4	2.0	1.2	2.6	9.7	24.1	13.9	-------	7.4	11.6	3.3	14.6	8.2	2.0	3.6	[e]27.4
				7.4	2.4	1.6	3.4	13.4	29.6	13.0	-------	11.7	2.9	5.0	10.7	18.0	2.3	4.2	7.5
				9.3	2.2	1.9	4.6	10.9	D	18.3	-------	13.9	15.6	5.1	-------	23.6	2.8	[e]5.8	27.9
				14.3	2.9	2.3	6.1	11.9	D	D	-------	20.6	27.4	9.1	[d]19.7	19.1	[d]3.4	10.0	17.5
D	1937	5.02 percent chromium steel	Plate	2.1	.9	.7	.7	2.3	4.5	5.8	4.9	4.1	4.5	.6	6.6	9.4	.4	1.8	17.1
				4.0	1.3	1.1	1.2	2.2	4.4	12.1	[e]10.0	5.9	6.6	1.6	-------	17.9	.9	3.8	18.1
				9.0	2.0	1.7	1.8	3.6	4.4	[e]3.5	19.1	7.5	14.8	1.1	[g]17.6	28.8	3.0	5.6	12.2
				11.1	2.1	1.7	2.2	2.8	10.0	[e]13.5	29.5	7.2	14.6	2.2	-------	43.1	4.8	6.0	7.9
				12.7	2.8	1.6	2.5	3.5	7.2	14.7	[b]22.8	7.8	17.2	1.9	-------	D	3.1	9.2	10.3
E	1937	4.67 percent chromium steel with 0.51 Mo	do	2.1	.9	.6	.7	2.5	4.2	7.9	5.2	3.9	4.1	.9	7.1	9.6	.4	1.7	12.2
				4.0	1.6	1.2	1.1	2.1	5.2	12.0	9.9	7.2	6.2	1.8	-------	16.3	.8	5.2	[e]11.7
				9.0	2.0	1.7	2.0	3.3	4.2	[e]5.2	19.5	6.4	13.2	1.4	[g]16.2	28.2	2.5	5.3	11.2
				11.1	2.3	1.6	2.3	2.1	10.2	[e]13.9	26.0	8.1	14.9	2.4	-------	36.8	4.9	5.4	5.7
				12.7	2.9	1.7	2.4	3.8	6.4	14.6	[b]18.1	9.5	15.0	2.6	-------	D	3.4	9.0	8.3
H	1937	5.76 percent chromium steel with 0.43 Mo	do	2.1	[b].8	.7	.7	2.5	5.9	8.4	5.0	3.5	4.6	.8	[b]8.3	[b]11.4	.2	[b]1.7	12.6
				4.0	1.4	1.1	1.3	2.2	5.0	14.5	10.2	[b]6.8	6.2	1.6	-------	14.3	.7	5.4	[e]12.9
				9.0	1.9	2.0	1.9	3.7	4.0	[e]5.0	17.6	6.1	14.2	[b]1.0	[g]16.7	-------	2.2	6.4	8.9
				11.1	2.0	1.8	2.4	2.1	9.0	12.2	29.1	-------	19.0	1.9	-------	[b]44.8	4.4	6.4	7.8
				12.7	2.7	1.8	[b]2.1	3.6	8.5	15.2	[b]31.0	[b]7.1	14.4	1.8	-------	[b]D	2.4	8.0	10.2

[a] Exposed for 1 year only.
[b] Data for 1 specimen. The other specimen was destroyed by corrosion.
[c] Data for 1 specimen. The other specimen was missing.
[d] Data for 4 specimens.
[e] Data for the individual specimens differed from the average by more than 50 percent.
[f] D, both specimens destroyed by corrosion.
[g] Data for 8 specimens.
[h] Data for 10 specimens.
[i] Specimens completely covered with a hard, black mill scale at the time of burial.
[j] Data for 3 specimens.
[k] Specimens composed of 3 layers as follows: outer layers—plain carbon steel, 0.036 in. thick; intermediate layer—2 percent nickel, 1 percent copper, 0.100 in. thick.

TABLE 22. *Maximum penetration of low-alloy irons and steels in different soils*

(Average of two specimens, in mils)

Identification		Material	Form	Average exposure	Aeration, test site number, and soil type														
Symbol	Year buried				Good aeration				Fair aeration			Poor aeration			Very poor aeration				
					Cecil clay loam	Hagerstown loam	Susquehanna clay	Chino silt loam	Docas clay	Mohave fine gravelly loam	Merced silt loam	Muck	Rifle peat	Sharkey clay	Acadia clay	Lake Charles clay	Carlisle muck	Tidal marsh	Cinders
				Soil	53	55	62	65	64	66	70	58	60	61	51	56	59	63	67
				Years															
H	1932	Open-hearth iron; 0.52 Cu, 0.15 Mo	Pipe	2.0	54	60	72	94	153	111	------	21	27	[a] 14	78	20	------	[c] 30	65
				5.4	65	75	86	97	137	[b] 145+	------	60	[c] 21	[c] 59	145+	65	5	[c] 49	118+
				7.4	92	68	78	117	145+	145+	------	145+	16	65	97	112+	[c] 10	104	80
				9.3	[c] 109+	93	[c] 86	106	145+	145+	------	96	[c] 61	82	------	[d] 145+	22	67	145+
				14.3	105+	89	84	104+	145+	145+	------	118+	106+	104+	[e] 105+	108+	[e] 38	[c] 74	145+
O	1937	Open-hearth iron; 0.45 Cu, 0.07 Mo	Plate	2.1	38	31	36	44	70	105	48	30	21	33	54	100	6	[d] 20	70
				4.0	74	44	38	65	75	84	[c] 97	48	28	66	------	116	20	[c] 48	55
				9.0	72	85	66	102	102	63	89	97	38	64	[f] 242+	174	66	74	80
				11.1	68	81	59	97	125	154	205+	106	55	74	------	243+	70	65	118
				12.7	64	76	51	116	143	145	224+	114	50	64	------	243+	58	60	140
N	1937	Open-hearth iron; 0.54 Cu, 0.13 Mo	do	2.1	38	29	36	32	72	132	51	32	20	32	66	77	6	33	50
				4.0	[c] 72	51	49	[c] 57	76	98	[c] 122	44	[c] 26	54	------	100	16	47	74
				9.0	53	92	56	52	70	62	92	102	35	70	[f] 171+	162+	68	50	58
				11.1	61	84	65	41	118	137	214+	118	43	78	------	250+	74	66	139
				12.7	59	67	68	44	129	141	179+	71	44	88	------	250+	54	78	152
MM	1939	Open-hearth iron; 0.51 Cu, 0.07 Mo	do	1.9	[d] 42	44	40	[d] 43	47	71	92	48	16	41	------	60	[d] 13	22	128
				6.9	86	49	42	107	[d] 84	144	80	116	40	62	[g] 124	160+	26	76	86
				9.0	94	62	47	98	88	156	197+	107	53	57	------	147+	67	81	250+
				10.6	98	69	55	78	62	122+	250+	90	34	66	------	187+	80	76	250+
				12.1	96	72	64	106	146	161	250+	121	62	87	------	250+	82	86	250+
H	1941	Open-hearth iron; 0.47 Cu, 0.08 Mo	Pipe	5.0	67	60	38	68	145+	145+	63	81	38	30	------	40	40	144+	145+
				[i] 7.2	77	52	41	96	138+	145+	135+	78	44	38	------	145+	51	108	145+
				8.7	74	56	38	145+	145+	121+	107	68	33	49	------	145+	72	100	145+
				[i] 11.0	78	66	48	132+	145+	145+	145+	96	59	78	------	145+	81	109	145+
J[h]	1937	Copper-nickel steel; 0.95 Cu, 0.52 Ni	Plate	2.1	38	34	38	49	60	108	48	26	25	53	63	82	6	14	58
				4.0	57	50	60	60	84	85	82	64	40	63	------	96	15	28	90
				9.0	38	77	69	58	76	67	136	72	57	84	[f] 148+	140+	33	40	102
				11.1	63	76	87	67	109	149	180	127	66	112	------	265+	39	48	218+
				12.7	68	72	93	79	132	172+	192	173	60	100	------	265+	47	50	[b] 133
B[h]	1937	Nickel-copper steel; 1.96 Ni, 1.01 Cu	do	2.1	26	34	51	45	66	38	50	36	20	62	54	100	6	22	64
				4.0	56	52	69	84	88	73	78	52	28	56	------	139	12	25	84
				9.0	45	88	70	75	80	51	142	97	73	80	[f] 161+	135	32	37	248+
				11.1	72	70	93	70	[c] 128	[c] 93	165	107	58	97	------	198+	41	46	164
				12.7	94	74	115	124	102	109	159	98	63	180	------	248+	56	55	138
D	1932	Nickel-copper steel, 2.57 Ni, 1.08 Cu	Pipe	2.0	23	32	42	41	98	58	------	23	[c] 28	[a] 12	68	20	------	[c] 24	101
				5.4	26	34	46	48	108	75	------	71	26	30	55	42	3	17	145+
				7.4	44	51	72	68	145+	141+	------	110+	14	51	70	145+	14	41	145+
				9.3	37	62	[c] 58	74	145+	[c] 96+	------	52	[c] 38	41	------	145+	14	[c] 70	145+
				14.3	42	71	68	73	145+	145+	------	106+	92	42	[e] 118+	145+	[e] 22	90	145+
Y	1941	Nickel-copper steel, 1.95 Ni, 1.04 Cu	do	5.0	56	64	57	96	210+	92	98	80	15	50	------	16	29	23	210+
				[i] 7.2	66	53	49	78	152	185+	178+	77	36	63	------	168+	39	47	210+
				8.7	77	58	46	86	160	210+	195+	82	29	76	------	172+	50	34	120
				[i] 11.0	80	61	59	95	195+	210+	210+	109	88	94	------	210+	48	61	210+
P	1941	Composite steel [j]	Plate	5.0	46	42	------	42	80	80	71	57	28	53	------	------	43	[d] 33	------
				[i] 7.2	52	54	39	63	116	87	101	61	26	55	------	------	48	54	172+
				8.7	56	50	43	73	172+	99	112	60	30	42	------	------	50	70	172+
				[i] 11.0	63	56	47	87	172+	172+	172+	101	42	60	------	------	58	81	172+

C	1937	Cr-Si-Cu-P Steel; 1.02 Cr, 0.42 Cu	do	2.0	40	40	36	50	42	56	66	71	23	30	58	52	14	31	58
				4.0	64	51	44	44	70	80	94	52	67	41	-------	77	42	41	47
				9.0	45	77	56	86	60	58	148+	98	112+	76	[f] 92	84	56	[d] 50	58
				11.1	68	79	83	95	86	[c] 119+	188+	110	118	67	-------	170+	53	61	147+
				12.7	[c] 78	92	88	105	62	128+	188+	106	107	56	-------	188+	64	58	138+
NN	1939	2 percent chromium steel with Mo	Pipe	1.9	65	59	40	51	40	145+	130+	46	18	42	-------	78	22	38	124+
				6.9	[d] 100	-------	61	98	106	145+	96	100	48	76	[g] 107	138+	23	48	145+
				9.0	104	88	68	121	97	145+	145+	103	63	72	-------	92	64	66	145+
				10.6	117+	108	82	132+	88	145+	145+	88	66	90	-------	77	85	72	145+
				12.1	132+	119	114	145+	112	145+	145+	113	76	87	-------	145+	94	70	145+
KK	1937	2.01 percent chromium steel with 0.57 Mo	Plate	2.0	40	26	26	56	56	78	102	29	19	31	35	38	22	20	58
				4.0	52	52	56	55	70	130+	94	42	26	35	-------	60	27	24	47
				9.0	69	84	58	76	70	80	110	67	57	76	[f] 110+	96+	34	41	58
				11.1	66	89	67	67	73	158+	175+	76	67	75	-------	175+	48	54	[c] 146+
				12.7	48	114	72	70	66	146+	175+	74	71	65	-------	175+	43	56	139+
P	1932	5.05 percent chromium steel	Pipe	2.0	46	42	52	68	124	86	-------	36	33	[a] 10	69	58	-------	43	64
				5.4	56	65	83	107	154+	133	-------	70	67	[c] 38	105	154+	32	87	112+
				7.4	57	88	125+	138+	154+	154+	-------	70	62	38	106	154+	[c] 20	89	65
				9.3	70	84	70	131+	154+	154+	-------	111	110	74	-------	136	20	136+	125+
				14.3	66	85	126	109+	154+	154+	-------	154+	154+	94	[e] 134+	154+	[e] 28	127+	137+
D	1937	5.02 percent chromium steel	Plate	2.1	43	34	32	37	48	59	87	48	32	30	62	66	18	62	53
				4.0	57	48	52	46	60	99	14	44	51	36	-------	95	39	70	68
				9.0	66	70	74	63	62	92	194	64	64	42	[f] 114	104	66	108	[c] 78+
				11.1	74	66	94	54	87	[c] 115	208	60	60	55	-------	188	71	118	[c] 109+
				12.7	84	56	113	66	154	126	[d] 158	68	69	42	-------	245+	55	136	81
E	1937	4.67 percent chromium steel with 0.51 Mo	do	2.1	36	34	26	39	46	81	79	39	26	26	50	62	20	46	46
				4.0	50	47	46	48	66	88	106	46	36	36	-------	80	26	73	57
				9.0	66	51	54	52	46	57	154	56	72	30	[f] 86	108+	55	88	48
				11.1	75	49	63	50	76	[c] 109+	172+	79	77	35	-------	165+	51	86	51
				12.7	98	54	74	70	74	[c] 124+	[d] 188+	88	74	38	-------	188+	46	98	60
H	1937	5.76 percent chromium steel with 0.43 Mo	do	2.1	[d] 32	30	32	50	46	72	88	48	26	24	64	[d] 60	18	[d] 42	56
				4.0	57	39	58	56	72	117	94	[d] 44	32	32	-------	90	33	72	52
				9.0	71	58	56	63	70	76	132+	52	76	[d] 38	[f] 109	-------	64	78	52
				11.1	77	51	65	56	78	141+	196+	-------	87	49	-------	203+	63	72	48
				12.7	82	54	[d] 70	68	90	152+	[d] 203+	[d] 60	100	44	-------	203+	55	108	55

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[a] Exposed for 1.0 year only.

[b] +, one or more specimens contained holes because of corrosion.

[c] Data for the individual specimens differed from the average by more than 50 percent.

[d] Data for 1 specimen. The other specimen was missing.

[e] Data for 4 specimens.

[f] Data for 8 specimens.

[g] Data for 10 specimens.

[h] The mill scale was not removed from these specimens.

[i] Data for 3 specimens.

[j] Specimens composed of 3 layers as follows: Outer layer—plain carbon steel, 0.036 in. thick; intermediate layer—2 percent nickel, 1 percent copper, 0.100 in. thick.

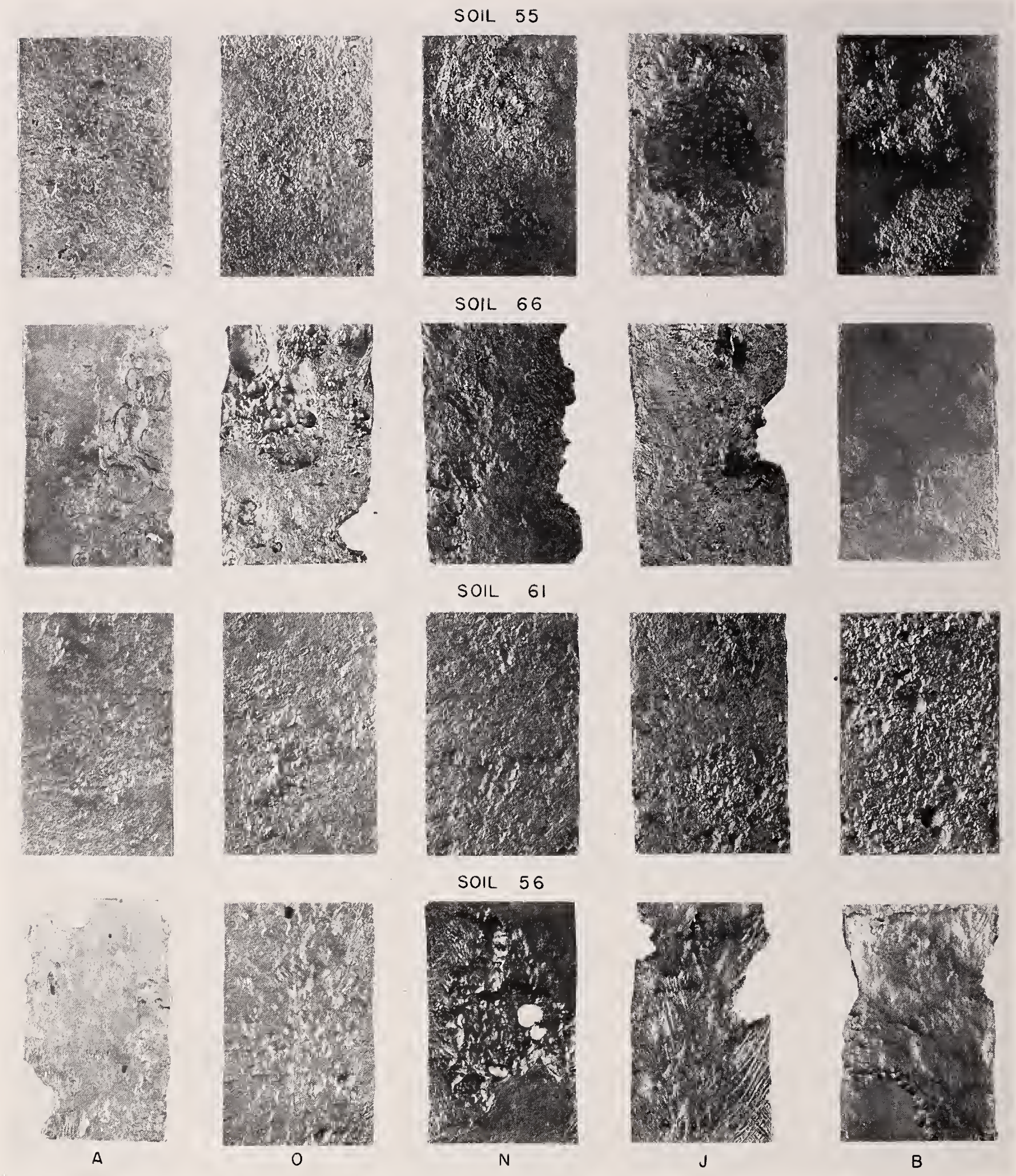

FIGURE 15. *Corrosion of plain steel, copper-molybdenum open-hearth irons, and nickel-copper steels in several soil environments.*

A, Open-hearth steel; O, open-hearth iron, 0.45 Cu, 0.07 Mo; N, open-hearth iron, 0.54 Cu, 0.13 Mo; J, steel, 0.95 Cu, 0.52 Ni; B, steel, 1.96 Ni, 1.01 Cu. Soil 55, well oxidized acid silt loam deficient in soluble salts; soil 66, fairly well aerated alkaline loam containing a high concentration of soluble material; soil 61, poorly aerated clay containing a moderate amount of soluble material; soil 56, very poorly aerated heavy clay containing a high concentration of soluble salts.

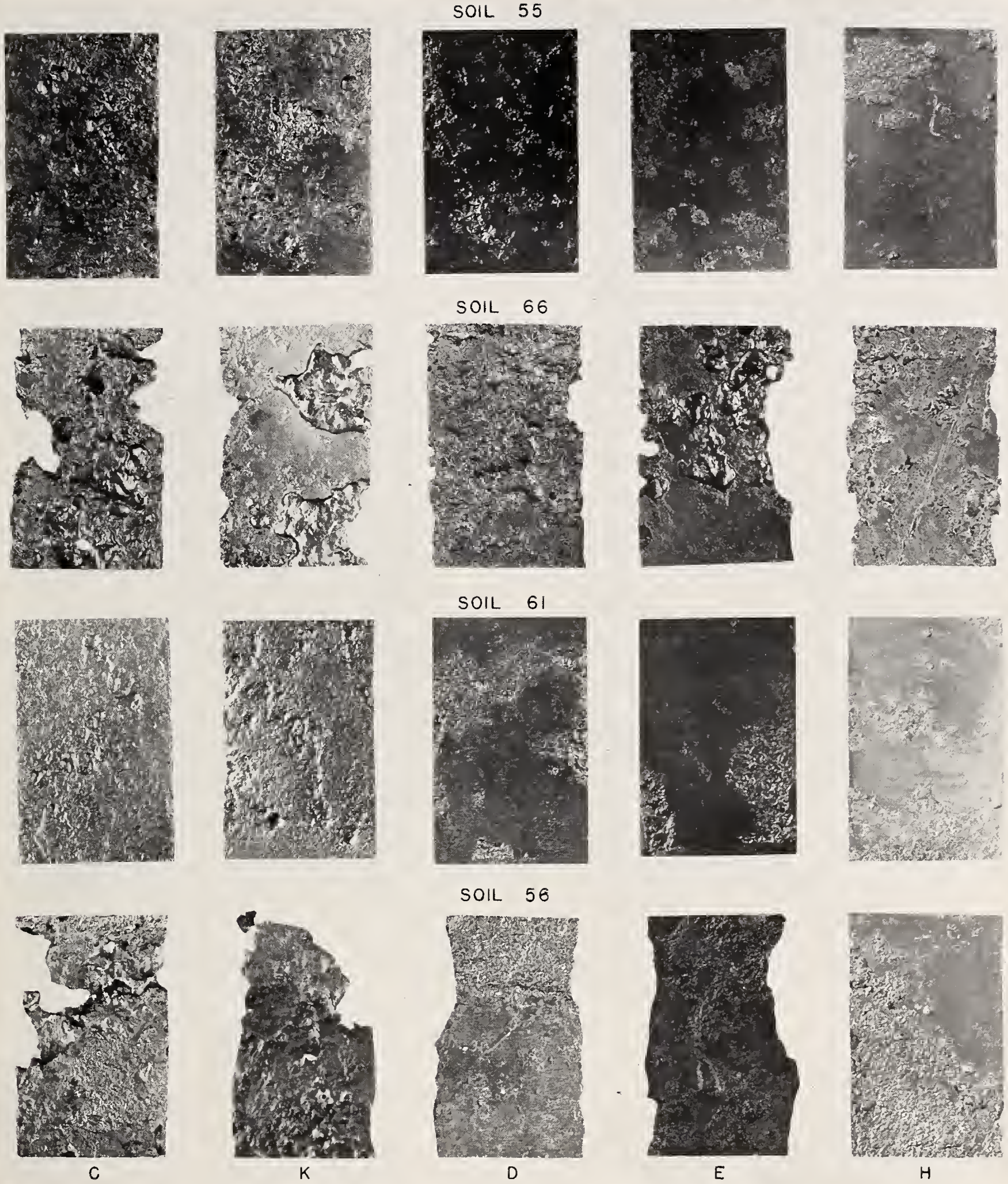

FIGURE 16. *Corrosion of chromium-containing steels in several soil environments.*

C, Cr-Si-Cu-P steel, 1.02 Cr, 0.42 Cu; K, steel, 2.01 Cr, 0.57 Mo; D, steel, 5.02 Cr; E, steel, 4.67 Cr, 0.51 Mo; H, steel, 5.76 Cr, 0.43 Mo. Soil 55, well oxidized acid silt loam deficient in soluble salts; soil 66, fairly well aerated alkaline loam containing a high concentration of soluble material; soil 61, poorly aerated clay containing a moderate amount of soluble material; soil 56, very poorly aerated heavy clay containing a high concentration of soluble salts.

represented as follows: Good aeration, soil 55; fair aeration, soil 66; poor aeration, soil 61; and very poor aeration, soil 56. Data for specimens of plain steel, wrought iron, and open-hearth steel, which were used as reference materials for comparison of the behavior of the low-alloy irons and steels, are reported in table 15.

Although the data in tables 21 and 22 indicate differences in the corrosion of the materials, statistical analysis of the data is needed to determine whether certain of these differences should not be ascribed to chance rather than to inherent differ-

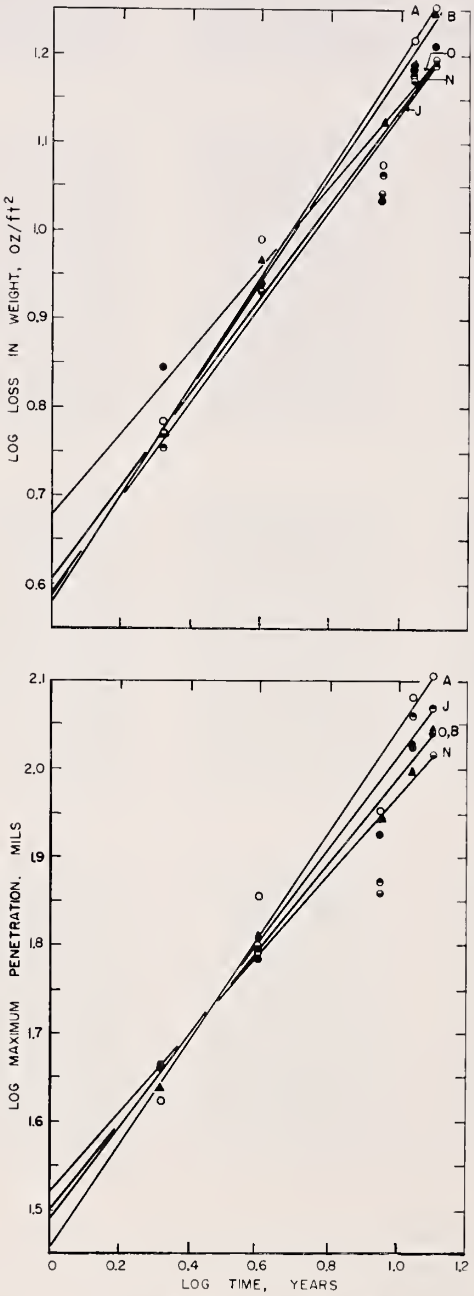

FIGURE 17. *Average loss in weight- and maximum-penetration-time curves for copper-molybdenum open-hearth irons and nickel-copper steels in 13 soils.*

A, Open-hearth steel; O, open-hearth iron, 0.45 Cu, 0.07 Mo; N, open-hearth iron, 0.54 Cu, 0.13 Mo; J, steel 0.95 Cu, 0.52 Ni; B, steel, 1.96 Ni, 1.01 Cu.

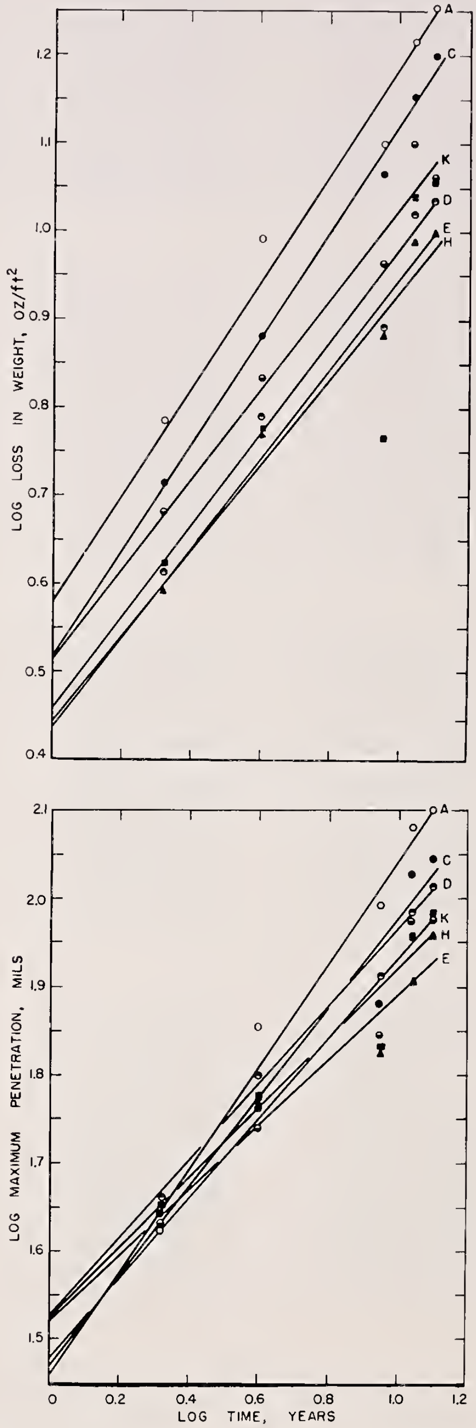

FIGURE 18. *Average loss in weight- and maximum-penetration-time curves for chromium and chromium-molybdenum steels in 13 soils.*

A, Open-hearth steel; C, Cr-Si-Cu-P steel, 1.02 Cr, 0.42 Cu; K, steel, 2.01 Cr, 0.57 Mo; D, steel, 5.02 Cr; E, steel, 4.67 Cr, 0.51 Mo; H, steel, 5.76 Cr, 0.43 Mo.

ences in corrodibility. As the first step in analyzing the data statistically, the progress of weight loss and pitting of each material was expressed by means of the equations

$$\log P = \log k + n \log T \qquad (4)$$
$$\log W = \log k' + u \log T. \qquad (5)$$

Equation (4) is identical with eq (2) of the preceding section, for expressing the relation between pit depth and time. By similar derivation, the linear equation expressing the relation between weight loss and time was obtained. Converting eq (4) and (5) to antilogarithms,

$$P = kT^n \qquad (6)$$
$$W = k'T^u, \qquad (7)$$

where P is the depth of the deepest pit at the time T, and W is the weight loss at time T.

Hence $n(u)$ is the slope of the line and $k(k')$ is the intercept on the $P(W)$ axis.

The over-all behavior of materials and the effect of the various alloying constituents on the corrosion of the iron and steel plate specimens in the soils is indicated by the weight-loss and pit-depth–time curves shown in figures 17 and 18, which conform to eqs (4) and (5). In preparing these curves, the values for weight loss and pit depth for each material in all of the soils, except 51[6] were averaged for each period of exposure. The logarithms of these average values were then plotted against the logarithms of the periods of exposure.

The constants of the equations, expressing the initial corrosion rate of the materials and the change in the rate with time, were calculated by the method of least squares for each material in each soil. By means of these constants, values of the average weight loss and pitting of each material in all of the soils were calculated for the maximum periods of exposure. These values, together with the constants of the equations and their standard errors, are given in table 23.

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[6] The data for the specimens in soil 51 were omitted because data were available for two periods only.

TABLE 23. *Calculated average values of weight loss and pit depth and constants of the weight-loss and pit-depth equations [a] for the low-alloy irons and steels after 13 years of exposure*

Identification	Material	Weight loss: Mean, $\overline{X}$ ($W_{T=13}$)	Standard error, $\overline{\sigma}$ ($W_{T=13\text{yr}}$)	Reduction in weight loss as compared with control A: $\overline{X}_1-\overline{X}_2$	Reduction in weight loss as compared with control A: Relative basis	t^b	Probability of the difference being due to chance	k'	$\overline{\sigma}_{k'}$	u	$\overline{\sigma}_u$
		oz/ft²	*oz/ft²*	*oz/ft²*	*Percent*		*Percent*	*oz/ft²*	*oz/ft²*		
A	Open-hearth steel	17.7	1.2	------	------	------	------	3.78	0.52	0.60	0.07
O	Open-hearth iron; 0.45 Cu, 0.07 Mo.	15.2	1.2	2.5	14	1.47	16	4.79	.75	.45	.08
N	Open-hearth iron; 0.54 Cu, 0.13 Mo.	15.2	0.8	2.5	14	1.74	10	4.02	.45	.52	.06
J	Copper-nickel steel; 0.95 Cu, 0.52 Ni.	15.6	.8	2.1	12	1.46	16	3.87	.37	.54	.05
B	Nickel-copper steel; 1.96 Ni, 1.01 Cu.	17.3	.6	0.4	2	0.30	77	3.93	.25	.58	.03
C	Cr-Si-Cu-P steel; 1.02 Cr, 0.42 Cu.	15.3	.6	2.4	14	1.79	10	3.30	.23	.60	.04
KK	2.01 percent chromium steel with 0.57 Mo.	12.0	.7	5.7	32	4.10	<1	3.27	.02	.51	.06
D	5.02 percent chromium steel	10.7	.6	7.0	40.	5.22	<1	2.85	.34	.52	.06
E	4.67 percent chromium steel with 0.51 Mo.	10.0	.5	7.7	44	5.92	<1	2.76	.28	.50	.05
H	5.76 percent chromium steel with 0.43 Mo.	10.1	1.6	7.6	43	3.80	<1	2.86	.29	.49	.16

Identification	Material	Maximum penetration: Mean, $\overline{X}$ ($P_{T=13\text{yr}}$)	Standard error, $\overline{\sigma}$ ($P_{T=13\text{yr}}$)	Reduction in maximum pit depth as compared with control A: $\overline{X}_1-\overline{X}_2$	Reduction in maximum pit depth as compared with control A: Relative basis	t^b	Probability of the difference being due to chance	k	$\overline{\sigma}_k$	n	σ_n
		Mils	*Mils*	*Mils*	*Percent*		*Percent*	*Mils*	*Mils*		
A	Open-hearth steel	127	9.3	------	------	------	------	28.8	4.2	0.58	0.07
O	Open-hearth iron; 0.45 Cu, 0.07 Mo.	110	5.0	17.3	14	1.64	12	31.4	2.9	.49	.05
N	Open-hearth iron; 0.54 Cu, 0.13 Mo.	102	7.7	25.1	20	2.09	2	33.2	5.0	.44	.08
J	Copper-nickel steel; 0.95 Cu, 0.52 Ni.	112	10.4	15.3	12	1.09	29	30.8	5.8	.50	.10
B	Nickel-copper steel; 1.96 Ni, 1.01 Cu.	110	3.6	17.1	13	1.72	10	31.1	2.0	.49	.03
C	Cr-Si-Cu-P steel; 1.02 Cr, 0.42 Cu.	107	7.0	20.2	16	1.74	10	29.3	3.9	.50	.07
KK	2.01 percent chromium steel with 0.57 Mo.	93	5.5	33.4	26	3.10	<1	30.3	3.6	.44	.06
D	5.02 percent chromium steel	100	3.0	24.4	19	2.50	2	33.5	1.9	.44	.03
E	4.67 percent chromium steel with 0.51 Mo.	86	4.2	41.1	32	4.03	<1	33.0	0.1	.37	.05
H	5.76 percent chromium steel with 0.43 Mo.	92	6.3	35.0	28	3.15	<1	33.5	4.6	.39	.07

[a] $W = k'T^u$, $P = kT^n$, where W is the weight loss at the time T, and P is the depth of the deepest pit at the time T.

[b] $t = \dfrac{\overline{X}_1 - \overline{X}_2}{\sqrt{\sigma_{\overline{X}_1}^2 + \sigma_{\overline{X}_2}^2}}$

In order to estimate the probability that the weight loss or pitting of each material was significantly different from the corresponding values for the reference material plain open-hearth steel, the standard *t*-test was applied, and from the calculated values of *t*, the probability of the differences due to chance alone was obtained [149]. The weight-loss and pitting data for the copper-molybdenum open-hearth irons O and N, and for the nickel-copper steels J and B, presented in figure 17 and in table 23, show that these alloys corroded slightly less than the plain steel A. However, the probability of the several observed differences is high on the supposition that they are due to chance alone.

The average depths of the deepest pits on these materials, given by the values of the constant k (y-intercept), indicate that the low-alloy steels had a greater initial pitting rate than the plain steel. However, as the exposure increased, the rate of pitting of the alloy steels diminished more rapidly than the rate for the plain steel, so that after 13 years the order of the materials was reversed.

The weight loss and pit depth data for the group of chromium and chromium-molybdenum steels, C, KK, D, E, and H, (fig. 18 and table 23) exhibit similar but somewhat greater effects of these alloying constituents than the copper-molybdenum and copper-nickel irons and steels. Chromium reduced the weight losses in a fairly regular manner, but increased the initial pitting rates of the steels. However, the rates of pitting of the alloy steels decreased more rapidly with time than the rate for plain steel.

The separate effects of chromium and molybdenum on the pitting of steel are difficult to determine because the chromium steels also generally contain molybdenum. It will be observed that steels C and D containing 1 and 5 percent of chromium, respectively, had pits of about the same depth. Within this range chromium alone in excess of 1 or 2 percent does not appreciably increase the resistance of the material to pitting. On the other hand, the influence of molybdenum in reducing pitting is quite definite because all of the chromium steels containing molybdenum, KK, E, and H, had shallower pits than the straight chromium steel D.

Microscopic examination reveals that there is a greater concentration of carbides around the grain boundries of steel E than those of steel D (fig. 19). Because this steel contains an appreciable amount of molybdenum, most of the carbon was probably combined with molybdenum, and the chromium remained in solution in the ferrite. This may account for the slightly improved resistance of steel E as compared with steel D.

Comparison of the average corrosion resistance of the different materials in all the soils reveals nothing concerning the behavior of these materials in any other soil or environment. Superior corrosion resistance of a material in any one environment might be obscured by inferior resistance in another. For comparison of the behavior of the low-alloy plate specimens under different environmental conditions, the corrosion data for the soils classified according to aeration (tables 21 and 22) were calculated on a relative basis for each material for all periods of exposure, the weight losses and pit depths of the reference steel A being taken as 100 percent. The averages of these values for all periods and for all soils in the same environmental groups are given in table 24. Because the data for soil 51 are incomplete, they were not included in calculating the relative values.

The relative corrodibility of the low-alloy irons and steels as measured by weight loss was not affected appreciably by differences in the aeration of the soils. However, the 4- to 6-percent-chromium steels were deeply pitted in all of the very poorly aerated soils, except cinders. These steels had higher initial rates of pitting than plain steel, but the rates decreased considerably with time in most of the soils. In the poorly aerated soils, however, this high rate of pitting continued throughout the exposure period, probably because conditions were not favorable to the formation of tubercles, which would have diminished the pitting rate. In contrast is the behavior of these steels in cinders (table 22 and fig. 20), where the initial

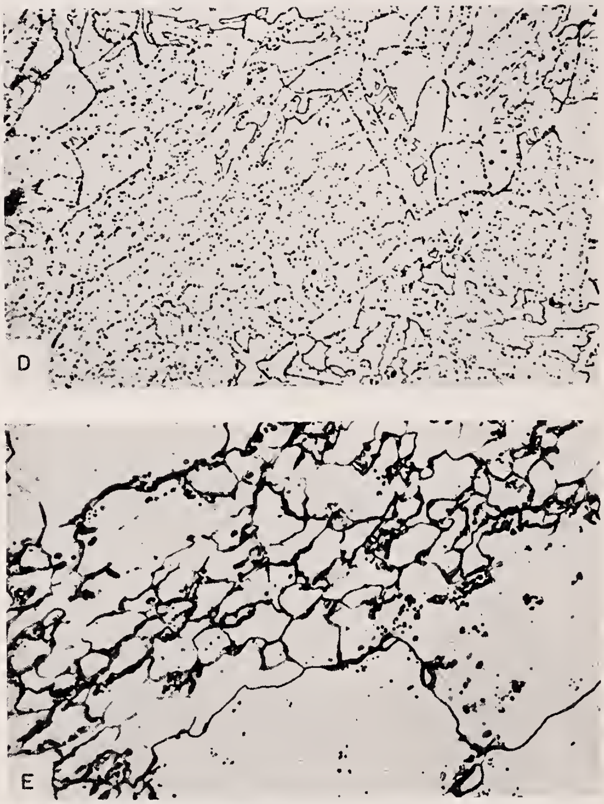

FIGURE 19. *Longitudinal sections of 4- to 6-percent-chromium-steel specimens.*

×500. D, 5.02-percent chromium; E, 4.67-percent chromium with 0.51-percent molybdenum.

Table 24. *Corrosion of low-alloy iron and steel specimens in soils classified according to aeration (maximum exposure 13 yrs)*

Identification	Composition of steel (percent)				Aeration of soils									
	Cr	Ni	Cu	Mo	Good	Fair	Poor	Very poor	Very poor cinders	Good	Fair	Poor	Very poor	Very poor cinders
					Average loss in weight [a]					Average maximum penetration [a]				
A	0.049	0.034	0.052	--------	100	100	100	100	100	100	100	100	100	100
O	.02	.15	.45	0.07	100	95	98	84	120	100	95	82	120	75
N	.02	.14	.54	.13	100	93	97	83	92	87	96	80	119	63
J	--------	.52	.95	--------	79	98	94	81	94	96	92	102	93	72
B	--------	1.96	1.01	--------	79	91	99	81	127	110	81	100	95	72
C	1.02	0.22	0.428	--------	94	83	95	76	80	101	84	116	115	64
KK	2.01	.07	.004	.57	90	82	80	63	66	97	91	78	103	60
D	5.02	.09	.008	--------	45	77	51	58	55	96	94	83	176	64
E	4.67	.09	.004	.51	46	79	53	56	40	84	83	78	149	54
H	5.76	.17	.004	.43	46	85	52	56	43	88	100	84	149	59

[a] Average for 5 periods of exposure, relative to open-hearth steel (A) = 100.

pitting of all the steels was about the same. The pitting of the plain steel continued at a high rate for the entire exposure period, but most of the pitting of the 4- to 6-percent-chromium steels occurred during the first 4 years of the test, there being only slight increases in pit depth of these steels after that time. This is even more marked in the case of the steels containing molybdenum in addition to chromium (E and H), in which there was practically no additional pitting after the first 6 years. The superior performance of the chromium steels in cinders is probably to be ascribed to the resistance that chromium steels offer to environments containing sulfides. The beneficial effect of chromium in steels from attack by solutions containing hydrogen sulfide has been demonstrated by Devine, Wilhelm, and Schmidt [150].

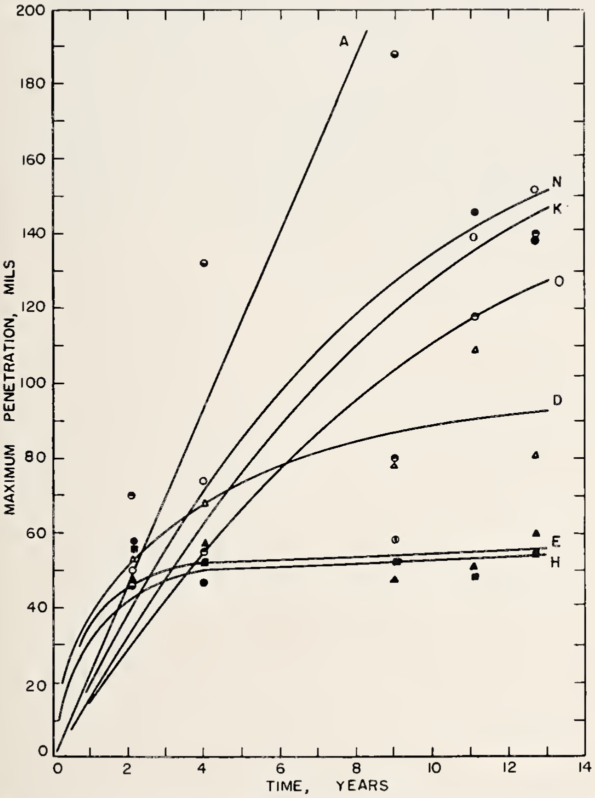

Figure 20. *Pit-depth–time curves of copper-molybdenum open-hearth irons, chromium, and chromium molybdenum steels in cinders.*

A, Open-hearth steel; N, open-hearth iron, 0.54 Cu, 0.13 Mo; K, 2 percent Cr-steel with Mo; D, 5.02 percent Cr-steel; E, 4.67 percent Cr-steel with Mo; H, 5.76 percent Cr-steel with Mo.

Steels O and N containing copper and molybdenum also show more resistance to pitting in cinders after 4 years of exposure than the plain steel, although to a lesser extent than the 4- to 6-percent-chromium steels. As a matter of interest, it may be noted that the addition of copper tends to increase slightly the loss in weight of steels in sea water but has little or no effect on pitting [151].

c. High-Alloy Steels

Corrosion data for the high-chromium and chromium-nickel steels, exposed for 14 years, are given in table 25, and the effects of composition on the corrosion of three of these steels in three soils are illustrated in figure 21. It is unfortunate that complete information concerning the rolling and heat treatment of the various steels is not available, because these factors may have played an important part in the corrosion of the materials. It is shown quite conclusively, however, that plain chromium steels are subject to severe pitting, and that steels containing 18 percent of chromium plus 9 percent of nickel are considerably more resistant than the straight chromium steels in these environments. Steels containing larger amounts of chromium and nickel, with and without molybdenum, were wholly resistant to corrosion.

The effect of up to 18 percent of chromium in steels in heavy, poorly drained clay soils is illus-

TABLE 25. *Loss in weight and depth of pits of high-chromium and chromium-nickel steels exposed for 14 years* [a]

M, Shallow metal attack, roughening of surfaces, but no definite pitting.
P, Definite pitting, but no pits greater than 6 mils.
+, One or more specimens contained holes because of corrosion.

Specimen	U[b]		V[c]		X		K		R		W[d]		Y[d]		CM		DT	
AISI type No.	410		430		430		304		304		302		309		316		---	
Number of specimens	5		5		2		2		2		5		5		2		2	
Composition:																		
C, %	0.065		0.070		0.12		0.08		0.05		0.093		0.144		0.07		0.07	
Mn, %	.38		.36		.42		.44		.46		.36		1.80		1.24		1.99	
Cu, %	---		.02		---		---		---		.02		0.02		---		1.07	
Cr, %	11.95		17.08		17.72		17.20		17.52		18.69		22.68		17.78		19.27	
Ni, %	0.48		0.09		0.29		8.95		8.85		9.18		12.94		10.96		22.12	
Mo, %	---		---		---		---		---		---		---		2.63		3.52	
Soil[e]	Loss in weight	Maximum penetration	Loss in weight	Maximum penetration	Loss in weight	Maximum penetration	Loss in weight	Maximum penetration	Loss in weight	Maximum penetration	Loss in weight	Maximum penetration	Loss in weight	Maximum penetration	Loss in weight	Maximum penetration	Loss in weight	Maximum penetration
	oz/ft²	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*
51	---	---	---	---	---	---	0.03	29+	---	---	---	---	---	---	0.009	M	0.004	0
53	---	---	---	---	---	---	.0009	0	---	---	---	---	---	---	.02	0	.03	0
55	0.0002	M	0.0001	0	---	---	---	---	---	---	0.0005	0	0.0003	0	.004	0	.001	0
56	---	---	---	---	---	---	.20	32+	---	---	---	---	---	---	.005	P	.0004	0
58	---	---	---	---	0.85	52	.002	0	0.0008	11	---	---	---	---	.0008	0	.0005	0
59	.0002	M	.001	M	---	---	.0007	0	---	---	.002	P	.001	P	.002	0	.001	0
60	5.4	37+	.17	16+	---	---	.0006	0	---	---	.003	M	.001	M	.006	0	.0007	0
61	---	---	---	---	---	---	.0004	P	---	---	---	---	---	---	.0004	0	0	0
62	---	---	---	---	.03	6	.0004	M	.003	6	---	---	---	---	.0002	0	.0001	0
63	---	---	---	---	.33	13	.06	P	.12	13	---	---	---	---	.001	0	.006	0
64	5.7	63+	1.4	63+	.34	48	.003	P	.04	7	.002	0	.0007	0	.002	0	.003	0
65	.46	62+	.74	61+	---	---	.01	16+	---	---	0	M	.00004	0	.0004	0	0	0
66	3.2	62+	2.3	62+	---	---	.0009	P	---	---	0	M	0	M	0	0	0	0
67	---	---	---	---	5.19	73	.0008	12	.002	8	---	---	---	---	.01	M	.009	0
70	---	---	---	---	---	---	---	---	---	---	---	---	---	---	.0001	0	.0002	0

[a] Specimens "CM" and "DT" were exposed to the soils for 13 yr. The remaining specimens were exposed 14 yr.

[b] Annealed at 1,400° F, pickled, lightly cold-rolled.

[c] Annealed at 1,600 F, pickled.

[d] Heated to 1,850° F, air quenched, pickled.

[e] See table 6 for names and location of soils.

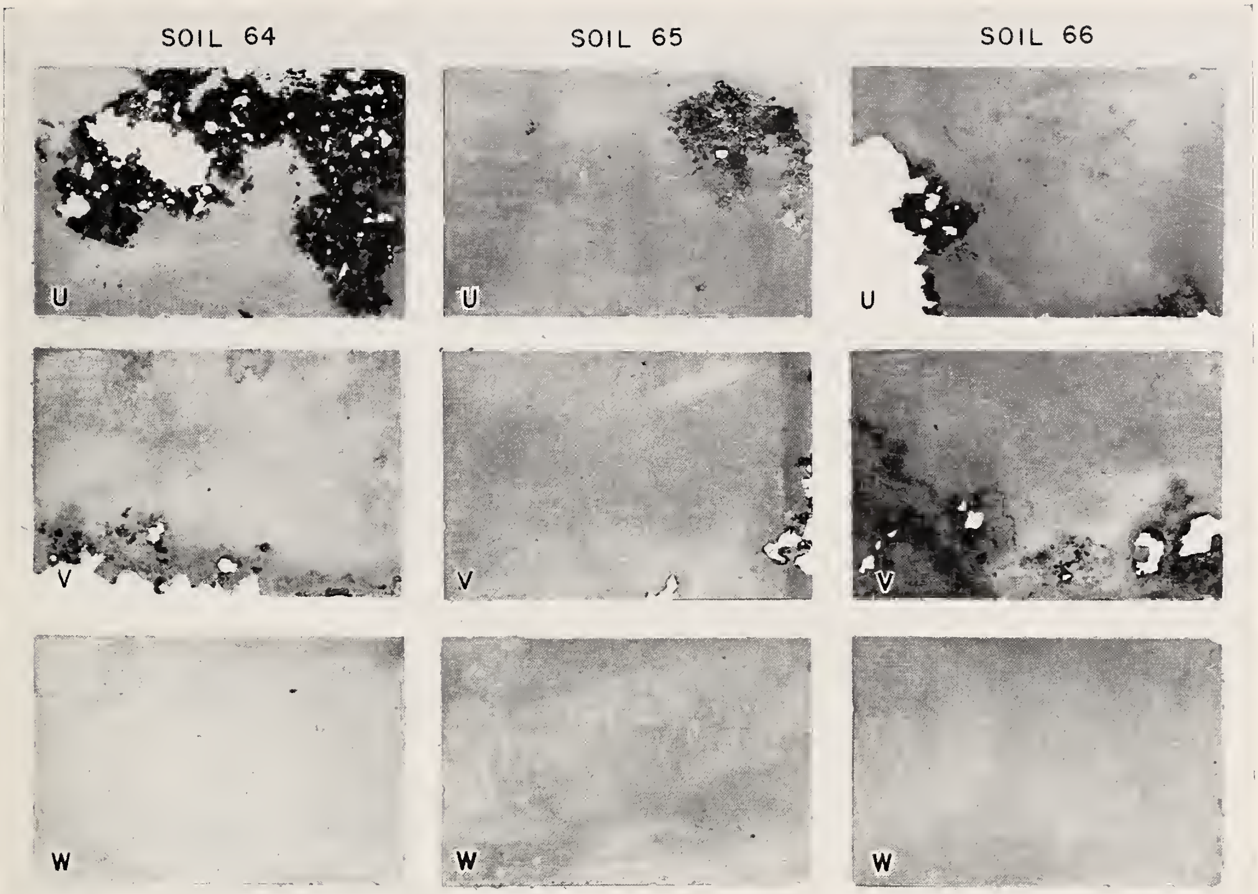

Figure 21. *Specimens of high-alloy steels after exposure for 14 years.*
U, 12-percent chromium steel; V, 18-percent chromium steel; W, 18-percent chromium, 9-percent nickel steel.

trated by the curves in figure 22. Although increasing the chromium content of steels causes a gradual decrease in weight loss throughout the entire range, the depths of pits are increased by additions of chromium beyond 6 percent. In fact, the pit-depth curves for Acadia clay and Lake Charles clay in figure 22 indicate that steels containing 18 percent of chromium may have deeper pits than plain steel. This tendency for chromium to increase the pitting of steels in other media has previously been noted; LaQue [151] cited the work of Speller on the corrosion of steels in river water, and on the basis of his own observations in sea water, concluded that addition of chromium to steels for the purpose of reducing weight losses in natural waters probably should not exceed 3 percent, because larger amounts may accelerate pitting.

The tendency of high concentrations of chromium to accelerate pitting in steels is apparently completely neutralized by alloying with sufficient nickel or nickel plus molybdenum to produce steels of the austenitic type.

High-chromium-nickel steels are known to be susceptible to pitting where oxygen is excluded locally. Hence the corrosion resistance shown by some of these steels in soils deficient in oxygen and high in chlorides is of considerable importance. The results of field tests of high-chromium and chromium-nickel steels and of a comparison with low-carbon steel in Docas clay, a fairly well aerated but poorly drained soil containing nearly 2 percent of sodium chloride, are given in table 26. These results indicate the beneficial effect of nickel in promoting corrosion resistance of these steels. Steels containing from 12 to 18 percent of chromium with small amounts of nickel, types 410 and 430, pitted deeply, perforations occurring within 2 years; but steels containing more than 9 percent of nickel showed little or no evidence of corrosion for the maximum periods of exposure.

Table 26. *Results of exposure of high-alloy steels to a poorly aerated soil containing sodium chloride (Docas clay, soil 64)*

M, Shallow metal attack, roughening at surface, but no definite pitting.
+, One or more specimens contained holes because of corrosion. The thickness of the specimen has been used as the maximum pit in this case.
D, Destroyed by corrosion.

Specimen	U	V	X	K	R	W	Y	CM	DT	N
AISI type No.	410	430	430	304	304	302	309	316	----------	Low-carbon steel
Composition (percent):										
C	0.065	0.070	0.12	0.08	0.05	0.093	0.144	0.07	0.07	----------
Mn	.38	.36	.42	.44	.46	.36	1.80	1.24	1.99	----------
Cu	----------	.02	----------	----------	----------	.02	.02	----------	1.07	----------
Cr	11.95	17.08	17.72	17.20	17.52	18.69	22.68	17.78	19.27	----------
Ni	.48	.09	.29	8.95	8.85	9.18	12.94	10.96	22.12	----------
Mo	----------	----------	----------	----------	----------	----------	----------	2.63	3.52	----------
	Loss in weight (oz/ft²)									
Period of exposure (yr):										
2	0.67	0.53	0.50	0.01	0.01	0.002	0.003	0.006	0.002	12.6
5	1.0	.28	.30	.002	.01	.002	.002	----------	----------	25.3
7	1.7	.44	([a])	.003	.02	.002	.005	.004	.004	35.6
9	3.2	1.2	([a])	.08	.06	.002	.006	.007	.002	D
14	5.1	1.4	.34	.003	.04	.002	.0007	.002	.003	D
	Maximum penetration (mils)									
2	63+	63+	([a])	17	8	8	5	M	O	130
5	63+	54+	10	<6	0	4	<6	----------	----------	154+
7	63+	63+	21	8	0	M	<6	M	0	154+
9	63+	63+	96	14+	36	<6	<6	0	0	154+
14	63+	63+	48	<6	7	0	0	0	0	154+

[a] Data not used because of corrosion caused by asphalt on the ends of the specimens.

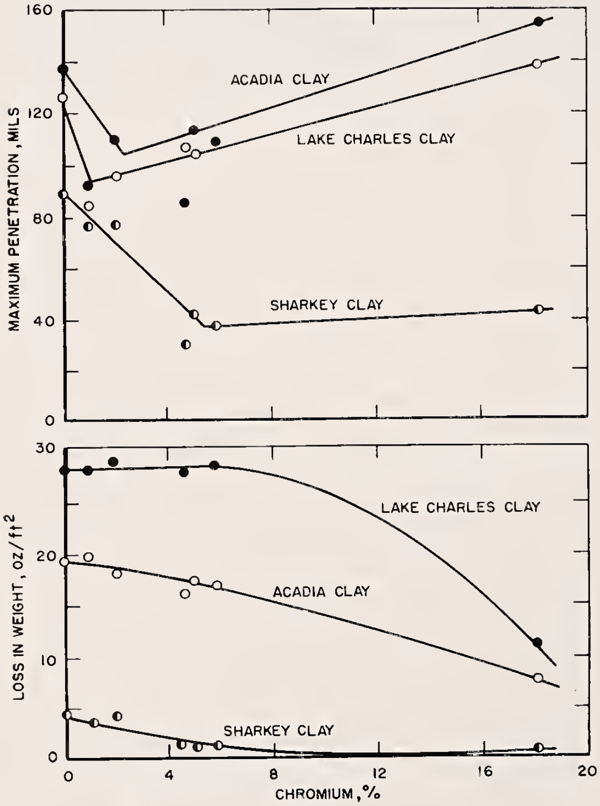

Figure 22. *Effect of chromium content on loss in weight and pitting of steels in three poorly aerated soils, exposure 9 years.*

8.3. Results on Cast Materials

a. Plain Cast Irons

The chemical compositions of the 6-in. specimens of cast-iron pipe buried in 1922, 1924, and 1928 are recorded in table 11. Most of the specimens were buried for 12 years, but in 19 of the least corrosive soils, specimens were exposed approximately 17 years. The loss in weight and maximum penetration of the various specimens are given in table 27.

A comparison of the deLavaud and pit-cast specimens buried in 1922 was made in Research Paper 883 [113], which reported the average depths of maximum pits of the specimens over an interval of 12 years. This comparison was made by the method previously described for wrought materials. However, the average maximum penetrations were not computed for the cast specimens because there were many soils in which the data were so erratic that averages would not be a satisfactory base for comparisons. This condition is in part due to the small number of specimens of the cast materials and, in part, to the great dispersion of the data.

There was no appreciable difference in the corrosion of the deLavaud and pit-cast irons. The data further indicated that the corrosion of the plain cast materials was determined more by soil conditions than by the composition of the material.

The maximum penetration and the weighted average maximum pit depths of specimens of the 6-in. cast-iron pipe exposed for approximately 12 or 17 years to the original 47 test sites are given in table 28. The data have been weighted in the table by averaging the four maximum pits from

TABLE 27. *Loss in weight and depth of maximum penetration of 6-in. cast-iron pipe buried in 1922 and 1928* [a, b]
(Data on one specimen for L, Z, and A, and the average of two specimens for C, CC, and I)

Soil		Duration of exposure	Loss in weight (oz/ft²)						Maximum penetration (mils)					
			Centrifugal process			Vert. cast in sand mold			Centrifugal process			Vert. cast in sand mold		
No.[c]	Type		deLavaud	deLavaud	Monocast	Northern ore	Southern ore	Southern ore	deLavaud	deLavaud	Monocast	Northern ore	Southern ore	Southern ore
	Material	------	C	CC[d]	I	L	Z	A	C	CC[d]	I	L	Z	A
		Years												
1	Allis silt loam	1.0	0.8	------	------	1.1	1.8	------	26	------	------	44	45	------
		3.6	3.4	------	------	3.8	3.7	------	60	------	------	72	141	------
		5.5	4.7	------	------	5.2	6.4	------	70	------	------	84	137	------
		7.7	6.0	------	------	7.4	7.2	------	64	------	------	221	209	------
		9.6	10.2	------	------	9.6	10.8	------	98	------	------	234	227	------
		11.6	12.7	------	------	13.5	13.0	------	127	------	------	152	301	------
2	Bell clay	2.1	------	0.8	------	1.6	2.3	------	------	16	------	38	44	------
		4.0	------	------	------	2.6	5.3	------	------	------	------	34	50	------
		5.9	------	[e]2.0	------	5.0	5.6	------	------	[e]45	------	89	53	------
		7.9	------	------	------	2.4	3.4	------	------	------	------	108	79	------
		9.9	------	6.4	------	------	------	------	------	48	------	------	------	------
		12.0	------	------	------	6.7	5.0	------	------	------	------	62	93	------
		15.5	------	4.7	------	------	------	------	------	104	------	------	------	------
		17.6	------	------	------	6.0	4.2	------	------	------	------	152	82	------
3(53)	Cecil clay loam	2.0	------	.6	------	2.5	1.5	------	------	<20	------	67	63	------
		4.1	------	------	------	3.4	5.0	------	------	------	------	50	83	------
		6.0	------	1.3	------	4.8	3.6	------	------	<20	------	144	108	------
		8.0	------	------	------	3.9	4.8	------	------	------	------	202	135	------
		10.1	------	3.2	------	6.5	4.2	------	------	62	------	176	144	------
		12.1	------	------	------	3.9	4.2	------	------	------	------	135	176	------
4	Chester loam	1.4	1.3	------	------	1.2	1.5	------	<10	------	------	<10	<10	------
		4.0	3.6	------	------	4.3	3.9	------	32	------	------	37	60	------
		6.1	4.4	------	------	4.4	4.6	------	62	------	------	44	52	------
		8.0	5.6	------	------	4.9	5.0	------	44	------	------	45	100	------
		12.0	10.2	------	------	10.8	10.1	------	124	------	------	95	103	------
5	Dublin clay adobe	1.9	------	2.6	------	.7	1.0	------	------	44	------	<10	34	------
		4.1	------	------	------	1.7	1.7	------	------	------	------	30	48	------
		6.2	------	9.7	------	4.2	5.4	------	------	70	------	72	82	------
		8.1	------	------	------	6.6	6.5	------	------	------	------	75	73	------
		10.2	------	10.6	------	------	------	------	------	76	------	------	------	------
		12.1	------	------	------	8.5	10.5	------	------	------	------	46	110	------
		15.6	------	12.8	------	------	------	------	------	90	------	------	------	------
		17.5	------	------	------	10.1	11.6	------	------	------	------	119	154	------
6	Everett gravelly sandy loam	1.9	------	.3	------	.1	.2	------	------	<10	------	<10	<10	------
		4.1	------	------	------	.3	.4	------	------	------	------	<20	<20	------
		6.2	------	1.4	------	.5	.6	------	------	<20	------	<20	<20	------
		8.1	------	------	------	.7	.9	------	------	------	------	<20	<20	------
		10.2	------	.8	------	------	------	------	------	22	------	------	------	------
		12.1	------	------	------	.9	1.2	------	------	------	------	<20	<20	------
		15.5	------	.6	------	------	------	------	------	56	------	------	------	------
		17.5	------	------	------	.9	.7	------	------	------	------	22	30	------
7	Maddox silt loam	1.0	.6	------	------	1.1	1.4	------	<10	------	------	<10	<10	------
		3.5	2.7	------	------	2.9	------	------	24	------	------	<20	36	------
		7.7	4.7	------	------	4.4	------	------	52	------	------	25	30	------
		11.5	6.8	------	------	5.7	8.0	------	88	------	------	149	77	------
		16.9	5.9	------	------	5.2	7.0	------	115	------	------	106	86	------
8	Fargo clay loam	1.1	.8	------	------	.7	2.1	------	<10	------	------	59	73	------
		3.8	1.9	------	------	2.7	5.4	------	34	------	------	76	61	------
		5.8	3.4	------	------	5.0	5.7	------	64	------	------	91	81	------
		7.7	5.6	------	------	5.0	7.5	------	107	------	------	85	78	------
		9.9	8.4	------	------	10.5	9.6	------	142	------	------	217	169	------
		11.8	16.8	------	------	20.3	30.8	------	179	------	------	240	239	------
9	Genesee silt loam	1.0	.7	------	------	.6	.8	------	<10	------	------	<10	<10	------
		3.5	1.4	------	------	2.4	2.2	------	31	------	------	35	40	------
		5.5	2.9	------	------	2.5	3.8	------	42	------	------	20	38	------
		7.7	4.0	------	------	3.3	4.1	------	54	------	------	28	53	------
		11.5	6.8	------	------	6.1	6.6	------	64	------	------	74	72	------
		16.9	5.6	------	------	5.3	5.9	------	87	------	------	112	110	------
10	Gloucester sandy loam	1.3	1.0	------	------	.8	1.2	------	17	------	------	<10	<10	------
		4.0	1.8	------	------	2.4	1.9	------	<20	------	------	<20	<20	------
		6.1	3.1	------	------	2.4	3.2	------	38	------	------	38	78	------
		7.9	4.2	------	------	3.9	4.0	------	36	------	------	35	51	------
		12.0	5.5	------	------	5.7	5.3	------	50	------	------	75	79	------
11(55)	Hagerstown loam	1.4	.1	------	------	.2	.2	------	36	------	------	<10	39	------
		4.0	.6	------	------	.4	1.4	------	27	------	------	27	45	------
		6.0	.6	------	------	1.0	1.3	------	22	------	------	32	59	------
		7.8	1.5	------	------	1.3	1.3	------	35	------	------	35	83	------
		10.0	1.2	------	------	1.1	1.8	------	40	------	------	40	84	------
		11.9	1.6	------	------	2.0	2.3	------	46	------	------	66	68	------

See footnotes at end of table.

TABLE 27. *Loss in weight and depth of maximum penetration of 6-in. cast-iron pipe buried in 1922 and 1928* [a], [b]—Continued

(Data on one specimen for L, Z, and A, and the average of two specimens for C, CC, and I)

Soil		Duration of exposure	Loss in weight (oz/ft²)						Maximum penetration (mils)					
			Centrifugal process			Vert. cast in sand mold			Centrifugal process			Vert. cast in sand mold		
No.[c]	Type		deLavaud	deLavaud	Monocast	Northern ore	Southern ore	Southern ore	deLavaud	deLavaud	Monocast	Northern ore	Southern ore	Southern ore
	Material	------	C	CC[d]	I	L	Z	A	C	CC[d]	I	L	Z	A
		Years												
12	Hanford fine sandy loam	1.9	------	[e]0.1	------	0.1	0.4	------	------	[e]<10	------	<10	<10	------
		4.1	------	------	------	1.1	2.0	------	------	------	------	26	66	------
		6.2	------	2.4	------	2.2	2.3	------	------	37	------	24	67	------
		8.0	------	------	------	.6	1.9	------	------	------	------	<20	<20	------
		12.1	------	------	------	5.7	4.5	------	------	------	------	59	89	------
		15.6	------	1.4	------	------	------	------	------	124	------	------	------	------
		17.5	------	------	------	4.1	3.4	------	------	------	------	94	70	------
13	Hanford very fine sandy loam	1.9	2.7	------	------	3.8	3.5	------	32	------	------	<10	62	------
		4.2	2.8	------	------	6.0	10.7	------	58	------	------	155	140	------
		5.9	6.5	------	------	------	12.8	------	32	------	------	------	217	------
		8.0	9.0	------	------	------	------	13.5	133	------	------	------	------	154
		10.2	------	5.0	------	------	------	11.4	------	80	------	------	------	180
14	Hempstead silt loam	1.1	.3	------	------	.1	.5	------	<10	------	------	30	25	------
		3.8	1.2	------	------	1.9	2.7	------	<20	------	------	<20	33	------
		5.8	2.1	------	------	4.3	5.0	------	25	------	------	42	38	------
		7.7	2.7	------	------	3.8	2.1	------	74	------	------	36	87	------
		9.9	3.3	------	------	5.7	5.9	------	70	------	------	66	60	------
		11.8	4.0	------	------	5.0	6.1	------	67	------	------	66	60	------
15	Houston black clay	2.0	------	2.4	------	.7	1.3	------	------	30	------	54	101	------
		4.0	------	------	------	2.7	4.0	------	------	------	------	60	37	------
		5.9	------	5.3	------	6.0	8.5	------	------	57	------	116	118	------
		8.0	------	------	------	4.8	4.0	------	------	------	------	78	89	------
		10.1	------	8.3	------	------	------	------	------	47	------	------	------	------
		12.0	------	------	------	8.4	6.9	------	------	------	------	131	114	------
		17.6	------	------	------	9.0	6.5	------	------	------	------	226	148	------
16	Kalmia fine sandy loam	2.0	------	1.6	------	2.8	2.2	------	------	32	------	42	49	------
		4.0	------	------	------	1.6	3.2	------	------	------	------	48	64	------
		6.0	------	3.7	------	6.3	5.5	------	------	90	------	162	62	------
		7.9	------	------	------	4.2	5.3	------	------	------	------	166	136	------
		10.0	------	------	------	8.5	8.2	------	------	------	------	179	189	------
		12.0	------	------	------	10.1	9.1	------	------	------	------	154	189	------
17	Keyport loam	1.2	1.4	------	------	1.4	3.3	------	<10	------	------	59	37	------
		3.8	3.6	------	------	3.2	4.2	------	21	------	------	26	22	------
		5.9	4.9	------	------	6.7	5.7	------	50	------	------	68	58	------
		7.7	7.2	------	------	6.6	5.9	------	46	------	------	26	38	------
		11.8	11.8	------	------	9.2	9.6	------	84	------	------	56	69	------
		17.0	9.1	------	------	9.9	8.9	------	86	------	------	175	67	------
18	Knox silt loam	1.2	.1	------	------	------	------	------	<10	------	------	66	<10	------
		3.8	.6	------	------	1.1	.9	------	38	------	------	99	92	------
		5.8	2.3	------	------	3.3	5.1	------	76	------	------	107	128	------
		7.7	2.0	------	------	3.2	2.7	------	<20	------	------	<20	<20	------
		9.8	3.5	------	------	4.8	4.6	------	69	------	------	138	142	------
		11.7	5.5	------	------	2.7	4.8	------	85	------	------	103	147	------
19	Lindley silt loam	1.1	.4	------	------	.6	.6	------	16	------	------	29	<10	------
		3.7	1.4	------	------	1.7	.8	------	36	------	------	70	70	------
		5.7	2.1	------	------	2.3	1.6	------	47	------	------	104	100	------
		7.6	2.6	------	------	3.0	2.8	------	74	------	------	159	177	------
		9.7	2.6	------	------	3.0	5.0	------	70	------	------	118	176	------
		11.6	3.1	------	------	5.5	4.6	------	69	------	------	207	259	------
20	Mahoning silt loam	1.0	.7	------	------	.9	1.3	------	<10	------	------	<10	<10	------
		3.6	1.8	------	------	2.3	2.4	------	<20	------	------	<20	<20	------
		5.5	3.2	------	------	3.6	3.9	------	68	------	------	62	38	------
		7.7	3.5	------	------	3.6	3.7	------	56	------	------	56	81	------
		9.6	5.3	------	------	6.6	4.7	------	82	------	------	108	106	------
		11.6	6.2	------	------	7.7	10.2	------	97	------	------	102	121	------
21	Marshall silt loam	1.5	1.6	------	------	2.4	2.1	------	17	------	------	<10	<10	------
		4.0	2.5	------	------	3.2	3.2	------	41	------	------	71	53	------
		6.0	4.4	------	------	5.0	6.3	------	56	------	------	101	57	------
22	Memphis silt loam	1.7	1.1	------	------	.6	.5	------	32	------	------	58	53	------
		3.7	2.5	------	------	4.3	3.9	------	50	------	------	102	85	------
		5.6	3.7	------	------	3.9	5.1	------	70	------	------	161	144	------
		7.6	6.4	------	------	5.3	5.2	------	114	------	------	86	176	------
		9.6	6.7	------	------	8.0	7.8	------	101	------	------	126	168	------
		11.6	9.2	------	------	8.5	8.1	------	106	------	------	173	180	------
23(70)	Merced silt loam	1.9	5.7	------	------	7.2	20.3	------	34	------	------	59	173	------
		4.3	12.3	------	------	22.4	35.2	------	143	------	------	194	[f]325+	------
		6.2	17.8	------	------	35.9	34.9	------	158	------	------	199	434+	------
		8.0	21.0	------	------	33.6	45.6	------	174	------	------	230	325	------
		10.2	29.6	------	------	28.3	62.3	------	184	------	------	292	325	------
		12.1	28.1	------	------	39.5	[g]D	------	242	------	------	322	440+	------

See footnotes at end of table.

TABLE 27. *Loss in weight and depth of maximum penetration of 6-in. cast-iron pipe buried in 1922 and 1928* [a, b]—Continued

(Data on one specimen for L, Z, and A, and the average of two specimens for C, CC, and I)

Soil		Duration of exposure	Loss in weight (oz/ft^2)						Maximum penetration (mils)					
			Centrifugal process			Vert. cast in sand mold			Centrifugal process			Vert. cast in sand mold		
No.[c]	Type		deLavaud	deLavaud	Monocast	Northern ore	Southern ore	Southern ore	deLavaud	deLavaud	Monocast	Northern ore	Southern ore	Southern ore
	Material	------	C	CC[d]	I	L	Z	A	C	CC[d]	I	L	Z	A
		Years												
24	Merrimac gravelly sandy loam	1.3	0.2	------	------	0.1	0.2	------	<10	------	------	<10	<10	------
		2.7	------	.4	------	------	------	0.4	------	<20	------	------	------	<20
		4.0	.2	------	------	.2	.5	------	<20	------	------	<20	<20	------
		6.1	.8	1.7	1.8	.4	1.1	1.1	<20	<20	<20	<20	<20	<20
		7.9	.7	------	------	.4	.7	------	<20	------	------	<20	<20	------
		10.6	------	1.9	------	------	------	1.2	------	46	------	------	------	36
		12.0	1.0	------	------	.7	.9	------	41	------	------	34	29	------
		17.2	.7	------	------	.5	.8	------	68	------	------	27	73	------
25	Miami clay loam	1.0	.5	------	------	.6	.4	------	14	------	------	<10	40	------
		3.7	1.1	------	------	1.6	1.8	------	38	------	------	<20	<20	------
		5.7	1.3	------	------	1.8	2.2	------	40	------	------	71	90	------
		7.6	2.1	------	------	1.6	3.1	------	<20	------	------	95	105	------
		11.7	3.7	------	------	3.4	3.3	------	50	------	------	107	111	------
		17.0	2.1	------	------	2.4	2.5	------	92	------	------	132	112	------
26	Miami silt loam	1.0	.8	------	------	1.0	1.1	------	<10	------	------	<10	<10	------
		3.5	2.0	------	------	2.7	3.9	------	34	------	------	32	48	------
		5.5	2.3	------	------	2.6	1.8	------	28	------	------	51	64	------
		7.7	1.8	------	------	1.8	2.3	------	42	------	------	67	83	------
		11.5	3.5	------	------	4.5	4.9	------	76	------	------	143	173	------
		16.9	2.9	------	------	3.2	3.9	------	68	------	------	94	157	------
27	Miller clay	2.0	------	2.3	------	.4	.5	------	------	28	------	44	<20	------
		4.0	------	------	------	2.7	3.3	------	------	------	------	60	65	------
		6.0	------	7.1	------	3.3	4.5	------	------	94	------	64	82	------
		8.0	------	------	------	4.7	3.6	------	------	------	------	144	143	------
		10.0	------	10.8	------	------	------	------	------	103	------	------	------	------
		12.0	------	------	------	6.6	8.2	------	------	------	------	179	185	------
		15.7	------	6.2	------	------	------	------	------	128	------	------	------	------
		17.6	------	------	------	7.4	8.6	------	------	------	------	200	204	------
28	Montezuma clay adobe	1.6	4.5	2.7	------	4.7	4.7	------	31	19	------	33	69	------
		5.6	[e]4.2	------	5.8	9.3	------	16.0	[e]45	------	111	172	------	190
		7.7	------	12.6	------	21.7	------	23.4	------	130	------	138	------	425
		9.6	10.4	[e]10.9	18.6	36.6	38.5	37.8	106	[e]65	147	353	196	196
29(58)	Muck	2.0	6.0	6.8	------	3.3	4.5	5.2	42	34	------	46	39	42
		4.1	------	------	------	7.8	12.6	------	------	------	------	45	57	------
		6.0	5.3	8.4	3.9	10.8	10.8	6.9	53	93	43	90	142	64
		8.0	11.3	16.9	4.9	12.9	14.5	12.2	56	84	62	206	225	102
		10.0	------	[e]53.2	------	15.2	17.4	23.3	------	[e]108	------	145	156	115
		12.0	------	------	------	34.4	20.8	------	------	------	------	203	186	------
30	Muscatine silt loam	1.1	1.2	------	------	1.2	1.3	------	<10	------	------	<10	<10	------
		3.6	1.6	------	------	1.7	2.0	------	<20	------	------	<20	<20	------
		5.7	3.0	------	------	2.0	3.6	------	32	------	------	25	34	------
		8.2	4.8	------	------	4.7	5.5	------	77	------	------	49	79	------
		11.6	9.3	------	------	12.5	9.8	------	136	------	------	143	117	------
		17.0	8.2	------	------	11.2	8.9	------	170	------	------	140	344	------
31	Norfolk fine sand	2.0	------	2.2	------	.3	1.2	------	------	41	------	<10	76	------
		4.1	------	------	------	1.5	2.2	------	------	------	------	35	38	------
		6.0	------	4.1	------	1.9	1.8	------	------	79	------	35	89	------
		8.0	------	------	------	1.8	1.6	------	------	------	------	35	83	------
		10.0	------	4.4	------	------	------	------	------	52	------	------	------	------
		12.0	------	------	------	2.3	3.8	------	------	------	------	21	76	------
		15.7	------	2.1	------	------	------	------	------	103	------	------	------	------
		17.7	------	------	------	2.1	3.2	------	------	------	------	62	58	------
32	Ontario loam	1.0	.5	------	------	.6	.2	------	<10	------	------	30	36	------
		3.7	1.6	------	------	2.0	2.0	------	46	------	------	42	37	------
		5.8	2.3	------	------	2.5	3.1	------	34	------	------	39	65	------
		7.6	2.6	------	------	3.2	3.7	------	56	------	------	158	179	------
		9.6	3.3	------	------	3.4	4.7	------	69	------	------	70	78	------
		11.7	4.2	------	------	4.1	6.4	------	74	------	------	105	144	------
33	Peat	1.0	.4	------	------	.2	.5	------	<10	------	------	<10	<10	------
		3.7	3.4	------	------	3.3	3.3	------	46	------	------	36	49	------
		5.8	3.4	------	------	1.4	3.0	------	46	------	------	43	61	------
		7.6	9.0	------	------	9.3	7.6	------	127	------	------	172	148	------
		9.7	13.0	------	------	14.3	12.1	------	116	------	------	150	185	------
		11.7	15.8	------	------	16.2	19.8	------	120	------	------	201	193	------
34	Penn silt loam	1.4	1.2	------	------	1.3	1.3	------	<10	------	------	<10	35	------
		4.0	1.7	------	------	1.9	1.7	------	28	------	------	<10	<10	------
		6.1	2.8	------	------	2.9	2.8	------	48	------	------	37	33	------
		8.0	4.6	------	------	3.6	4.2	------	54	------	------	35	70	------
		9.9	5.5	------	------	6.0	6.3	------	92	------	------	104	128	------
		12.0	7.6	------	------	7.0	7.5	------	100	------	------	78	60	------

See footnotes at end of table.

TABLE 27. *Loss in weight and depth of maximum penetration of 6-in. cast-iron pipe buried in 1922 and 1928* [a, b]—Continued

(Data on one specimen for L, Z, and A, and the average of two specimens for C, CC, and I)

Soil		Duration of exposure	Loss in weight (oz/ft²)						Maximum penetration (mils)					
			Centrifugal process			Vert. cast in sand mold			Centrifugal process			Vert. cast in sand mold		
No.[c]	Type		deLavaud	deLavaud	Monocast	Northern ore	Southern ore	Southern ore	deLavaud	deLavaud	Monocast	Northern ore	Southern ore	Southern ore
	Material	------	C	CC[d]	I	L	Z	A	C	CC[d]	I	L	Z	A
		Years												
35	Ramona loam	1.9	------	1.1	------	0.6	1.7	------	------	<10	------	<10	48	------
		4.1	------	------	------	2.2	3.6	------	------	------	------	29	37	------
		6.2	------	1.3	------	.9	1.6	------	------	<20	------	<20	30	------
		8.0	------	------	------	2.1	1.9	------	------	------	------	55	<20	------
		10.2	------	2.7	------	------	------	------	------	99	------	------	------	------
		12.1	------	------	------	2.0	6.5	------	------	------	------	33	53	------
		17.5	------	------	------	4.7	.7	------	------	------	------	122	44	------
36	Ruston sandy loam	2.0	------	.8	------	.8	1.1	------	------	32	------	44	54	------
		4.1	------	------	------	1.3	1.4	------	------	------	------	42	63	------
		6.0	------	.4	------	1.5	1.9	------	------	61	------	99	151	------
		8.0	------	------	------	1.3	.8	------	------	------	------	138	218	------
		10.0	------	3.6	------	------	------	------	------	69	------	------	------	------
		12.0	------	------	------	1.9	2.9	------	------	------	------	61	51	------
		15.7	------	1.6	------	------	------	------	------	75	------	------	------	------
		17.7	------	------	------	1.5	1.8	------	------	------	------	78	102	------
37	St. John's fine sand	2.0	------	4.0	------	1.4	1.9	------	------	<10	------	<10	<10	------
		4.1	------	------	------	4.1	4.1	------	------	------	------	<20	<20	------
		6.0	------	6.0	------	5.0	5.6	------	------	<20	------	37	70	------
		8.0	------	9.2	------	6.1	6.8	------	------	45	------	39	58	------
		10.1	------	12.0	------	9.2	8.3	------	------	98	------	66	108	------
		12.0	------	------	------	9.3	20.9	------	------	------	------	73	119	------
38	Sassafras gravelly sandy loam	1.4	.1	------	------	.1	.1	------	<10	------	------	<10	<10	------
		4.0	.3	------	------	.3	.5	------	<20	------	------	<20	<20	------
		6.1	1.1	------	------	.8	1.2	------	<20	------	------	<20	23	------
		8.0	1.4	------	------	1.2	1.3	------	<20	------	------	<20	<20	------
		12.0	2.2	------	------	2.2	2.2	------	32	------	------	<20	<20	------
		17.2	1.7	------	------	1.6	1.8	------	65	------	------	50	73	------
39	Sassafras silt loam	1.4	1.2	------	------	1.3	1.6	------	<10	------	------	<10	<10	------
		4.0	2.8	------	------	3.3	2.7	------	36	------	------	37	39	------
		6.1	3.6	------	------	4.4	5.0	------	40	------	------	43	58	------
		8.0	6.0	------	------	4.6	6.1	------	59	------	------	40	62	------
		9.9	5.7	------	------	6.8	7.3	------	82	------	------	90	83	------
		12.0	8.8	------	------	9.3	14.3	------	106	------	------	60	125	------
40(61)	Sharkey clay	2.0	------	2.4	------	1.9	2.6	------	------	38	------	27	37	------
		4.1	------	------	------	5.5	6.1	------	------	------	------	42	68	------
		6.0	------	5.8	------	9.3	9.1	------	------	84	------	99	110	------
		8.0	------	7.7	------	8.8	9.6	------	------	73	------	82	88	------
		10.0	------	18.6	------	10.4	9.1	------	------	68	------	74	93	------
		12.0	------	------	------	11.4	13.6	------	------	------	------	74	103	------
41	Summit silt loam	1.5	0.4	------	------	1.2	1.2	------	<10	------	------	15	38	------
		4.0	1.8	------	------	2.5	2.7	------	<20	------	------	42	43	------
		6.0	2.2	------	------	2.8	3.8	------	36	------	------	30	40	------
		7.9	2.5	------	------	3.6	3.8	------	44	------	------	35	59	------
		12.0	4.5	------	------	5.4	5.4	------	49	------	------	63	66	------
		17.4	3.5	------	------	6.1	6.0	------	58	------	------	55	94	------
42(62)	Susquehanna clay	2.0	------	2.3	------	6.2	3.5	3.6	------	52	56	100	100	63
		4.1	------	------	------	7.5	11.1	------	------	------	------	194	115	------
		6.0	------	5.8	3.6	14.6	10.3	7.5	------	117	145	159	273	196
		8.0	------	3.7	------	11.3	11.2	3.4	------	94	------	117	179	164
		10.1	------	5.9	------	11.3	21.8	7.0	------	76	------	172	197	180
		12.0	------	------	------	17.8	30.4	------	------	------	------	230	311	------
[h]43(63)	Tidal marsh	1.3	1.0	------	------	1.4	1.0	------	53	------	------	<10	<10	------
		2.8	------	3.6	------	------	------	2.2	------	176	------	------	------	86
		4.1	3.2	------	------	4.8	2.9	------	56	------	------	27	172	------
		6.2	5.7	12.5	4.0	6.4	7.2	5.0	54	181	157	31	105	89
		8.0	10.5	17.2	------	7.2	7.5	9.5	102	158	------	83	108	246
		9.9	12.9	------	------	11.4	9.4	------	173	------	------	157	121	------
		10.7	------	33.0	------	------	------	------	------	277	------	------	------	142
		12.0	20.3	------	------	14.9	15.3	------	178	------	------	241	151	------
44	Wabash silt loam	1.1	1.7	------	------	.3	1.0	------	<10	------	------	<10	30	------
		3.6	1.0	------	------	1.4	.9	------	46	------	------	81	59	------
		5.7	1.0	------	------	1.2	2.2	------	40	------	------	50	37	------
		7.6	1.6	------	------	1.4	2.5	------	36	------	------	44	53	------
		11.6	3.8	------	------	3.3	4.0	------	72	------	------	65	69	------
45	Unidentified alkali soil	1.2	1.3	------	------	2.0	1.2	------	<10	------	------	58	32	------
		2.6	------	2.1	------	------	------	4.4	------	47	------	------	------	32
		3.8	7.8	------	------	4.5	3.9	------	46	------	------	62	47	------
		5.8	2.3	------	------	2.4	2.7	------	40	------	------	67	35	------
		6.5	------	16.5	7.4	------	------	13.6	------	118	102	------	------	153
		7.7	3.9	------	------	4.4	7.4	------	70	------	------	99	70	------
		8.7	------	21.8	------	------	------	18.0	------	113	------	------	------	144
		9.8	15.1	------	------	17.6	17.2	------	150	------	------	232	------	------
		10.6	------	37.5	------	------	------	36.8	------	155	------	------	------	236
		11.7	12.6	------	------	------	15.0	------	128	------	------	------	140	------

See footnotes at end of table.

TABLE 27. *Loss in weight and depth of maximum penetration of 6-in. cast-iron pipe buried in 1922 and 1928* [a, b]—Continued

(Data on one specimen for L, Z, and A, and the average of two specimens for C, CC, and I)

Soil		Duration of exposure	Loss in weight (oz/ft^2)						Maximum penetration (mils)					
			Centrifugal process			Vert. cast in sand mold			Centrifugal process			Vert. cast in sand mold		
No.[c]	Type		deLavaud	deLavaud	Monocast	Northern ore	Southern ore	Southern ore	deLavaud	deLavaud	Monocast	Northern ore	Southern ore	Southern ore
	Material	------	C	CC[d]	I	L	Z	A	C	CC[d]	I	L	Z	A
		Years												
46	Unidentified sandy loam	1.5	0.5	------	------	2.5	1.8	------	15	------	------	35	36	------
		4.0	2.2	------	------	4.0	5.5	------	< 20	------	------	55	53	------
		5.1	2.2	------	------	2.3	3.6	------	26	------	------	29	70	------
		8.0	5.6	------	------	5.3	6.6	------	50	------	------	63	104	------
		10.2	4.5	------	------	4.0	8.1	------	54	------	------	38	86	------
		12.0	4.2	------	------	5.6	8.1	------	68	------	------	67	102	------
47	Unidentified silt loam	1.5	.6	------	------	.5	.7	------	< 10	------	------	< 10	< 10	------
		4.1	1.9	------	------	2.1	2.6	------	< 20	------	------	< 20	< 20	------
		6.1	2.7	------	------	2.6	2.9	------	< 20	------	------	< 20	< 20	------
		8.0	3.1	------	------	1.8	3.0	------	54	------	------	< 20	< 20	------
		12.1	4.2	------	------	3.5	4.3	------	72	------	------	17	33	------
		17.4	6.0	------	------	3.6	6.5	------	83	------	------	32	62	------
52	Lake Charles clay loam	2.0	------	------	7.4	5.9	------	8.5	------	------	76	37	------	91
		5.4	------	------	16.2	21.1	------	29.3	------	------	168	163	------	195
		7.5	------	------	28.5	22.8	------	39.8	------	------	228	174	------	333
54	Fairmount silt loam	1.9	------	------	1.5	1.1	------	1.1	------	------	44	17	------	28
		5.2	------	------	1.6	2.4	------	2.2	------	------	56	35	------	36
		7.3	------	------	3.4	4.5	------	3.6	------	------	71	78	------	42
68	Gila clay	1.7	------	------	------	4.2	------	5.1	------	------	------	72	------	39
		5.1	4.3	------	------	5.0	------	5.5	82	------	------	138	------	93
		7.2	3.7	------	------	5.1	------	14.4	120	------	------	114	------	154
101	Billings silt loam (low alkali)	1.9	------	------	5.5	7.4	------	6.4	------	------	76	49	------	41
		4.1	------	------	7.9	8.2	------	8.2	------	------	103	128	------	61
		9.3	------	------	8.0	11.0	------	10.2	------	------	165	203	------	128
102	Billings silt loam (moderate alkali)	1.9	------	------	4.7	4.6	------	5.5	------	------	63	54	------	57
		4.1	------	------	9.2	9.0	------	14.4	------	------	99	90	------	130
		9.3	------	------	23.1	25.6	------	25.7	------	------	247	293	------	410
103	Billings silt loam (high alkali)	1.9	------	------	6.3	14.1	------	13.7	------	------	85	99	------	96
		4.1	------	------	28.1	14.6	------	42.8	------	------	215+	132	------	208
		9.3	------	------	45.2	42.4	------	58.6	------	------	215	361	------	418
104	Cecil clay	1.9	------	------	2.0	2.8	------	2.7	------	------	49	44	------	60
		4.1	------	------	3.7	3.9	------	4.1	------	------	81	75	------	74
		11.7	------	------	5.9	5.3	------	6.8	------	------	108	92	------	92
105	Cecil clay loam	2.0	------	------	3.5	4.2	------	4.8	------	------	90	88	------	88
		4.0	------	------	4.3	4.5	------	4.4	------	------	138	140	------	137
		11.7	------	------	4.1	4.6	------	4.5	------	------	119	156	------	106
106	Cecil clay loam	1.9	------	------	4.1	3.6	------	4.6	------	------	80	86	------	93
		4.1	------	------	5.0	5.2	------	5.4	------	------	110	151	------	92
		11.7	------	------	7.7	8.7	------	8.0	------	------	174	296	------	136
107	Cecil fine sandy loam	1.9	------	------	1.8	1.9	------	2.4	------	------	60	64	------	64
		4.1	------	------	2.5	2.8	------	3.3	------	------	72	60	------	61
		11.7	------	------	3.5	3.5	------	3.1	------	------	129	79	------	98
108	Cecil gravelly loam	1.9	------	------	2.8	3.3	------	4.2	------	------	68	65	------	87
		4.0	------	------	5.2	5.1	------	5.0	------	------	142	129	------	142
		11.7	------	------	4.9	5.5	------	4.4	------	------	171	266	------	258
109	Fresno fine sandy loam (low alkali)	1.9	------	------	6.1	7.1	------	7.7	------	------	114	174	------	92
		4.0	------	------	11.6	9.7	------	16.9	------	------	150+	249	------	173
		9.2	------	------	20.9	17.2	------	30.1	------	------	227	288	------	269
110	Fresno fine sandy loam (moderate alkali)	1.9	------	------	4.0	3.6	------	6.5	------	------	102	120	------	124
		4.0	------	------	9.9	12.4	------	7.4	------	------	124	224	------	198
		9.2	------	------	19.2	17.0	------	17.9	------	------	277	251	------	280
111	Fresno fine sandy loam (high alkali)	1.6	------	------	4.3	4.7	------	4.4	------	------	82	68	------	113
		3.7	------	------	10.9	9.4	------	8.8	------	------	96	158	------	97
		8.9	------	------	24.4	22.8	------	26.7	------	------	166	167	------	265
112	Imperial clay (moderate alkali)	1.9	------	------	8.4	7.8	------	9.2	------	------	110	213	------	123
		4.0	------	------	18.8	18.4	------	17.7	------	------	296+	259	------	213
		5.9	------	------	D	31.3	------	24.5	------	------	296+	265+	------	303+
113	Imperial clay (high alkali)	1.9	------	------	10.5	7.0	----	13.0	------	------	139	115	------	188
		4.0	------	------	32.0	21.2	------	31.5	------	------	220+	261	------	242
		5.9	------	------	D	28.6	------	D	------	------	250+	280+	------	347+
114(56)	Lake Charles clay	.9	------	------	1.6	1.5	------	1.6	------	------	< 10	< 10	------	< 10
		3.0	------	------	4.2	3.4	------	5.4	------	------	32	20	------	< 20
		10.5	------	------	14.1	13.6	------	16.0	------	------	76	78	------	77
115	Memphis silt loam	2.0	------	------	1.5	2.0	------	2.2	------	------	76	82	------	64
		4.1	------	------	2.7	2.8	------	3.7	------	------	90	91	------	91
		11.7	------	------	2.0	2.3	------	2.4	------	------	91	95	------	158

See footnotes at end of table.

Table 27. *Loss in weight and depth of maximum penetration of 6-in. cast-iron pipe buried in 1922 and 1928* [a, b]—Continued

(Data on one specimen for L, Z, and A, and the average of two specimens for C, CC, and I)

Soil		Duration of exposure	Loss in weight (oz/ft²)						Maximum penetration (mils)					
			Centrifugal process			Vert. cast in sand mold			Centrifugal process			Vert. cast in sand mold		
No.[c]	Type		deLavaud	deLavaud	Monocast	Northern ore	Southern ore	Southern ore	deLavaud	deLavaud	Monocast	Northern ore	Southern ore	Southern ore
	Material	------	C	CC[d]	1	L	Z	A	C	CC[d]	I	L	Z	A
		Years												
116	Merced clay	1.9	-------	-------	7.7	5.8	-------	10.3	-------	-------	82	106	-------	129
		4.0	-------	-------	18.2	17.1	-------	20.1	-------	-------	161	127	-------	241
		9.3	-------	-------	33.4	37.0	-------	43.9	-------	-------	230	250	-------	270
117(57)	Merced clay loam adobe	1.9	-------	-------	6.7	6.6	-------	9.2	-------	-------	94	90	-------	123
		4.0	-------	-------	12.4	11.5	-------	18.6	-------	-------	146	142	-------	231
		9.3	-------	-------	15.2	21.1	-------	17.6	-------	-------	167	175	-------	204
118	Niland gravelly sand (low alkali)	1.9	-------	-------	6.9	7.8	-------	9.6	-------	-------	95	105	-------	153
		4.0	-------	-------	17.4	13.8	-------	18.2	-------	-------	205	190	-------	268
		5.9	-------	-------	18.9	19.3	-------	29.7	-------	-------	257	200	-------	302
119	Norfolk sandy loam	2.0	-------	-------	.5	.4	-------	.4	-------	-------	< 10	< 10	-------	< 10
		4.0	-------	-------	4.6	4.7	-------	4.6	-------	-------	118	141	-------	129
		11.7	-------	-------	5.8	7.0	-------	5.9	-------	-------	102	148	-------	156
120	Norfolk sand	2.0	-------	-------	2.7	3.4	-------	2.6	-------	-------	86	99	-------	95
		4.0	-------	-------	.8	.7	-------	.7	-------	-------	< 20	< 20	-------	< 20
		11.6	-------	-------	1.1	.4	-------	.8	-------	-------	52	19	-------	33
121	Norfolk sand	2.0	-------	-------	.8	.6	-------	.7	-------	-------	< 10	< 10	-------	< 10
		4.0	-------	-------	.7	.6	-------	.5	-------	-------	< 20	< 20	-------	< 20
		11.7	-------	-------	1.2	.2	-------	.3	-------	-------	60	31	-------	26
122	Panoche clay loam	1.9	-------	-------	1.8	1.9	-------	2.0	-------	-------	< 10	< 10	-------	< 10
		4.0	-------	-------	2.5	2.5	-------	4.6	-------	-------	52	34	-------	50
		9.3	-------	-------	3.5	1.8	-------	5.8	-------	-------	84	83	-------	90
123	Susquehanna clay	2.0	-------	-------	2.9	4.3	-------	3.7	-------	-------	38	47	-------	36
		4.1	-------	-------	6.6	7.2	-------	5.9	-------	-------	62	170	-------	94
		11.7	-------	-------	9.9	9.7	-------	8.8	-------	-------	135	211	-------	272
124	Susquehanna silt loam	.9	-------	-------	2.6	3.6	-------	4.2	-------	-------	32	41	-------	28
		2.7	-------	-------	4.9	5.3	-------	5.7	-------	-------	59	66	-------	57
		10.5	-------	-------	6.6	7.2	-------	6.2	-------	-------	149	83	-------	66
125	Susquehanna fine sandy loam	2.0	-------	-------	3.8	4.2	-------	5.3	-------	-------	32	56	-------	28
		4.1	-------	-------	6.3	5.5	-------	6.4	-------	-------	72	92	-------	86
		11.8	-------	-------	9.9	8.6	-------	8.8	-------	-------	120	101	-------	102

[a] See table 11 for composition of materials.

[b] See table 6 for properties of soils.

[c] The soil number in parentheses is the number assigned to the same site in a later series of tests. (See table 29).

[d] Outside of pipe only exposed to soil. The inside was coated.

[e] Data for 1 specimen only.

[f] The plus sign indicates that 1 or both specimens contained holes because of corrosion.

[g] D, specimens destroyed, no weight-loss data.

[h] Site 43 is not identical with site 63 geographically, but the soil environment, tidal marsh, is the same.

each 6-in. specimen. Any comparison of these data with those for the 1½- and 3-in. wrought pipe specimens (table 16) must be restricted to weighted data for specimens exposed for the same periods of time. Unweighted pit depths for specimens of different sizes should not be compared. For example, the average maximum-pit-depth data in table 27 cannot be compared with similar data for wrought pipe of the same age but of different dimensions (table 13).

b. Alloy Cast Irons

Corrosion of cast iron in soils in general is characterized by the development of an adherent layer of corrosion products that increases in thickness as corrosion progresses. The thickening of this layer is partly due to electrochemical action between the ferritic and graphitic constituents of cast iron and partly to differences in potential that arise from contact of the cast metal with the soil, as, for example, by differential aeration. To the extent that corrosion of cast iron is caused by differences in potential within the metal itself, improved corrosion resistance would be expected to result from improvement in the quality of the casting. Wesley, Copson, and LaQue [152] showed that small amounts of nickel or nickel plus chromium alter the structure of cast iron in such manner that galvanic action between the different constituents is reduced considerably. Larger additions of these alloying elements, in amounts sufficient to produce an austenitic structure, were shown to be considerably more effective in reducing corrosion under the experimental conditions because of the ennobling effect of nickel and chromium on the potential of iron.

In order to evaluate the effect of nickel or nickel plus chromium and copper on the corrosion of cast iron in soils, samples of a high-alloy austenitic cast-iron pipe (1½-in. diameter) were buried at 15 test sites in 1932, and in 1941 samples of several low-alloy cast irons of the same size were buried at 13 of these same sites and at 1 other site. Data obtained upon the completion of the exposure tests in 1952 on low-alloy materials and high-alloy cast iron (material E)

TABLE 28. *Maximum pit depth and weighted maximum pit depth of 6-inch cast-iron pipe during the maximum exposure period*[a]

Soil[b]	Maximum exposure[d]	Maximum penetration				Weighted maximum penetration[c]			
		Centrifugal process		Vertically cast in sand mold		Centrifugal process		Vertically cast in sand mold	
		deLavaud (2)	deLavaud (2)	Northern ore (1)	Southern ore (1)	deLavaud (2)	deLavaud (2)	Northern ore (1)	Southern ore (1)
	Material	C	CC	L	Z	C	CC	L	Z
	Years	*Mils*	*Mils*	*Mils*	*Mils*	*Mils*	*Mils*	*Mils*	*Mils*
1	11.6	127	------	234	301	115	------	183	224
2	17.6	------	104	152	82	------	78	110	72
3	12.1	------	62	202	176	------	45	122	147
4	12.0	124	------	95	103	108	------	90	90
5	17.5	------	90	119	154	------	68	114	132
6	17.5	------	56	22	30	------	53	19	27
7	16.9	115	------	149	86	88	------	87	78
8	11.8	179	------	240	239	156	------	217	288
9	16.9	87	------	112	110	72	------	95	103
10	12.0	50	------	75	79	43	------	68	63
11	11.9	46	------	66	84	42	------	43	71
12	17.5	------	124	94	89	------	98	85	65
13	10.2	133	------	------	------	129	------	------	------
14	11.8	74	------	66	87	51	------	50	45
15	17.6	------	------	226	148	------	------	168	130
16	12.0	------	------	179	187	------	------	153	170
17	17.0	86	------	175	69	76	------	96	62
18	11.7	85	------	138	147	69	------	109	135
19	11.6	74	------	207	259	48	------	187	171
20	11.6	97	------	108	121	90	------	104	110
21	6.0	56	------	101	57	51	------	88	52
22	11.6	114	------	173	180	81	------	156	158
23	12.1	242	------	322	440+	220	------	303	440+
24	17.2	68	------	34	73	61	------	27	38
25	17.0	92	------	132	112	71	------	98	97
26	16.9	76	------	143	173	72	------	115	157
27	17.6	------	128	200	204	------	104	188	168
28	9.6	106	130	353	196	92	121	342	169
29	12.0	------	108	206	225	------	80	177	202
30	17.0	170	------	143	344	150	------	123	201
31	17.7	------	103	62	89	------	98	50	72
32	11.7	74	------	158	179	68	------	126	150
33	11.7	127	------	201	193	112	------	160	180
34	12.0	100	------	104	128	90	------	82	85
35	17.5	99	------	122	53	189	------	100	49
36	17.7	------	75	138	218	------	68	115	145
37	12.0	------	98	73	119	------	80	57	104
38	17.2	------	------	50	73	53	------	36	47
39	12.0	106	------	90	125	95	------	79	100
40	12.0	------	84	99	110	------	66	75	78
41	17.4	58	------	63	94	55	------	52	84
42	12.0	------	117	230	311	------	106	193	274
43	12.0	178	------	241	172	142	------	164	102
44	11.6	72	------	81	69	60	------	60	52
45	11.7	150	155	232	142	133	147	196	140
46	12.0	68	------	67	102	55	------	61	98
47	17.4	83	------	32	62	80	------	24	58

[a] See table 11 for identification of the materials.

[b] See table 6 for properties of the soils.

[c] Average of the 4 deepest pits on 1 L or Z specimen or 4 pits on each of 2 C specimens.

[d] The CC specimens were exposed approximately 2 years less than the time indicated.

[e] The number in parentheses indicates the number of specimens removed from each site. When more than 1 specimen was removed the average value is given.

are presented in tables 29 and 30. Four removals with a maximum exposure of 11 years are represented by the data for the low-alloy materials buried in 1941, whereas five removals with a maximum exposure of 14 years are represented by the data for the high-alloy cast iron and other low-alloy cast irons buried prior to 1941.

High-alloy cast iron E was considerably more resistant to corrosion, as measured by both weight loss and maximum pitting (except for loss in weight in soil 58), than either plain cast iron A or low-alloy cast irons B, C, D, NC, and N. It is noteworthy that, except in cinders, the deepest pit measured on the specimens of material E in 14 years of exposure was only 80 mils.

The effect of composition on the corrosion of the low-alloy cast irons can be observed to somewhat better advantage by calculating the weight losses of these specimens on a relative basis. This would have the effect of eliminating the differences in corrosivity of the soils due to differential aeration and emphasizing the effect of graphitic corrosion. In table 31 the weight losses of materials B, C, and D are shown for each soil and for each period of exposure relative to plain cast iron A. Except for the well-drained soils of high resistivity (soils 53, 55, and 62), and soil 66, in which accelerated corrosion of the alloy cast irons occurred, the relative weight losses of the specimens during the initial period of exposure is seen to have decreased with increasing content of nickel. For example, during the first period of 5 years' duration the

TABLE 29. *Loss in weight of plain and alloy cast iron in different soils*

(Average of two specimens, in ounces per square foot)

Identification		Material	Form	Average exposure	Aeration, test site number, and soil type														
Symbol	Year buried				Good aeration				Fair aeration			Poor aeration			Very poor aeration				
					Cecil clay loam	Hagerstown loam	Susquehanna clay	Chino silt loam	Docas clay	Mohave fine gravelly loam	Merced silt loam	Muck	Rifle peat	Sharkey clay	Acadia clay	Lake Charles clay	Carlisle muck	Tidal marsh	Cinders
				Soil	53	55	62	65	64	66	70	58	60	61	51	56	59	63	67
				Years															
G	1932	Rattled cast iron [a]	Pipe	2.0	4.7	2.7	6.7	10.3	12.6	6.0	-------	5.8	10.6	[b]1.1	11.9	9.5	-------	3.8	26.8
				5.4	2.0	2.4	5.6	6.2	21.8	6.2	-------	12.1	7.2	4.8	18.4	14.8	2.6	3.2	48.2
				7.4	2.6	3.1	5.0	7.1	35.5	5.6	-------	19.0	4.9	4.5	20.8	22.0	[c]3.9	1.4	23.0
				9.3	3.2	3.6	8.1	7.6	[d]D	4.0	-------	20.1	20.8	7.1	-------	D	[c]3.6	6.1	D
				14.3	3.3	2.4	8.5	9.0	D	D	-------	D	28.6	12.3	[e]D	[f]D	[e]6.8	[c]13.1	D
A	1941	Plain cast iron	do	5.0	3.2	2.2	3.6	8.6	19.7	6.2	7.5	6.8	6.5	6.8	-------	6.5	14.4	3.8	D
				[g]7.2	5.1	3.8	6.7	5.6	22.1	29.6	35.3	6.4	13.6	6.6	-------	19.4	10.3	5.9	D
				8.7	6.0	5.1	8.7	11.9	24.2	25.6	34.4	6.8	14.2	7.9	-------	19.4	15.6	4.5	D
				[g]11.0	5.9	3.5	5.6	3.4	25.1	5.3	D	5.4	10.1	4.0	-------	19.3	16.0	4.3	D
I	1932	Low-alloy; 0.51 Cu, 0.28 Mn	do	2.0	3.0	2.8	6.5	11.9	15.5	5.1	-------	4.6	9.8	[b]0.9	14.9	5.1	-------	2.8	30.3
				5.4	1.7	1.5	4.2	8.1	26.6	5.4	-------	12.4	7.2	5.6	24.8	9.5	2.3	2.8	48.9
				7.4	1.7	2.4	4.2	8.0	39.4	4.7	-------	20.6	7.2	5.3	21.1	24.7	[c]3.0	3.5	29.8
				9.3	2.8	2.7	6.6	11.0	46.8	8.2	-------	24.1	[c]18.2	7.5	-------	37.3	4.1	[c]10.0	[h]61.4+
				14.3	2.3	2.3	6.7	12.3	49.6	18.6	-------	37.1	33.6	11.0	[i]27.6+	42.0	[e]5.1	7.4	D
J	1932	Low-alloy; 0.62 Cu, 0.83 Mn	do	2.0	3.1	3.9	6.8	11.0	15.9	6.0	-------	3.7	7.8	[b]1.0	14.7	5.1	-------	4.6	24.6
				5.4	1.8	1.5	4.6	9.2	26.7	7.0	-------	11.5	7.2	6.2	22.9	12.5	2.5	3.6	51.4
				7.4	1.8	2.4	4.8	9.0	44.1	7.6	-------	20.0	5.7	5.3	21.0	22.7	3.2	3.0	36.5
				9.3	2.6	2.1	6.4	10.3	44.6	12.2	-------	27.1	[c]17.0	6.9	-------	33.7	2.9	[c]11.4	[h]65.0+
				14.3	3.4	2.6	7.5	12.5	57.7	22.6	-------	[h]39.6+	30.7	10.7	[i]31.1+	[f]43.0	[e]6.2	8.5	[h]51.5+
C	1932	Low-alloy; 0.30 Cr, 0.15 Ni	do	2.0	3.9	3.4	6.4	12.9	14.4	8.3	-------	9.0	9.0	[b]1.2	15.1	7.2	-------	3.1	21.5
				5.4	1.9	1.5	4.6	12.2	31.2	11.2	-------	14.3	6.7	4.7	29.3	10.4	1.9	1.8	35.9
				7.4	1.6	2.0	2.5	11.1	44.7	6.0	-------	18.0	4.3	5.0	23.7	19.6	2.2	[f]2.1	26.7
				9.3	2.2	2.0	6.9	14.6	[f]41.9	10.7	-------	21.9	[c]13.1	7.2	-------	29.7	[c]2.4	2.6	45.7
				14.3	3.5	3.3	6.6	17.5	[h]36.1+	D	-------	D	25.3	10.8	[e]D	[h]34.0+	[e]5.0	[c]4.5	D
B	1941	Low-alloy; 1.27 Ni, 0.32 Cu	do	5.0	3.9	2.5	3.5	7.7	20.4	8.2	4.8	4.4	2.0	5.7	-------	3.9	13.3	2.4	D
				[g]7.2	4.2	3.5	5.1	3.1	20.4	27.5	34.4	4.8	12.1	5.4	-------	20.5	8.3	3.9	D
				8.7	6.3	4.8	9.0	6.6	24.7	28.5	D	7.6	13.8	7.8	-------	18.3	11.3	6.1	D
				[g]11.0	4.7	3.8	6.5	3.0	14.8	6.8	D	4.3	16.8	3.7	-------	21.7	15.5	4.8	D
C	1941	Low-alloy; 1.71 Ni, 0.98 Cu	do	5.0	3.5	2.6	3.8	9.9	18.7	9.3	4.2	3.5	1.9	5.6	-------	4.1	11.1	2.3	D
				[g]7.2	4.9	3.8	4.9	3.4	17.2	27.8	31.4	4.2	10.8	5.3	-------	20.9	8.7	4.8	D
				8.7	5.7	4.8	7.7	5.5	14.5	D	D	5.8	12.8	5.6	-------	20.8	13.2	4.6	D
				[g]11.0	5.5	4.1	6.7	2.6	23.6	9.5	D	4.5	6.2	3.4	-------	20.3	15.6	3.6	D
NC	1941	Low-alloy; 2.08 Ni, 1.10 Cu	Plate	5.0	3.3	1.6	3.1	7.9	15.5	6.6	7.0	3.6	4.4	3.4	-------	4.8	5.4	[f]4.3	D
				[g]7.2	4.1	2.8	1.8	4.9	23.4	29.9	26.8	4.8	10.4	5.0	-------	18.8	8.7	5.3	D
				8.7	4.4	3.4	5.8	8.6	37.5	21.7	25.4	5.2	11.7	4.9	-------	15.7	9.0	3.9	D
				[g]11.0	3.2	3.8	4.9	7.4	26.5	9.0	37.2	5.3	8.0	3.1	-------	26.6	16.0	8.0	D
N	1941	Low-alloy; 3.10 Ni	do	5.0	3.0	2.1	2.5	8.2	15.8	[f]10.2	7.6	3.2	3.6	3.4	-------	7.3	5.4	[f]3.5	D
				[g]7.2	3.2	3.1	4.5	4.2	23.1	27.7	26.1	5.1	9.7	4.7	-------	16.2	8.5	4.6	D
				8.7	3.4	3.1	5.9	9.7	35.7	22.4	25.5	5.5	11.7	4.1	-------	15.6	9.0	3.7	D
				[g]11.0	3.7	4.1	5.2	8.6	25.0	8.6	38.1	6.7	9.7	2.9	-------	27.2	16.4	6.4	D
D	1941	Low-alloy; 3.32 Ni	Pipe	5.0	3.5	2.6	2.6	7.0	14.4	8.3	3.7	1.4	3.5	5.2	-------	2.9	7.6	0.6	D
				[g]7.2	4.6	4.2	5.1	2.3	9.5	28.6	D	6.1	11.8	5.1	-------	16.3	9.1	6.2	D
				8.7	5.9	4.5	8.5	6.0	15.0	D	D	6.0	14.9	6.2	-------	20.7	11.1	4.2	D
				[g]11.0	5.1	4.3	5.4	3.7	21.1	9.4	D	3.7	7.3	3.5	-------	19.4	15.4	2.0	D
E	1932	High-alloy; 15.0 Ni, 6.6 Cu, 2.6 Cr	do	2.0	1.2	.8	1.7	1.5	4.4	3.1	-------	0.8	4.2	[b]0.3	4.6	3.3	-------	.6	17.6
				5.4	.7	.6	1.1	3.0	3.1	3.0	-------	4.9	4.9	1.8	4.1	4.6	.4	.6	38.4
				7.4	.7	.7	1.0	2.0	5.8	3.5	-------	8.6	[f]1.3	1.7	3.9	9.4	[c].6	.7	24.3
				9.3	1.4	.7	2.7	[c]2.6	12.8	[c]3.3	-------	9.9	[c]10.0	2.3	-------	14.6	.7	1.6	52.3
				14.3	1.2	1.1	2.3	3.1	4.8	7.6	-------	10.0	11.6	5.2	[e]9.7	17.3	[e]1.3	1.5	D

[a] Ordinary cast iron horizontally cast in green-sand molds and rattled to remove sand.
[b] Exposed for 1.0 yr only.
[c] Data for the individual specimens differed from the average by more than 50 percent.
[d] D, both specimens destroyed by corrosion.
[e] Data for 4 specimens.
[f] Data for 1 specimen. The other specimen was missing.
[g] Data for 3 specimens.
[h] Data for 1 specimen. The other specimen was destroyed by corrosion.
[i] Data for 3 specimens. The other specimen was destroyed by corrosion.

TABLE 30. *Maximum penetration of plain and alloy cast iron in different soils*

(Average of two specimens, in mils)

Identification		Material	Form	Average exposure	Aeration, test site number, and soil type														
					Good aeration				Fair aeration			Poor aeration			Very poor aeration				
Symbol	Year buried				Cecil clay loam	Hagerstown loam	Susquehanna clay	Chino silt loam	Docas clay	Mohave fine gravelly loam	Merced silt loam	Muck	Rifle peat	Sharkey clay	Acadia clay	Lake Charles clay	Carlisle muck	Tidal marsh	Cinders
				Soil	53	55	62	65	64	66	70	58	60	61	51	56	59	63	67
				Years															
F	1932	Sand-coated cast iron	Pipe	2.0	48	48	70	46	131	56	-------	34	50	[a]24	90	41	-------	38	129
				5.4	49	66	66	74	116	71	-------	104	60	48	[b]250+	119	52	43	250+
				7.4	102	126	106	86	150	122	-------	200+	35	56	250+	250+	46	52	250+
				9.3	[c]75	98	90	145	250+	118	-------	250+	[c]163+	78	-------	250+	44	131	250+
				14.3	128	135	109	182+	210+	250+	-------	250+	142	98	[d]250+	[e]250+	[d]64	[c]164+	250+
G	1932	Rattled cast iron[f]	do.	2.0	42	48	64	50	124	60	-------	26	52	[a]43	118	36	-------	24	160
				5.4	51	50	95	94	126	79	-------	179+	68	55	250+	109	33	74	250+
				7.4	71	126	118	112	122	181+	-------	250+	26	76	250+	250+	52	61	210+
				9.3	57	123	[c]81	131	250+	152	-------	250+	175+	78	-------	250+	52	114	250+
				14.3	138	149	140	146	250+	250+	-------	250+	[c]197+	98	[d]250+	250+	[d]70	156	250+
A	1941	Plain cast iron	do.	5.0	179+	110	53	113	151	67	104	106	52	78	-------	124	89	99	250+
				[g]7.2	131	108	76	109	242+	209+	250+	160+	71	93	-------	202+	81	111	250+
				8.7	194+	116	74	121	240+	189+	217	116	66	96	-------	188+	76	55	250+
				[g]11.0	145	132	117	111	214+	160+	250+	151+	71	85	-------	250+	107	92	250+
I	1932	Low-alloy; 0.51 Cu, 0.28 Mn	do.	2.0	30	28	100	56	136	57	-------	41	38	[a]30	102	22	-------	20	128
				5.4	47	56	71	95	116	60	-------	107	50	83	305+	98	43	60	[c]217+
				7.4	50	90	94	110	146	149	-------	192	80	90	304+	191	44	[c]90	240
				9.3	58	108	91	172	317+	214	-------	240	[c]140	113	-------	249	74	104	327+
				14.3	92	132	103	141	261+	350+	-------	298+	218	118	[d]317+	210	[d]93	130	350+
J	1932	Low-alloy; 0.62 Cu, 0.83 Mn	do.	2.0	54	36	68	58	120	54	-------	28	38	[a]26	106	30	-------	51	108
				5.4	45	59	80	100	104	70	-------	109	57	60	309+	93	35	83	[c]210+
				7.4	60	97	84	118	156	200	-------	179	25	78	260	184	57	72	276+
				9.3	62	[c]96	[c]63	156	246	193	-------	233	[c]130	80	-------	215	49	85	266+
				14.3	47	108	112	150	256+	350+	-------	314+	152	124	[d]350+	[e]230	[d]57	[e]78	314+
C	1932	Low-alloy; 0.30 Cr, 0.15 Ni	do.	2.0	39	26	80	58	142	68	-------	44	34	[a]15	112	32	-------	10	119
				5.4	40	58	76	91	146	120	-------	124	72	44	250+	101	11	12	250+
				7.4	88	95	83	128	143	161	-------	176	18	53	250+	150	[c]20	[e]132	250+
				9.3	[c]66	123	80	161	[e]250+	141	-------	250+	[c]93	119	-------	216+	24	40	195+
				14.3	171+	184	124	193+	226+	250+	-------	250+	250+	137	[d]250+	222+	[d]56	144	250+
B	1941	Low-alloy; 1.27 Ni, 0.32 Cu	do.	5.0	124	114	77	148	187+	80	106	140	39	122	-------	96	89	102	250+
				[g]7.2	131	118	89	114	237+	227+	250+	171+	69	108	-------	210+	84	97	250+
				8.7	129	115	110	117	185+	141	250+	121	64	136	-------	250+	80	58	250+
				[g]11.0	136	158	199+	114	213+	142	250+	190+	61	172	-------	250+	107	152+	250+
C	1941	Low-alloy; 1.71 Ni, 0.98 Cu	do.	5.0	144	123	112	129	210+	80	90	109	32	112	-------	64	111	86	250+
				[g]7.2	122	114	122	123	229+	250+	250+	168+	72	110	-------	188	78	104	250+
				8.7	215+	117	120	154	161	250+	250+	82	54	133	-------	208+	86	58	250+
				[g]11.0	132	114	180+	112	206+	143	250+	168+	65	122	-------	213+	103	124+	250+
NC	1941	Low-alloy; 2.08 Ni, 1.10 Cu	Plate	5.0	133	110	94	149	138	88	101	118	56	84	-------	110	78	24	250+
				[g]7.2	138	123	89	110	206	237	254	148	74	113	-------	198	82	105	250+
				8.7	148	148	143	163	220	218	268+	123	68	121	-------	220	93	42	250+
				[g]11.0	149	147	152	154	178	153	268+	206	81	139	-------	216	113	55	250+

See footnotes at end of table.

TABLE 30. *Maximum penetration of plain and alloy cast iron in different soils*—Continued

(Average of two specimens, in mils)

Identification		Material	Form	Average exposure	Aeration, test site number, and soil type													
					Good aeration				Fair aeration			Poor aeration			Very poor aeration				
Symbol	Year buried				Cecil clay loam	Hagers-town loam	Susque-hanna clay	Chino silt loam	Docas clay	Mohave fine gravelly loam	Merced silt loam	Muck	Rifle peat	Sharkey clay	Acadia clay	Lake Charles clay	Carlisle muck	Tidal marsh	Cinders
				Soil	53	55	62	65	64	66	70	58	60	61	51	56	59	63	67
				Years															
N	1941	Low-alloy; 3.10 Ni	do	5.0	120	113	76	100	138	[c]80	107	119	66	96	-------	120	80	[e]110	250+
				[g]7.2	131	119	84	102	191	221	240	139	78	107	-------	183	89	114	250+
				8.7	144	140	139	152	218	230	255+	118	65	128	-------	231	92	62	250+
				[g]11.0	163	171	144	158	195	147	265+	143	79	104	-------	248	128	187	250+
D	1941	Low-alloy; 3.32 Ni	Pipe	5.0	136	96	104	157	226+	80	93	144	94	104	-------	50	87	106	250+
				[g]7.2	120	115	135	107	175+	250+	250+	168+	75	116	-------	179	76	121	250+
				8.7	139	126	175+	197+	189+	250+	250+	100	60	122	-------	250+	86	58	250+
				[g]11.0	120	157	223+	185+	250+	115	250+	136	56	132	-------	192+	106	226	250+
E	1932	High-alloy; 15.0 Ni, 6.6 Cu, 2.6 Cr	do	2.0	30	30	[c]43	26	28	26	-------	50	24	[a]36	30	42	-------	22	94
				5.4	36	37	49	42	27	36	-------	34	[c]80	39	50	32	14	16	250+
				7.4	51	41	37	42	40	38	-------	[c]58	[e]22	30	35	53	28	55	250+
				9.3	33	34	53	35	72	40	-------	53	[c]45	[c]36	-------	58	26	[c]32	250+
				14.3	44	51	60	59	34	54	-------	54	72	58	[d]78	72	[d]30	30	250+

[a] Exposed for 1.0 yr only.
[b] +, one or more specimens contained holes because of corrosion.
[c] Data for the individual specimens differed from the average by more than 50 percent.
[d] Data for 4 specimens.
[e] Data for 1 specimen. The other specimen was missing.
[f] Ordinary cast iron horizontally cast in green-sand molds and rattled to remove sand.
[g] Data for 3 specimens.

TABLE 31. *Weight losses of pipe specimens of low-alloy cast irons on a relative basis*

(Relative to weight loss of plain cast iron A = 100)

Soil [a]	Exposure	1.27 Ni 0.32 Cu Pipe B	1.71 Ni 0.98 Cu Pipe C	3.32 Ni Pipe D
INORGANIC-OXIDIZING SOILS				
	Years			
53	5	122	109	109
	7	82	96	90
	9	105	95	98
	11	80	93	86
55	5	114	118	118
	7	92	100	110
	9	94	94	88
	11	84	91	96
62	5	97	106	72
	7	76	73	76
	9	103	88	98
	11	116	120	96
65	5	90	115	81
	7	55	61	41
	9	55	46	50
	11	88	76	109
INORGANIC-REDUCING SOILS				
66	5	132	150	134
	7	93	94	97
	9	111	136	136
	11	117	179	177
56	5	60	63	45
	7	106	108	84
	9	94	107	107
	11	112	105	101
61	5	84	82	76
	7	82	80	77
	9	98	71	78
	11	92	85	88
64	5	104	95	73
	7	92	78	43
	9	102	60	62
	11	99	94	84
ORGANIC-REDUCING SOILS				
58	5	65	48	20
	7	75	66	95
	9	112	85	88
	11	80	83	68
59	5	92	77	53
	7	81	84	87
	9	72	85	71
	11	97	98	96
60	5	31	29	54
	7	89	79	87
	9	97	90	105
	11	67	61	72
63	5	63	61	16
	7	66	81	105
	9	136	102	93
	11	112	84	46

[a] See table 6 for names, locations, and properties of the soils.

weight losses of material D in soils 58 and 63 were only 20 and 16 percent, respectively, of the weight losses of plain cast iron in the same soils for the same period. However, this initial advantage from the addition of nickel was usually not maintained, with the result that the weight losses of the alloy cast irons exposed for the maximum period usually did not differ greatly from the losses of plain cast iron. Hence, it would appear that the rates of corrosion of the alloys containing the higher amounts of nickel decrease less with time than do the rates

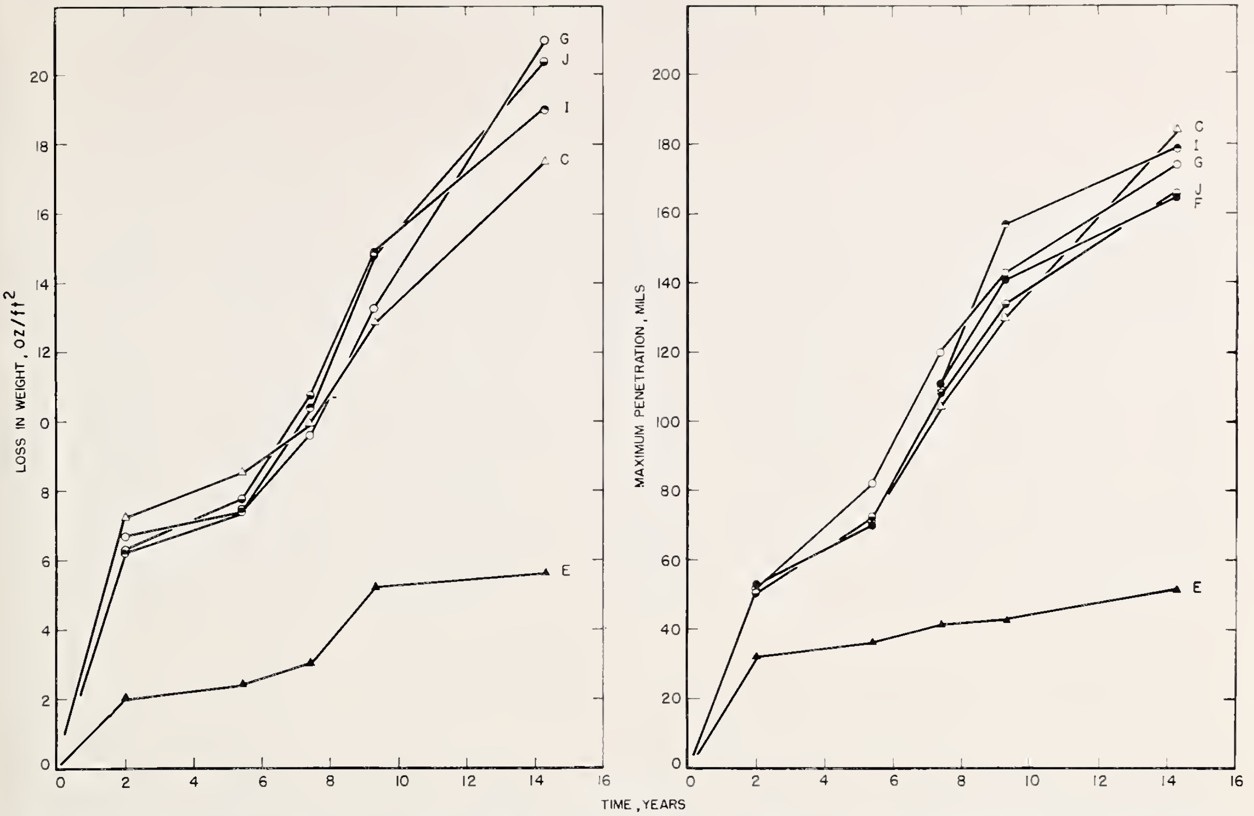

FIGURE 23. *Average loss in weight and maximum-penetration–time curves of cast-iron pipe specimens exposed in 14 soils.*

G, Rattled cast iron; F, sand-coated cast iron; I, cast iron, 0.51-percent Cu, 0.28-percent Mn; J, cast iron, 0.62-percent Cu, 0.83-percent Mn; C, cast iron, 0.30-percent Cr, 0.15-percent Ni; E, cast iron, 15.0-percent Ni, 6.6-percent Cu, 2.6-percent Cr.

for the alloys containing the lower amounts of nickel and plain cast iron.

The corrosion data (tables 29 and 30) for the low-alloy materials I, J, and C, do not indicate any significant improvement in comparison with the plain cast iron, materials A, F, and G.

Following the procedure employed in studying the corrosion of the wrought specimens, the data for weight loss and pitting for each of the cast irons were averaged for all of the soils for each period of exposure. From the results for the pipe specimens buried in 1932, shown as weight-loss and pit-depth–time curves in figure 23, it is evident that weight loss and maximum penetration for all materials were approximately the same for each period of exposure except for the high-alloy austenitic cast-iron specimen, E, which corroded considerably less than the other materials.

c. High-Silicon Cast Iron

Among the materials exposed in 47 test sites in 1922 were specimens of cast iron, containing approximately 14 percent of silicon, which is used extensively for chemical plumbing because of its resistance to many acids. Because of its brittleness, which is characteristic of this material, some of the specimens were injured, and it was not possible to determine accurately for the injured specimens the losses in weight resulting from corrosion.

With very few exceptions, the loss in weight due to corrosion after 10 to 12 years of exposure was negligible. In only one soil, Montezuma clay adobe, soil 28, were the specimens seriously damaged by corrosion. These specimens were split and definitely corroded along the breaks. Similar corro-

TABLE 32. *Average loss in weight of high-silicon cast iron*
(Average of two specimens)

Soil [a]	Duration of exposure	Loss in weight	Soil [a]	Duration of exposure	Loss in weight
	Years	*oz/ft²*		*Years*	*oz/ft²*
1	11.6	0.20	27	10.1	2.35
2	9.9	.06	28	9.6	([b])
4	12.0	.14	29	6.0	[c] 0.21
5	10.2	.44	30	11.6	1.69
6	10.2	.04	31	10.0	0.04
7	11.5	.27	32	11.7	.12
8	11.8	.04	33	11.7	.97
9	11.5	.10	35	10.2	.75
10	12.0	.06	36	10.0	.04
11	11.9	.22	37	10.0	.03
14	11.8	.02	38	12.0	.01
15	10.1	.18	39	12.0	.23
19	11.6	.01	40	10.1	.08
20	11.6	.18	41	12.0	.003
22	11.6	.05	42	10.0	.03
23	12.1	.10	43	12.0	2.52
24	12.0	.06	44	11.6	0.04
26	11.5	.04	46	12.0	.01
			47	12.1	.90

[a] See table 6 for identification of soils.
[b] Both specimens cracked by corrosion.
[c] Data for 1 specimen. The other specimen was cracked.

Table 33. *Corrosion of malleable cast iron and cast steel*

Soil		Duration of exposure	Malleable cast-iron ell, S. Loss in weight	Cast steel ell, E. Loss in weight	High-tensile-strength cast iron, V		Gray cast iron, L	
No.	Type				Loss in weight	Maximum penetration	Loss in weight	Maximum penetration
		Years	*oz/ft²*	*oz/ft²*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*
13	Hanford very fine sandy loam	10.16	13.41	19.81	10.87	126	-----	-----
24	Merrimac gravelly sandy loam	10.63	1.11	4.02	1.06	40	4.74	27
28	Montezuma clay adobe	9.60	13.44	16.03	-----	-----	[a]36.65	[a]353
29	Muck	10.08	10.58	11.69	11.89	100	15.21	145
42	Susquehanna clay	10.05	7.14	7.44	5.73	104	11.27	172
43	Tidal marsh	10.73	21.35	8.69	11.70	163	11.42	157
45	Unidentified alkali soil	10.55	17.62	19.94	22.05	161	17.65	232

[a] Duration of exposure, 11.7 years.

sion of the specimens of this material had been observed in the same soil (soil 28) after exposure for 5 years. Slight rusting or etching was observed in a few other soils, but in no other soil did the corrosion appear to be significant. Table 32 gives the losses in weight for the high-silicon cast-iron specimens for the maximum exposure in each soil.

d. Malleable Cast Iron

The corrosion of gray cast iron starts at and tends to follow the boundaries between the graphite plates and the ferrite crystals. The heat treatment that malleable iron receives slightly reduces the total carbon content, and the free carbon takes the form of small rounded particles. The Bureau tests did not include a sufficient number of specimens to justify a generalization as to the relative corrodibility of gray and malleable cast iron.

The data on malleable iron, high-tensile-strength cast iron, cast steel and, for comparison, ordinary gray cast iron, are given in table 33. The malleable-iron and cast-steel specimens were in the form of elbows, and it was not possible to determine pit depths with available apparatus. However, visual inspection indicated that the pitting did not differ greatly in form and extent from that on ordinary cast iron under the same conditions. A little additional information on the relative corrodibility of malleable cast iron and steel will be found in the section on the corrosion of bolts (table 42).

The specimens reported in table 33 differ considerably in the area exposed and in shape. The gray cast-iron specimens were much larger than the others, were buried at different times, and were exposed for somewhat different periods. The other materials appeared to corrode somewhat less than the gray cast iron, but the differences are not large and may not be significant. Because of the differences in dimensions and exposure conditions, it is not possible to make a strict comparison of the corrosion characteristics.

8.4. Comparison of Wrought and Cast Ferrous Materials

Photographs of specimens of unalloyed steel pipe N and of plain cast-iron pipe G after exposure for 14 years in the various soils are shown in figures 24 and 25, respectively. The corrosion products had been removed by methods described in appendix 2.

Representative corrosion-time curves for the wrought materials that behaved essentially like plain carbon steel are shown in figure 26. Each point on these curves is the average of the weight loss or maximum penetration, in a particular soil, of two specimens of each of the following materials: Low-carbon steel N, hand-puddled wrought iron A, mechanically puddled wrought iron B, and copper-molybdenum open-hearth iron H. Curves for the cast materials are similar but less consistent than those for the wrought materials in this series of exposures.

When the data for both wrought and cast materials are replotted on logarithmic coordinates, the resulting linear projections conform reasonably well to the equations employed previously for comparison of the plain and low-alloy irons and steels, i.e., $P=kT^n$ and $W=k'T^u$. Values for the constants k or k' and n or u, calculated by the method of least squares and presented in table 34, are in agreement with the values reported for other soils in table 18. The relatively large values of k for the group of six soils of fair to good aeration (table 34) were ascribed largely to the depolarization of the cathodic areas by the available oxygen, whereas the low values of k for the poorly aerated soils were considered the result of cathodic polarization because of the deficiency of oxygen in these soils.

The differences between the values of weight loss and pitting for steel and cast iron at 14 years (table 34) were calculated and the standard errors of these differences computed as recorded in table 35. Because the differences between the mean values for weight loss of the cast and wrought materials were, with few exceptions, less than twice the respective standard errors of the differences, it was concluded that no generally significant difference between the weight losses of the two materials can be detected. With respect to maximum penetration, values less than twice the standard error of the difference were noted in the four soils for which the data could be statistically treated; in the remaining five soils, the greater depth of pits on the cast specimens should be considered significant.

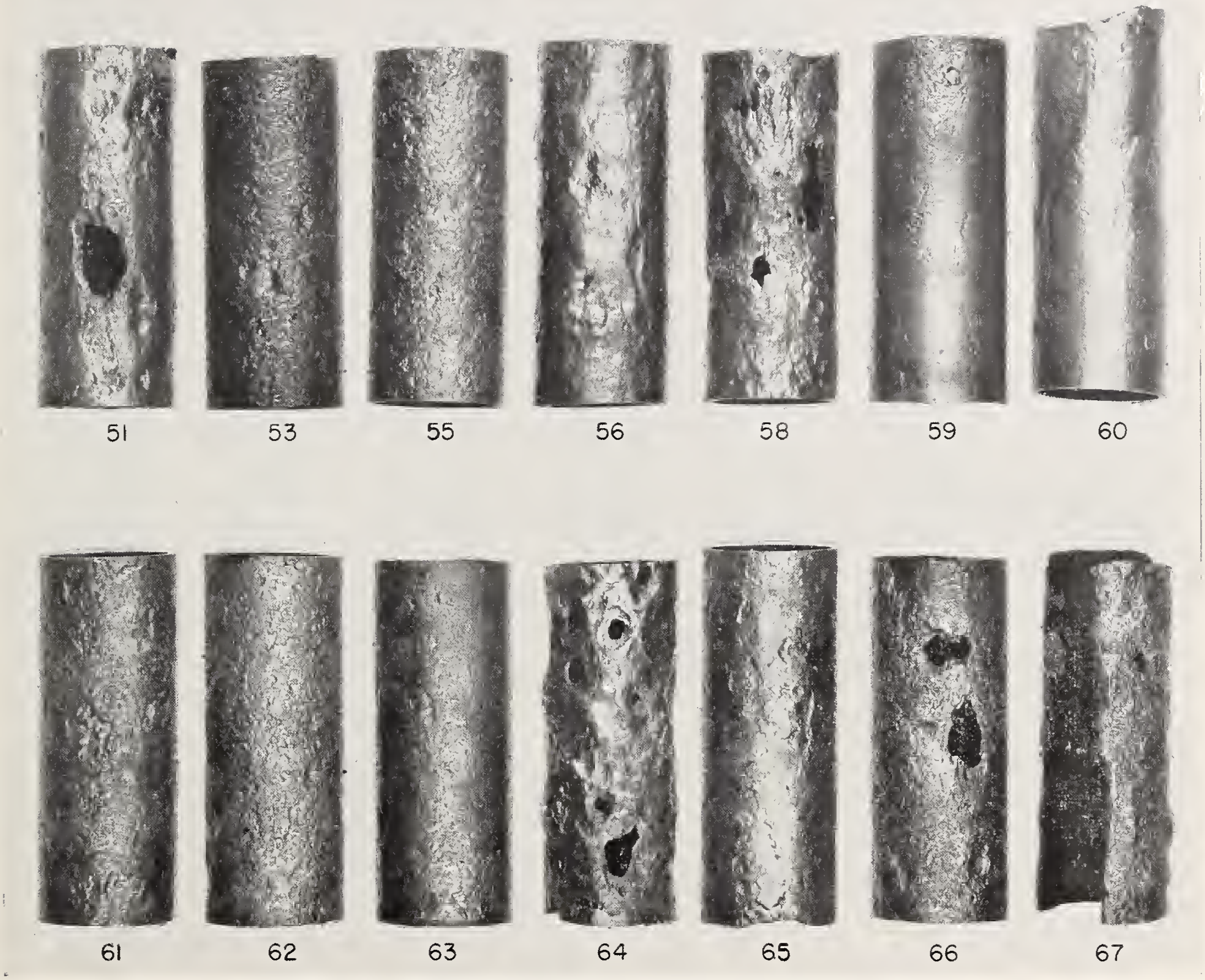

FIGURE 24. *Corrosion of plain carbon steel N exposed 14 years at 14 test sites.*
See table 6 for identification of soils and table 10 for identification of steel N.

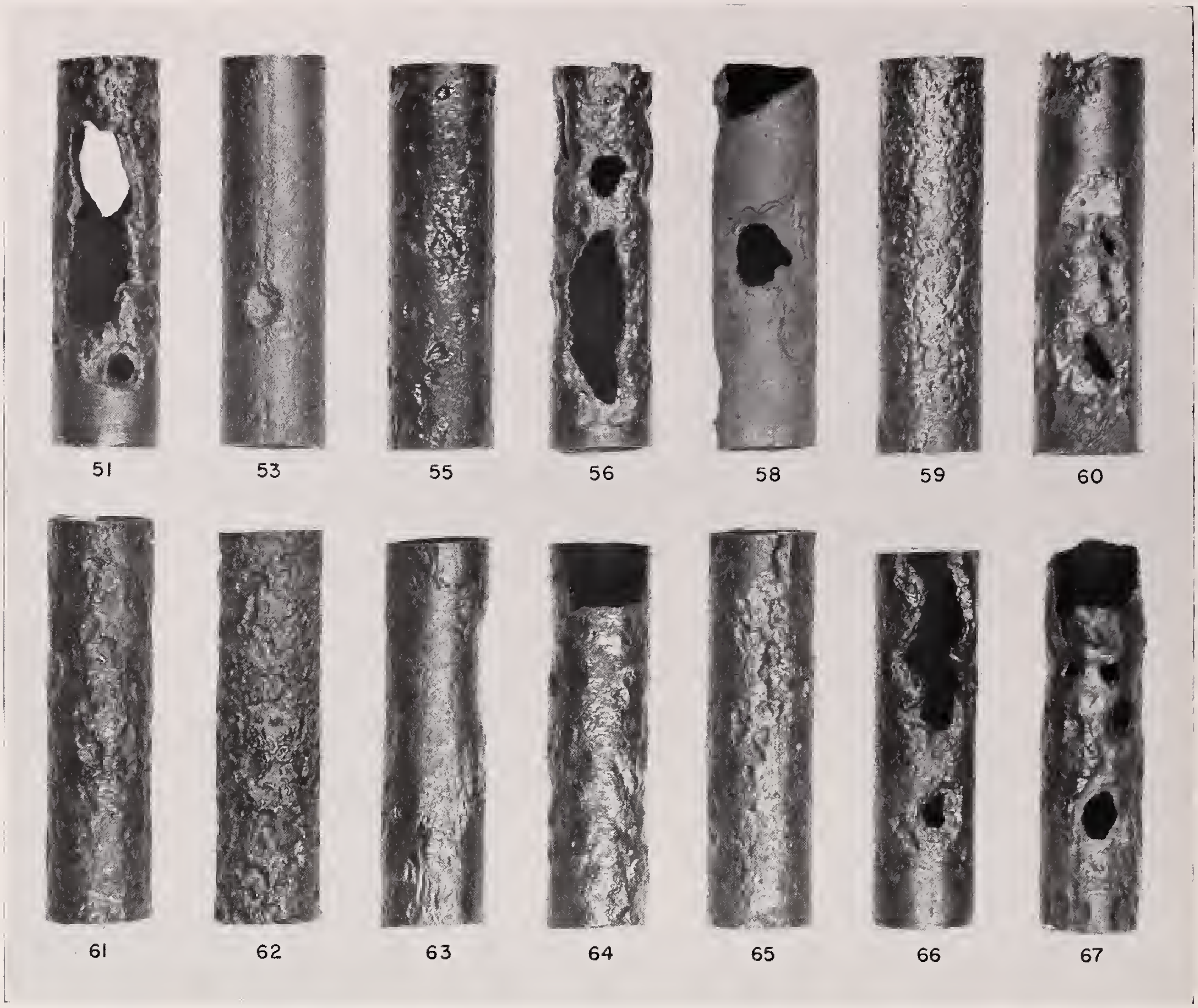

Figure 25. *Corrosion of plain cast iron G exposed 14 years at 14 test sites.*
See table 6 for identification of soils and table 11 for identification of cast iron G.

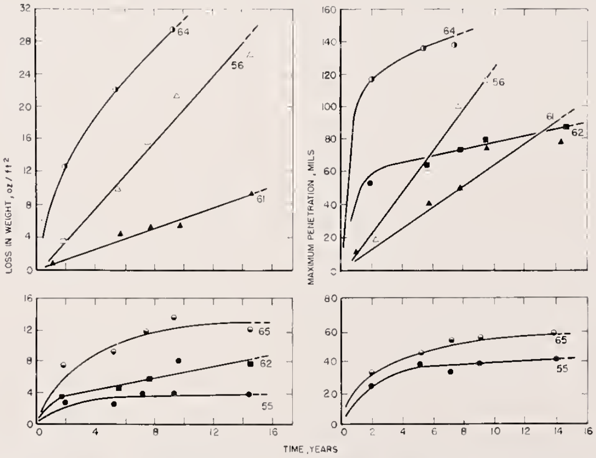

Figure 26. *Weight-loss and pit-depth–time curves for wrought materials in soils of different corrosivities.*

TABLE 34. *Corrosion of wrought and cast materials at 14 years and constants of equations connecting weight loss and maximum penetration with duration of exposure* [a]

Soil		Aeration	Weight loss						Maximum penetration					
No.	Type		$W_{T=14\ yr}$	$\bar{\sigma}_{P_{T=14\ yr}}$	k'	$\bar{\sigma}_{k'}$	u	$\bar{\sigma}_u$	$P_{T=14\ yr}$	$\bar{\sigma}_{P_{T=1\ yr}}$	k	$\bar{\sigma}_k$	n	$\bar{\sigma}_n$
						WROUGHT MATERIALS								
			oz/ft²	*oz/ft²*	*oz/ft²*	*oz/ft²*			*Mils*	*Mils*	*Mils*	*Mils*		
64	Docas clay	Fair	50.9	9.0	8.41	1.71	0.68	0.13	(b)					
66	Mohave fine gravelly loam	do	15.0	1.6	7.12	1.12	.28	.09	(b)					
65	Chino silt loam	Good	13.1	1.1	6.04	.89	.29	.08	108	9	57.9	8.9	0.24	0.08
62	Susquehanna clay	Fair	6.9	1.0	3.18	.87	.29	.14	83	5	55.7	6.4	.15	.06
55	Hagerstown loam	Good	3.4	.4	2.08	.52	.19	.13	82	6	40.8	5.6	.27	.08
53	Cecil clay loam	do	4.2	.4	2.46	.44	.20	.09	77	8	34.1	6.3	.31	.09
60	Rifle peat	Poor	17.8	6.2	2.61	1.78	.73	.33	56	16	16.4	9.0	.46	.27
63	Tidal marsh	Very poor	7.7	1.5	1.58	.64	.60	.20	81	11	13.8	3.8	.67	.14
61	Sharkey clay	Poor	9.3	.8	1.12	.14	.80	.07	92	8	13.5	1.7	.72	.06
56	Lake Charles clay	Very Poor	30.5	2.3	1.72	.25	1.09	.08	(b)					
58	Muck	Poor	21.0	1.8	1.85	.31	.92	.08	194	54	9.1	2.8	1.16	.17
59	Carlisle muck	Very poor	4.1	.1	.49	.02	.81	.02	36	2	4.4	.7	.80	.07
51	Acadia clay	Poor	20.9	.2	5.59	.10	.50	.09	(b)					
67	Cinders	Very poor	41.0	3.0	8.67	.76	.59	.06	(b)					
						CAST MATERIALS								
64	Docas clay	Fair	58.0	5.8	9.12	1.4	0.70	0.09	140	20	120	20	0.06	0.10
62	Susquehanna clay	do	5.9	1.1	5.53	1.8	.03	.16	98	10	70.5	14.0	.13	.10
65	Chino silt loam	Good	10.7	1.4	9.91	2.4	.03	.12	163	14	40.5	6.4	.53	.08
66	Mohave fine gravelly loam	Fair	8.0	1.5	5.78	.68	.12	.16	224	58	34.5	13.3	.71	.22
53	Cecil clay loam	Good	2.4	.5	3.13	1.4	−.11	.22	81	10	28.5	6.8	.39	.12
61	Sharkey clay	Poor	10.1	1.0	1.12	.17	.84	.08	110	8	28.1	3.0	.52	.05
60	Rifle peat	do	17.0	8.0	4.45	4.3	.51	.43	72	68	23.7	29.0	.42	.59
55	Hagerstown loam	Good	2.3	.4	2.82	.96	−.07	.17	146	17	20.5	4.3	.74	.11
58	Muck	Poor	32.0	2.4	3.05	.35	.89	.06	369	26	14.9	1.3	1.22	.05
63	Tidal marsh	Very poor	6.1	2.3	1.96	1.5	.70	.09	126	7	14.8	1.8	.81	.06
56	Lake Charles clay	do	40.5	6.8	3.12	1.0	.97	.16	369	51	12.1	2.0	1.30	.11
59	Carlisle muck	do	5.4	.5	.51	.16	.89	.14	67	11	10.5	4.3	.70	.26
51	Acadia clay	Poor	29.6	6.0	11.4	.96	.36	.16	(b)					
67	Cinders	Very poor	60.3	14.0	19.4	7.0	.43	.20	(b)					

[a] $W=k'T^u$, $P=kT^n$, where W = weight loss at the time, T; and P = depth of the deepest pit at the time, T.
[b] Specimens perforated at an early period. See tables 15 and 22 for data on pit depths.

TABLE 35. *Comparison of wrought and cast materials at 14 years*

Soil [a]	Loss in weight (oz/ft²)							Maximum pit depth (mils)						
	Wrought materials		Cast materials		Difference between the means	Standard error of the difference [b]		Wrought materials		Cast materials		Difference between the means	Standard error of the difference [b]	
	Mean	Standard error	Mean	Standard error				Mean	Standard error	Mean	Standard error			
	$\bar{X}_1$	$\bar{\sigma}_1$	$\bar{X}_2$	$\bar{\sigma}_2$	$\bar{X}_1-\bar{X}_2$	$\bar{\sigma}_D$	$2\sigma_D$	X_1	$\bar{\sigma}_1$	$\bar{X}_2$	$\bar{\sigma}_2$	$\bar{X}_1-\bar{X}_2$	$\bar{\sigma}_D$	$2\sigma_D$
51	20.9	0.2	29.6	6.0	−8.7	6.0	12.0							
53	4.2	.4	2.4	.5	+1.8	.7	1.4	77	8	81	10	−4	12	24
55	3.4	.4	2.3	.4	+1.1	.6	1.2	82	6	146	17	−64	18	36
56	30.5	2.3	40.5	6.8	−10.0	7.2	14.4							
58	21.0	1.8	32.0	2.4	−9.0	3.0	6.0	194	54	369	26	−175	60	120
59	4.1	.1	5.4	.5	−1.2	.5	1.0	36	2	67	11	−30	11	22
60	17.8	6.2	17.0	8.0	+.8	10.1	20.2	56	16	72	68	−16	70	140
61	9.3	.8	10.1	1.0	−.8	1.3	2.6	92	8	110	8	−18	11	22
62	6.9	1.0	5.9	1.1	+.9	1.5	3.0	83	5	98	10	−16	11	22
63	7.7	1.5	6.1	2.3	+1.6	2.8	5.6	81	11	126	7	−45	13	26
64	50.9	9.0	58.0	5.8	−7.1	10.7	21.4							
65	13.1	1.1	10.7	1.4	+2.4	1.8	3.6	108	9	163	14	−55	17	33
66	15.0	1.6	8.0	1.5	+7.0	2.2	4.4							
67	41.0	3.0	60.3	14.0	−19.0	14.3	28.6							

[a] See table 6 for type, location, and properties of soils.

[b] $\sigma_D=\sqrt{\frac{\sigma_1^2}{N_1}+\frac{\sigma_2^2}{N_2}}$, in which N_1 and N_2 are the number of observations made on the specimens of wrought and cast iron, respectively.

8.5. Effect of Corrosion on Bursting Strength

One of the characteristics of the corrosion of cast iron in soils is the conversion of the metal into a layer consisting chiefly of iron oxides and graphite. This phenomenon is not readily detectible on visual examination prior to thorough cleaning of the specimens, as shown in figure 27. It is generally recognized that corroded cast iron retains some of its original strength, but the extent to which cast-iron pipe may corrode underground and still retain sufficient strength to withstand the pressures commonly used in water- and gas-distribution systems has not been investigated thoroughly.

In 1928, two 3-ft. sections of 6-in. cast-iron pipe were buried in four test sites. The specimens were equipped with connections so that hydraulic pressures up to 400 lb/in.^{2} could be applied periodically

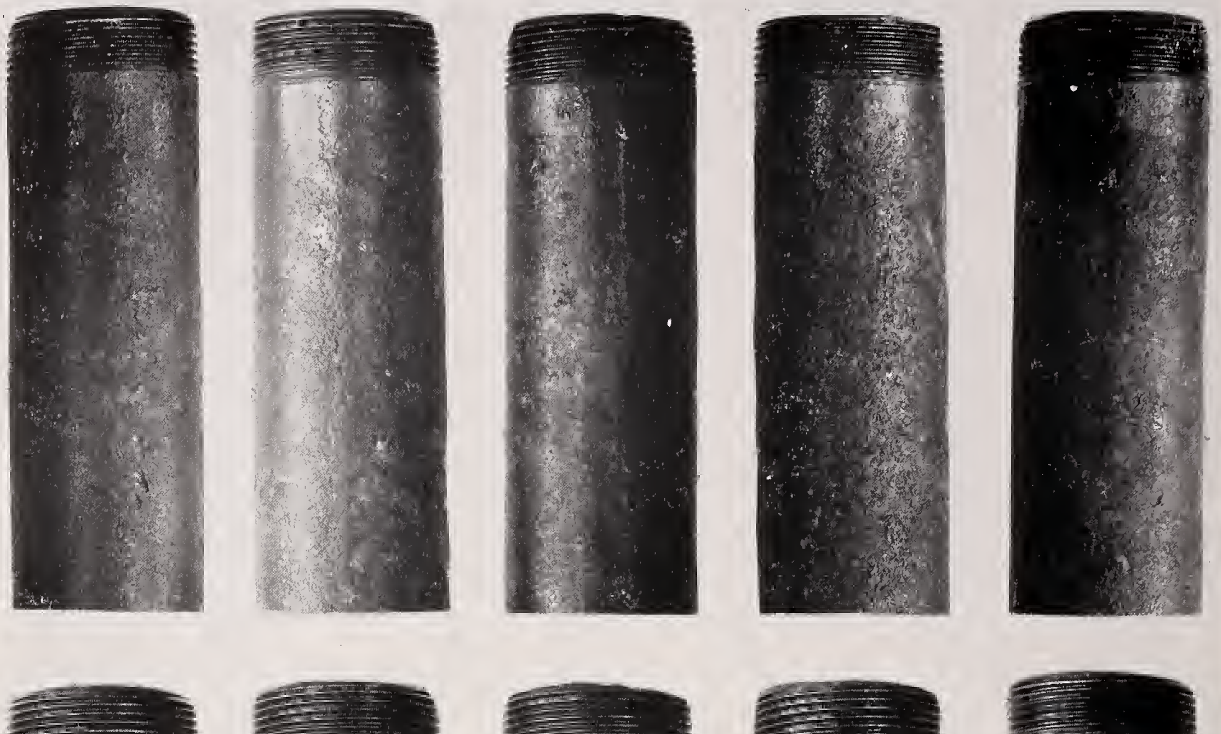

Figure 27. *Condition of cast iron exposed for approximately 11 years to highly corrosive soils before (top row) and after (bottom row) removal of the corrosion products.*

A, Lake Charles clay, soil 56; B, muck, soil 58; C, tidal marsh, soil 63; D, Docas clay, soil 64; E, Merced silt loam, soil 70. For identification of soils see table 6.

to the buried specimens. These specimens were all of class 150 pipe, i.e., they were designed to withstand hydraulic pressures of 150 lb/in.² The results obtained are recorded in table 36, together with data for pit depth and weight loss obtained from exposure to the same soils of similar pipes. Results in table 36 show that the undisturbed specimens maintained their ability to resist hydraulic pressure long after similar specimens were removed from the burial sites, and after cleaning, were found to to be deeply pitted or even perforated.

An additional investigation of the effect of corrosion of cast iron on its resistance to hydraulic pressure was made on 1½-in. specimens of cast-iron pipe after they had been exposed up to 11 years in some of the more corrosive soils. The specimens had been in storage in the laboratory for 6 months to a year after their removal from the burial sites and were not cleaned before the hydraulic tests were made. During the storage period cracks and bulges developed in some of the corroded areas because of drying-out effects and also because of atmospheric oxidation of the corrosion products. The changes that occur during storage plus the possible damage to the corroded areas, through handling and shipping, obviously would affect the hydraulic bursting strength. The data in table 37 show that most of the specimens were able to withstand pressures up to 500 lb/in.², even though the same specimens, after cleaning, were completely perforated by the corrosion products. At least some of the failures that occurred, at pressures below 500 lb/in.², were caused or influenced by the storage and handling operations.

Specimens of standard (0.250-in. wall thickness) and lightweight (0.125-in. wall thickness) steel pipe were subsequently tested in the same sites and under the same conditions as for the cast-iron specimens recorded in table 36. The lightweight pipe exposed in soil 15, and the standard pipe in all four test sites, withstood 400-lb. pressure when last tested, at the end of 12 years of exposure. By that time the pipes should have been perforated by corrosion, as indicated by the short steel-pipe specimens removed from the same sites. On the other hand, the lightweight steel specimens exposed in soils 64, 70, and 113 all failed at pressures of 150 lb/in.² or less, after only 3 years of exposure. These short-time failures presumably reflect a difference in the type and coherence of the corrosion products formed on cast iron and steel in the same soil.

These results on both cast iron and steel indicate that serious corrosion and even complete perforation by corrosion products does not always destroy the ability of the pipe to transport liquids.

Table 36. *Condition of cast-iron pipe withstanding a maximum hydraulic pressure of 400 lb/in.² [127]*

Soil		Specimens exposed for measurement of weight loss and pitting				Specimens exposed for application of hydraulic pressure of 400 lb/in.²	
Number	Type	Exposure	Wall thickness	Maximum pit depth	Average penetration	Maximum period of exposure	Wall thickness
		Years	*Mils*	*Mils*	*Mils*	*Years*	*Mils*
15	Houston black clay.	17.6	450	226	14.9	24	450
64	Docas clay	5.0	250	250+	30.4	12.5	450
70 (23)	Merced silt loam	6.2	450	450+	58.4	24	450
113	Imperial clay	5.9	450	347	49.3	24	450

Table 37. *Hydraulic pressure data and number of perforations of cast-iron pipe samples, 1.5-inch diameter, 0.250-inch wall thickness [127]*

Soil	Exposure	Sample	Pipe A		Pipe B		Pipe C		Pipe D	
			Bursting pressure	Number of holes	Bursting pressure	Number of holes	Bursting pressure	Number of holes	Bursting pressure	Number of holes
	Years		*lb/in.²*		*lb/in.²*		*lb/in.²*		*lb/in.²*	
56	7.2	a	350	2	500+	1	---	---	---	---
		b	500+	1	500+	1	---	---	---	---
	8.7	a	500+	3	500+	1	500+	3	500+	2
		b	---	---	500+	1	---	---	500+	1
	10.9	a	500+	1	500+	1	---	---	---	---
		b	500+	5	500+	10	500+	6	500+	8
58	7.2	a	500+	1	500+	1	500+	1	500+	1
	10.9	a	500+	1	500+	1	500+	2	---	---
64	7.2	a	500+	6	0	7	50	10	500+	3
		b	500+	5	200	5	150	6	---	---
	8.8	a	425	4	500+	4	---	---	500+	1
	11.0	a	500+	2	500+	3	375	4	500+	2
		b	500+	10	---	---	225	6	500+	3
		c	---	---	---	---	---	---	350	7
66	7.2	a	450	5	---	---	500+	3	---	---
		b	500+	2	---	---	0	6	0	7
	8.8	a	500+	1	---	---	500+	6	275	3
		b	---	---	---	---	350	4	500+	5
	11.0	a	500+	1	---	---	---	---	---	---
70	7.2	a	500+	5	0	14	500+	6	500+	7
		b	500+	4	0	11	0	12	0	14
	8.8	a	---	---	500+	6	0	12	0	12
		b	---	---	425	8	500+	7	300	9
	11.0	a	500+	12	175	18	---	---	500+	9
		b	50	16	500+	6	---	---	---	---
		c	500+	11	---	---	---	---	---	---

8.6. Miscellaneous Factors in Corrosion of Ferrous Materials

Field tests to establish the effect of some of the miscellaneous factors, discussed in section 4, are recorded herewith.

a. Depth of Burial

As discussed in a previous section, the rate of corrosion will be influenced by the depth of burial. For example, pipeline operators have often reported more severe corrosion where their lines are deeper than usual.

In order to investigate the effect of depth of burial, samples of 3-in. steel pipe were buried in 1928 at different depths in 7 soils, with results shown in table 38. In 5 of the 7 soils, the specimens corroded more at the greater depths, but in 2 of the soils the reverse was true. This may be due to the subsoils, for instance, in the case of St. John's sand (soil 37) there is an impervious hardpan layer about 6 in. thick, at about 18 in. below the surface of the ground. Pipes laid in or above this layer may corrode very rapidly because at times they may be surrounded by water that cannot drain through the layer. Pipes laid deeper will be in sand from which the water will drain more readily and corrosion will be less severe. In some of the arid Western soils, alkali may concentrate near the surface or at considerable depths, and corrosion of the pipe will depend upon the alkali concentration at the depth of burial. This accounts for the variable behavior of alkali soils 103, 110, 113, and 117. Thus it can be seen that, although corrosion in general increases with depth of burial, there are exceptions because of drainage factors and other characteristics of soil horizons.

TABLE 38. *Effect of depth of burial on corrosion of 3-inch steel pipe*

(Average of four specimens)

Soil No.	Soil Type	Duration of exposure	Depth of burial	Loss in weight	Maximum penetration
		Years	*in.*	*oz/ft²*	*Mils*
37	St. John's fine sand	11.7	12	10.1	67
			24	9.0	64
			36	5.3	50
			48	4.7	44
103	Billings silt loam (alkali)	9.3	14	16.3	118
			22	18.0	136
			28	17.7	143
			48	20.8	172
104	Cecil clay	11.7	18	5.6	80
			30	8.2	102
			36	9.1	110
			52	7.9	166
107	Cecil fine sandy loam	11.7	12	3.9	53
			24	4.4	64
			36	4.8	89
110	Fresno fine sandy loam (alkali)	9.2	19	14.0	113
			26	18.2	124
			42	18.6	159
113	Imperial clay (alkali)	5.9	12	17.9	166
			22	20.0	211
			28	21.7	212
			40	21.7	198
117	Merced clay loam adobe (alkali)	9.3	12	20.3	127
			24	19.1	122
			36	19.7	87
			48	12.1	83

b. Mill and Foundry Scale

In order to study the influence of the surface condition on corrosion, specimens of several cast and hot-rolled materials were buried in six soils in 1926. Samples of each material were buried in their original condition and with the scale removed by a lathe or grinder. Table 39 shows the average rates of corrosion of these specimens after approximately 8 years of exposure.

It is evident from table 39 that the specimens from which the scale had been removed corroded somewhat less than those having a coating of mill scale, but the improvement is very slight. Evidently, the effects of discontinuities in the oxide coating are less important for the thick coatings formed at high temperatures than for the thin, passive film formed at room temperatures.

TABLE 39. *Effect of mill and foundry scale on corrosion*

(Period of exposure was approximately 8 years)

Soil		Pit cast iron		deLavaud cast iron		Steel		Wrought iron	
No.	Type	Normal, A	Machined, MC	Normal, C	Machined, MD	Normal, P	Ground and polished, M	Normal, K	Rough ground, D
	RATE OF LOSS IN WEIGHT (oz/ft²/yr)								
13	Hanford very fine sandy loam	1.12	1.29	0.05	1.10	1.70	1.51	1.12	1.01
24	Merrimac gravelly sandy loam	.11	.13	.17	.16	---------	---------	.22	.18
29	Muck	2.31	.99	5.28	1.27	1.21	1.06	1.18	1.22
42	Susquehanna clay	.70	.43	.59	.47	.89	.94	.88	.80
43	Tidal marsh	1.08	1.00	3.08	1.20	.86	1.14	.67	.67
45	Unidentified alkali	3.50	---------	3.55	2.59	2.64	2.26	2.51	2.17
	RATE OF PENETRATION (mils/yr)								
13	Hanford very fine sandy loam	17.8	12.8	7.8	9.1	19.3	15.3	11.9	11.1
24	Merrimac gravelly sandy loam	3.6	3.2	3.8	2.4	---------	---------	4.7	3.8
29	Muck	11.4	5.0	10.7	8.9	10.5	9.8	6.3	7.3
42	Susquehanna clay	17.9	15.9	7.0	8.9	8.8	10.0	10.3	9.4
43	Tidal marsh	14.1	5.2	27.5	11.5	10.8	8.1	15.3	9.7
45	Unidentified alkali	22.3	---------	14.3	15.7	16.6	13.0	12.9	18.2

c. Area Effects

Correlation of laboratory or exposure test results with pipeline performance involves many factors, including the area under observation. It was recognized early in the Bureau's studies that comparison of results obtained from specimens of the same sizes and diameters was more practical than when different sizes and diameters were involved. For example, the exponential equations for pit depth and weight loss applied reasonably well to the wrought materials of the same size and diameter shown in figure 26, but did not apply so well to cast materials of different diameters and areas, in the same exposure program.

To obtain data on this area effect, specimens of 1½-in.- and 3-in.-diameter pipe were buried in 1922 in a number of soils. The maximum pit depths after 12 years of exposure, as recorded in table 40, tended to occur on the larger areas, with considerable variation from soil to soil and from one material to another. This tendency is contrary to the conclusion of Shepard [154], that the greater curvature of the small diameter specimens should tend to intensify pitting in the smaller areas.

Scott [155] in 1934 published the results of an extended investigation of this area effect, based on a review of the Bureau's data available at that time for wrought ferrous materials, together with measurements of pits in areas up to 10,000 ft^2 on oil and gas steel lines. The method of calculation used by Scott was as follows: The depth of the average deepest pit in a unit area defined as one length of pipe in an 8-in. pipeline or one 3-in. diameter specimen in the Bureau's tests, was determined. The average depth of the deepest pits in areas twice as great was found, and the process was extended until the entire areas had been covered. When the logarithms of the mean pit depths for the successively increasing areas were plotted against the logarithms of the corresponding areas, a curve that was very nearly a straight line was obtained. Its slope gave the value of a, and its y intercept at log $A=0$ (area$=1$) gave the logarithm of b. These values were then used in an equation, for pitting corrosion, as follows:

$$P=bA^a$$

where P is the maximum pit depth, in mils; a and b are the constants referred to above; and A is the unit area, 7 ft^2 (one 20-ft length of an 8-in. pipeline) or 0.4 ft^2 for a 3-in. specimen. In this connection, it should be pointed out that recent advances in statistical theory have provided a theoretical explanation for this logarithmic relationship. This theory is concerned with certain basic characteristics common to extreme values, such as maximum pit depths and other maximum phenomena. A study of the statistical behavior of extreme values leads to simple results, among which is the logarithmic relationship, that have been found useful in the field of corrosion. The statistical theory has been developed in a set of lectures by Gumbel [155a], and reports of successful application of this theory to corrosion are beginning to appear [155b,155c,155d].

The above equation is similar in form to the exponential equations previously used in this report for pit depth and weight loss, but Scott's equation emphasizes area as a factor, whereas the other equations emphasize the effect of time.

Scott determined values for constants a and b for a number of soils in the Bureau's test sites and was thereby able to correlate results of available data on wrought materials. He also found the

TABLE 40. *Effect of area inspected on the observed maximum pit depths after 12-year exposures*

(Pit depths in mils)

Soil ↓	Depth of maximum pit			
	Bessemer steel		Wrought iron	
Area →	[a]66 in.^{2}	[b]126 in.^{2}	66 in.^{2}	126 in.^{2}
1	119	101	81	83
3	71	72	90	96
4	85	84	88	93
5	49	55	52	46
6	19	40	22	38
7	46	65	43	48
8	77	119	103	84
9	36	50	46	47
10	43	60	54	52
12	57	72	58	91
15	58	85	61	83
16	61	69	67	60
17	42	47	40	42
18	44	50	48	43
19	78	61	71	79
20	78	56	52	51
22	71	71	66	60
24	25	31	25	29
26	48	39	47	45
27	73	83	52	59
30	61	69	52	56
31	36	45	31	46
32	48	70	47	67
33	92	103	108	111
34	42	60	42	66
35	28	90	42	59
36	54	47	49	50
37	79	99	73	82
38	37	52	44	29
39	53	113	58	74
40	73	83	71	70
41	87	80	127	89
42	131	97	95	98
43	108	90	80	173
44	63	99	58	73
45	113	137	106	92
46	75	136	72	80
47	30	29	59	38
Average for 38 soils	63	74	63	68

[a] Specimens 1½ in. in diameter. [b] Specimens 3 in. in diameter.

equation applicable to data obtained from pipelines exposed in soil similar to that of one or another of the Bureau test sites. Logan, Ewing, and Denison [106] described subsequent work done at the Bureau on Scott's equation and developed modifications in it. Statistical analysis, by the method of Shewhart [156], of the a values for a number of soils failed to establish a correlation between those values and any specific property of the different soils, although there was a suggestion that the area constant may be influenced by the drainage factor.

Ewing [85] showed that when the pit-depth–area relationship was determined by rearrangements of the same data to obtain the maximum pit on different areas, the shape of the pit-depth–area curve depended on the way in which the measurements on a unit area were grouped. After developing a method for a random arrangement of the data, Ewing found that on the average, the following equation fitted the data better than did Scott's equation:

$$P = P_1\,(C \log A + 1),$$

where P is the maximum pit depth on a total area, A; P_1 is the maximum pit depth on a unit area; and C is a constant varying with soil conditions.

It was concluded that these empirical equations approximate the relation between area and pit depth but do not represent the relation as accurately as might be desired. It is obvious that different results would be expected to be obtained from specimens of such large diameter that they were exposed in more than one soil horizon, as compared with small specimens exposed in only one horizon in the same test site. However, the data in table 40 showed that doubling the area, 1½- and 3-in.-diameter specimens, did not have a large or consistent effect, and attempts to explain data obtained from long lengths of pipelines, on the basis of the area factor, have not been completely successful, probably because of inability to hold all other factors constant over a length of pipeline.

d. Pit-Depth–Time Relations

The relation between the maximum pit depth and the time of exposure was the subject of extensive investigation at the Bureau and elsewhere during a 10-year period beginning about 1930.

Scott [161] proposed the equation

$$P = \frac{UT}{B+T},$$

where P is the pit depth at time T, and U and B are constants for the soil or soils. Subsequent work at the Bureau led to the development of the equation $P = kT^n$, which appeared to be more applicable to the Bureau's data, and which has been used in preceding sections of this report. Denison [106] established the applicability of this equation to Bureau test data, and Ewing [85] found that the development of leaks in some gas pipelines was consistent with the equation.

From studies of individual pipelines, equations of different types were developed by Fetherstonhaugh [157], Putnam [158], and Brennan [159]. Brennan's equation was $y = (A + BZ) \log [x/(h+1)]$, where y is the pit depth at time x, Z is the Corfield soil-corrosivity index [160], and A, B, and h are derived constants. Putnam [158] proposed the equation $P = KT^{0.61}$, which resembles the Bureau's equation, although Putnam uses a single exponential value, indicating that the pit-depth–time relationship is the same for all soils. Fetherstonhaugh's equation [157] was $D = A^3 T^{\frac{1}{3}}$, where D is the pit depth at time T, and A is the pit depth for unit time of exposure.

Each of these three equations was applicable to specific sets of data, but the Bureau's equation $P = kT^n$ is generally more applicable.

9. Engineering Significance of Results on Ferrous Materials

There are so many diverse factors that affect the corrosion of pipes and other structures underground that the planning of adequate tests and the proper interpretation of the results are matters of considerable difficulty. It is not surprising, therefore, that even experienced corrosion engineers often interpret the same experimental data in different ways. For this reason, it is necessary to guard against the acceptance of too far-reaching or erroneous conclusions, which may be based upon insufficient data or which may be due to failure to take into consideration all the pertinent facts. On the other hand, it is necessary to make as much use as possible of the limited data because the cost of tests sufficiently extensive to warrant definite conclusions on a statistical basis would be prohibitive, even if such tests were feasible.

In interpreting the data obtained in the National Bureau of Standards soil-corrosion investigation, the reader should keep in mind that information about the causes of corrosion underground was nonexistent at the start of the investigation and that many of the early burial programs were exploratory in nature. Much information has been derived from the various attempts to establish the importance of individual factors, or the results of the combined action of several factors, on the progress of underground corrosion, and the results of these NBS tests have been major contributions to the clarification of questions of underground corrosion, but the final answer and the complete understanding of the phenomenon have not yet been attained.

In reviewing the NBS data at this time, it appears that not enough attention was given to the amount of moisture present at the surface of the specimens, the continuity of maintenance of this moisture content, and the periodicity of replenishment. This may be a factor in explaining the observed discrepancies in results from duplicate specimens and from exposure for successive time intervals in the same test site, which frequently are unduly irregular even for corrosion test results. Moisture content, drainage, and other factors were combined by several of the experimenters under the general heading of "aeration," but moisture or water now appears to be important by itself, aside from its effects on the availability of atmospheric oxygen. It seems obvious that in very dry soils, corrosion by atmospheric oxygen will not be serious. In other words, the corrosivity of any soil will vary in different locations and, even in the same test site, will vary from year to year, depending upon the amount and frequency of the rainfall. In atmospheric exposures it is now accepted that, at any one test site, damage incurred during the first year of exposure varies with the season of the year the exposure was started, and, furthermore, the annual damage varies from year to year, all for reasons not yet completely understood.

The foregoing comments indicate the difficulty to be effected in attempting to extrapolate or predict from the results of underground-corrosion tests, unless complete information is available in regard to all factors and to their interrelated action. This complete information is not available today and was certainly not available when the underground-corrosion investigation was in progress. Thus the test results for a particular soil apply primarily to a particular location or test site and to a particular year or years. Even so, the divergence of test results may be so great that generalities must be drawn with care, and any attempt to extend test results or to extrapolate from them can be done only in approximate fashion.

This inability to make precise quantitative interpretations of, and predictions from, underground-corrosion test data was recognized by several of the NBS investigators, although the difficulties were not as well understood as they are today. Logan [85] discussed computations that were based on a combination of Ewing's pit-depth–time and pit-depth–area equations, in the hope that the combined equations would yield more quantitative results than could be derived from either equation alone. The combined equation was $P=kT^n\,(C\log A+1)$. The computations were confined to data from wrought ferrous materials, i.e., open-hearth iron, wrought iron, Bessemer steel, and plain and copper-bearing open-hearth steel, which were satisfactorily consistent; the data for cast iron were more erratic and, therefore, were not used. Further computations developed values for the deepest pit to be effected in 30 years, for the length of pipe in which a perforation could be effected in 30 years, and for the time for perforation to occur in a 1,000-ft. length of pipe, for wrought ferrous materials exposed in different soils at 47 NBS test sites. The values in table 41 are condensed from the extended discussion of this subject by Logan [4,84]. The values for the

TABLE 41. *Calculated pit depths and leaks on a pipeline according to Ewing's combined equations*

(Based on measurements on a pipeline in which the length of a unit section was 1,000 feet; diameter of pipe, 8.625 inches; thickness of pipe wall, 322 mils)

Soil		Deepest pit in 30 years	Standard error	Length of pipe per puncture in 30 years	Time for puncture per 1,000 feet of pipe
No.	Type				
		Mils	*Mils*	*ft*	*Years*
1	Allis silt loam	351	53	3.1×10^2	25
2	Bell clay	195	42	1.6×10^7	130
3	Cecil clay loam	235	36	1.9×10^5	190
4	Chester loam	390	130	9.1×10	22
5	Dublin clay adobe	211	61	1.8×10^6	74
6	Everett gravelly sandy loam	55	9	--------	--------
7	Maddox silt loam	149	22	1.3×10^{11}	160
8	Fargo clay loam	266	35	2.4×10^4	55
9	Genesee silt loam	169	54	1.4×10^8	1,700
10	Gloucester sandy loam	237	64	1.0×10^5	62
11	Hagerstown loam	272	42	1.4×10^4	51
12	Hanford fine sandy loam	159	208	2.4×10^9	6,500
13	Hanford very fine sandy loam	275	100	8.8×10^3	74
14	Hempstead silt loam	545	116	4.0	10
15	Houston black clay	178	39	1.2×10^9	190
16	Kalmia fine sandy loam	252	63	7.8×10^4	64
17	Keyport loam	108	26	8.7×10^{15}	9,400
18	Knox silt loam	134	35	8.2×10^{12}	4,000
19	Lindley clay loam	188	17	2.0×10^8	140
20	Mahoning silt loam	234	58	1.2×10^5	63
21	Marshall silt loam	364	52	1.7×10^2	24
22	Memphis silt loam	149	11	6.9×10^{12}	1,200
23	Merced silt loam	640	144	.7	8
24	Merrimac gravelly sandy loam	80	19	1.1×10^{20}	8.8×10^6
25	Miami clay loam	125	16	7.7×10^{15}	780
26	Miami silt loam	211	93	3.6×10^6	85
27	Miller clay	343	76	4.4×10^2	27
28	Montezuma clay adobe	865	362	.02	10
29	Muck	783	154	.50	7
30	Muscatine silt loam	187	100	6.0×10^7	84
31	Norfolk fine sand	117	22	9.1×10^{12}	----------
32	Ontario loam	229	51	2.2×10^5	84
33	Peat	585	197	2.6	13
34	Penn silt loam	280	96	7.9×10^3	39
35	Ramona loam	229	60	7.3×10^4	120
36	Ruston sandy loam	114	11	1.2×10^{17}	5.2×10^4
37	St. Johns fine sand	328	60	7.8×10^2	28
38	Sassafras gravelly sandy loam	109	15	5.6×10^{14}	3.3×10^3
39	Sassafras silt loam	297	45	3.2×10^3	35
40	Sharkey clay	365	76	1.8×10^2	23
41	Summit silt loam	210	78	1.3×10^7	90
42	Susquehanna clay	279	14	1.5×10^4	48
43	Tidal marsh	605	90	2.8	17
44	Wabash silt loam	260	52	2.6×10^4	60
45	Unidentified alkali soil	530	174	3.6	16
46	Unidentified sandy loam	331	52	7.1×10^2	26
47	Unidentified silt loam	134	28	1.2×10^{10}	550

various constants in the formulas are given in these references.

As Logan pointed out, these numerical values express the corrosivity of the soils at the test sites qualitatively, but attempts to compare these numerical values with the very limited amount of data available for actual pipeline operations were not very satisfactory. This is only natural when it is considered that the test specimens were small, isolated from one another, and exposed in a single trench in one soil at a site free from stray currents. On the other hand, a long pipeline usually has had protective coatings applied, frequently passes through different types of soil or different horizons of the same soil, may have different metals in contact because of attached fittings or of repair operations when new pipe is connected to old, and may suffer from galvanic or stray-current corrosion and from climatic conditions different from those of the test site.

Logan [85] cited one instance of good agreement and other instances of more or less agreement with the computed values. An 8-in. steel pipeline exposed in Merced silt loam developed leaks in 5 years, whereas the calculated time-to-perforation for this type of soil (23) was 8 years. Muck (soil 29) is one of the most corrosive soils listed in table 41 and water mains in the vicinity of the test site have corroded rapidly. For Miller clay (soil 27) Ewing's equations indicate 27 years for the time-to-perforation of an 8-in. pipe, whereas a 12-in. line developed frequent leaks in 9 years. Allis silt loam (soil 1) is a corrosive soil, and severe corrosion of service pipes in this soil has been reported. The computations indicate that soils 9 and 15 are not corrosive, but a 6-in. steel line had to be renewed after 14 years in Genesee silt loam and severe corrosion of cast iron and steel in Houston black clay has been reported. The time-to-perforation computed for Ontario loam (soil 32) is 84 years; a 36-in. wrought-iron main with a ⅜-in. wall did not have any leaks after 61 years in this soil, but a nearby, parallel 38-in. steel water main (⅝-in. wall) developed numerous leaks in 42 years.

The difference in the performance of the two pipelines may be explained in several ways. It has been shown [78], in certain cases at least, that when a new pipe is connected to an old one, the latter is protected at the expense of the former. As for the difference between the results calculated from the tests and the leak records of the two pipelines, it is obviously impossible for the experimental results to agree with both experiences. Most of the leaks on the steel line occurred on the top three-fifths of the pipe. This is rather unusual, as most cases of severe corrosion occur on the bottom of the line. The severe corrosion of the steel line may be the result of a difference in soil conditions at the top and the bottom of the pipe, packing of the backfill, or because the coating on the top of the pipe was injured by the backfill. The record of these pipelines illustrates very well how conditions not duplicated in a test may alter the results when the material tested is used in a practical way.

It is evident, from the foregoing examples, that underground test data have value in a restricted area but that quantitative interpretations or extrapolation outside of the restricted area should be attempted only when more complete information is available than is now at hand.

10. Field and Laboratory Studies of Bolt Materials

10.1 Bolts in NBS Test Sites

Plain carbon-steel and cast-iron bolts used in joints of underground pipe assemblies frequently fail in severely corrosive soils, especially at the threaded ends. The costs of shutdowns and repairs resulting from these failures are generally high and led the Bureau to bury some bolt specimens in the test sites. In 1924, exposures were started on sherardized steel, lead-coated steel, and uncoated carbon-steel bolts in soils at 7 test sites. Exposures on malleable-iron, high-strength plain carbon-steel, and plain carbon-steel bolts were started at 4 different sites during 1932; and during 1939, exposure tests were started on charcoal cast-iron and plain carbon-steel bolts at 14 other sites. The soil conditions at these sites ranged from moderately corrosive to severely corrosive. The bolts were inserted in pieces of cast iron under moderate stress and the assembly buried. Descriptions of the bolts are given in table 12, and the corrosion data obtained in these tests are presented in tables 42 and 43. The pit-depth measurements were made only on the heads of the bolts because it was practically impossible to accurately measure the pits on the shank. The data indicate that there was no great difference in the corrosion rate of the malleable iron and carbon-steel bolts. The sherardized bolts, and to a lesser extent lead-coated bolts, were more corrosion resistant than uncoated steel bolts. Photographs of specimens of the cast-iron and carbon-steel bolts exposed at 14 test sites are shown in figure 28, and the weight loss data are given in table 43. Comparable to the data in table 42, there is no great difference in behavior of these materials, both having high corrosion rates in corrosive soils and lower rates in less-corrosive soils.

TABLE 42. *Corrosion of ¾-inch bolts buried in soils during 1924 and during 1932*

Soil		Malleable-iron bolts						Steel bolts			
				Decarburized		Not decarburized		High strength		Plain bolts	
No.	Type	Number of specimens of each kind	Duration of test	Loss in weight	Maximum pit depth[a]	Loss in weight	Maximum pit depth[a]	Loss in weight	Maximum pit depth[a]	Loss in weight	Maximum pit depth[a]
			Years	*g*	*Mils*	*g*	*Mils*	*g*	*Mils*	*g*	*Mils*
55	Hagerstown loam	2	9.1	5.26	65	5.11	46	7.89	76	5.56	42
56	Carlisle muck	2	9.1	7.46	20	5.89	12	6.57	26	6.00	12
61	Sharkey clay	2	9.5	9.95	51	11.08	43	5.25	29	5.18	20
62	Susquehanna clay	2	9.4	8.05	58	8.93	70	9.74	58	8.10	54

Soil		Coated steel bolts and nuts							
				Loss in weight					
				Sherardized steel		Lead-coated steel		Uncoated steel	
No.	Type	Number of specimens of each kind	Duration of test	Bolt	Nut	Bolt	Nut	Bolt	Nut
			Years	*g*	*g*	*g*	*g*	*g*	*g*
13	Hanford very fine sandy loam	4	10.2	3.20	1.23	6.50	2.02	24.99	8.43
24	Merrimac gravelly sandy loam	4	10.6	2.37	.90	1.43	.78	3.04	1.29
28	Montezuma clay adobe	1	9.6	19.32	8.63	---------	---------	29.11	13.60
29	Muck	4	10.1	13.45	4.60	18.93	7.92	23.63	9.45
42	Susquehanna clay	3	10	4.47	1.80	6.52	2.62	15.30	5.41
43	Tidal marsh	4	10.7	24.32	8.05	13.05	7.54	37.52	5.47
45	Unidentified alkali soil	4	10.6	15.19	8.09	42.23	14.40	16.71	5.60

[a] On head of bolt only.

TABLE 43. *Loss in weight of steel and cast-iron bolts exposed approximately 13 years.*[a, b]

(Average of 2 specimens, in grams)

Soil		Steel bolt[c]	Charcoal cast iron bolt[d]
No.	Type		
53	Cecil clay loam	16.6	22.2
55	Hagerstown loam	8.8	12.7
56	Lake Charles clay	90.0	122.0
58	Muck	14.6	19.5
59	Carlisle muck	9.7	8.4
60	Rifle peat	29.3	26.3
61	Sharkey clay	13.6	26.6
62	Susquehanna clay	7.5	13.0
63	Tidal marsh	28.4	24.3
64	Docas clay	16.1	13.8
65	Chino silt loam	79.0	26.2
66	Mohave fine gravelly loam	[e] D	35.2
67	Cinders	D	D
70	Merced silt loam	34.5	36.8

[a] See table 6 for locations and properties of the soils.

[b] One steel and one cast-iron bolt joined two cast-iron plates (0.5 in. by 3.5 in.) that overlapped by 1.5 in.

[c] The steel bolts originally weighed approximately 132 g.

[d] The cast-iron bolts originally weighed approximately 168 g.

[e] D, destroyed.

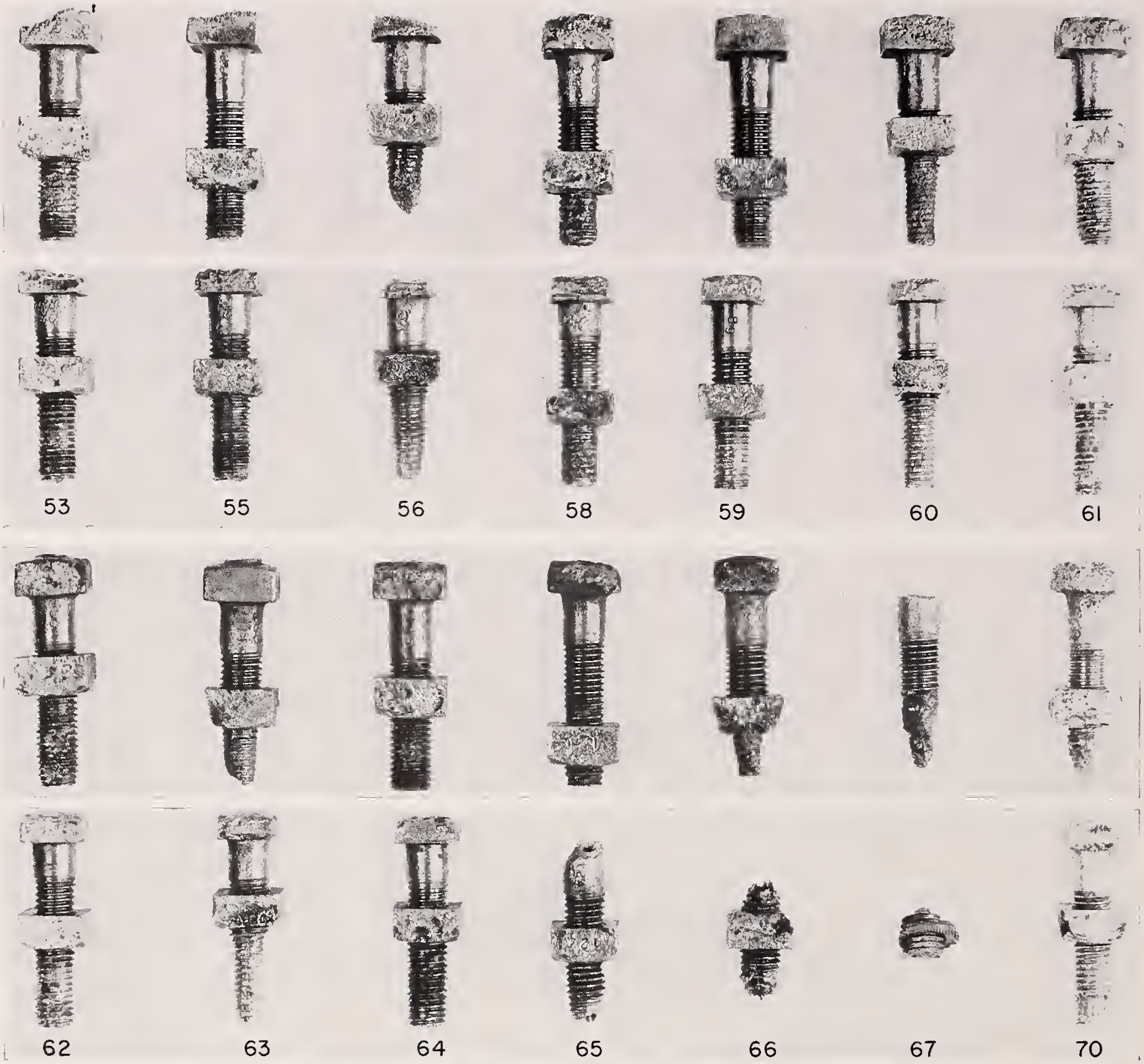

FIGURE 28. *Bolts removed from couples after exposure for 13 years at 14 NBS test sites.*

A pair of bolts, cast iron (upper row) and steel (lower row), shown above the site numbers were components of a joint. Each pair of bolts (0.625 in.) joined two cast-iron plates (0.5 by 3.5 by 12 in.) that overlapped by 1.5 in.

10.2. Laboratory Studies on the Galvanic Behavior of Bolt Materials

Bolt failures in corrosive soils often occur long before the structures to which they are coupled are appreciably damaged. The galvanic action between the bolts and the structures is primarily responsible for such failures, in addition to the normal effects of accelerated corrosion due to stress and edge effects.

It would appear that the elimination of galvanic corrosion could be accomplished by using bolts fabricated from materials that are cathodic to the structure. Although ferrous bolts may be made cathodic to iron by alloying, they are not widely used because of the higher cost. Also, because of the potential difference between the couple formed by the structure and the bolts, excessive localized attack could occur on the adjacent anodic structure. However, experimental work of some investigators [162,163,164] indicates that this is not always true. The corrosion rates of materials, or their resistance to corrosion, can be determined by measuring their polarizing characteristics. In the case of iron exposed to all soils, it has been shown by laboratory studies involving a corrosion cell, that an increase in cathodic polarization is accompanied by a reduced rate of corrosion [142]. Direct current flowing in a couple composed of plain cast iron, stainless-steel, or nickel-copper alloy (70–30) in soils caused marked polarization because these materials are relatively free of potent local action. Thus, the coupling of relatively small areas of such materials to plain cast-iron or carbon-steel structures will not result in harmful galvanic corrosion to the structure. Also, whatever the galvanic current, the weight loss on the adjacent anodic structure will not be increased by an amount equivalent to the magnitude of the current because of polarization effects [142, 165].

Donoho and MacKenzie [166] and Landau [167] found that the alloying elements of either nickel or copper cause iron to be cathodic to plain cast iron, and predicted that alloys of iron containing both nickel and copper should be even more cathodic. This effect was substantiated by Schwerdtfeger [168] in a laboratory investigation. Galvanic couples consisting of cast-iron gland sections and bolts of carbon steel or cast iron alloyed with as much as 2 percent of nickel and 1 percent of copper (table 44) and bolts of high-alloy cast iron (15 Ni, 6.6 Cu, 2.6 Cr) and nickel-copper alloy (70 Ni, 30 Cu) were exposed, for a period of 1 year, in the laboratory to a very corrosive tidal marsh soil, from Atlantic City, N. J. The assembly of the couple is shown in figure 29. The soil had a *p*H of 4.4 and a resistivity of 140 ohm-cm, and was maintained at a constant moisture content during the period of test. During the early part of the test, measurements of the galvanic currents between the components of the couples and of the open-circuit potentials of the components were made at definite intervals. At the conclusion of the test, prior to disassembling the couples, data for cathodic-polarization curves were obtained, and after the couples were disassembled, weight losses were determined [168].

TABLE 44. *Potentials of bolts in puddled soil*

Bolt material	Exposure time	Potential, referred to saturated calomel		
		Initial [a]	Final [a]	Average [b]
	Days	*v*	*v*	*v*
Cast iron (1 Cu)	13	−0.661	−0.678	−0.674
Cast iron (1 Ni, 1 Cu)	13	−.648	−.666	−.661
Cast iron (2 Ni, 1 Cu)	13	−.645	−.663	−.657
Plain carbon steel	13	−.673	−.670	−.670
Cr-Ni-Cu-Si steel (1 Cr, 0.5 Ni, 0.5 Cu, 0.5 Si)	13	−.653	−.663	−.661
Ni-Cu Steel (1.5 Ni, 1 Cu)	13	−.646	−.656	−.654
High-alloy cast iron (15 Ni, 6.6 Cu, 2.6 Cr)	45	−.470	−.533	−.506
Nickel-copper alloy (70–30)	45	−.295	−.403	−.368

[a] Average of 2 bolts.

[b] Average for the exposure period (9 pairs of measurements in as many days for bolts exposed for 13 days and 19 pairs of measurements covering the 45-day exposure period).

The magnitude of the potential difference between a bolt and gland section, after opening the circuit, depended upon the amount of current developed by the galvanic action in the closed circuit, that is, larger potentials were associated with larger charges in current. As a result, reduction in corrosion of the bolts was observed because the galvanic current, which developed between the bolts and the gland sections, made the bolts cathodic throughout the test period. Thus, for bolts made from each of the three varieties of plain and low-alloy cast iron and plain carbon steel, the larger galvanic currents generally provided better protection of the bolts. This is indicated by the larger open-circuit potentials (table 44) and the correspondingly lower weight losses (table 45). The corrosion on the bolts was appreciably reduced by making them cathodic to the gland sections. The results of these tests are shown in table 45. These data show the beneficial effects of relatively small amounts of alloying constituents, particularly of 1.5 to 2 percent of nickel plus 1 percent of copper. The cathodic nature of the high-alloy cast iron and nickel-copper alloy resulted in negligible corrosion of the bolts fabricated of these materials (table 45).

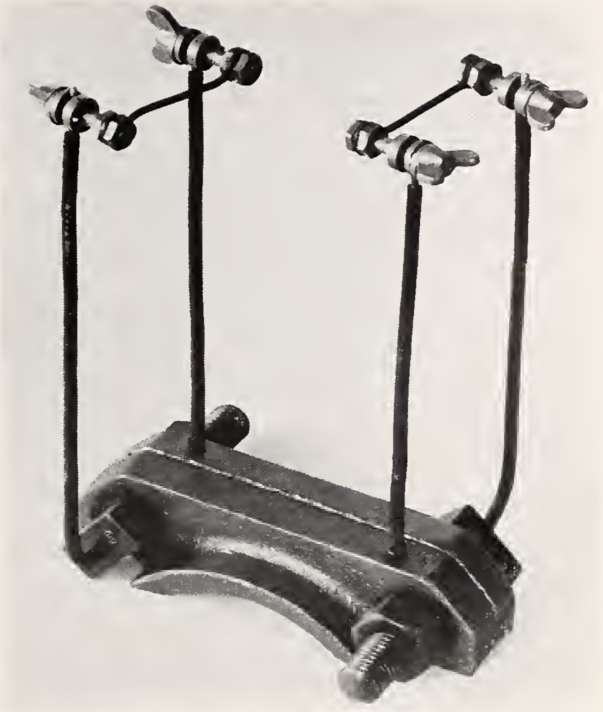

FIGURE 29. *Couple of the type exposed to soil in the laboratory.*

Gland sections were cut from 4-in. cast-iron pipe glands. Bolts are 0.75 by 3.5 in.

Schwerdtfeger also investigated the effect of exposure time on the corrosion rates of bolts having varying composition. The relative degrees of protection produced by the galvanic currents on the

TABLE 45. *Comparison of weight losses of uncoupled and coupled bolts*

Bolt material	Weight loss of bolt after 368 days of exposure [a]		Reduction in weight loss of coupled bolts based on control (uncoupled)	
	Control uncoupled	Coupled cathodic	Based on the actual weight loss	Based on the calculated corrosion rate at the end of the exposure period [b]
	g	*g*	*Percent*	*Percent*
Cast iron (1 Cu)	28.5	5.3	81.4	89.5
Cast iron (1 Ni, 1 Cu)	25.6	9.1	64.4	88.7
Cast iron (2 Ni, 1 Cu)	33.8	3.5	89.7	97.9
Plain carbon steel	16.4	7.6	53.7	56.7
Cr-Ni-Cu-Si steel	19.7	7.1	64.0	77.7
Ni-Cu steel	14.2	3.8	73.2	71.9
High-alloy cast iron	8.8	.61	93.1	>95
Nickel-copper alloy	.95	.19	80.0	>95

[a] Average of 2 bolts.

[b] Weight loss (grams) $=KtI$, where $K=2.8938\times10^{-4}$ g/coulomb; $t=368$ days, expressed in seconds; and $I=0.83\ I_p$ in amperes [168].

bolts after exposure for 1 year were determined by comparing the actual with the calculated weight losses in accordance with the Faraday equation. Such calculations based on cathodic polarization curves have been shown to be reliable for calculating the corrosion rate of ferrous metals in soils [142]. Comparison of the data in the last two columns of table 45 indicates, in general, that the corrosion rate of all of the bolts decreased with time of exposure. The corrosion attack on the cast-iron bolt containing 2 percent of nickel and 1 percent of copper was negligible after 368 days of exposure.

Even though galvanic current between a cathodic bolt and a structure will produce weight losses in accordance with Faraday's law, the laboratory data show that local action on the structure is reduced by the galvanic current and that the over-all effect is apparently not detrimental. This should be particularly true if the area of the structure is relatively large, in relation to the area of the bolt.

10.3. Considerations in Bolt Replacement

a. Graphitization of Cast Iron

Wesley, Copson, and LaQue [145] investigated the effect of graphitization on the normal corrosion rate of cast iron and also the potential developed by the galvanic action resulting from a couple consisting of graphitized cast iron and ungraphitized cast iron. Their results showed that graphitized cast iron was cathodic to ungraphitized cast iron and the resulting potential depended upon the thickness and porosity of the graphite coating.

Specimens to study the effect of time on the potentials of graphitized and ungraphitized cast iron were obtained by cutting from the corners of a graphitized cast-iron plate that had been exposed to a corrosive soil in field tests for 13 years [168]. The cut edges were coated with a bituminous paint to eliminate the uncorroded metal from the cell. These specimens were coupled to ungraphitized plates and duplicate couples were exposed to the same tidal marsh soil described in the previous section. Under these conditions, a decrease in potential difference between the graphitized and ungraphitized specimens with time was observed (fig. 30). After about 200 days of exposure both of the graphitized specimens were cathodic to the previously unexposed pieces. Therefore, when replacing bolts on a cast-iron pipeline, consideration should be given to the fact that new cast-iron bolts will be anodic to graphitized areas on the pipe.

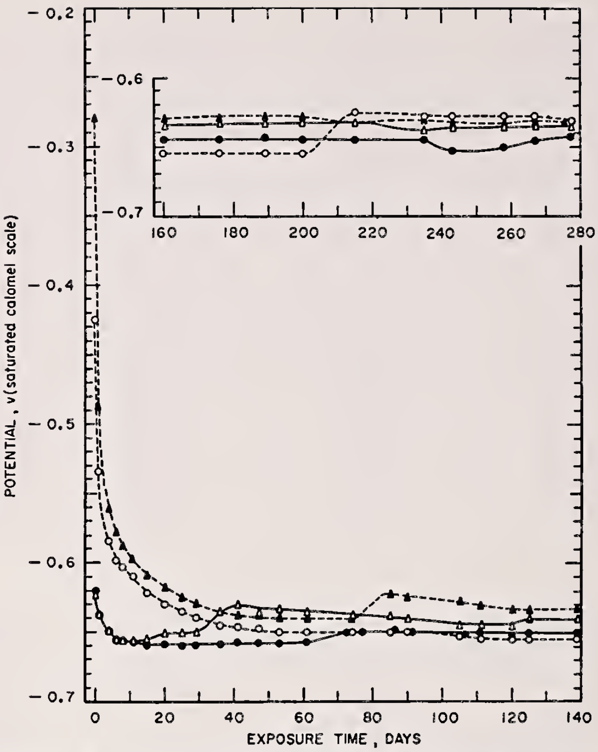

Figure 30. *Potential relations between previously unexposed cast iron and graphitized cast iron in puddled soil.*

●, Previously unexposed; △, previously unexposed; ○, graphitized, previously exposed for 13 years; ▲, graphitized, previously exposed for 13 years.

b. Potentials of Low-Alloy Steels

After long exposure in a soil, cast iron and even plain carbon steel became cathodic when coupled with similar unexposed materials. This condition is encountered with replacement bolts. Because of this, it became desirable to measure the potentials of alloys from which the bolts may be fabricated. Galvanic potentials determined for steels containing between 2 and 5.76 percent of chromium and a cast iron containing 3.1 percent of nickel are given in table 46. These average values are directly comparable with the average potentials recorded in table 44, being made in the same soil and under the same conditions. Despite the differences of exposure periods shown in tables 44 and 46, this comparison is feasible because the average potentials were calculated after they became relatively stable. The potential variation between two specimens for each of the alloys was less than 2 mv. The effect of chromium on the potential is marked, the steels containing 4.67, 5.02, and 5.76 percent of chromium being significantly cathodic to a steel containing 2 percent of chromium and to plain carbon steel and cast iron. The potential measurements were continued for a considerably longer period than for most of the measurements shown in table 44 because the potentials continued to become progressively

Table 46. *Potentials of low-alloy ferrous materials in puddled soil*

Material		Exposure time	Potential, referred to saturated calomel		
Composition	Identification		Initial [a]	Final [a]	Average [b]
		Days	*v*	*v*	*v*
Steel (2 Cr, with Mo)	KK	45	−0.662	−0.666	−0.663
Steel (4.67 Cr, with Mo)	E	45	−.653	−.629	−.636
Steel (5.02 Cr)	D	45	−.650	−.616	−.623
Steel (5.76 Cr, with Mo)	H	45	−.653	−.609	−.623
Cast iron (3.1 Ni)	N	45	−.638	−.651	−.649

[a] Average of 2 specimens.

[b] Average of 19 measurements made on each pair of specimens throughout the exposure period.

more cathodic as time went on. This is borne out by the data in table 46. The data in tables 44 and 46 show that steel alloyed with about 5 percent of chromium is cathodic to plain carbon steel or cast iron by at least 50 mv, indicating that it might be a desirable material for the fabrication of bolts, especially for replacement purposes. The increase of nickel content in cast iron also seems to have a significant effect on the potential, by making it more cathodic.

c. Effect of Exposure on Coupling Galvanized Iron with Bare Iron

Long-time underground-exposure tests [125] have shown that galvanized steel is more corrosion resistant than plain carbon steel, particularly in alkaline soils, as discussed in section 16.2. However, it cannot be concluded that galvanized bolts should be more corrosion resistant than plain steel bolts on underground pipe joints because in this application galvanic rather than local corrosion is predominant. Under such conditions the zinc coating would soon be completely removed by corrosion and the zinc-iron alloy layer exposed to the soil. A discussion of these effects are presented later in this section.

In atmospheric exposure tests of galvanized steels, many of which have been reported by Committee A–5, Corrosion of Iron and Steel, of the American Society for Testing Materials,[7] the zinc coatings have never been observed to be cathodic to steel. However, Britton [169], Gilbert [170], and Hoxeng [171] observed, while experimenting with couples composed of zinc-iron alloy and uncoated iron underlying galvanized coatings, that the zinc-iron-alloy layer became cathodic to the iron under certain conditions. Romanoff measured the potentials of zinc, zinc-iron-alloy layer, and steel in 12 soils by the method [136] described in section 16.2. The soils varied in *p*H from 3.1 to 8.0 and the resistivities of eight of the soils were below 400 ohm-cm. The zinc-iron-alloy layer was prepared by electrolytic stripping of the outer zinc coating and should not be confused with the surface resulting from exposure to soil corrosion of galvanized iron that was anodic to steel in all the soils. In none of these soils was zinc observed to be cathodic to plain carbon steel, but in 11 soils the zinc-iron-alloy layer was cathodic to steel by approximately 100 mv.

The findings of the above investigators suggest that as long as the zinc layer was intact on the steel, the bolts were anodic, but that when the zinc-iron alloy was exposed, it was observed that the bolts did become cathodic to the structure. To investigate such a possibility under somewhat extreme conditions, Schwerdtfeger [168] exposed a couple, composed of hot-dipped galvanized iron pipe and low-carbon steel, to a 0.2-percent potassium-chloride solution in the laboratory at room temperature. This solution is equivalent in resistivity (approximately 400 ohm-cm) to a very corrosive soil. As the area ratio of structure to bolt is relatively large on underground systems, a similar large area relationship was used in the laboratory experiment. The relation between the galvanic current, measured with a zero resistance milliameter, and time of exposure is shown in figure 31. The results of this experiment showed that the zinc coating offered no particular advantage, as it was rapidly removed by galvanic action as indicated by the rapid decrease in current, but that the secondary effect of potential reversal represents partial electrochemical protection of the exposed alloy layer. The experiment also suggests the likelihood of similar action underground, especially in soils of higher or perhaps even equivalent resistivity.

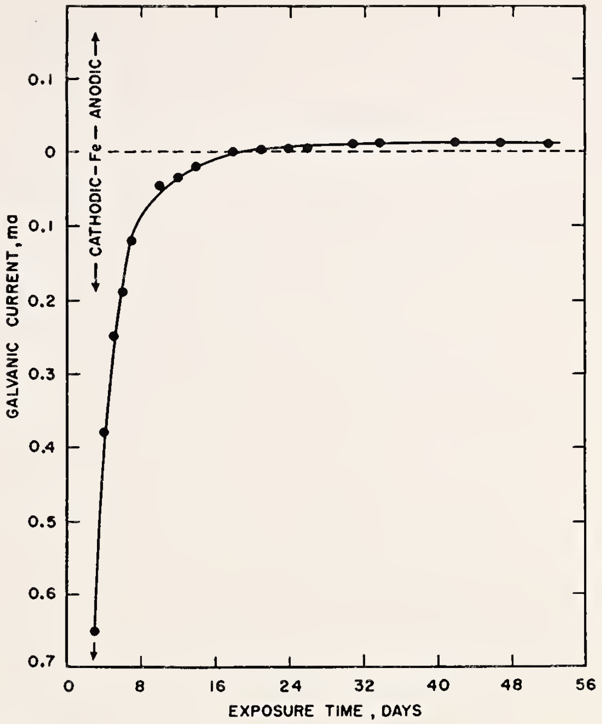

Figure 31. *Effect of exposure time on the galvanic current of a galvanized iron-iron couple exposed to a 0.2-percent potassium-chloride solution at room temperature.*

Galvanic current was initially 15 ma. After 5 additional months of exposure, the direction and magnitude of the galvanic current remained unchanged.

The data obtained in both the field and in the laboratory tests on actual bolt specimens and on materials that might be considered suitable for fabrication of bolts, without taking economic factors into consideration, indicate that the approximate order of the corrosion resistance of the materials to be as follows: Nickel-copper alloy (70–30), high-alloy cast iron (15 Ni, 6.6 Cu, 2.6 Cr), 4- to 6-percent-chromium steels, nickel-copper steel (2 Ni, 1 Cu), galvanized iron, sherardized bolts, lead-coated bolts, lower alloys of iron and steel, malleable iron, and plain cast irons and steels. In view of the discussion on galvanized bolts, consideration should be given to their use only under conditions where the potential of the underlying zinc-iron-alloy layers of the galvanized bolt would become cathodic to the structure.

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[7] See annual reports of Committee A-5, Proceedings ASTM.

11. Field Tests on Copper and Copper Alloys

11.1. Description of the Materials

The original burials in the soil-corrosion investigation were initiated in 1922 in 47 test sites and were concerned primarily with ferrous materials. The initial results indicated that in some soil environments these materials corroded rapidly. In view of this, it was deemed desirable to obtain similar data on nonferrous materials that might be used in underground installations. Brass in the form of cocks and valves has been used underground for many years, and in more recent years copper and brass have been used for service pipe and, in some instances, for small distribution mains.

In 1924 a few copper and copper-alloy sheets were buried at six of the original test sites. The data for these specimens have been published [114] and will not be repeated here. In 1926 a burial of pipe specimens was made in the 47 test sites. In order to obtain more detailed information on copper alloys, specimens of 12 compositions of pipe (table 47) were installed at 14 additional test sites in 1932, and in 1939, plate specimens of arsenical brass were buried at the same sites. The exposed area of most of the specimens was approximately 0.4 ft^2.

11.2 Copper and Copper-Silicon Alloys

The results of the specimens of copper and copper alloys buried in 1926 and 1932 are given in tables 48 and 49, respectively. As stated in the discussion of the ferrous materials, rates of corrosion change with the duration of exposure. Hence, corrosion data of this type are only applicable to the specific period under consideration and cannot be utilized to predict corrosion behavior for periods of unlike duration or time intervals. The data for the maximum exposure periods in tables 48 and 49 show that, for soils in general, the losses in weight and the maximum pit depths of the copper alloys were slight, with the following exceptions, which were all associated with poor aeration: in cinders (soil 67), in soils having high concentrations of sulfides (soils 43 and 63), of organic and inorganic acidity (soils 29, 33, 37, 40, 58, and 60), and of chlorides (soil 64).

The progress of corrosion with time for these materials was reported in Research Paper 2077 [123]. Charts were presented in which weight loss and maximum pit depth for each material and soil were plotted against the time of exposure. The weight-loss curves indicated that except for soils high in sulfides, the deoxidized copper and copper-silicon alloys showed higher losses than the tough-pitch copper. With the exception of soil 66, the pit-depth–time curves indicate that the deoxidized copper, copper-silicon alloys D and N, and tough-pitch copper have similar pit depths for similar corrosion periods in the same environments. In all soils except 60 and 63, copper-silicon alloy "E" pitted considerably more than tough-pitch copper.

11.3. Copper-Zinc and Copper-Nickel-Zinc Alloys

a. Loss in Weight and Depth of Pitting

The results of the corrosion tests on copper-zinc and copper-nickel-zinc alloys, tables 48 and 50, show that in most soils the losses in weight and the maximum pit depths for the maximum exposure period were not appreciable. This type of data, however, does not show the extent of deterioration of these materials due to dezincification or selective corrosion. Dezincification is a type of corrosion that is common to brasses containing about 20 percent or more of zinc, involving the loss of zinc from the alloy, and leaving as a residue or deposit in situ, a porous mass of copper. This results in subsequent loss in strength but not of pipe contour. According to McKay and Worthington [172], dezincification occurs as a result of variations in the corroding environment or in the type of alloy, that form concentration or galvanic cells. Because of the higher concentration of copper ions in solution at the anodic areas, in comparison with that at the cathodic areas, metal-ion concentration cells are formed, which redeposits the copper at or near the points where the corrosion occurs. This deposition of copper causes additional galvanic cells to develop, and in this manner a cycle is developed by which the corrosion attack spreads and penetrates the metal. The acid around the anode dissolves the zinc that diffuses into the solution. According to the authors, the most favorable conditions for dezincification are a good conducting solution and a slightly acid condition, with the presence of oxygen.

There are two general types of dezincification. The first type, commonly known as "plug type", is highly localized and severely penetrating; and the second type, or "uniform type", is spread over large areas of the entire surface and penetrates the wall of the alloy over the entire area affected.

In certain of the soils, table 51, the corrosion of the high-zinc-brass specimens H, J, K, and L was partly attributed to dezincification. Hence, some of the weight-loss values for these materials, table 50 necessarily include some loss due to this form of corrosion. However, as the porous copper residue resulting from dezincification was not removed in measuring the depth of the pits in the dezincified areas, the values of maximum pit depth given in table 50, do not show the effects of dezincification on the specimens.

The complete evaluation of the condition of the corroded brass specimens in terms of weight loss and pitting necessarily entails removal of the dezincified copper residue. Since this was not feasible, specimens corroded appreciably by dezincification were excluded in the comparison made of the different materials. This comparison is more readily evident from a series of weight-loss and pit-depth–time curves published in Research Paper 2077 [123] than from the actual data in table 50.

With the exception of soils high in sulfides, a progressive increase in weight loss with increasing zinc content was observed. Conversely, in poorly aerated sulfide soils (59 and 63) the weight loss tends to decrease with increasing zinc content. This tendency was also noted for soil 60, although the trend was not as pronounced as in soils 59 and 63 because of seasonal drying and oxidation of the sulfides to sulfates. Exception to this general conclusion was noted in soil 60, in which the high rates of corrosion for materials J and L for the final period are unaffected by dezincification. As will be seen later, dezincification was not observed in any of the soils high in sulfides. The relatively high resistance of the high-zinc brasses to corrosion by sulfur compounds in other environments has been previously reported by other investigators [173].

The pit-depth–time relations do not show a correlation between maximum penetration and zinc content. Contrary to predictions based on weight-loss data, the tough-pitch copper C and red brass F did not show greater resistance to pitting than the copper-zinc alloys. Tough-pitch copper and red brass occupy an intermediate position in relation to maximum pit depths in all soils except 51, 56, and 66, in which they show a resistance comparable to that of any of the high-zinc-brass specimens.

b. Effect of Dezincification

For the determination of the depth of dezincification the pipe specimens were sectioned both longitudinally and transversely. The as-cut edges of the sections were then examined with the aid of a magnifying lens for evidence of dezincification, which was identified by the copper-colored areas penetrating the wall of the pipe. Additional cuts were made in the sections to locate the areas having the maximum depth of dezincification. The depth of dezincification was measured in mils on a scale under the magnifying lens. The accuracy of this procedure was checked by measuring the depth of dezincification on photographs of transverse sections enlarged to 15 magnifications.

The form and depth of dezincification on the specimens of high-zinc brass, B, H, K, J, and L, are given in table 51. No dezincification were observed in the specimens of red brass F and copper-nickel-zinc alloy G at any of the test sites. A transverse section of a typical uniformly dezincified area of a Muntz metal specimen removed from Sharkey clay (soil 61) is shown in figure 32. The microstructures of a partially dezincified section of a leaded silicon-brass specimen removed from the same soil is shown in figure 33.

Based on the alloys examined, it is evident from the depths of dezincification data, table 51, that values of weight loss and maximum penetration, table 50, may be entirely misleading in determining the extent of corrosion of brasses containing more than 27 percent of zinc. If, for example, only the values for average penetration and maximum

TABLE 47. *Composition of copper and copper-alloy materials*

Material	Identification	Year buried	Number of specimens buried	Form	Nominal width or diameter	Length	Wall thickness	Cu	Zn	Sn	Pb	Ni	Fe	Si	Other elements
					Inch	*Inch*	*Inch*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Copper:															
Copper	E	1926	36	Pipe	1.1	17	0.108	99.97							
Tough pitch copper	C	1932	150	do	1.7	12	.145	99.9							0.0 P
Deoxidized copper	A	1932	150	do	1.7	13	.144	99.94							.018 P
Copper	P	1926	276	do	.9	12	.06	99.94							.015 P
Do	M	1926	276	do	.9	12	.06	99.93							
Do	H	1924	40	Sheet	2.0	6	.05	99.+							
Copper with soldered fittings	M	1932	150	Pipe	1.5	12	.062								
Brass:															
Red brass	F	1932	150	Pipe	1.7	12	.143	85.18	14.80				0.01		
Brass	H	1926	36	do	1.1	17	.108	84.99	14.97		0.01		.03		
Admiralty metal	H	1932	150	do	1.7	12	.143	71.28	27.39	1.30	.01		.02		
Cartridge brass	B	1924	40	Sheet	2.0	6	.05	70	30						
Two and one leaded brass	K	1932	150	Pipe	1.7	12	.08	67.08	31.07		.84		Trace	1.01	
Brass	J	1932	150	do	1.7	13	.145	66.50	33.06		.42		.02		
Muntz metal	L	1932	150	do	1.7	12	.08	60.06	39.58		.36		Trace		
Do	B	1926	276	do	.8	12	.103	60	40						
Do	Me	1926	276	Ell	.7	2	.16	59.00	38.50		2.50				
Muntz metal with arsenic	B	1939	150	Plate	2.5	12	.25	62.37	37.54		.005		.007		.08 As.
Miscellaneous alloys:															
Bronze	E	1932	150	Pipe	1.7	12	.141	97.15		1.80			.01	1.04	
Do	L	1924	40	Plate	2.0	6	.25	90		10					
Copper-silicon	N	1932	180	Pipe	1.7	12	.145	98.11		.14		0.01	.11	1.49	.18 Mn.
Do	D	1932	150	do	1.7	12	.143	95.46				.08	.21	3.19	1.06 Mn.
Copper-aluminum	N	1926	276	Rod	.4	12		87.0					3.5		9.5 Al.
Copper-nickel	G	1932	150	Pipe	1.7	12	.145	74.45	4.99			20.04			.52 Mn.
Copper-zinc-nickel	A	1926	276	Rod	.4	12		47.0	40.0		2.5	10.0			

TABLE 48. *Corrosion of copper-rich alloys buried in 1926*

(For the condition, the letters indicate the worse of 2 specimens. The figures are rates of maximum pit depth, in mils per year.)

M, Shallow metal attack, roughening of the surface but no definite pitting.
P, Definite pitting, no pits greater than 6 mils.
U, Unaffected by corrosion.
S, severe uniform corrosion, impossible to measure penetration because of even destruction of surface.
D, selective corrosion such as dezincification over large areas.
d, selective corrosion in spots.
Z, destroyed by dezincification.

Soil	Duration of test	Average rate of loss in weight (oz/ft²)/yr						Condition of surface and pit depth (mils)				
		Copper pipe		Brass		Cu-Zn-Ni rod,	Cu-Al rod,	Copper pipe		Brass pipe,	Cu-Zn-Ni rod,	Cu-Al rod,
				Pipe,	Ell,							
		M	P	B	Me	A	N	M	P	B	A	N
	Years											
1	8.1	0.060	0.063	0.097	0.185	0.157	0.057	1.5	P	M, D	P, d	M, D
2	13.5	.023	.016	.065	.090	.101	.019	P	P	P, D	P, D	M
3	8.0	.027	.029	.074	.109	.156	.063	P	P	1.2, d	1.2, d	D
4	7.9	.019	.019	.144	----	.176	.070	1.3	M	P, D	1.3, d	D
5	13.4	.030	.032	.059	.317	.118	.045	0.6	P	P, D	0.5, D	P
6	13.3	.011	.0093	.017	.025	.056	.0023	P	P	P, d	P, D	P
7	13.4	.036	.026	.188	----	.155	.032	P	P	S, D	0.07	P
8	8.0	.024	.019	.018	.319	.136	.026	1.5	1.3	M, d	1.5, d	1.9, d
9	13.4	.030	.036	.174	.092	.165	.011	P	P	0.5, D	0.9, D	P
10	13.2	.076	.095	.235	----	.207	.037	0.8	0.5	0.6, D	0.8, D	P
12	8.0	.312	.278	.222	----	.199	.090	1.5	S	P, D	M, d	P, d
13	8.0	.023	.031	.101	.024	.012	.028	P	P	M, D	M, d	M, d
14	8.0	.040	.025	.044	.089	.096	.017	P	0.9	P, d	1.9, d	M, d
15	8.0	.013	.016	.030	----	.045	.026	M	M	D	d	d
16	8.0	.057	.058	.170	.166	.234	.093	3.3	1.9	1.3, D	0.9, d	d
17	8.0	.037	.040	.059	.257	.108	.049	M	M	M, d	P, d	D
18	8.0	.0076	.0077	.021	.070	.044	.013	U	M	M, d	1.3, d	U
19	8.0	.039	.040	.122	.067	.165	.027	1.1	P	P, D	1.3, d	M, d
20	8.1	.042	.039	.044	.193	.138	.044	1.5	1.2	P, d	P, d	D
22	8.0	.068	.070	.195	.283	.277	.075	1.9	1.0	1.1, D	P, d	M, D
23	8.0	.118	.135	.752	1.85	.288	.169	1.9	1.3	Z	U	D
24	13.2	.019	.018	.025	----	.030	.018	P	P	P, d	P, D	P
25	8.0	.012	.011	.051	.142	.126	.043	P	U	P, D	P, d	D
26	13.4	.013	.012	.072	.058	.118	.034	P	P	P, D	P, D	P
27	13.6	.012	.012	.046	.080	.063	.023	P	P	P, D	P, D	P
28	8.0	.084	.079	.080	----	.163	.017	P	P	M, D	P, d	M, D
29	8.0	.123	.116	.275	----	.257	.082	P	P	P, D	1.9, d	M, d
30	13.4	.0078	.0097	.014	.048	.032	.0071	P	P	P, D	P, D	P
31	13.7	.0083	.0086	.019	.026	.022	.026	P	P	P, d	P, D	M
32	7.9	.049	.018	.089	.152	.129	.016	U	M	1.0, D	1.3, d	d
33	8.0	.137	.117	.175	.218	.208	.040	0.9	1.0	P, D	1.3, d	M, d
34	8.0	.016	.022	.057	.080	.177	.021	M	P	M, D	P, d	d
35	8.0	.017	.016	.020	.422	.063	.039	M	P	D	1.0, d	D
36	13.6	.019	.019	.049	.039	.087	.014	P	P	0.7, D	0.7, D	P
37	8.0	.169	.162	.152	.274	.175	.060	1.8	1.3	P, D	P, d	M, d
38	8.0	.025	.043	.028	.037	.034	.019	M	P	M, d	P, d	U
40	8.0	.125	.168	.349	.330	.385	.092	2.3	4.1	1.8, D	1.9, d	d
41	13.4	.027	.030	.083	----	.126	.035	P	P	P, D	0.5, D	P
42	8.0	.047	.049	.095	.089	.154	.057	P	1.1	P, D	1.9, d	P, D
43	8.0	.635	.555	.026	.022	.007	.022	S	S	M, d	U	2.3
44	8.0	.079	.061	.175	----	.248	.026	P	P	1.3, D	2.4, d	P, d
45	8.0	.033	.030	.016	.214	.081	.030	1.0	1.0	d	1.0, d	D
47	13.4	.032	.035	.037	.30	.101	.056	1.2	0.8	P, D	P, D	P

TABLE 49. *Loss in weight and maximum pit depth of copper and copper-silicon alloys buried in 1932*

(Average of two specimens)

Identification	Material	Average exposure	Test site number and soil type													
			51	53	55	56	58	59	60	61	62	63	64	65	66	67
			Acadia clay	Cecil clay loam	Hagerstown loam	Lake Charles clay	Muck	Carlisle muck	Rifle peat	Sharkey clay	Susquehanna clay	Tidal marsh	Docas clay	Chino silt loam	Mohave fine gravelly loam	Cinders
		LOSS IN WEIGHT (OUNCES PER SQUARE FOOT) [a]														
		Years														
A	Deoxidized copper	2.0	0.40	0.12	0.14	0.10	0.16	------	1.47	[b]0.06	0.16	1.13	1.41	1.71	0.28	3.98
		5.4	1.01	.15	.14	.51	1.56	0.12	3.82	.35	.26	2.45	2.22	[c]1.02	[c].75	9.33
		7.4	.40	.20	.15	.80	1.72	[c].11	1.10	.38	.38	4.25	3.00	[c]2.37	[c]1.32	4.89
		9.3	------	.22	.18	.78	2.10	.11	5.01	.35	.48	4.22	5.32	.24	[c].62	11.50
		14.3	[d].60	.24	.16	.89	2.39	[d].21	11.97	.66	.52	6.57	5.17	1.07	.54	13.77
C	Tough-pitch copper	2.0	.42	.12	[e].14	.12	.13	------	1.37	[b].09	.15	1.31	.67	.50	.11	3.15
		5.4	.91	.16	.19	.34	1.40	.13	4.68	.34	.26	2.99	.96	.47	.16	8.04
		7.4	.35	.23	.17	.60	1.66	[c].09	1.03	.37	.33	4.33	1.56	.55	.32	1.42
		9.3	------	.24	.20	.71	1.95	.12	7.26	.33	.36	4.46	2.80	.26	.45	9.84
		14.3	[d].46	.23	.16	.61	1.98	[d].19	[c]14.66	.58	.49	8.31	1.04	.47	.27	6.71
N	Copper-silicon alloy	2.0	.35	.19	.14	.16	.11	------	1.57	[b].14	.25	1.45	1.32	1.03	.22	5.37
		5.4	1.02	.24	.28	.32	1.36	.22	4.13	.42	.40	4.37	2.10	.53	[c].67	15.51
		7.4	.48	.38	.23	.40	1.70	[c].14	1.06	.38	.42	4.57	1.74	2.42	.55	1.99
		9.3	------	.30	.30	.62	1.97	[c].24	[c]3.96	.48	.57	6.96	4.87	.62	[c].51	22.51
		14.3	.53	.51	.38	.60	2.80	[d].26	10.65	.77	.54	8.30	4.59	.66	.53	9.46
[f]N_1	Copper-silicon alloy	2.0	------	------	------	.14	------	------	.79	[b].12	.15	1.98	1.48	1.23	.14	5.90
		5.4	------	.21	------	------	------	.26	------	.24	------	------	1.38	------	------	------
		7.4	------	.25	------	------	1.56	------	------	------	------	------	------	2.74	------	------
		9.3	------	------	------	------	------	------	1.82	------	------	------	------	------	.34	23.17
		14.3	------	------	.29	.55	------	.20	------	------	.44	6.84	------	------	------	------
E	Copper-silicon alloy	2.0	.51	.24	.29	.23	.19	------	1.61	[b].19	.33	1.16	.79	.48	.38	3.25
		5.4	1.04	.28	.29	.48	1.64	.28	3.76	.51	.61	1.93	1.26	.72	.51	5.63
		7.4	.97	.38	.24	.60	1.67	[c].23	1.03	.65	.52	3.53	1.44	1.17	1.22	1.47
		9.3	------	.37	.35	.76	2.11	.17	[c]3.22	.61	.69	[c]4.38	2.30	.96	[c]1.53	8.76
		14.3	[d]1.40	.45	.26	.70	2.73	[d].31	9.32	.87	.70	4.84	2.82	1.42	1.82	8.49
D	Copper-silicon alloy	2.0	.45	.18	.15	.10	.11	------	1.33	[b].13	.24	1.23	.67	1.10	.21	4.23
		5.4	1.07	.25	.20	.35	1.70	.10	3.32	.52	.42	2.64	1.14	[c].62	[c].53	20.95
		7.4	.41	.39	.28	.52	1.75	[c].18	.72	.61	.50	4.86	1.43	[c]1.28	.40	2.69
		9.3	------	.36	.28	.63	2.12	.15	4.46	.52	.60	5.32	2.88	.48	.55	13.47
		14.3	[d].55	.48	.24	.77	2.49	[d].21	9.74	.88	.66	5.16	2.81	1.24	.45	17.34
		MAXIMUM PIT DEPTH (MILS)														
		Years														
A	Deoxidized copper	2.0	[g]M	<6	<6	M	M	------	7	[b]<6	<6	M	<6	<6	6	38
		5.4	<6	7	<6	<6	12	<6	28	[c].23	9	M	9	10	7	54
		7.4	<6	10	<6	<6	10	<6	8	8	14	8	<6	18	8	44
		9.3	------	<6	<6	<6	[c].14	<6	38	8	8	10	[c].16	<6	10	88
		14.3	[d]<6	8	<6	<6	19	[d]6	48	24	10	10	10	9	10	64
C	Tough-pitch copper	2.0	M	M	[e]<6	M	<6	------	<6	[b]<6	<6	<6	7	<6	<6	26
		5.4	<6	<6	6	<6	12	6	33	[c]15	6	<6	8	9	<6	56
		7.4	<6	11	7	8	14	6	9	16	6	7	14	20	<6	24
		9.3	------	6	8	<6	10	<6	40	8	8	6	[c]14	10	<6	51
		14.3	[d]<6	6	<6	<6	16	[d]6	46	20	10	14	14	12	<6	42
N	Copper-silicon alloy	2.0	M	<6	<6	<6	M	------	7	[b]<6	<6	<6	10	6	15	46
		5.4	<6	6	8	<6	7	<6	17	11	<6	<6	10	16	[a]18	80
		7.4	<6	<6	6	<6	9	<6	<6	11	6	6	12	20	14	31
		9.3	------	<6	<6	<6	12	M	10	10	<6	12	21	20	13	[h]145+
		14.3	[d]<6	6	7	<6	15	[d]<6	24	17	6	16	16	12	10	42
[f]N_1	Copper-silicon alloy	2.0	------	------	------	<6	------	------	7	[b]<6	<6	<6	10	15	M	40
		5.4	------	<6	------	------	------	<6	------	<6	------	------	12	------	------	------
		7.4	------	9	------	------	16	------	------	------	------	------	------	24	------	------
		9.3	------	------	------	------	------	------	8	------	------	------	------	------	<6	90
		14.3	------	------	7	<6	------	11	------	------	8	11	------	------	------	------
E	Copper-silicon alloy	2.0	<6	12	13	12	11	------	24	[b]<6	14	16	20	23	12	38
		5.4	8	14	16	9	33	11	22	26	15	<6	19	21	16	49
		7.4	6	14	15	12	33	6	12	35	<6	14	12	33	15	33
		9.3	------	12	20	12	53	20	18	[c]37	22	10	34	22	22	102
		14.3	[d]15	20	20	12	54	[d]16	35	42	23	11	22	23	21	78
D	Copper-silicon alloy	2.0	M	<6	7	M	M	------	<6	[b]M	6	<6	19	<6	<6	34
		5.4	11	10	10	M	8	M	15	7	10	<6	11	11	[c]12	90
		7.4	<6	<6	10	7	12	<6	<6	6	12	13	12	14	16	28
		9.3	------	8	8	M	12	<6	21	<6	6	9	[c]16	11	9	80
		14.3	[d]<6	8	10	<6	16	[d]<6	28	13	10	10	24	13	10	74

[a] Each ounce per square foot corresponds to an average penetration of 0.0014 inch.

[b] Exposed for 1.0 yr only.

[c] Data for the individual specimens differed from the average by more than 50 percent.

[d] Data for 4 specimens.

[e] Data for only 1 specimen—the other specimen was missing.

[f] These specimens had welded joints—data for only 1 specimen.

[g] M, shallow metal attack, roughening of the surface, but no definite pitting.

[h] +, both specimens contained holes because of corrosion.

TABLE 50. *Loss in weight and depth of maximum pit depth of copper-zinc alloys and copper-nickel-zinc alloy*

(Average of two specimens)

Identification	Material	Average exposure	Test site number and soil type														
			51	53	55	56	58	59	60	61	62	63	64	65	66	67	70
			Acadia clay	Cecil clay loam	Hagerstown loam	Lake Charles clay	Muck	Carlisle muck	Rifle peat	Sharkey clay	Susquehanna clay	Tidal marsh	Docas clay	Chino silt loam	Mohave fine gravelly loam	Cinders	Merced silt loam
			LOSS IN WEIGHT (OUNCES PER SQUARE FOOT) [a]														
		Years															
C	Tough-pitch copper	2.0	0.42	0.12	0.14	0.12	0.13	------	1.37	[b]0.09	0.15	1.31	0.67	0.50	0.11	3.15	------
		5.4	.91	.16	.19	.34	1.40	0.13	4.68	.34	.26	2.99	.96	.47	.16	8.04	------
		7.4	.35	.23	.17	.60	1.66	[c].09	1.03	.37	.33	4.33	1.56	.55	.32	1.42	------
		9.3	------	.24	.20	.71	1.95	.12	7.26	.33	.36	4.46	2.80	.26	.45	9.84	------
		14.3	[d].46	.23	.16	.61	1.98	[d].19	[c]14.66	.58	.49	8.31	1.04	.47	.27	6.71	------
F	Red brass	2.0	.33	.12	.13	.11	.12	------	1.47	.11	.15	.55	.33	.52	.18	3.36	------
		5.4	.97	.16	.22	.34	1.44	.17	4.11	.38	.27	.54	.33	.27	.32	12.95	------
		7.4	.45	.25	.16	.64	1.43	[c].12	.80	.49	.39	1.10	52	.58	.48	2.37	------
		9.3	------	.25	.25	.70	2.06	.12	3.55	.41	.43	0.75	[c]1.12	.28	.77	8.46	------
		14.3	[d].61	.28	.18	.65	2.46	[d].24	[c]13.04	.69	.43	[c]1.88	.78	.60	.63	18.73	------
G	Copper-nickel-zinc alloy	2.0	.28	.12	.12	.07	.15	------	1.38	[b].12	.18	.64	.08	.17	.20	2.08	------
		5.4	.88	.14	.20	.33	[c]1.35	.14	3.64	.33	.31	2.89	.10	.29	.37	2.87	------
		7.4	.45	.29	.15	.56	1.22	[c].08	.92	.69	.44	2.85	.27	.43	.38	1.25	------
		9.3	------	.27	.20	.78	1.40	.09	3.61	.43	.47	3.55	[c].74	.44	[c].60	6.28	------
		14.3	[d].58	.39	.18	.68	1.70	[d].17	10.23	.94	.60	5.61	.59	.54	.54	3.55	------
H	Admiralty metal	2.0	.32	.14	.15	.08	.19	------	1.13	[b].17	.20	.25	.02	.31	.23	5.55	------
		5.4	1.07	.21	.25	.29	2.16	.10	3.56	.60	.36	.11	.24	.34	.43	14.71	------
		7.4	.57	.29	.23	.46	1.87	.10	1.16	.77	.43	.18	.40	.87	.44	2.96	------
		9.3	------	.29	.25	.57	2.09	.09	[c]2.85	.51	.53	.18	.98	.58	.80	8.27	------
		14.3	[d].73	.35	.24	.64	2.91	[d].16	[c]8.98	1.18	.62	.22	.73	.78	.79	17.15	------
K	Leaded silicon brass	2.0	.17	.25	.20	.16	.25	------	1.14	[b].11	.29	.47	.24	.14	.25	6.85	------
		5.4	.36	.33	.25	.32	1.10	.15	2.97	.56	.55	.15	.21	[c]1.00	[c].82	[f]D	------
		7.4	.50	.48	.27	.48	1.59	[c].10	.85	.61	.55	.35	.80	1.03	[c]1.24	D	------
		9.3	------	.47	.36	.89	[c]1.66	.20	[c]3.22	.87	.71	[c].52	[c]1.07	1.39	.95	D	------
		14.3	[d].48	.58	.37	.76	3.76	[d].24	[c]12.30	1.89	.71	.51	.68	1.50	.84	D	------
J	Yellow brass	2.0	.33	.10	.18	.08	.21	------	1.71	[b].11	.22	.04	.57	1.37	.35	16.56	------
		5.4	1.41	.22	.34	.38	1.52	.01	5.14	1.00	.55	.02	1.31	1.17	.92	D	------
		7.4	.79	.42	.37	.74	2.20	.01	1.52	1.35	.51	.07	2.11	3.10	.88	D	------
		9.3	------	.41	.30	.94	3.33	.03	[c]4.21	1.22	.94	.08	1.94	1.60	[c]1.16	D	------
		14.3	[d]1.23	.51	.39	.91	3.98	[d].02	[c]27.30	2.42	.75	.08	1.66	2.52	.96	D	------
L	Muntz metal	2.0	.68	.19	.19	.14	.20	------	1.73	[b].16	.33	.14	4.02	2.43	.63	D	------
		5.4	1.45	.30	[c].58	.46	3.47	.02	4.42	1.75	1.20	.06	6.91	1.56	1.68	D	------
		7.4	1.04	.61	.66	.71	4.61	.02	1.43	2.97	1.08	.09	9.79	3.38	1.50	D	------
		9.3	------	.52	.77	1.21	5.25	.03	[c]4.56	2.58	1.79	.10	11.53	1.45	1.41	D	------
		14.3	[d]1.19	.62	.65	1.43	4.83	[d].03	[c]20.43	4.21	1.10	.09	15.38	1.73	2.06	D	------
B	Muntz metal with arsenic.	2.1	------	.18	.16	.55	.54	.30	1.87	.40	.32	.04	.47	.21	.30	15.2	.28
		7.0	[g].77	.75	.32	1.12	1.55	1.09	3.46	1.61	.96	.06	.46	.69	.38	26.3	.23
		9.0	------	.74	.42	0.74	1.38	1.32	4.89	[c].82	.92	.05	1.11	.46	.39	16.5	.42
		10.6	------	.81	.37	.84	1.42	1.28	5.21	.94	1.02	.05	1.31	.60	.42	21.4	.47
		13.0	------	.79	.46	1.10	1.73	1.38	6.13	1.21	.98	.06	1.39	.72	.47	27.5	.54
			MAXIMUM PIT DEPTH (mils)														
C	Tough-pitch copper	2.0	[b]M	M	<6	M	<6	------	<6	[b]<6	<6	<6	7	<6	<6	26	------
		5.4	<6	<6	6	<6	12	6	33	[c]15	6	6	8	9	<6	56	------
		7.4	<6	11	7	8	14	6	9	16	6	7	14	20	<6	24	------
		9.3	------	6	8	<6	10	<6	40	8	8	6	[c]14	10	<6	51	------
		14.3	[d]<6	6	<6	<6	16	[d]6	46	20	10	14	14	12	<6	42	------
F	Red brass	2.0	M	6	11	M	M	------	9	[b]<6	8	<6	13	6	<6	29	------
		5.4	8	8	11	<6	9	<6	24	[c]17	17	<6	<6	13	8	56	------
		7.4	<6	12	11	<6	<6	8	6	20	12	10	8	12	14	32	------
		9.3	------	10	7	<6	10	M	34	7	14	6	[c]26	<6	<6	[c]54	------
		14.3	[d]<6	15	8	<6	9	[d]6	42	32	12	[c]18	18	16	<6	62	------
G	Copper-nickel-zinc alloy	2.0	M	<6	6	M	[c]8	------	10	[b]<6	<6	<6	<6	<6	M	24	------
		5.4	<6	<6	9	M	9	<6	32	[c]14	15	11	6	<6	8	29	------
		7.4	<6	<6	<6	<6	8	<6	11	21	12	<6	13	10	<6	26	------
		9.3	------	8	6	<6	<6	<6	32	<6	12	<6	18	<6	<6	36	------
		14.3	[d]<6	10	6	<6	7	[d]<6	44	18	15	10	11	<6	10	34	------
H	Admiralty metal	2.0	M	8	20	M	<6	------	6	[d]6	15	M	14	30	M	50	------
		5.4	<6	13	35	M	29	M	25	32	19	<6	6	9	25	88	------
		7.4	8	21	20	<6	37	8	14	36	26	<6	<6	31	[c]56	47	------
		9.3	------	20	20	<6	26	<6	16	[c]35	24	<6	[c]46	13	<6	68	------
		14.3	[d]<6	17	17	<6	35	[d]<6	34	48	26	<6	26	12	31	86	------
K	Leaded silicon brass	2.0	M	M	M	M	M	------	<6	[b]<6	<6	M	M	M	M	41	------
		5.4	7	<6	<6	M	<6	M	15	<6	9	<6	<6	8	<6	D	------
		7.4	<6	<6	6	<6	12	6	<6	<6	12	<6	10	6	7	D	------
		9.3	------	<6	7	<6	[c]<6	<6	[c]12	6	<6	<6	[c]15	<6	<6	D	------
		14.3	[d]<6	<6	7	<6	<6	[d]<6	32	6	<6	<6	18	8	6	D	------

TABLE 50. *Loss in weight and maximum pit depth of copper-zinc alloys and copper-nickel-zinc-alloy*—Continued

(Average of two specimens)

Identification	Material	Average exposure	Test site number and soil type														
			51	53	55	56	58	59	60	61	62	63	64	65	66	67	70
			Acadia clay	Cecil clay loam	Hagerstown loam	Lake Charles clay	Muck	Carlisle muck	Rifle peat	Sharkey clay	Susquehanna clay	Tidal marsh	Docas clay	Chino silt loam	Mohave fine gravelly loam	Cinders	Merced silt loam
MAXIMUM PIT DEPTH (mils) Continued																	
J	Yellow brass	2.0	M	6	10	M	M	------	14	[b]6	<6	<6	<6	M	M	D	------
		5.4	12	11	10	<6	<6	<6	35	16	15	<6	17	16	9	D	------
		7.4	9	9	8	6	13	<6	14	9	14	<6	24	20	18	D	------
		9.3	------	6	10	<6	8	M	[c] 33	6	13	M	20	18	8	D	------
		14.3	[d] 8	<6	6	<6	7	[d] <6	[e] 104	22	<7	<6	10	10	8	D	------
L	Muntz metal	2.0	M	<6	6	M	<6	------	9	[b] <6	<6	M	<6	M	<6	D	------
		5.4	7	6	<6	M	10	<6	34	13	8	<6	16	M	8	D	------
		7.4	<6	6	6	<6	8	<6	8	20	6	<6	6	12	6	D	------
		9.3	------	6	6	<6	6	<6	[c] 27	12	<6	<6	6	<6	<6	D	------
		14.3	[d] <6	8	<6	10	<6	[d] <6	55+	20	<6	<6	6	7	9	D	------
B	Muntz metal with arsenic	2.1	------	<6	<6	12	6	<6	13	<6	<6	<6	<6	<6	8	122	12
		7.0	[g] 8	7	6	6	6	6	20	8	6	6	13	10	6	150	6
		9.0	------	6	6	8	<6	<6	8	[e] 8	9	<6	19	<6	8	120	6
		10.6	------	6	8	6	<6	<6	14	10	8	<6	18	<6	<6	124	<6
		13.0	------	9	10	6	7	<6	22	12	12	<6	24	<6	6	145	7

[a] Each ounce per square foot corresponds to an average penetration of 0.0014 in.

[b] Exposed for 1.0 yr only.

[c] Data for the individual specimens different from the average by more than 50%.

[d] Data for 4 specimens.

[e] Data for only 1 specimen. The other specimen was missing.

[f] D, specimens destroyed by dezincification.

[g] Data for 10 specimens.

[h] M, shallow metal attack, roughening of the surface, but no definite pitting.

TABLE 51. *Maximum depth of dezincification on brasses exposed for 14 years* [a]

+, one or both specimens dezincified through wall thickness of pipe.
P, plug type of dezincification.
U, uniform type of dezincification.

Soil	Admiralty metal		Leaded silicon brass		Yellow brass		Muntz metal		Muntz metal with arsenic	
	71.28% Cu 27.39% Zn 1.30% Sn		67.08% Cu 31.07% Zn 0.84% Pb 1.01% Si		66.50% Cu 33.06% Zn 0.42% Pb		60.06% Cu 39.58% Zn 0.36% Pb		62.37% Cu 37.54% Zn 0.08% As	
	H		K		J		L		B [b]	
	Maximum depth	Type	Maximum depth	Type	Maximum depth	Type	Maximum depth	Type	Maximum depth	Type
			Mils		*Mils*		*Mils*		*Mils*	
51	0	--------	[c] 60+	U	38	P	73+	U	0	--------
53	0	--------	6	U	18	U	0	--------	0	--------
55	0	--------	[d] 10	U	0	--------	0	--------	0	--------
56	0	--------	0	--------	[d] 14	P	68	U	0	--------
58	0	--------	48+	U	66	U	80+	U	0	--------
59	0	--------	0	--------	0	--------	0	--------	0	--------
60	0	--------	0	--------	0	--------	0	--------	0	--------
61	0	--------	80+	U	80	P	32	U	0	--------
62	0	--------	28	U	22	P	4	U	0	--------
63	0	--------	0	--------	0	--------	0	--------	0	--------
64	[d] 22	U	28	P	50	U	80+	U	0	--------
65	7	P	80+	U	76	U	80+	U	0	--------
66	[d] 72+	P	[d] 40+	U	26	U	72+	U	0	--------
67	0	--------	80+	U	145+	U	80+	U	0	--------
70	--------	--------	--------	--------	--------	--------	--------	--------	0	--------

[a] Average for 2 specimens except in soils 51 and 59, which represent the average for 4 specimens.

[b] The arsenical Muntz metal specimens (B) were exposed for 13 yr.

[c] Average of 3 specimens. The other specimen was unaffected by dezincification.

[d] Only one specimen affected by dezincification. The other specimen was unaffected.

[e] Intergranular corrosion.

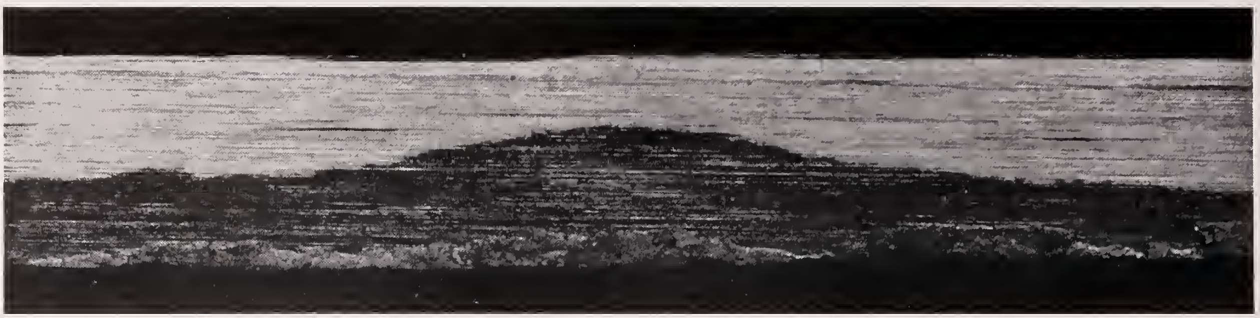

FIGURE 32. *Dezincification of Muntz metal exposed 14 years to Sharkey clay, soil 61.*
Transverse section showing transition from uncorroded metal to the uniformly dezincified layer, ×15.

FIGURE 33. *Leaded silicon brass (K) exposed 9.5 years to Sharkey clay, soil 61.*

Transverse section showing partial dezincification. The dezincification is more severe at the left, as indicated by the dark, spongelike areas with irregular boundaries. Light grains of the alpha phase in dezincified areas show that the grains of the beta phase are dezincified first, ×250.

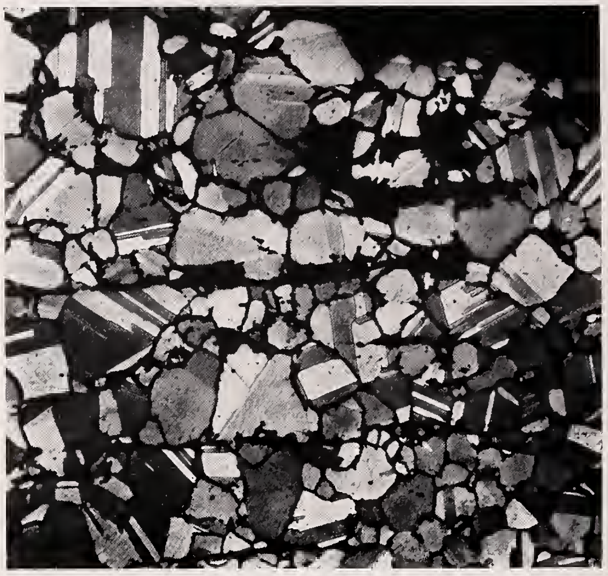

FIGURE 34. *Microstructure of Muntz metal containing 0.08 percent of arsenic.*

Transverse section of specimen exposed 7 years to cinders (site 67) showing intergranular corrosion, ×100.

pit depth tabulated below are considered, one would conclude that materials H and K are equally resistant to corrosion in soil 51.

Material	Average penetration	Maximum pit depth	Depth of dezincification
	Mils	*Mils*	*Mils*
H	1.0	6	0
K	.7	6	60+
J	1.7	8	38
L	1.7	6	73+

However, when the data for dezincification are considered, it is evident that the values for pit depth define accurately the condition of brass H only, because brasses K, J, and L have dezincfied.

The microstructure of leaded silicon brass K, which contained approximately 40 percent of zinc, consisted of the alpha and beta phases (fig. 33). As the beta phase is higher in zinc than the alpha phase, it is more susceptible to dezincification, Dezincification of the two-phase copper-zinc alloys. K and L, was fairly general, and the specimens of these alloys showed evidence of dezincification in most of the soils (table 51). The much greater dezincification of these high-zinc brasses relative to that of the single-phase admiralty metal H was, of course, to be expected because the presence of 1 percent of tin in the alloy has been observed to inhibit dezincification appreciably in sea water [172]. The specimens of 60–40 Muntz metal L showed severe dezincification in 8 of the 14 soils to which they were exposed. However, the addition of 0.08 percent of arsenic to this alloy inhibited the dezincification reaction, and no dezincification was noted in any of the same soils up to 13 years in the 60–40 brass containing arsenic.

Arsenical brasses normally exhibit good resistance to dezincification, but occasionally they are susceptible to intergranular corrosion in environments other than true soils, such as cinders [173]. Specimens of arsenic-bearing brass B examined after exposure showed that only those specimens exposed to cinders had intergranular corrosion. (fig. 34).

It is evident that dezincification of brasses in soils is influenced largely by alloy composition, and also to some extent by the nature of the environment. The occurrence and intensity of dezincification is not associated with the weight loss and pit depths resulting from normal corrosion of brasses. For example, in the corrosive, high-sulfide Rifle peat, soil 60, the materials H, K, J, and L, which were normally prone to dezincification in the other environments, showed no evidence of this type of attack. The fact that dezincification did not occur either in this or other soils high in sulfides, 59 and 63, indicates that sulfides in high concentration may act as inhibitors of dezincification. The corrosion resistance of high-zinc brasses to sulfur and sulfur compounds have been previously reported [174].

11.4. Soldered and Welded Joints in Copper

Hiers [175] reported that serious galvanic action between lead-tin solders and copper pipe may take place in sea water in which the solder is anodic to copper. It has also been reported [176] that the bond formed by the soldering operation is the result of an alloying reaction between tin and copper and that the copper-tin alloy thus formed is cathodic to copper. This introduces the probability of a couple that might lead to the galvanic corrosion of copper.

In order to investigate galvanic action of the cell existing between the solder used in joints in underground construction and the copper pipe assembly, specimens were prepared by connecting two 6-in. lengths of 1¼-in. plain copper pipe with a coupling 2¼-in. in length. The ends of the assembly were closed with streamlined caps, and the joints were sweated in with 50–50 lead-tin solder.

Inspection of the soldered assemblies from 14 test sites after exposure for periods ranging up to 14 years showed no indication of deleterious galvanic corrosion of either the solder or copper. This was due to the fact that in practically all of the soils to which the specimens were exposed, a dense, hard protective coating or film of white corrosion products covered the entire surface of the exposed solder, and thereby protected the solder and underlying alloy layer from further local or galvanic attack. These observations were similar to those reported by Crampton [173] from tests of sweated joints made with various commercial solders and exposed for 2 years to a saline solution at 60°C and with those obtained by Tracy [177] from 6-year tests designed to determine the effect of the carbon-dioxide content of hot circulating water on the corrosion rate of solders having different compositions.

Results of previous studies indicated by inference that there was a possibility the oxide formed by a welding operation might be cathodic to the pickled parent copper surface. In order to ascertain the probability of the existence of this effect, a series of soil tests was inaugurated. Specimens for this purpose were prepared by arc-welding two 6-in. lengths of copper pipe, 1.5 in. in diameter, by means of a circumferential butt weld. The welding rod was of the same nominal composition as the pipe. Neither the depths of the maximum pits nor the distribution of corrosion on the welded specimens after exposure for 14 years (material N_1, table 49) gave any indication of accelerated corrosion resulting from the weld.

12. Field Tests of Lead, Zinc, and Aluminum

12.1. Description of the Materials

The form, dimensions, and composition of the zinc, lead, and aluminum-alloy specimens are given in table 52. The lead alloys contained copper, antimony, tellurium, or tin in various amounts to improve the hardness and mechanical properties. Die-casting zinc alloy CZ is substantially the same as ASTM alloy AC41A. The composition of material Z corresponds approximately to that of commercial "high-grade" zinc slab.

12.2. Lead

Lead alloys are used underground in the form of water service pipes and cable sheaths. Cable sheaths are generally placed in fiber, cement, or vitrified-clay ducts and are in contact with soil only as it is washed in from manholes, but occasionally may be laid directly in the ground. Lead-coated ferrous metals are not used much because of accelerated corrosion of any exposed iron or steel due to lead being cathodic (see section 16.3).

Table 53 shows the losses in weight and maximum pit depths of antimonial lead, A, and commercial lead, H, cable sheaths for exposures of 10 to 17 years, beginning in 1922. The area of the antimonial lead sheath was in most cases 370 in.^{2}, and that of the commercial lead 150 in.^{2}

TABLE 52. *Composition of zinc, lead, and aluminum-alloy materials*

Material	Symbol	Year buried	Number of specimens in test	Form	Nominal width or diameter	Length	Thickness	Zn	Al	Cu	Fe	Pb	Sn	Bi	Sb	Si	Mn	Other elements
					Inch	*Inch*	*Inch*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Rolled zinc:																		
Commercial	Z	1937	150	Plate	2.3	12	0.15	Rem	------	------	0.009	0.095	------	------	------	------	------	0.0038 Cd
Zinc alloy	CZ	1937	150	do	4.44	6.8	.122	Rem	4.00	1.05	.018	< .003	<0.001	------	------	------	------	0.003 Cd, 0.02 to 0.05 Mg
Zinc	P	1924	40	Sheet	2.0	6	.062	99. +	------	------	------	------	------	------	------	------	------	------
Do	Z_1	1924	40	do	2.0	6	.062	99.5	------	------	------	------	------	------	------	------	------	------
Cast zinc	Z_2	1924	40	Plate	2.0	6	.25	99.5	------	------	------	------	------	------	------	------	------	------
Lead:																		
Hearth refined lead	NN	1924	40	Plate	2.0	6	.25	------	------	.002	------	Rem	------	0.004	------	------	------	------
Chemical lead	N	1924	40	do	2.0	6	.25	------	------	.57	------	Rem	------	------	------	------	------	0.009 Ag
Do	O	1937	150	Pipe	1.5	12	.177	------	------	.056	------	Rem	------	.002	0.0011	------	------	------
Tellurium lead	T	1937	150	do	1.5	12	.177	------	------	.082	------	Rem	------	------	.0011	------	------	0.043 Te
Antimonial lead	A	1922	281	Sheet	8.5	22	.12	------	------	.062	------	Rem	------	------	.82	------	------	------
Do	B	1937	150	Pipe	1.5	12	.177	------	------	.036	------	Rem	------	.016	5.31	------	------	------
Commercial lead	H	1922	281	Sheet	3.5	22	.11	------	------	.013	------	Rem	------	.037	------	------	------	------
Calcium lead	M	1941	150	Pipe	1.25	15	.172	------	------	------	------	Rem	0.25	------	------	------	------	0.02 Ca, 0.02 Mg, plus usual impurities in lead.
Aluminum:																		
Commercial aluminum	C_1	1924	40	Sheet	2.0	6	.062	------	Rem	.09	.33	------	------	------	------	0.3	0.03	------
Aluminum with manganese	C_2	1924	40	do	2.0	6	.062	0.02	Rem	.16	.51	------	------	------	------	.44	1.12	------
Duralumin	C_3	1924	40	do	2.0	6	.062	------	Rem	4.10	.30	------	------	------	------	.23	0.62	0.52 Mg

TABLE 53. *Loss in weight and maximum pit depth of lead cable sheath buried in 1922*

Soil		Duration of exposure	Antimonial lead A		Commercial lead H	
No.	Type		Loss in weight	Maximum penetration	Loss in weight	Maximum penetration
		Years	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*
1	Allis silt loam	11.65	4.02	120+	2.01	112+
2	Bell clay	15.48	1.56	45	1.20	30
3	Cecil clay loam	10.02	.63	8	.59	18
4	Chester loam	12.00	1.79	64	2.13	51
5	Dublin clay adobe	15.56	3.51	120+	6.66	112+
6	Everett gravelly sandy loam	15.53	.37	22	.26	28
7	Maddox silt loam	16.94	1.47	39	1.60	32
8	Fargo clay loam	11.76	.73	12	------	------
10	Gloucester sandy loam	11.95	.89	26	1.05	15
11	Hagerstown loam	11.92	.48	36	.38	15
12	Hanford fine sandy loam	15.59	1.88	30	1.85	43
14	Hempstead silt loam	11.76	2.13	68	.57	24
15	Houston black clay	10.06	.52	16	.36	25
17	Keyport loam	11.78	.43	36	.33	20
18	Knox silt loam	11.71	.50	20	.18	10
19	Lindley silt loam	11.63	1.31	36	.46	15
20	Mahoning silt loam	11.65	3.54	78	3.12	51
22	Memphis silt loam	11.65	1.72	32	1.00	19
24	Merrimac gravelly sandy loam	11.95	.25	18	.18	19
25	Miami clay loam	11.67	.53	44	.33	28
26	Miami silt loam	11.52	.47	22	.21	29
27	Miller clay	15.69	1.37	39	.67	31
28	Montezuma clay adobe	9.60	2.12	52	.66	10
29	Muck	10.08	3.55	14	3.45	34
30	Muscatine silt loam	17.04	2.28	56	1.04	51
31	Norfolk fine sand	15.73	.37	<6	.28	15
32	Ontario loam	11.66	.59	12	.33	18
34	Penn silt loam	12.00	3.12	120+	.81	112+
35	Ramona loam	15.59	.19	12	.31	37
36	Ruston sandy loam	15.69	.69	17	.48	22
38	Sassafras gravelly sandy loam	12.01	.38	14	.30	25
39	Sassafras silt loam	12.00	1.77	47	1.18	36
41	Summit silt loam	17.41	.77	41	.50	27
43	Tidal marsh	12.02	.51	28	.23	15
44	Wabash silt loam	11.61	.82	22	.44	13
45	Unidentified alkali soil	11.73	.45	19	.24	23
46	Unidentified sandy loam	12.00	.98	42	.18	14
47	Unidentified silt loam	17.43	1.12	32	.79	30

Between 1937 and 1941 four compositions of lead-alloy pipe, such as is used for water service, were buried in 5 soils that had been included in the 1922 tests and in 10 additional soils. The loss-in-weight and pit-depth data for these specimens are given in table 54. The data in tables 53 and 54 show that the rates of corrosion of commercial lead was similar to that of lead containing hardening agents, such as antimony, tellurium, and calcium, in the amounts present in these specimens. This conclusion agrees with the results obtained by Burns [178] from field tests of a variety of lead alloys in five typical Indiana soils. The results of the field tests conducted by the National Bureau of Standards extend considerably the available data to include a broader range of soil conditions to which the conclusions of Burns applied.

TABLE 54. *Loss in weight and maximum pit depth of lead alloys buried in 1937 and 1941* [a]

Identification	Material[b]	Average exposure	Test site number and soil type														
			51	53	55	56	58	59	60	61	62	63	64	65	66	67	70
			Acadia clay	Cecil clay loam	Hagerstown loam	Lake Charles clay	Muck	Carlisle muck	Rifle peat	Sharkey clay	Susquehanna clay	Tidal marsh	Docas clay	Chino silt loam	Mohave fine gravelly loam	Cinders	Merced silt loam
		LOSS IN WEIGHT (oz/ft²)															
		Years															
O	Chemical lead	2.1	0.62	0.22	0.37	0.21	1.56	0.36	0.18	1.46	0.30	0.05	0.20	0.14	0.10	3.67	0.03
		4.0	------	.21	.20	.45	2.41	.81	.28	2.21	.93	.02	.19	.13	.10	12.21	.12
		9.0	3.06	.53	.37	2.02	2.49	1.76	.54	1.22	.67	.10	.46	.45	.34	11.21	.26
		11.2	------	.64	.41	3.49	2.82	2.06	.75	3.03	.94	.02	.60	.35	.18	3.06	.19
T	Tellurium lead	2.1	1.21	.25	.34	.38	1.68	.23	.15	1.21	.36	.06	.25	.17	.25	3.35	.09
		4.0	------	.31	.28	.82	2.80	1.08	.20	1.75	.64	[c].02	.18	.16	.12	13.22	.15
		9.0	3.82	.73	.54	2.30	2.60	2.09	.57	1.44	1.37	.13	.48	.59	.58	11.28	.32
		11.2	------	.67	.57	4.60	3.47	1.77	.84	3.40	1.00	.02	.88	.40	.36	3.42	.28
B	Antimonial lead	2.1	1.05	.25	.19	.31	1.45	.20	.10	.94	.27	.04	.12	.17	.06	3.14	.10
		4.0	------	.22	.15	.50	2.12	1.04	.22	1.75	1.03	.01	.19	.21	.12	4.21	.14
		9.0	3.09	.62	.30	1.65	2.24	1.97	.54	1.16	.77	[c].05	.45	.51	.28	12.27	.20
		11.2	------	.70	.35	4.54	3.02	1.09	.79	3.78	1.24	.01	.96	.35	.20	4.28	.16
M	Calcium lead	5.0	------	.43	.17	.52	.54	1.23	.74	.82	.69	.18	.50	.42	.24	1.18	.35
		7.2	------	[d].46	.27	4.98	.70	.82	[d].61	[d].63	[d].64	.20	.40	.38	.39	2.23	.18
		8.7	------	.64	.39	3.47	1.22	1.74	.79	1.48	.91	.14	.48	.40	.34	8.40	.19
		[d]10.9	------	.71	.46	5.20	2.09	1.85	.88	1.69	1.02	.22	.59	.53	.55	10.56	.26
		MAXIMUM PIT DEPTH (mils)															
O	Chemical lead	2.1	40	18	24	38	34	21	18	35	32	14	24	40	44	79	48
		4.0	------	12	26	37	28	15	15	39	29	18	16	24	34	104	14
		9.0	68	26	19	86	46	14	16	31	26	29	25	32	36	135	24
		11.2	------	18	31	100	52	20	33	70	34	12	25	15	24	85	24
T	Tellurium lead	2.1	54	12	26	30	55	8	29	33	19	10	21	22	23	71	16
		4.0	------	20	26	48	56	12	10	30	31	[c]12	11	16	41	94	27
		9.0	66	18	26	110	33	18	36	43	25	32	20	21	30	104	37
		11.2	------	16	30	107	53	21	23	73	40	8	17	20	23	61	16
B	Antimonial lead	2.1	56	10	26	39	50	9	6	31	12	<6	12	6	12	56	11
		4.0	------	10	18	52	58	7	<6	42	30	16	12	15	15	90	12
		9.0	63	14	15	74	66	20	20	62	26	[c]44	10	26	24	125	20
		11.2	------	9	16	104	51	12	28	89	14	6	19	7	16	46	9
M	Calcium lead	5.0	------	12	15	30	18	25	13	24	18	36	21	19	34	26	28
		7.2	------	[d] 13	8	58	8	8	[d] 8	[d] 18	[d] 10	8	10	12	18	15	10
		8.7	------	19	18	67	31	19	16	34	26	12	12	16	22	67	16
		[d]10.9	------	16	23	94	49	25	21	62	29	18	26	19	38	88	21

[a] Average loss in weight or depth of maximum pitting for 2 specimens except when indicated otherwise.
[b] See table 52 for composition of materials.
[c] Data for 1 specimen only. The other specimen was missing.
[d] Data for 3 specimens.

The data (table 54) for the lead alloys show that the maximum pit depths decreased with increasing aeration of the soil, similar to plain irons, steels, and copper. The data also shows that in general a decrease of weight loss is associated with increasing aeration. Exceptions were noted for soils 60 and 63 where low corrosion rates were due to the inhibitive effect of sulfates which were present in high concentration. The fact that appreciable corrosion of lead occurred in soil 51, which contains a high concentration of sulfates but less than that in soils 60 and 63, does not necessarily contradict this conclusion, since ions present in concentrations less than that required for passivation tend to accelerate the corrosion of lead [178]. The partially inhibitive effect of bicarbonate, chloride, and sulfate ions is indicated by the data for the group of alkaline soils of fair to good aeration, 64, 65, 66, and 70. In spite of their high contents of soluble salts these soils, which are severely corrosive to ferrous metals, are not as corrosive to lead as are soils of similar aeration but low in soluble salts, namely, soils 53, 55, and 62. This reduction in the rate of corrosion of lead is attributed to anodic polarization from the deposition of corrosion products of low solubility in close proximity to the anodic areas.

The weight loss-time relation for specimens of lead exposed to two soils differing in aeration but similar in their chemical properties are shown in

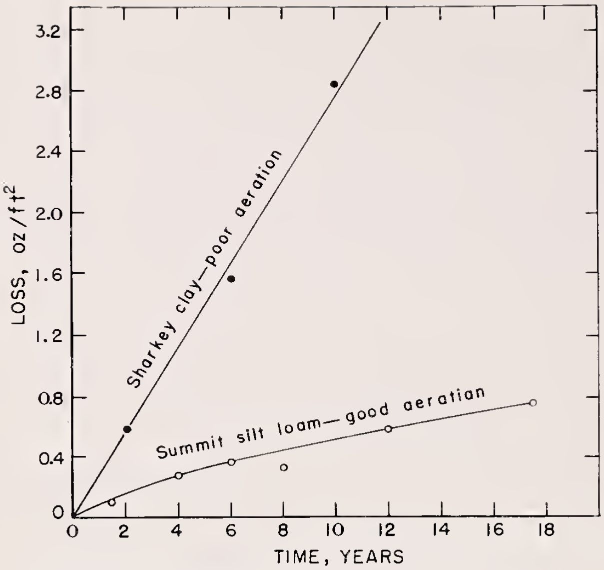

Figure 35. *Effect of aeration on the corrosion of lead.*

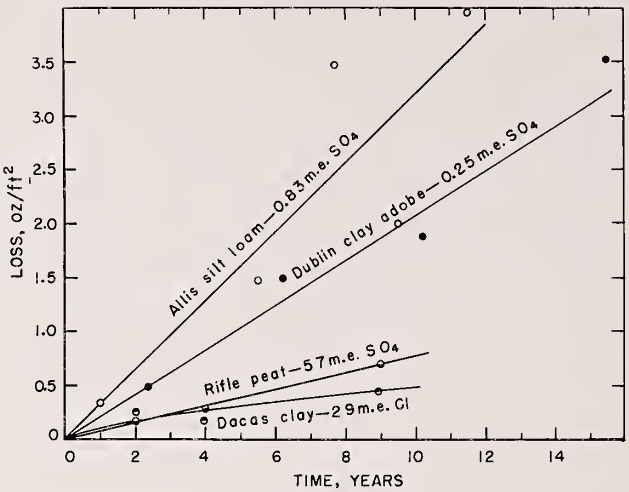

Figure 36. *Effect of sulfates and chlorides in inhibiting the corrosion of lead.*

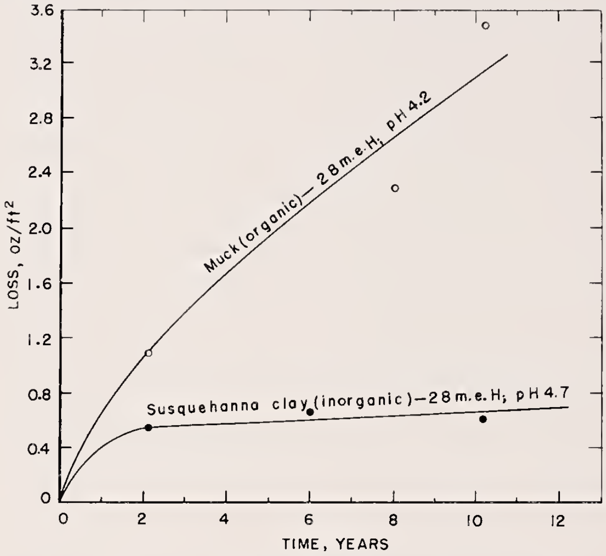

Figure 37. *Effect of organic and inorganic acidity on the corrosion of lead.*

figure 35. It is evident that the abundant supply of oxygen in the Summit silt loam is associated with a low corrosion rate; whereas in the poorly aerated Sharkey clay high corrosion rates continued throughout the test. Additional evidence of high corrosion rates of lead in soils deficient in oxygen is shown by the curves for the poorly aerated soils, Allis silt loam and Dublin clay loam, shown in figure 36. The effect of organic acidity in the corrosion of lead is illustrated by the weight loss-time curve for muck, figure 37. For comparison with an inorganic soil having the same total acidity, derived from the weathering of aluminosilicates, the curve for lead in the Susquehanna clay, which is moderately corrosive to iron and steel, is also shown. The corrosiveness of the organic soil is due to the fact that certain organic salts of lead, the acetate for example, are water soluble and do not form protective deposits.

The strongly inhibitive action of sulfates and chlorides on the corrosion of lead is illustrated in figure 36. In these and other environments high in soluble salts in which lead is highly resistant to corrosion, ordinary ferrous materials and copper and copper alloys, as shown previously, corrode readily. It can be concluded that lead is corroded chiefly under soil conditions associated with deficiency of oxygen, in soils of high organic acidity and in cinders. Unless ions having an inhibitive effect on lead, such as sulfates, chlorides, carbonates and silicates, are present in relatively high concentration, lead may be corroded appreciably underground.

12.3. Zinc

Zinc is not used extensively as pipe or structural members for underground assemblies. Practical interest in the corrosion of zinc in soils arises principally from its use for the protection of ferrous metals, either as a coating applied to iron or steel surfaces, or as an expendable anode for cathodic protection. For the latter use it is essential that it corrode continuously as it is the current resulting from corrosion of the zinc that protects the other metal. In this section the data will show the effect of soil conditions on the corrosion of zinc. Sections 16.2 and 23.5 c and d will be devoted to the use of zinc as protective coatings and expendable anodes.

Two compositions of rolled zinc were studied, (1) commercial zinc and (2) zinc alloy containing 4.00 percent of aluminum and 1.05 percent of copper. The corrosion of commercial zinc is illustrated by photographs of specimens of rolled zinc exposed for 13 years, figure 38. Weight losses and maximum depths of pits of the two materials of rolled zinc are recorded in table 55. The weight losses show no significant differences in the corrosion of the two varieties of zinc, but the maximum pit depths were definitely less on the commercial zinc than on the alloy, except in soils 60, 67, and 70 in which both materials failed after relatively short exposures.

The poorly and very poorly aerated soils are corrosive to zinc, although high average penetration is not always associated with deep pitting (soil 51). Soils of fair to good aeration but containing high concentrations of chlorides and sulfates may induce relatively deep pitting (64, 65, and 66) probably because soluble salts diminish anodic polarization. The rather severe corrosion in soil 70 may be attributed to its high alkalinity (*p*H 9.4) and to its content of soluble salts. The effect of soil reaction on the corrosion of zinc is also indicated by the very large values for average and maximum penetration in the very acid soil 60 (*p*H = 2.6). In general, zinc is corroded under the same conditions that have been found to be corrosive to uncoated ferrous materials.

TABLE 55. *Loss in weight and maximum pit depth of rolled zinc buried in 1937* [a]

Identification	Type of rolled zinc[b]	Average exposure	Test site number and soil type														
			51	53	55	56	58	59	60	61	62	63	64	65	66	67	70
			Acadia clay	Cecil clay loam	Hagerstown loam	Lake Charles clay	Muck	Carlisle muck	Rifle peat	Sharkey clay	Susquehanna clay	Tidal marsh	Docas clay	Chino silt loam	Mohave fine gravelly loam	Cinders	Merced silt loam
LOSS IN WEIGHT (oz/ft²)																	
		Years															
Z	Commercial zinc	2.1	2.0	0.2	0.4	1.1	3.3	0.7	4.6	0.5	0.6	1.2	0.7	0.5	1.7	[c]4.6	1.7
		4.0	------	.6	.6	3.4	5.1	1.7	10.4	1.0	1.2	[d]2.3	.6	.8	[d]2.6	[c]12.2	[c]1.6
		9.0	4.8	1.1	.7	4.5	7.4	4.6	[f]D	1.1	1.2	[e]2.0	1.4	1.4	.9	D	3.6
		11.2	------	1.6	1.3	6.6	7.6	3.9	D	2.1	1.3	3.8	1.6	1.1	[d]4.4	12.0	D
		12.7	------	2.2	1.2	[d]9.0	7.5	4.6	D	2.0	1.7	4.1	2.0	1.8	5.5	D	D
CZ	Zinc alloy	2.1	2.6	.3	.4	2.2	3.7	.9	7.5	[d].5	.4	.9	1.3	1.2	3.6	10.6	2.0
		4.0	------	.5	.6	5.0	6.3	1.6	15.0	1.1	.6	1.4	2.5	.8	4.7	13.1	[c]2.2
		9.0	5.0	1.0	.8	6.3	7.4	[e]3.9	D	1.2	.8	3.1	2.5	2.0	1.4	D	1.7
		11.2	------	1.5	1.1	6.7	9.7	3.9	D	[d]2.7	1.0	3.9	[e]4.0	2.1	3.8	17.0	16.3
		12.7	------	2.7	1.4	9.2	9.6	4.9	D	2.4	1.7	4.3	3.6	2.4	4.8	D	D
MAXIMUM PIT DEPTH (mils)																	
Z	Commercial zinc	2.1	30	10	13	10	38	<6	53	12	9	26	16	30	25	[g]107+	56
		4.0	------	10	8	[d]26	66	10	100	8	9	34	18	36	[d]28	118+	[d]102+
		9.0	28	13	8	29	58	22	150+	14	12	[e]25	79	56	44	150+	84
		11.2	------	16	10	42	75	28	150+	17	11	30	35	40	56	78	150+
		12.7	------	17	9	[d]53	50	18	150+	14	9	43	[d]21	56	34	150+	150+
CZ	Zinc alloy	2.1	33	15	21	25	108+	12	74	[d]14	[d]12	12	18	22	95	57	34
		4.0	------	22	20	30	125+	36	125+	28	16	24	20	16	124+	125+	[d]80+
		9.0	52	26	30	56	125+	[e]96	125+	36	19	34	45	33	36	125+	38
		11.2	------	22	20	71	125+	86	123+	28	27	36	[e]46	32	86+	48	125+
		12.7	------	31	34	87	125+	99	125+	37	32	47	52	51	125+	125+	125+

[a] Average loss in weight or depth of maximum penetration for 2 specimens, except when indicated otherwise.

[b] See table 52 for composition of materials.

[c] Data for 1 specimen only. The other specimen was destroyed by corrosion.

[d] Data for the individual specimens differs from the average by more than 50 percent.

[e] Data for 1 specimen only. The other specimen was missing.

[f] D, both specimens destroyed by corrosion.

[g] +, one or both specimens contained holes due to corrosion.

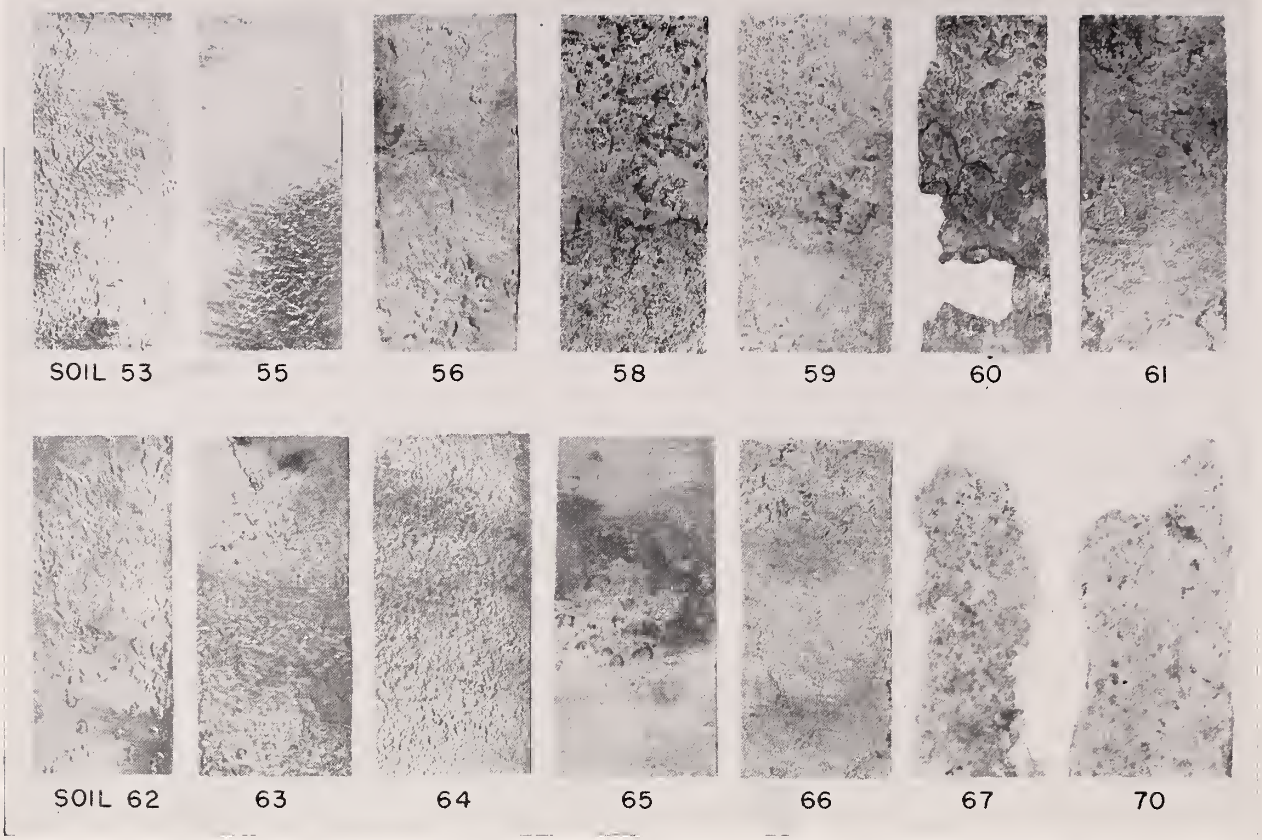

FIGURE 38. *Condition of specimens of rolled commercial zinc after exposure for 13 years to 14 soils.*

12.4. Aluminum

A few data were obtained on commercial aluminum, duralumin, and aluminum alloyed with 1.12 percent of manganese, exposed in 1926 to only five soils on specimens of sheet measuring 2 by 6 by 0.062 in. In some of the soils, the duralumin was completely converted to a greenish-white paste. The aluminum alloys were susceptible to intergranular corrosion. In the advanced stages, this type of attack caused ridges and blisters to occur on the surface, beneath which was a white powder on some of the specimens. The unalloyed specimens were the best of the group. Table 56 shows the loss of weight and maximum penetration of the thin aluminum specimens, exposed approximately 10 years, and similar data for the same soils on zinc and iron for comparison. None of the thin materials was satisfactory for use unprotected in the corrosive soils to which they were exposed. Great strides have been made during recent years in the development of aluminum alloys which might be more corrosion resistant than the specimens buried at the Bureau's test sites.

TABLE 56. *Loss in weight and maximum pit depth of zinc and aluminum exposed in 1926*

Duration of exposure (years)		10.16		10.08		10.05		10.73		10.55	
Material	Symbol	Soil 13		Soil 29		Soil 42		Soil 43		Soil 45	
		Hanford very fine sandy loam		Muck		Susquehanna clay		Tidal marsh		Unidentified alkali soil	
		Loss in weight	Maximum pit depth	Loss in weight	Maximum pit depth	Loss in weight	Maximum pit depth	Loss in weight	Maximum pit depth	Loss in weight	Maximum pit depth
		oz/ft²	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*
Sheet zinc	Z_1	3.52	40	4.66	39	0.85	17	2.48	36	[a]D	[b]62+
Cast zinc	Z_2	3.47	71	5.37	55	.79	18	2.38	73	9.93	104
Sheet zinc	P	1.89	53	3.85	62+	1.06	20	4.85	40	D	62+
Aluminum	C_1	.086	21	D	62+	.35	62+	.18	<6	.49	46+
Al-Mn-alloy	C_2	.38	45+	[c].97	62+	.20	14	.22	13	.33	20
Duralumin	C_3	D	D	D	D	1.39	62+	.15	<6	[c].56	62+
Open-hearth iron	A	9.92	125+	5.86	62	5.61	70	D	125+	D	125+
Steel+0.2% Cu	S	D	62+	6.91	62+	5.40	59	D	62+	D	62+

[a] D = destroyed by corrosion.
[b] + = 1 or both specimens punctured because of corrosion.
[c] Data on 1 specimen only. The other specimen was destroyed by corrosion.

13. Comparison of the Corrosion of Ferrous and Nonferrous Metals

Copper, zinc, and lead, together with iron and steel are the metals most commonly found in underground construction and a comparison of their corrosion resistances would be useful. For the purpose of making such a comparison, the soils in which all four of these metals had been exposed were grouped into four environments, as follows: (1) well aerated, acid soils low in soluble salts, 53, 55, 62; (2) poorly

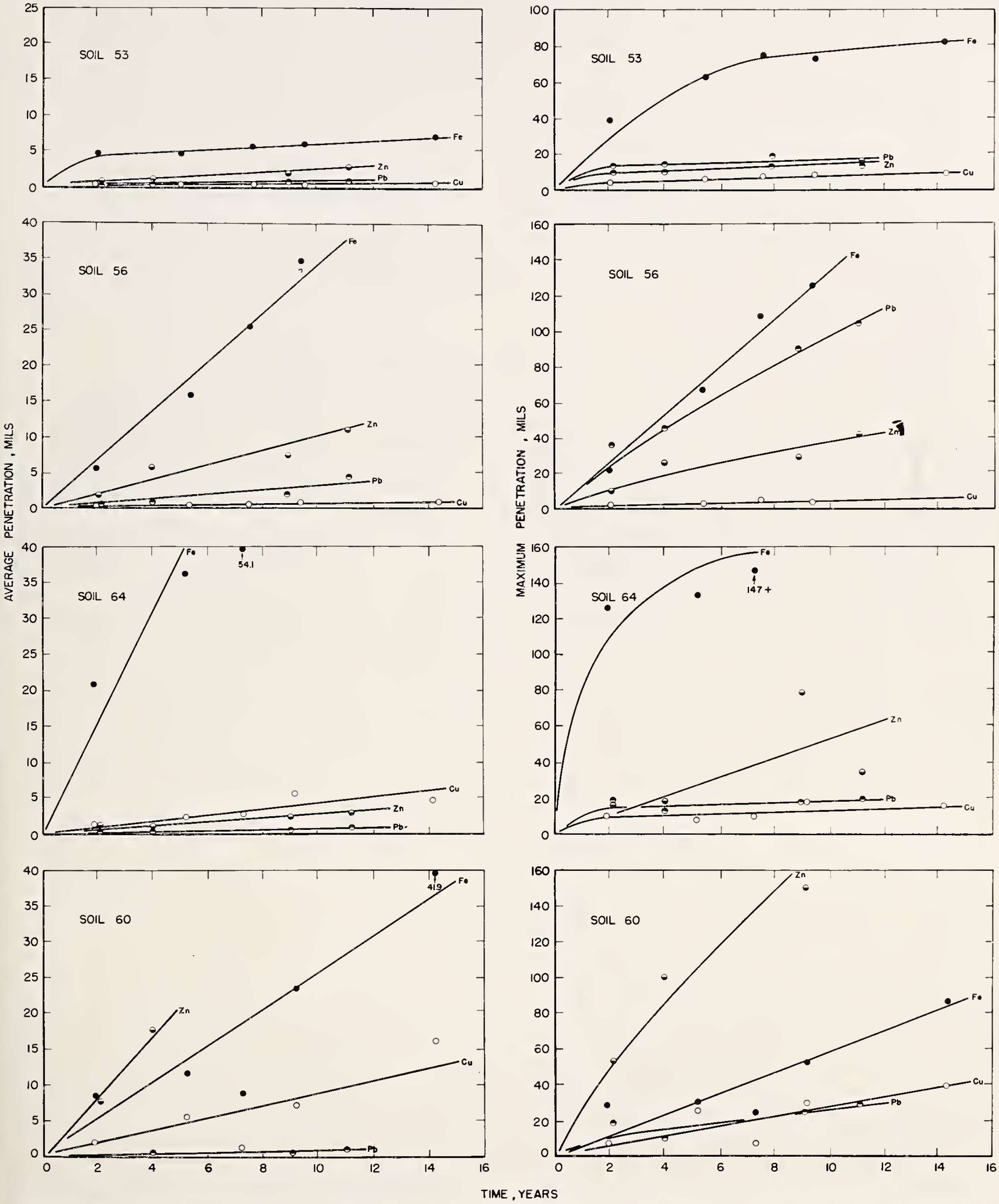

Figure 39. *Average and maximum penetration–time curves of steel, copper, lead, and zinc in representative soil environments.*

aerated soils, 51, 56, 58, 61; (3) alkaline soils high in soluble salts, 64, 65, 66, 70; and (4) soils high in sulfides, 59, 60, 63. Corrosion-time curves for soils typical of these environments are shown in figure 39. Each plotted point for copper is the average of a total of eight measurements, made on specimens of four compositions of copper and copper-silicon alloys. For zinc, each point is the average of two measurements made on the specimens of rolled zinc, and for lead, each point is the average of six measurements, made on three compositions of lead. To show the average behavior of steel and other wrought ferrous metals, each point for steel is the average of eight measurements made on specimens of carbon steel, mechanically-puddled wrought iron, hand-puddled wrought iron, and copper-molybdenum open-hearth iron. The wall thickness of the copper and steel specimens was 0.145 in., and that of the zinc and lead specimens 0.150 and 0.177 in., respectively.

The ferrous metals corroded at considerably higher rates than any of the other metals in all of the environments except Rifle peat (soil 60) in which the corrosion rate of steel was exceeded by zinc. Because of the poor aeration and high concentrations of soluble salts, including sulfides, in soil 60, lead is the only metal of this group that would be expected to withstand the corrosive action of this soil for a long period.

Representative corrosion curves for well-aerated soils (53) low in soluble salts and poorly aerated soils (56) are shown in figure 39. In these environments which are representative of most of the soils found in the United States, copper shows a higher resistance to corrosion than the other metals. This is especially pronounced in the poorly aerated environment of soil 56. In the well-aerated environment, soil 53, all of the metals of reasonable thickness would be expected to provide adequate service.

The curves for soil 64 show the effect of high concentrations of chlorides in accelerating the corrosion rate of iron and its passivating action on lead.

14. Effect of Interconnecting Different Metals

In order to determine the effect of interconnecting different metals underground, there were included in the soil-corrosion investigation in 1924, specimens consisting of four varieties of cast-brass alloy caps each connected to short nipples of Muntz metal (60:40 brass), lead, and galvanized-steel pipe. The cast caps each weighed about 150 g (5.3 oz). The nipples were cut from ½-in. pipe, each having an exposed length of 2 in., that is, about 5 in^2. Table 57 shows the composition of the brass caps.

Table 57. *Composition of cast brass caps*

Brass No.	Cu	Sn	Zn	Pb	Fe
1	85.5	3.5	6.2	4.8	
2	87.0	5.9	5.3	1.8	
3	91.8	.1	7.7	.3	
4	75.0	1.4	20.0	2.6	1.0

To determine whether differences in the composition of the caps had significant effects upon the corrosion of the metal coupled to it, the average performance of each material had been determined for all soils in which all varieties of specimens were buried, figure 40. It is apparent, that there was no great difference in the results which could be attributed to differences in composition of the caps. The differences between the results for each group of materials, e.g., the Muntz metal nipples, are not greater than the standard errors of the averages of that group and probably are the result of chance. For this reason the data for the four varieties of brass caps have been averaged for each soil in table 58 and figure 41. It is evident that the connecting

Table 58. *Loss in weight of brass, lead, and galvanized-stee nipples attached to brass caps exposed for approximately 10 years*

(In ounces per square foot)

Soil [a]	Cast brass caps	Brass nipples	Lead nipples	Galvanized steel nipples
1	0.2	6.6	19.3	24.7
2	.08	.7	(b)	2.3
3	.1	.5	4.2	3.1
4	.2	2.8	5.2	6.5
5	.1	3.2	9.6	13.9
6	.08	.2	1.6	1.2
7	.1	.3	3.7	6.3
8	.06	1.0	1.5	5.1
9	.2	1.8	5.2	4.0
10	.2	2.2	5.7	7.1
11	.2	2.1	5.4	6.7
13	.04	.8	3.6	7.7
14	.04	.3	5.6	2.6
15	.03	.5	3.3	4.2
17	.4	2.6	7.8	11.6
19	.2	1.4	5.4	3.7
20	.2	1.6	6.6	5.7
22	.1	2.0	6.9	9.0
24	.06	.2	1.1	.8
25	.1	.8	4.6	2.0
26	.1	.9	3.2	2.2
27	.04	1.2	3.9	2.9
29	.3	5.6	(b)	19.2
30	.07	.7	3.0	4.3
31	.04	.3	4.2	3.0
32	.07	1.2	2.8	2.6
33	.6	3.4	3.1	6.3
35	.05	.04	.4	1.3
36	.09	.5	4.1	2.2
37	.2	1.7	4.3	7.4
38	.06	.2	2.3	2.2
40	.2	2.6	5.0	6.7
41	.09	1.0	6.3	2.6
42	.09	1.0	7.8	6.5
43	1.6	.2	.3	17.0
44	.1	.4	3.0	3.7
45	.3	1.6	1.4	[c] D
46	.08	.5	1.5	7.3
47	.1	.2	1.0	4.7

[a] See table 6 for soil type and locations.
[b] Data could not be used because threads of nipple were stripped.
[c] D, destroyed by corrosion.

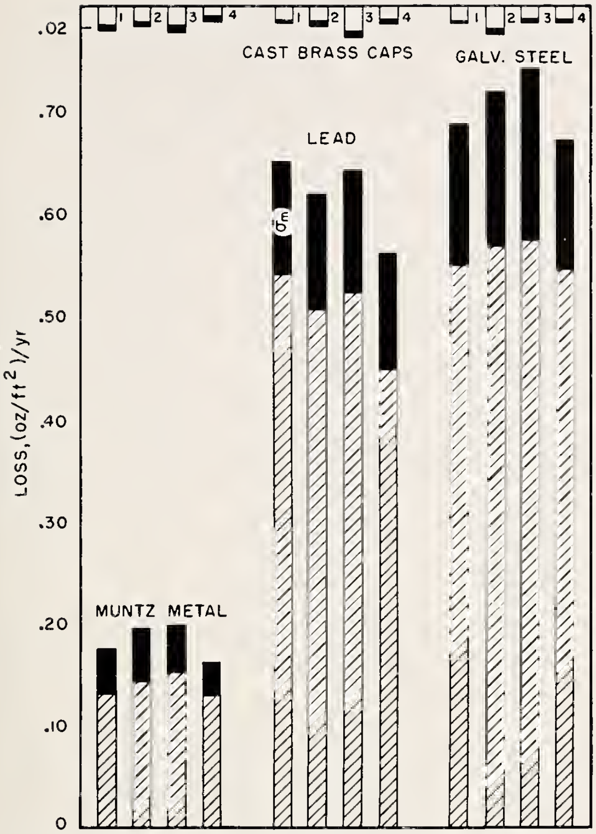

FIGURE 40. *Average rates of corrosion of cast-brass fittings and attached nipples in 15 soils.*

At the top of the figure are shown the average rates of corrosion of four cast-brass caps. Below are the rates of corrosion of the nipples attached to each variety of cast cap. The solid ends of the columns show the standard errors of the averages (σ_m).

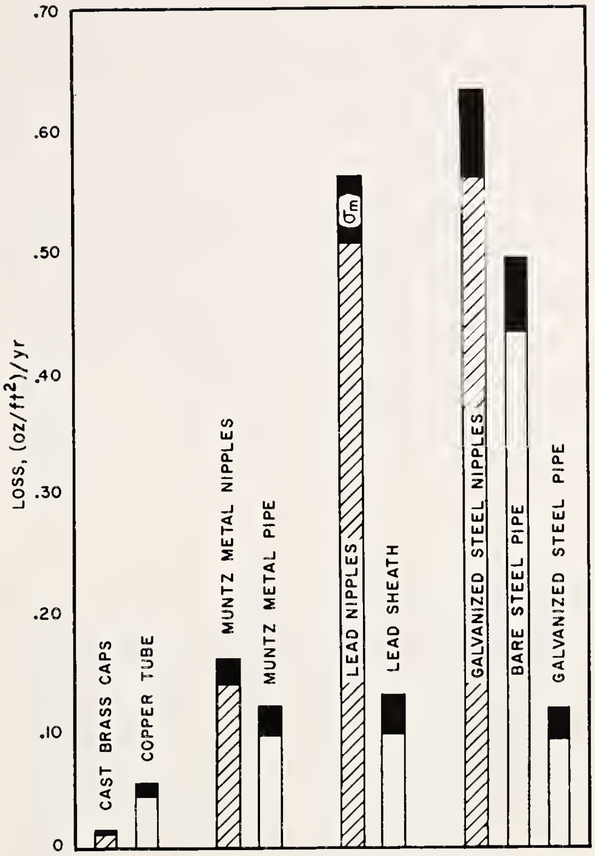

FIGURE 41. *Effect of interconnecting different metals.*

The unshaded columns show the normal corrosion rates of uncoupled metal. The diagonally shaded columns show the average rates of corrosion of the same materials coupled to brass caps. The solid ends of the columns show the standard errors (σ_m) of the averages.

of the different materials accelerated the corrosion of the brass, lead, and galvanized-steel nipples, and reduced the corrosion of the brass caps. Figure 41 shows that rate of loss in weight of the brass caps was about half that for uncoupled copper in the same soils, probably the result of cathodic protection.

The corrosion loss for the Muntz metal nipples was somewhat higher than for the uncoupled pipes of the same material. The losses for galvanized nipples coupled to brass caps were about six times that for galvanized pipe exposed by itself in the same soils, and were about 25 percent greater than for unprotected steel pipe. This is attributed to the fact that there was no zinc on the threaded portion of the nipples and that the zinc coating on the nipples was thinner than that on the galvanized pipe.

15. Field Tests on Nonmetallic Materials

15.1. Asbestos-Cement Pipe

The lack of information on the effect of exposure to different soil conditions on the properties of asbestos-cement pipe prompted the National Bureau of Standards to include some of this material in its comprehensive investigations of materials for underground construction. The use of asbestos-cement pipe began in Italy about 1916 and subsequently it has been used more or less extensively in other European countries and to a considerable extent in Japan. More recently, it has been used in the United States for transporting water and sewage, farm irrigation, mine drainage, salt water disposal, and for handling industrial process liquids.

a. Description of the Materials and Test Procedures

Asbestos-cement pipe is a mixture of approximately 80 percent by weight of portland cement and 20 percent asbestos fibers. Practically all of the asbestos-cement pipe used in the United States is formed by a continuous process on a revolving steel mandrel, with the material being built up and compacted under heavy pressure, then subjected to a curing operation [121, 124, 128]. When the required thickness has been obtained the seal between the mandrel and the pipe is released by the introduction of air between the mandrel surface and the pipe. This operation, necessarily carried out without the high pressures used while the pipe is being formed, adds to the outside surface a small thickness of relatively uncompacted stock known as the calendar layer.

The NBS field tests of asbestos-cement pipe, started in 1937 and 1939, included 6-in. pipe from one source and 4-in. pipe from another. All the pipe was class 150 pipe, i.e., it was designed to withstand 150 lb/in.^{2} pressure. Both sizes of pipe were fabricated in essentially the same manner, but there were minor differences in the techniques used. After removal from the mandrel, the 6-in. pipe was cured by a high-pressure steam process in which heat and pressure were applied to the pipe in a moisture-saturated atmosphere. Silica flour had been added to the slurry during the manufacture of these pipes to facilitate the chemical reactions resulting from steam curing. The 4-in. pipe was cured by submersion in water for 2 to 3 weeks. After curing, all pipes were trimmed and machined.

The ends of the 6-in. diameter pipe were not sealed and since it was the intent to limit exposure to the soil to the exterior surface, the interior surface and the ends were coated with a resinous varnish. The 4-in. specimens were tapered 2½ in. from each end and closures were placed at the junction of the tapered and untapered portions to confine the action of the soil to the external surface. A sufficient number of specimens of the pipes were installed at each of 15 test sites to provide for removal of two samples after each period of exposure with a maximum exposure period of 13 years.

After periodic removal from the test sites, the specimens were returned to the laboratory for determination of the effects of exposure to the soils. Measurements of pit depth and loss in weight, the criteria used to evaluate metallic materials, were unsuitable for this material. Criteria used for the asbestos-cement pipe were hydrostatic bursting strength, crushing strength, water absorption, apparent specific gravity, and softening of the surface. Representative samples from each of the 4-in. and 6-in. "as manufactured" pipe, which had been stored indoors at the Bureau, were tested to supply reference data. In addition, a section from each length of pipe from which the 4-in. diameter specimens were cut was subjected to tests by the manufacturer and the Pittsburgh Testing Laboratory in accordance with the procedures employed at the Bureau. Both the exposed and unexposed 6-in. specimens were immersed in water for 48 hr before making the bursting and crushing tests, in order to simulate service conditions with respect to moisture. However, the 4-in. specimens were tested in the air-dry condition because the reference samples had already been tested in this condition.

The depth of softening of the surfaces of the specimens removed after the shorter periods of exposure was estimated by scratching the external surface, allowing for the original condition of the outermost or calendar layers. During the latter part of the investigation, quantitative measurements of the depth of surface softening were made by a method developed by the Johns-Manville Research Center [128, 180]. By this method, the surface layers, which had been softened by contact with the soil, were removed by grinding under carefully controlled conditions until the surface hardness, as indicated by a scratch test, was equal to that below the calendar layer of the unexposed reference pipe. The thickness of the removed layers was then taken as a measure of the softening of the surface.

The 4-in. specimens were prepared for the hydrostatic bursting tests by removing the closures and the tapered ends, the length of the specimens thereby being reduced to 11 in. The 6-in. specimens required no alteration in their size or shape. These tests were made on only one specimen for each exposure period from each of the test sites.

The apparatus (fig. 42) for determining the bursting strength was provided with internally fitting rubber gasketed heads to close the ends of the pipe and was so designed that the pipe was not subjected to end compression during the test. After filling the pipe with water, the entrapped air was allowed to escape and the hydrostatic pressure was applied at a rate of approximately 10 lb/in.^{2}/sec until the pipe failed. The minimum and average wall thickness along the fracture as well as the location and character of failure of each specimen were noted. The type of failure noted in most specimens was characterized by an initial fracture in which an end section of the pipe split out and a crack propagated from this fracture the length of the specimen, as illustrated in figure 43. Others failed by cracking in either one or two places simultaneously along the entire length of the specimen.

Direct comparison between the bursting pressures of specimens is not valid unless the variations of wall thickness and diameter are taken into account. This was accomplished by computing the tensile strength according to the following modification of the Birnie formula [181] adapted to asbestos-cement pipe

$$f=\frac{P(d+1.7t)}{2t}$$

where f = tensile strength in pounds per square inch; P = bursting pressure at failure in pounds per square inch; d = internal diameter in inches; and t = wall thickness in inches.

Crushing strengths were determined on two lengths of pipe prepared by circumferentially cutting in half one specimen for each exposure period from each site. The tests were made according to the procedure described in Federal Specifications for asbestos-cement pipe [182], using the three-edge bearing method as illustrated in figure 44. The load was applied at a rate of approximately 1,000 lb/min until failure occurred. The directions of load application were 90 degrees apart for the two sections cut from the same specimen.

The modulus of rupture of the individual specimens was calculated from the values of crushing strength according to the formula given below which is used generally in the asbestos-cement industry.

$$f=\frac{0.9P\ (d+t)}{Lt^2}$$

where f = modulus of rupture in pounds per square inch; P = load to produce failure in pounds; d = internal diameter in inches; t = wall thickness in inches; L = length in inches.

Samples for determination of water absorption and apparent specific gravity were prepared from sound sections of the specimens which had been subjected to the hydrostatic and crushing tests.

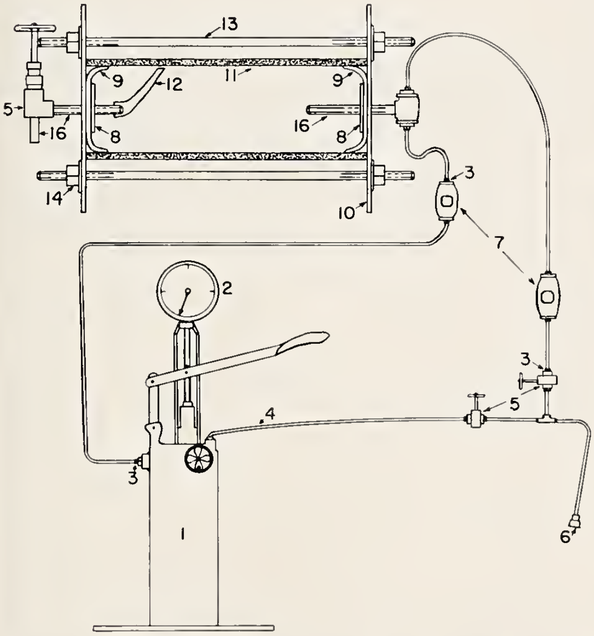

FIGURE 42. *Arrangement of apparatus for hydrostatic bursting tests.*

1, Hand-operated hydraulic pump; 2, pressure gage; 3, ½-in. pipe thread connector with 7/16-in. compression screw for connection to ¼-in. copper tubing; 4, ¼-in. copper tubing; 5, ¼-in. needle valves; 6, ¾- to ½-in. reducer for connection to main water supply; 7, ¼-in. high pressure check valves; 8, steel disks, 2½ or 4½ in. in diameter, which screws on the ¾-in. threaded pipe to hold the rubber gaskets in place; 9, 4- or 6-in. rubber gaskets for testing the appropriate size of pipe; 10, steel plates, 9 by 9 by ½ in.; 11, asbestos-cement pipe specimen under test, approximately 12 in. in length; 12, overflow or air vent, 13; ½-in.-diameter steel rods, threaded on both ends; 14, ½-in. nut with washer; 15, ½-in. needle valve for expelling air; 16, ½-in. threaded pipe.

FIGURE 43. *Specimen of asbestos-cement pipe after failure in the bursting apparatus.*

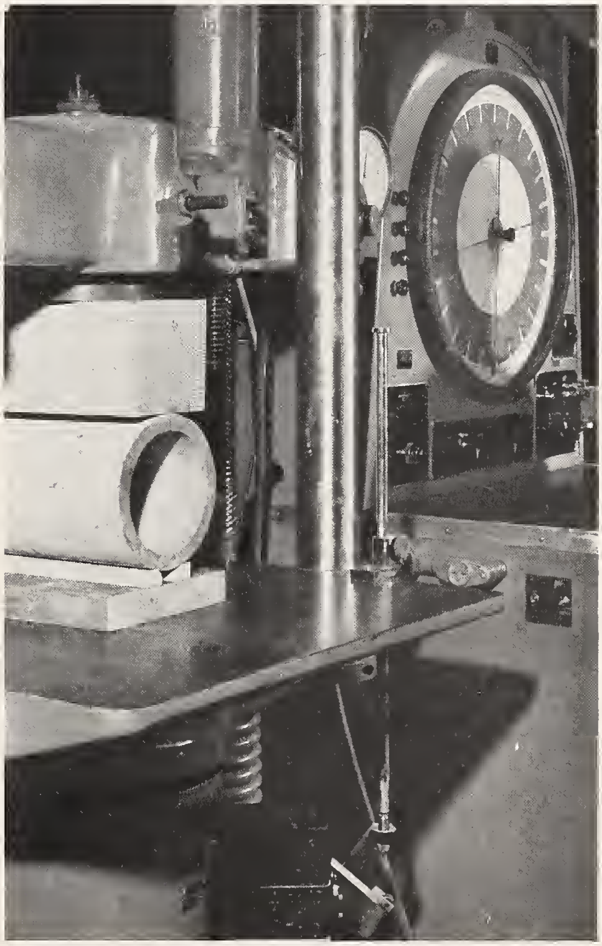

FIGURE 44. *Determination of crushing strength of a section of asbestos-cement pipe.*

b. Mechanical and Physical Properties of the Exposed and Unexposed Samples

The properties of the 4- and 6-in. specimens of asbestos-cement pipe removed from the test sites after five periods of exposure are given in tables 59 and 60, respectively. The initial properties of the unexposed reference specimens are given in tables 61 and 62. The letter symbols given in columns 4 and 8 of table 59 identify the pipe sections from which the samples of 4-in. pipe were cut. Comparison with the values for the 4-in. unexposed specimens recorded in table 61 was used to determine the changes that exposure produced in the tensile strength, modulus of rupture, water absorption, and apparent specific gravity values given in table 59. For the 6-in. pipe the differences between the properties of the exposed and unexposed could not be calculated by this procedure because the sections of pipe from which these samples of pipe were cut were not recorded. Hence, it was necessary to use average values for the properties of the unexposed 6-in. samples (table 62) in calculating the differences given in table 60.

The data for water absorption, apparent specific gravity and depth of surface softening reported in tables 59 and 60 represent the average of the measurements. In evaluating the data for depth of surface softening, it should be noted that the external or soft outer (calendar) layers of unexposed asbestos-cement pipe have an average depth of approximately 0.02 in. Consequently, values up to 0.02 in. reported in the tables do not reflect softening as the result of exposure to the soils. The depth of softening of specimens exposed to 3 of the more corrosive soils for approximately 13 years are shown in figure 45.

The bursting and crushing strengths of the samples, both before and after exposure, were without exception greater than the requirements of Federal Specification, SS-P-351a, Pipe, Asbestos-Cement [182]. This specification requires that the pipe withstand hydrostatic pressure of three and one-half times the maximum working pressure for the given class of pipe. For example, pipe of class 150 is required to withstand a hydraulic pressure of 525 lb/in^2. The specifications also require that pipe sections tested by the three-edge bearing method shall not fail until the crushing load exceeds 5,400 lb/linear ft for 4-in. and 6-in. pipe of class 150. The minimum observed bursting strength for exposed specimens was 675 lb/in.^{2}; the minimum crushing strength was 7,410 lb/linear ft.

Table 59. *Mechanical and physical properties of 4-inch asbestos-cement pipe after exposure to soils* [1, 2]

Soil		Exposure	Bursting strength[3]				Crushing strength[4]				Water absorption[5]		Apparent specific gravity[5]		Depth of Softening[6]
			Identification of pipe from which specimen was cut	Bursting pressure	Tensile strength		Identification of pipe from which specimen was cut	Crushing load	Modulus of rupture						
No.	Type				Value	Difference from unexposed			Value	Difference from unexposed	Value	Difference from unexposed	Value	Difference from unexposed	
		Years		*lb/in.*^{2}	*lb/in.*^{2}	*lb/in.*^{2}		*lb/linear ft*	*lb/in.*^{2}	*lb/in.*^{2}	*Percent*	*Percent*			*Inch*
51	Acadia clay	7.0	P	1,300	5,210	750	P	13,060	12,030	2,470	9.2	−5.4	1.94	0.07	<0.06
			I	1,075	4,360	90	T	13,090	10,510	2,370	11.8	−3.7	1.86	.06	< .06
			Q	775	3,550	190	U	10,930	11,590	2,640	11.1	−4.0	1.88	.06	<.06
			O	825	3,600	310	V	12,470	10,620	3,160	10.3	−5.4	1.90	.11	<.06
			L	1,075	4,290	90	K	12,740	11,010	1,300	10.6	−5.4	1.90	.09	<.06
53	Cecil clay loam	1.9	C	1,050	4,070	880	T	10,030	8,350	210	14.4	−1.2	1.76	−.05	<.02
		6.8	S	1,150	5,000	740	E	11,440	9,720	960	9.2	−5.4	1.94	.10	<.02
		9.1	V	1,245	4,890	770	S	10,060	10,890	2,420	11.2	−2.8	1.89	.05	<.02
		10.6	B	1,170	4,600	60	H	12,830	11,170	2,470	11.8	−3.3	1.88	.05	.018
		12.8	M	1,100	4,060	−40	D	9,540	9,210	1,310	15.7	−1.6	1.79	.03	.043
55	Hagerstown loam	2.0	S	1,000	4,120	−140	G	12,930	11,190	1,670	11.4	−2.1	1.78	−.07	<.02
		7.1	O	1,000	4,590	1,300	J	13,240	11,510	1,190	10.3	−6.0	1.90	.12	<.02
		9.1	C	885	3,680	490	F	16,080	11,030	1,430	12.1	−3.4	1.86	.05	<.02
		10.8	H	1,480	5,520	1,080	N	12,560	11,080	1,880	12.8	−3.1	1.85	.04	.045
		13.1	D	1,020	4,020	1,060	H	13,380	10,930	2,230	12.8	−4.1	1.88	.11	.061
56	Lake Charles clay	1.9	T	1,250	4,750	470	H	12,400	9,030	330	12.7	−.4	1.84	.00	<.02
		6.7	N	1,200	4,720	900	F	16,660	12,650	3,050	9.4	−6.1	1.94	.10	<.06
		9.1	N	950	3,970	150	J	12,310	10,700	380	12.7	−3.0	1.87	.04	<.06
		10.6	J	1,290	5,000	270	M	13,360	9,220	550	13.0	−3.0	1.86	.04	.130
		12.8	I	1,040	4,140	−130	---	---	---	---	17.9	0.0	1.75	.00	.140
58	Muck	1.9	V	1,275	5,060	940	R	11,340	8,820	460	12.9	−1.6	1.84	.01	<.15
		6.8	I	1,425	5,500	1,230	K	13,910	12,290	2,580	10.4	−6.7	1.90	.12	<.06
		9.1	J	1,290	5,000	270	T	13,180	10,280	2,140	11.9	−2.4	1.88	.04	<.06
		10.6	N	1,060	4,190	370	O	8,500	10,120	1,320	13.4	−3.0	1.82	.04	.043
		12.8	F	1,300	4,810	530	M	13,460	10,240	1,570	13.8	−2.2	1.85	.02	.047

TABLE 59. *Mechanical and physical properties of 4-inch asbestos-cement pipe after exposure to soils* [1, 2]—Continued

Soil		Exposure	Bursting strength[3]				Crushing strength[4]				Water absorption[5]		Apparent specific gravity[5]		Depth of Softening[6]
			Identification of pipe from which specimen was cut	Bursting pressure	Tensile strength		Identification of pipe from which specimen was cut	Crushing load	Modulus of rupture						
No.	Type				Value	Difference from unexposed			Value	Difference from unexposed	Value	Difference from unexposed	Value	Difference from unexposed	
		Years		*lb/in.*^{2}	*lb/in.*^{2}	*lb/in.*^{2}		*lb/linear ft*	*lb/in.*^{2}	*lb/in.*^{2}	*Percent*	*Percent*			*Inch*
59	Carlisle muck	1.9	V	1,350	5,610	1,500	Q	7,730	8,660	550	12.0	−1.9	1.89	0.02	<.06
		7.0	N	1,200	4,860	1,020	B	13,120	11,350	1,940	10.4	−4.7	1.92	.10	<.06
		9.0	C	1,000	4,040	850	S	9,980	9,440	970	15.1	.6	1.80	−.04	<.06
		10.6	A	1,160	4,890	690	M	13,260	10,490	1,820	13.9	−1.4	1.84	.01	.076
		13.0	B	1,250	4,840	300	B	11,770	10,420	1,010	13.7	−.7	1.86	.01	.106
60	Rifle peat	1.9	M	1,250	4,690	590	M	12,890	8,680	−10	14.8	−1.7	1.79	−.02	<.15
		7.0	G	1,375	5,490	1,180	D	8,500	7,510	−390	14.6	−2.8	1.79	.03	<.15
		9.0	A	950	3,950	−250	B	10,530	8,170	−1,240	14.1	−.2	1.84	.00	<.15
		10.6	E	850	3,330	−610	T	10,620	7,820	−490	20.2	3.4	1.68	−.12	.212
		13.0	G	830	3,370	−940	I	10,590	7,410	−900	23.4	6.1	1.58	−.19	.202
61	Sharkey clay	1.9	E	1,375	5,490	1,550	A	7,990	9,940	−500	13.8	−1.8	1.85	.02	<.02
		6.8	H	1,350	4,850	410	V	12,710	11,770	2,820	9.2	−5.8	1.93	.09	<.06
		9.1	W	1,100	4,110	830	Q	10,330	10,230	2,120	12.3	−2.8	1.85	.04	<.06
		10.6	R	1,200	4,480	760	V	13,020	10,820	3,360	12.4	−2.6	1.87	.05	.040
		12.8	R	1,200	4,490	770	W	14,440	10,600	2,540	13.2	−1.6	1.84	.01	.038
62	Susquehanna clay	1.9	O	800	3,680	390	P	10,440	9,360	−200	12.3	−4.7	1.80	.06	<.02
		6.8	Q	975	3,950	590	C	12,730	11,340	2,750	9.8	−6.2	1.90	.11	<.02
		9.1	L	1,195	4,740	540	W	12,750	9,170	1,110	11.2	−3.6	1.88	.06	<.02
		10.6	U	1,190	4,850	740	K	15,520	11,990	2,280	11.9	−3.2	1.89	.05	.062
		12.8	V	1,220	4,730	610	S	12,500	10,870	2,400	11.9	−2.1	1.89	.05	.067
63	Tidal marsh	1.9	L	1,125	4,350	150	H	14,410	9,630	930	11.7	−4.1	1.88	.06	<.02
		6.7	E	1,200	4,830	890	E	12,860	10,780	2,020	9.6	−6.0	1.94	.11	<.02
		9.0	U	1,100	4,440	330	L	12,160	10,580	730	11.4	−3.4	1.90	.05	<.02
		10.5	O	1,110	4,790	1,500	R	14,360	11,900	3,540	11.6	−4.8	1.85	.08	.026
		12.7	U	1,330	5,360	1,250	R	13,000	11,850	3,490	10.3	−4.6	1.92	.09	.032
64	Docas clay	1.9	J	1,400	5,530	800	G	12,330	10,440	920	10.8	−4.7	1.91	.07	<.02
		6.9	I	1,125	4,590	320	S	13,760	11,730	3,260	8.6	−7.1	1.96	.16	*
		9.1	J	1,340	5,330	600	L	13,460	12,450	2,600	9.2	−6.4	1.94	.11	*
		10.7	O	960	4,260	970	T	14,030	10,800	2,660	9.4	−5.6	1.90	.11	.019
		12.9	C	950	3,800	610	N	13,820	12,210	3,010	9.2	−6.6	1.92	.11	.026
65	Chino silt loam	1.9	K	1,100	4,460	200	M	12,900	9,780	1,110	11.6	−4.7	1.85	.04	<.02
		6.9	Q	1,075	4,320	960	D	10,090	9,540	1,640	11.4	−5.8	1.86	.12	*
		9.1	U	1,195	4,710	600	B	16,630	12,890	3,480	10.2	−4.0	1.94	.08	*
		10.7	F	1,280	4,920	640	G	14,520	12,710	3,190	8.7	−7.3	1.94	.12	.022
		12.9	F	1,370	5,140	860	K	14,780	11,670	1,960	9.0	−7.0	1.94	.12	.026
66	Mohave fine gravelly loam	1.9	D	1,100	4,410	1,450	P	11,190	9,910	350	14.6	−3.4	1.80	.08	<.02
		6.9	I	1,350	5,420	1,150	T	14,180	10,510	2,370	8.6	−7.0	1.94	.15	*
		9.1	E	1,245	4,860	520	T	12,460	9,590	1,450	10.4	−4.0	1.92	.08	*
		10.6	G	1,500	5,910	1,600	------	------	------	------	10.0	−6.7	1.93	.13	.012
		12.8	W	1,240	4,660	1,380	U	12,580	11,530	2,580	9.0	−5.0	1.94	.09	.016
67	Cinders	1.9	O	800	3,560	270	A	9,570	9,850	−590	12.7	−4.3	1.80	.06	<.06
		7.0	R	1,325	4,840	1,120	F	12,210	9,560	−40	10.7	−4.9	1.90	.08	<.15
		9.0	S	1,245	4,870	610	Q	8,010	7,970	−140	14.9	0.0	1.78	−.03	<.15
		10.6	W	990	3,670	390	K	11,860	9,640	−70	12.1	−3.0	1.86	.04	.068
		13.0	K	1,130	4,420	160	J	13,460	10,490	170	12.8	−3.0	1.86	.04	.067
70	Merced silt loam	1.9	F	1,425	5,420	1,140	P	11,310	10,000	440	10.4	−4.9	1.90	.06	<.02
		6.9	M	1,375	5,140	1,040	D	8,260	8,230	330	9.7	−7.6	1.90	.13	*
		9.1	R	1,340	4,940	1,220	S	14,630	11,970	3,500	10.5	−4.2	1.91	.09	*
		10.7	A	1,150	5,150	950	E	14,200	12,650	3,890	9.5	−5.4	1.94	.08	.016
		12.9	Q	1,050	4,490	1,130	V	14,290	11,560	4,100	10.4	−5.0	1.90	.10	.018

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[1] See table 61 for properties of the unexposed specimens and table 6 for properties of the soils.

[2] Hydrostatic bursting and crushing tests were performed on air-dry specimens. Average dimensions: internal diameter, 3.99 ±0.05 inch; wall thickness, 0.63 ±0.10 inch; length of samples for crushing tests, 5.13+0.32, or −0.81 inch; length of samples for bursting tests, 11 inches.

[3] Data are for one specimen.

[4] Data are two measurements made on samples from one specimen.

[5] Average of 12 measurements made on 4 samples from the bursting test specimen and 8 samples from the crushing test specimen. Water absorption and apparent specific gravity measurements were not made on the specimens subjected to crushing tests for the 2-year exposures.

[6] Average of the maximum condition of the two specimens. Average thickness of the calendar layer is 0.02 inch. The values are the maximum depth of softening in inches. Condition of surface: *—hardening of the calendar layer.

TABLE 60. *Mechanical and physical properties of 6-inch asbestos-cement pipe after exposure to soils*[1, 2]

Soil		Exposure	Bursting strength[3]			Crushing strength[4]			Water absorption[5]		Apparent specific gravity[5]		Depth of softening[6]
			Bursting pressure	Tensile strength		Crushing load	Modulus of rupture						
No.	Type			Value	Difference from unexposed		Value	Difference from unexposed	Value	Difference from unexposed	Value	Difference from unexposed	
		Years	*lb/in.*^{2}	*lb/in.*^{2}	*lb/in.*^{2}	*lb/linear ft*	*lb/in.*^{2}	*lb/in.*^{2}	*Percent*	*Percent*			*Inch*
51	Acadia clay	2.1	995	4,980	170	12,440	10,770	110	7.3	−2.5	1.90	0.00	<0.06
		9.0[7]	1,025	5,130	320	10,170	9,800	−860	10.9	1.1	1.86	−.04	.024
53	Cecil clay loam	2.1	1,140	5,460	650	14,150	13,630	2,970	8.6	−1.2	1.88	−.02	<.02
		4.0	1,010	5,080	270	10,840	10,970	310	7.3	−2.5	1.88	−.02	<.02
		8.9	950	4,860	50	11,120	11,630	970	7.1	−2.7	2.00	.10	.011
		11.2	1,000	4,860	50	13,480	13,340	2,680	8.2	−1.6	1.90	.00	.024
		12.7	1,025	5,100	290	12,650	11,420	760	10.4	.6	1.82	−.08	.041
55	Hagerstown loam	1.9	1,085	5,400	590	12,130	12,560	1,900	10.0	.2	1.84	−.06	<.02
		3.9	1,100	5,450	640	12,870	13,030	2,370	10.0	.2	1.81	−.09	<.02
		9.0	1,150	5,820	1,010	10,290	9,890	−770	8.8	−1.0	1.92	.02	.017
		11.0	910	4,420	−390	13,180	11,450	790	11.1	1.3	1.80	−.10	.060
		12.6	825	4,100	−710	10,380	9,550	−1,110	10.4	.6	1.83	−.07	.059
56	Lake Charles clay	2.1	995	5,070	260	13,140	13,010	2,350	5.6	−4.2	1.97	.07	<.02
		4.0	1,050	5,160	350	12,590	12,810	2,150	7.9	−1.9	1.86	−.04	<.06
		8.9	1,050	5,410	600	9,260	9,650	−1,010	7.5	−2.3	1.96	.06	.020
		11.1	935	4,600	−210	10,500	10,990	330	10.6	.8	1.90	.00	.043
		12.7	900	4,510	−300	9,200	8,880	−1,780	15.2	5.4	1.78	−.12	.069
58	Muck	2.1	1,140	5,560	750	12,760	12,570	1,910	9.9	.1	1.82	−.08	<.06
		4.0	925	4,630	−180	12,260	11,230	570	6.8	−3.0	1.89	−.01	<.06
		8.9	-------	-------	-------	7,850	9,240	−1,420	7.6	−2.2	1.88	−.02	.021
		11.2	855	4,520	−290	9,220	9,390	−1,270	13.8	4.0	1.81	−.09	.048
		12.7	925	4,510	−300	10,170	9,120	−1,540	13.0	3.2	1.80	−.10	.053
59	Carlisle muck	2.1	1,255	6,070	1,260	12,050	12,200	1,540	8.7	−1.1	1.89	−.01	<.06
		4.0	1,215	6,340	1,530	11,730	11,540	880	9.0	− .8	1.88	−.03	<.06
		9.1	1,125	5,830	1,020	11,540	10,530	−130	13.8	4.0	1.85	−.03	.035
		11.1	1,100	5,300	490	11,300	10,900	240	15.5	5.7	1.78	−.12	.043
		12.7	875	4,410	−400	9,760	8,550	−2,110	14.4	4.6	1.78	−.12	.089
60	Rifle peat	2.1	1,010	5,080	270	12,120	11,970	1,310	9.9	.1	1.80	−.10	<.15
		4.0	1,165	5,770	960	12,120	11,330	670	8.8	−1.0	1.88	−.02	<.15
		9.1	1,125	5,760	950	9,920	10,070	−590	18.5	8.7	1.72	−.18	.110
		11.1	1,050	5,220	410	9,790	9,410	−1,250	18.4	8.6	1.74	−.16	.126
		12.7	900	4,360	−450	9,130	7,770	−2,890	16.6	6.8	1.74	−.16	.156
61	Sharkey clay	2.1	1,205	6,040	1,230	14,930	13,960	3,300	6.4	−3.4	1.91	.01	<.02
		4.0	1,065	5,330	520	9,690	10,710	50	5.1	−4.7	1.96	.06	<.02
		8.9	975	4,870	60	9,990	9,600	−1,060	12.2	2.4	1.82	−.08	.024
		11.2	1,000	4,760	−50	9,420	9,530	−1,130	13.3	3.5	1.85	−.05	.056
		12.7	1,075	4,930	120	11,150	9,560	−1,100	9.6	− .2	1.88	−.02	.040
62	Susquehanna clay	2.1	1,095	5,410	600	15,650	14,460	3,800	5.9	−3.9	1.95	.05	<.02
		4.0	1,125	5,700	890	12,980	12,840	2,180	10.0	.2	1.84	−.06	<.02
		8.9	900	4,570	−240	10,080	10,860	200	10.8	1.0	1.92	.02	.025
		11.2	1,125	5,450	640	12,700	12,630	1,970	10.8	1.0	1.90	.00	.029
		12.7	850	4,290	−520	9,000	8,330	−2,330	13.3	3.5	1.81	−.09	.052
63	Tidal marsh	2.1	1,175	5,620	810	17,370	14,680	4,020	10.4	.6	1.84	−.06	<.02
		4.0	1,150	5,570	760	14,980	14,820	4,160	7.7	−2.1	1.90	.00	<.02
		8.9	775	4,290	−520	11,430	10,960	300	8.2	−1.6	1.86	−.04	.013
		11.2	1,000	4,940	130	12,720	11,960	1,300	13.3	3.4	1.86	−.04	.022
		12.6	1,025	5,030	220	10,200	9,980	−680	7.5	−2.3	1.93	.03	.024
64	Docas clay	2.1	1,100	5,810	1,000	14,410	13,900	3,240	6.3	−3.5	1.96	.06	<.02
		4.0	1,150	5,570	760	15,200	14,290	3,630	4.5	−5.3	1.96	.06	*
		9.0	750	3,930	−880	11,750	11,930	1,270	4.9	−4.9	2.06	.16	.010
		11.2	1,195	5,890	1,080	11,600	10,650	−10	5.8	−4.0	1.88	−.02	.028
		12.8	1,075	5,400	590	11,100	10,210	−450	7.4	−2.4	1.94	.04	.032
65	Chino silt loam	2.1	935	4,800	−10	15,980	15,750	5,090	7.0	−2.8	1.84	−.06	<.02
		4.0	1,070	5,420	610	13,160	12,300	1,640	6.3	−3.5	1.89	−.01	<.02
		9.0	975	4,990	180	11,680	11,290	630	5.3	−4.5	1.98	.08	.021
		11.2	1,125	5,400	590	13,650	12,640	1,980	6.4	−3.4	1.92	.02	.029
		12.7	1,125	5,510	700	10,990	9,610	−1,050	10.8	1.0	1.86	−.04	.035
66	Mohave fine gravelly loam	2.1	1,215	5,820	1,010	14,500	13,900	3,240	6.0	−3.8	1.94	.04	<.02
		4.0	1,240	6,210	1,400	13,680	14,170	3,510	6.2	−3.6	1.88	−.02	*
		9.0	1,075	5,470	660	11,110	10,710	50	10.3	.5	1.88	−.02	.013
		11.2	1,100	5,400	590	-------	-------	-------	8.9	−.9	1.94	.04	-------
		12.7	1,275	5,950	1,140	10,960	9,750	−910	12.0	2.2	1.86	−.04	.026

TABLE 60. *Mechanical and physical properties of 6-inch asbestos-cement pipe after exposure to soils* [1, 2]—Continued

Soil		Exposure	Bursting strength [3]			Crushing strength [4]			Water absorption [5]		Apparent specific gravity [5]		Depth of softening [6]
			Bursting pressure	Tensile strength		Crushing load	Modulus of rupture						
No.	Type			Value	Difference from unexposed		Value	Difference from unexposed	Value	Difference from unexposed	Value	Difference from unexposed	
		Years	*lb/in.*^{2}	*lb/in.*^{2}	*lb/in.*^{2}	*lb/linear ft*	*lb/in.*^{2}	*lb/in.*^{2}	*Percent*	*Percent*			*Inch*
67	Cinders	2.1	1,030	5,100	209	15,650	14,680	4,020	7.2	−2.6	1.90	0.00	<.06
		4.0	1,105	5,410	600	11,140	11,320	660	8.9	−.9	1.85	−.05	<.15
		9.0	675	3,570	−1,240	11,270	11,430	770	12.0	2.2	1.85	−.05	.042
		11.2	910	4,680	−130	9,700	9,840	−830	15.4	5.6	1.80	−.10	.101
		12.7	800	3,900	−910	8,870	8,130	−2,530	17.3	7.6	1.73	−.17	.130
70	Merced silt loam	2.1	1,155	5,720	910	13,180	13,380	2,720	9.0	−0.8	1.86	−.04	*
		4.0	1,285	6,020	1,210	14,260	13,330	2,670	5.8	−4.0	1.92	.02	*
		11.1	1,025	5,220	410	12,790	12,730	2,070	6.4	−3.4	1.88	−.02	0.033
		12.8	1,150	5,770	960	12,930	12,820	2,160	9.3	−.5	1.90	.00	.057

[1] See table 62 for properties of unexposed specimens and table 6 for properties of the soils.

[2] Hydrostatic bursting and crushing strength tests were performed on water-saturated specimens. Average dimensions—internal diameter, 5.93 ±0.07 inch; wall thickness, 0.72 ±0.05 inch; length of samples for crushing tests, 5.86 ±0.13 inch; length of samples for bursting tests, 12 inches.

[3] Data are for one specimen except as noted.

[4] Data are for two measurements made on one specimen except as noted.

[5] Average of 12 measurements made on 4 samples from the bursting test specimen and 8 samples from the crushing test specimen.

[6] Average of the maximum condition of the two specimens. Average thickness of the calendar layer is 0.02 inch. The values are the maximum depth of softening in inches. Condition of the surface: *—hardening of the calendar layer.

[7] Average of measurements on four specimens.

TABLE 61. *Mechanical and physical properties of unexposed specimens of air-dry asbestos-cement pipe 4 in. in diameter* [a]

Designation of original pipe from which section was cut	Bursting strength		Crushing strength		Water absorption	Apparent specific gravity
	Bursting pressure	Tensile strength	Crushing load	Modulus of rupture		
	lb/in.^{2}	*lb/in.*^{2}	*lb/linear ft*	*lb/in.*^{2}	%	
A	950	4,070	9,630	10,130	14.7	1.86
A [b]	1,000	4,330	10,570	10,760	13.6	1.84
B	1,120	4,440	11,770	9,410	14.1	1.86
B [4]	1,200	4,650			14.6	1.83
C	820	3,190	9,510	8,710	15.9	1.78
C [b]			10,270	8,710	15.0	1.81
C [b]			9,150	8,340	16.0	1.84
D	730	2,960	8,760	7,900	18.0	1.72
E	1,020	3,940	10,050	8,760	15.6	1.83
F	1,150	4,280	11,970	9,600	15.3	1.84
G	1,080	4,310	10,650	9,520	16.7	1.80
H	1,190	4,440	13,030	8,700	15.9	1.81
I	1,100	4,270	10,010	8,310	17.9	1.75
J	1,225	4,730	12,580	10,320	15.5	1.84
K	1,060	4,260	11,780	9,710	16.3	1.81
L	940	3,830	10,950	9,850	16.0	1.81
L [b]	1,100	4,570			15.6	1.83
M	1,100	4,100	11,760	8,670	16.5	1.81
N	950	3,730	12,120	9,200	16.1	1.80
N [b]	1,000	3,920			15.5	1.84
O	750	3,290	7,690	8,880	17.0	1.74
P	1,100	4,460	10,740	9,560	14.6	1.87
Q	790	3,360	8,390	8,110	16.3	1.78
R	1,000	3,720	9,050	8,360	15.9	1.79
S	1,050	4,260	11,100	8,470	13.5	1.85
T	1,100	4,280	9,850	8,140	13.1	1.84
U	1,000	4,110	11,240	8,950	13.9	1.87
V	1,050	4,120	9,600	7,460	14.5	1.83
W	750	2,860	9,910	8,450	14.6	1.81
W [b]	950	3,700	10,380	7,670	13.5	1.85

[a] Average dimensions—internal diameter, 3.99 ±0.05 inch; wall thickness, 0.64 ±0.09 inch; length of samples for crushing tests, 4.13 +0.75, or −0.18 inch; length of samples for bursting tests, 11 inches.

[b] Measurements made by the National Bureau of Standards. Measurements on the other reference specimens were made by the Pittsburgh Testing Laboratories and the research laboratories of the manufacturer.

TABLE 62. *Mechanical and physical properties of unexposed specimens of water-saturated asbestos-cement pipe 6 in. in diameter* [a]

Specimen	Bursting pressure	Tensile strength	Crushing load	Modulus of rupture	Water absorption	Apparent specific gravity
	lb/in.^{2}	*lb/in.*^{2}	*lb/linear ft*	*lb/in.*^{2}	*Percent*	
1	995	5,010			9.6	1.81
2	940	4,670			10.9	1.88
3	970	4,750			10.0	1.93
4 [a]			9,940	10,160	9.6	1.92
4 [b]			10,270	10,470	9.1	1.90
5 [a]			11,840	11,660	9.6	1.90
5 [b]			10,530	10,360	9.8	1.93
Average	990	4,810	10,640	10,660	9.8	1.90

[a] Average dimensions: internal diameter, 5.94 ±0.93 inch; wall thickness, 0.71 ±0.05 inch; length of samples for crushing tests, 5.81 ±0.23 inch; length of samples for bursting tests, 12 inches.

There is a relationship between water absorption of a specimen and the bursting and crushing strength. Data obtained in the laboratory for the differences between the amount of water absorbed by the unexposed specimens and by those exposed for different periods (tables 59 and 60) show, in general, that increases in the bursting and crushing strengths are associated with decreases in the amount of water absorbed, and vice versa. This is shown more effectively by a series of curves previously published [128].

The changes in strength of the 4- and 6-in. specimens during exposure to the different soils are shown graphically in figures 46 and 47, respec-

SOIL 56

SOIL 58

SOIL 60

FIGURE 45. *Cross sections of asbestos-cement pipe exposed in different soils for 13 years.* ×3. The depth of softening is indicated by the thickness of the dark layers shown by the arrows.

tively, in which differences in tensile strength and modulus of rupture between the exposed and unexposed specimens are plotted against the duration of exposure. In general, the curves show an increase in strength during the early exposure periods followed by a decrease in strength during the balance of the periods. The increased strength observed during the early exposure periods is associated with a residual curing process that normally takes place in cement products subjected to moist environments and occurred in these specimens after exposure to the soil. The maximum values for bursting and crushing strength and the minimum values for water absorption indicate the completion of the residual curing of the asbestos-cement pipe. The sections of the curves to the right of these points are considered to represent the effect of weathering resulting from the action of the soils in altering the asbestos cement. Therefore, a comparison of the heights of these curves at various points to the right of the maxima is a relative measure of the extent and rate of weathering in a selected soil.

The curves for the 4-in. specimens of asbestos cement (fig. 46) indicate a high degree of resistance to deterioration, after the curing process is completed, in all the soils except in organic soils 58, 59, and 60, a poorly drained inorganic soil (56), cinders (67), and a well-drained inorganic soil (53). Two other well-drained inorganic soils (55 and 62) were much less corrosive than was soil 53. Although the high strength maintained by the 4-in. specimens might be taken to indicate that asbestos cement is resistant to soil 63 (tidal marsh), this inference is not supported by the behavior of the 6-in. specimens in this soil (fig. 47). The greater losses in strength for the 6-in. specimens also generally occurred in the soils high in organic matter.

Cement products are altered by the process of hydrolysis and the rate of alteration is accelerated by acidity which generally occurs in soils as carbonic acid. Since the decomposition of organic matter provides a large amount of carbonic acid to the ground water, and so increases its activity, relatively greater losses in strength of portland cement would be expected in soils high in content of organic matter. The water absorption data for the 4-in. specimens (table 59) are consistent with this view. For example, in the alkaline soils 64, 65, 66, and 70, in which the concentration of free carbon dioxide is negligible, the 4-in. specimens show no definite tendency to absorb increasing amounts of water with increase in time of exposure, and no definite tendency to decrease the tensile strength and modulus of rupture (fig. 46). On the other hand, in the acid inorganic soils (53, 55, 61, and 62), in the organic soils (58, 59, and 60) and in the inorganic soil high in organic matter (56), all of which contain hydrogen ions in relatively high concentration, progressive increase in the absorption of water with time is generally indicated by the data (table 59). This is consistent with the curves in figure 46 which indicate that weathering of asbestos-cement proceeds in these soils at an appreciable rate. Marked absorption of water and a correspondingly high rate of incipient deterioration is indicated by the data for the extremely acid soil 60 (*p*H 2.6). The slight tendency for water to be absorbed by the specimens in the organic soil 63 and in cinders (67) are not consistent with this explanation.

The water absorption data for the 6-in. pipe (table 60) show similar tendencies as noted for the 4-in. pipe, except that weathering of the 6-in. specimens generally has progressed at a greater rate after completion of the residual curing period during exposure to the soils. This may reflect the different initial curing processes that were applied to the two sizes of pipe; water curing for the 4-in. and steam curing for the 6-in. pipe.

The over-all effect of exposure to the soils on the 4- and 6-in. samples of the asbestos-cement pipe is shown in figures 48 and 49. Except for soil 51 for which sufficient data was not available, the values for tensile strength, modulus of rupture, percentage of water absorbed, and apparent specific gravity in all of the soils (tables 59 and 60) were averaged for each period of exposure and for each size of asbestos-cement pipe. The standard deviations of these mean values are also indicated in the figures. The data in figure 48 for the 4-in. specimens, which were tested in the air-dried condition, were adjusted to the water-saturated condition by reducing the values for tensile strength and modulus of rupture by 15 percent, the average difference in strength between the water-saturated and the air-dry condition [179].

The average tensile strength of the 4-in. pipe (fig. 48) increased about 700 lb/in.^{2} during exposure periods up to 7 years but thereafter the trend was for the tensile strength to decrease slightly as the time of exposure increased. However, the tensile strength after exposure of 13 years was still higher than that of the unexposed pipe.

The modulus of rupture of the 4-in. pipe also tended to increase with exposure up to 7 years and then to remain constant. The residual curing of the pipe was completed in 7 years, as indicated by the maximum values for rupture and tensile strengths, and also by the positions of the maximum in the specific gravity-time curve and the minimum in the water absorption-time curve.

The average tensile strength of the 6-in. pipe (fig. 49) increased during the exposure periods up to 4 years and was then followed by a decrease in strength during the remaining periods. Its tensile strength after exposure of 13 years was still slightly higher than that of the unexposed pipe.

The time curves for the modulus of rupture and water absorption of the 6-in. pipe indicate an increase in strength up to 2 years, and a decrease in water absorption up to 4 years, and thereafter show a decrease in strength and an increase in water absorption for the remaining periods. The curve for the apparent specific gravity does not show any significant change until the 9-year exposure period, which is followed by a decrease in density.

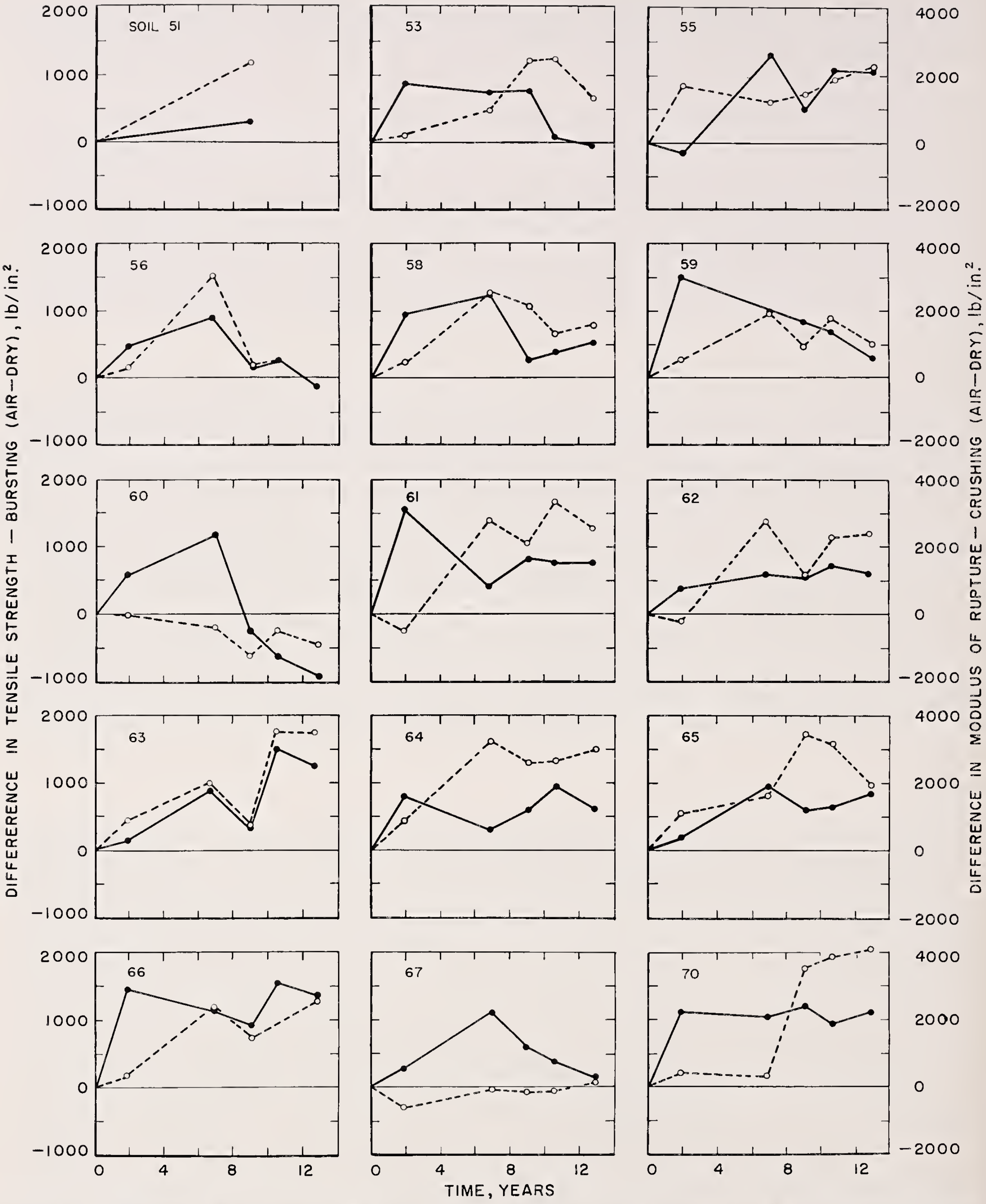

FIGURE 46. *Differences in tensile strength and modulus of rupture between unexposed specimens of 4-in. pipe and similar specimens exposed underground for different periods.*

●, Tensile strength; ○, modulus of rupture. The properties of the soils are given in table 6.

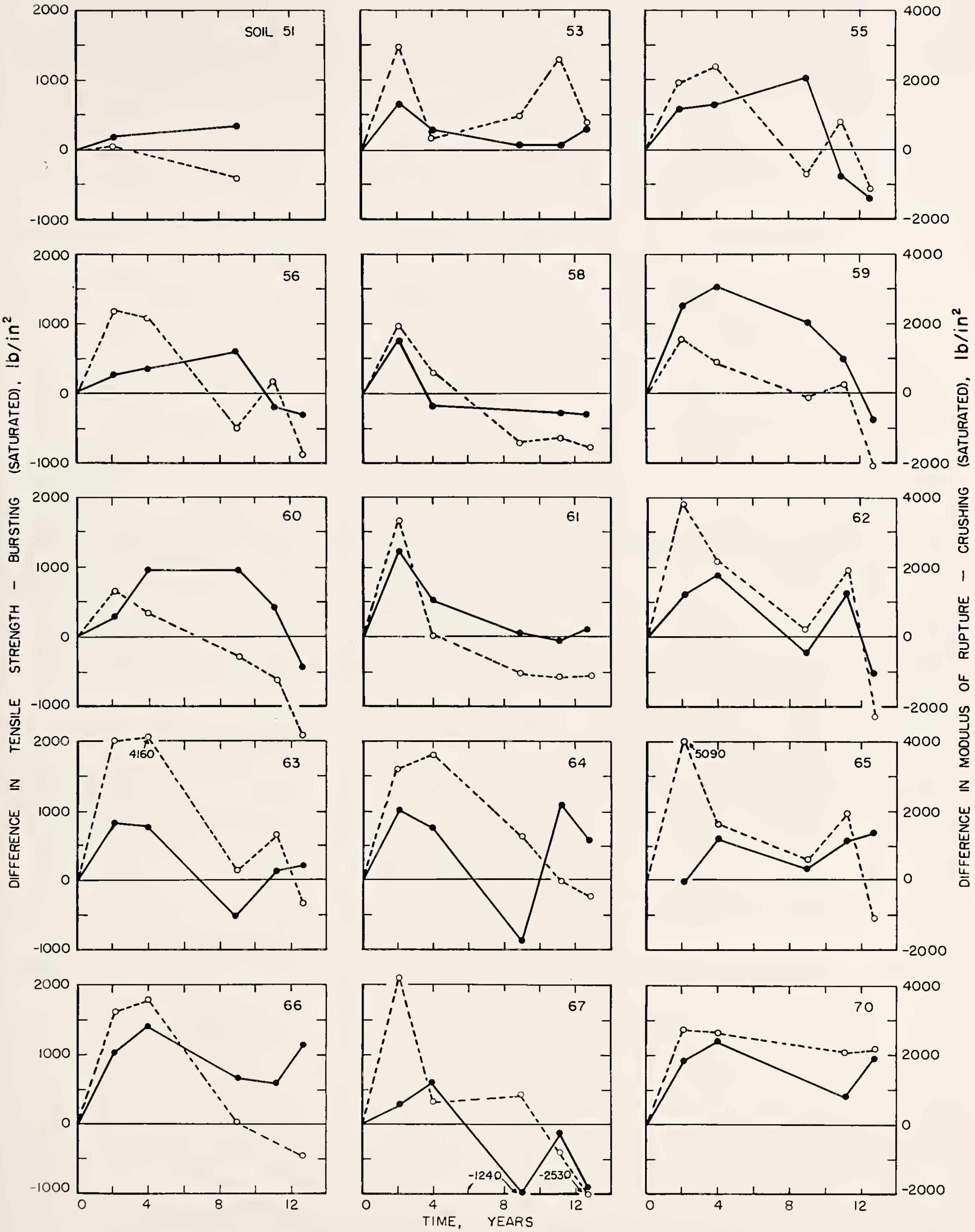

Figure 47. *Differences in tensile strength and modulus of rupture between unexposed specimens of 6-in. pipe and similar specimens exposed underground for different periods.*

●, Tensile strength; ○, modulus of rupture. The properties of the soils are given in table 6.

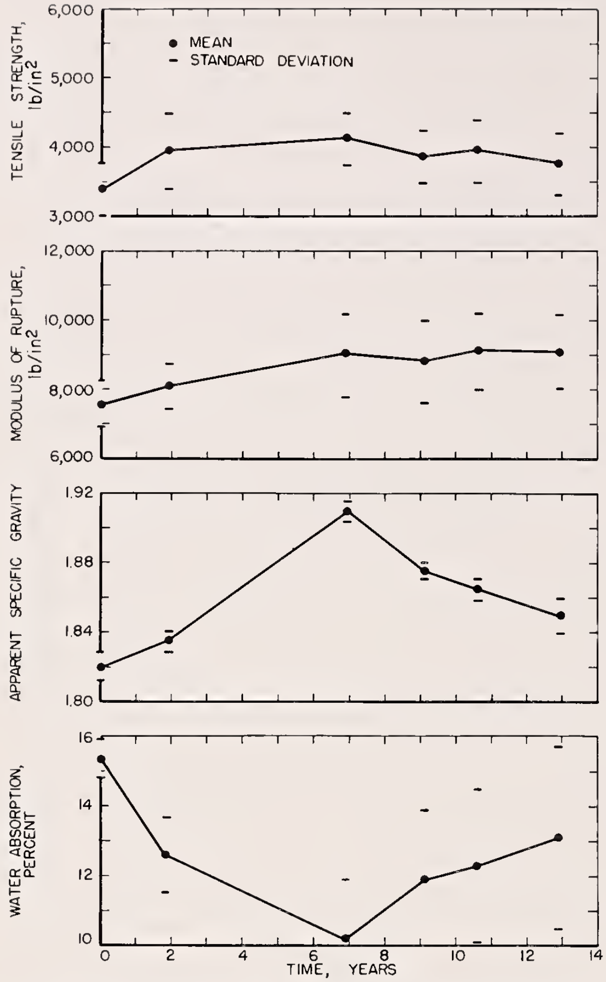

Figure 48. *Average tensile strength, modulus of rupture, apparent specific gravity, and water absorption of 4-in. specimens in 14 soils for different periods of exposure.*

Data for the tensile strength and modulus of rupture adjusted to the saturated condition.

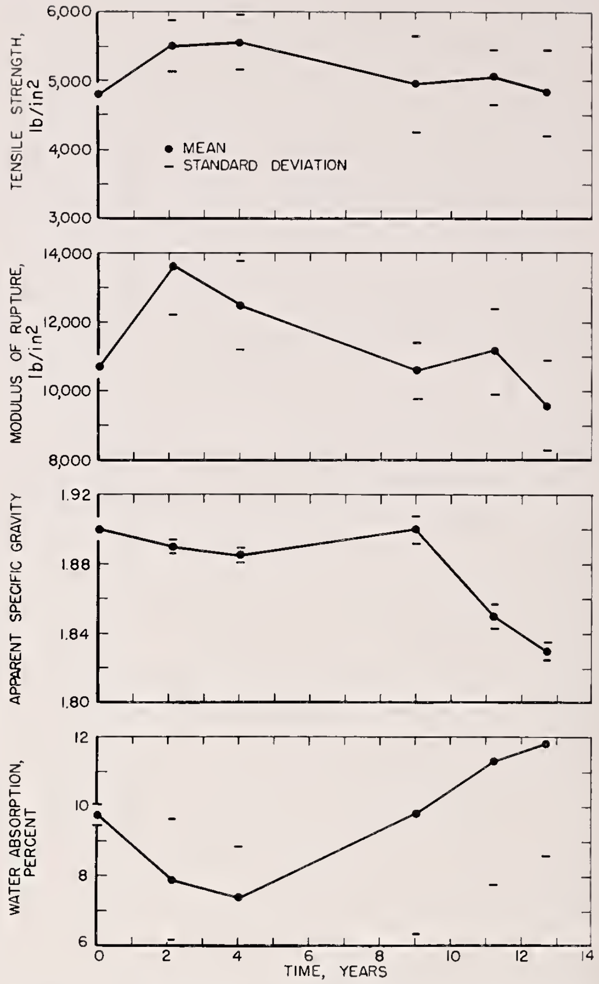

Figure 49. *Average tensile strength, modulus of rupture, apparent specific gravity, and water absorption of 6-in. specimens in 14 soils for different periods of exposure.*

Measurements of tensile strength and modulus of rupture made on specimens in the saturated condition.

The tensile and rupture strengths and water absorption indicate that the curing period during the first years of exposure was 2 to 4 years for the 6-in. steam-cured pipe, which is a shorter time than the 7 years required for the 4-in. water-cured pipe. A comparison of the data given in figures 48 and 49 show that both the tensile and rupture strengths of the unexposed specimens were higher for the 6-in. steam-cured than for the 4-in. water-cured pipe. The 6-in. pipe also appears to be a denser material, as is indicated by the higher initial values of apparent specific gravity and low values for water absorption, as compared with the water-cured 4-in. specimens. However, it should be noted that the differences in strength between the two materials can not be ascribed solely to the different processes of curing because of the differences in dimensions, composition of cement, and in the method of fabrication of the two varieties of pipe.

Hansen [183] reviewed the literature on the chemical reactions and changes which may occur during the curing of portland cement products at ordinary temperatures and at the elevated temperatures in steam curing. According to the report of the Committee 716 of the American Concrete Institute [184], higher strength properties and greater stability are obtainable for cement products with high pressure steam curing than by the damp curing process; while high strength developed in a few hours of steam curing is in part due to the acceleration of the normal process of hardening, a material contribution to strength comes from the reaction resulting in the formation of a hydrated calcium silicate from the lime and silica present. The more stabilized form of cement attributable to pressure steam curing results, in part, from the conversion (or partial conversion) of the amorphous calcium silicates to crystalline forms, which do not swell or shrink as much as do the amorphous forms with increase or decrease in moisture content. It also has been observed by the Committee that the series of compounds that are known as hydrogarnets, which result from steam curing of cement products, are very stable and highly resistant to the action of sulfate solutions.

15.2 Wood-Fiber Pipe

Specimens of sulfur-impregnated wood-fiber pipe coated with a bituminous substance were buried at 47 test sites in 1924. These specimens were buried in an early stage of the development of this material and are not representative of the materials now marketed. The manufacturers believe that their more recent products have overcome the weakness shown by the specimens.

After 6 years of exposure the bituminous coating on the pipe blistered in some soils, while in others it cracked and lost its plasticity. The fiber absorbed sufficient moisture to cause some of the specimens to elongate about 5 percent. In a few places there were evidences of deterioration of the coating. The fiber in some locations appeared to be somewhat softened, but the extent to which the specimens were weakened was not determined. The results of the test suggested that the pipe material itself should be more nearly moisture-proof since tests on bituminous coatings have demonstrated that moisture penetrates most thin bituminous coatings.

16. Behavior of Metallic Protective Coatings in Soils

16.1. Description of the Materials

Between 1922 and 1937, a series of metallic coated specimens were buried at the field exposure test sites. The specimens consisted of zinc-coated iron and steel pipe and sheet, lead-coated steel pipe, and tinned copper tubing prepared by the hot-dip process, and calorized steel pipe, together with control specimens (table 63).

Coatings of these types initially protect the underlying metal mechanically. When the continuity of the coating is destroyed the underlying metal may be protected either galvanically or mechanically by the formation of a protective film. However, if these protective factors are not operative the corrosion rate for the base metal is either normal or increased above normal, depending on the solution potentials of the coating and the underlying metal.

Table 63. *Metallic-coated specimens*

Material[a]	Identification	Year buried	Number of specimens buried	Form	Nominal width or diameter	Length	Wall thickness	Average weight of coating	Average thickness of coating[a]
Zinc coatings:[b]					*in.*	*in.*	*in.*	*oz/ft²*	*in.*
Bessemer steel	B	1922	124	Pipe	2.0	24	0.154	1.81	0.0032
Pure open-hearth iron	A	1923	208	do	2.0	17	.154	2.82	.0050
Wrought iron	D	1923	24	do	3.0	17	.216	3.48	.0061
Do	D	1923	28	do	1.5	17	.145	4.99	.0088
Copper-bearing open-hearth steel	Y	1923	56	do	3.0	17	.216	3.47	.0061
Pure open-hearth iron	A_2	1924	28	Sheet	6.0	12	.062	1.79	.0032
Do	A_3	1924	188	do	6.0	12	.062	1.98	.0035
Do	A_4	1924	28	do	6.0	12	.062	2.65	.0047
Copper-bearing steel	Y_2	1924	28	do	6.0	12	.062	1.57	.0028
Do	Y_3	1924	188	do	6.0	12	.062	2.15	.0038
Do	Y_4	1924	28	do	6.0	12	.062	2.76	.0048
Do	Y_5	1924	28	do	6.0	12	.062	2.92	.0051
Bessemer steel	B	1924	188	do	6.0	12	.062	1.62	.0028
Pure open-hearth iron	CA	1924	56	do	6.0	12	.050	1.87	.0033
Bessemer steel	CB	1924	56	do	6.0	12	.050	1.66	.0029
Copper-bearing steel	CY	1924	56	do	6.0	12	.050	2.12	.0037
Steel	T	1937	300	Pipe	1.5	14	.145	3.08	.0052
Lead coatings:									
Steel	L	1924	376	do	1.5	6	.145	--------	.00105
Do	CA	1932	150	do	1.5	13	.145	--------	.0015
Aluminum coatings:									
Wet calorized steel	--------	1924	48	Pipe	2.0	6	.154	--------	--------
Dry calorized steel	--------	1924	56	do	2.0	6	.154	--------	--------
Tin coating:									
Tinned copper	--------	1937	150	do	1.5	12	.060	--------	.00089

[a] Uncoated specimens of the same base metals were also buried.

[b] Each ounce per square foot of coating is equivalent to an average thickness of 0.00172 in.

16.2. Zinc-Coated (Galvanized) Steel

Hot-dipped zinc coatings are used extensively for the protection of small-diameter iron or steel pipes, especially for water and gas services. In 1934, Ewing [185] estimated that one-third of the utility companies distributing gas in the United States used galvanized iron or steel pipe. At the time of this survey, galvanized coatings constituted the most important method for protecting service pipe from corrosive attack. As the conditions of exposure considered in this survey were not controlled, it was not possible to evaluate data in respect to the protection to be expected under varying soil and climatic conditions. However, galvanized service pipe is in contact with other parts of the main supply system and couples of dissimilar metals may be set up which will lead to accelerated corrosive attack due to galvanic action. Lauderbaugh [186] considers in detail various galvanic effects which induce failure in gas distribution systems.

Similar relationships are observed in water systems and potential measurements made by Wahlquist and Fanett [187] on several thousand feet of galvanized water pipe connected to cast-iron mains illustrated the deleterious effect of this type of coupling. These results showed that shortly after installation the difference of potential between the galvanized sections and a copper-copper sulfate half cell was −0.875 v, and after approximately a year the potential of the galvanized system was increased to −0.65 v, which remained constant for a 2-year period. However, as the latter potential is essentially that of the base metal, the conclusion would follow that the protective coating had been removed during the first year of exposure.

The corrosion (or protection) of a galvanized coating in any environment is complex. Because of diffusion during the hot-dipping operation, such a coating will have a graduated series of zinc-iron alloys (without clearly defined layers) between the base metal and the fairly pure zinc surface layer. ASTM weather exposure tests [188] show that the relative protection afforded the underlying steel is a function of the total amount of zinc and not of the method of application. There is some evidence that in certain environments the zinc-iron alloy may afford better protection that the zinc layer. For example, in the Preece Test the solution rate of galvannealed coatings (a coating consisting of only zinc-iron alloy phases) is about half that of the regular hot-dipped or electrogalvanized coatings [189].

Laboratory measurements made on soils are not strictly comparable to similar measurements made in the controlled underground field tests, due to the fact that the varying moisture conditions inherent in the field tests cannot be duplicated in the laboratory. Other uncontrolled factors encountered in the field tests such as, variations in corrosion products, film formation and polarization also prevent correlation between data obtained from the laboratory and field tests. Hence, the evaluation of zinc coatings presented herein is based primarily on the results of field tests.

a. Distribution of Coating Thickness

Nonuniformity in distribution in the thickness of the zinc coating on hot-dipped products has been recognized for many years. Rawdon [190] reported that the zinc coating on a 24 ft^2 sheet of steel ranged from a minimum of 1.79 oz/ft^2 to a maximum of 3.06 oz/ft^2, with an average of 2.67 oz/ft^2. ASTM specifications, for example, A93–52T [191], allows a minimum of 2.00 oz/ft^2 as determined by the spot test for galvanized sheet having a specified coating weight of 2.75 oz/ft^2. Magne-gage measurements were made to determine the distribution of the coating thickness on 1½-in. galvanized pipe specimens having a specified coating weight of 3.08 oz/ft^2 as determined by difference in weight methods.[8] These specimens were unexposed sections of the same lot of pipe that was buried at the field test sites in 1937. The measurements (fig. 50)

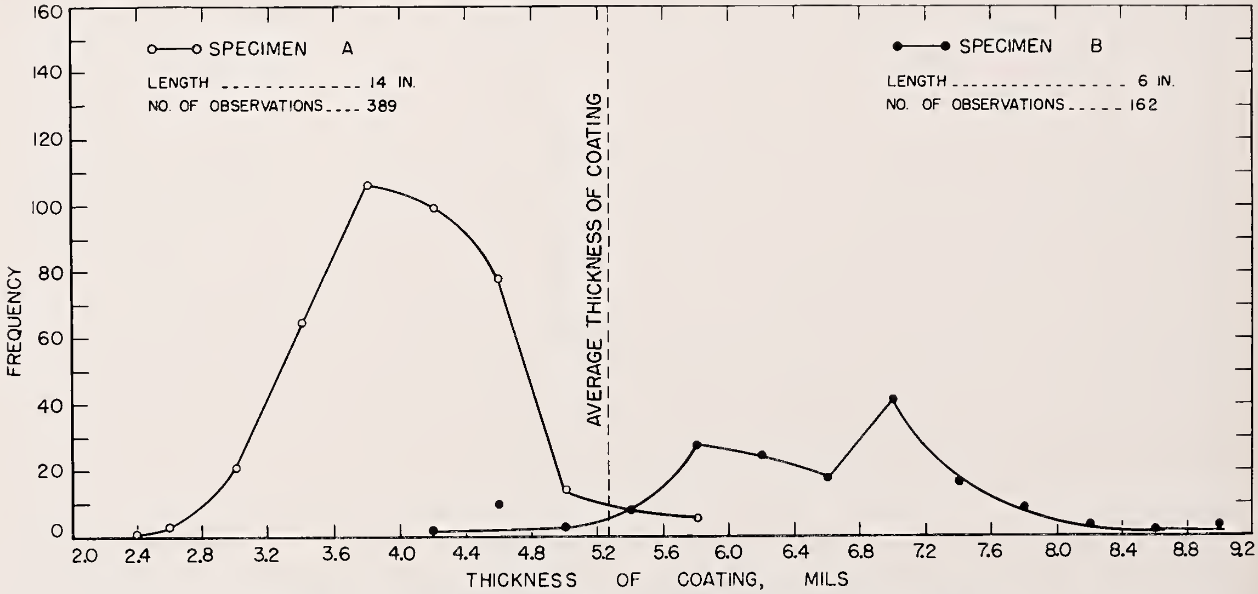

Figure 50. *Distribution of coating on unexposed galvanized pipe specimens.*

Nominal weight of coating, 3.08 oz./ft.^{2}. This is the weight of coating on the exposed surface. Each ounce per square foot of coating is equivalent to 0.00172 in. in thickness.

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[8] This is the weight of coating on one side of the pipe. Each ounce per square foot of coating is estimated to be the equivalent of 0.00172 in. in thickness.

show that the coating thickness of the specimens differed widely, not only between specimens but in the distribution of the coating on the individual specimens.[8] The variation in the distribution of the coating observed did not fall in any particular pattern.

Thickness distribution of the zinc and zinc-iron alloy on this lot of pipe was determined by Denison and Romanoff [125] utilizing an electrolytic stripping method; these data were utilized to derive current-time curves (fig. 51). The contour of the curves consisted of two different characteristic slopes which could be interpreted in terms of coating thickness. Each zone of the coating has a characteristic potential which produced a horizontal on the current-time curve, and when the underlying zone was exposed a rapid decrease in current was observed. The current became constant when the overlying zone was entirely removed. Therefore, the maximum thickness of a particular coating zone is determined by the time interval from the initiation of one horizontal to the initiation of the second, whereas the minimum thickness of the layer is determined by the time interval the current remained constant. Hence, the minimum thickness of the pure zinc layer (fig. 51) is measured by the time interval of the horizontal portion of the curve terminating at point A, and the maximum thickness of zinc by the time interval terminating at point B. Likewise, the minimum thickness of the zinc-iron alloy zones is represented by the time interval represented by distance BC, and the maximum thickness by the time interval represented by distance AD. The horizontal portion of the curve originating at point D represents complete exposure of the underlying steel. The reported thicknesses (table 64) were computed from the areas under the curve. The area representative of the thickness of zinc coating was taken as the area under the curve from the origin to point B, and the thickness of the alloy zone was taken as that area under the portion of the curve represented by the distance BD. Ellinger and coworkers [189] obtained similar results in electrolytic stripping tests on zinc-coated wires.

The maximum thickness of the pure zinc coating and of the alloy zone at several points on two specimens are recorded in table 64. These data indicate that a large part of the zinc applied to steel pipe was converted to zinc-iron alloy.

Table 64. *Thickness of the outer zinc coating, of the zinc-iron alloy, and of the total coating on galvanized specimens*

(In mils)

Specimen	Zinc layer	Alloy layer	Total coating
A	1.8	2.3	4.1
A	.9	3.4	4.3
A	2.0	2.3	4.3
A	2.0	3.0	5.0
B	2.7	3.2	5.9
B	2.8	3.2	6.0

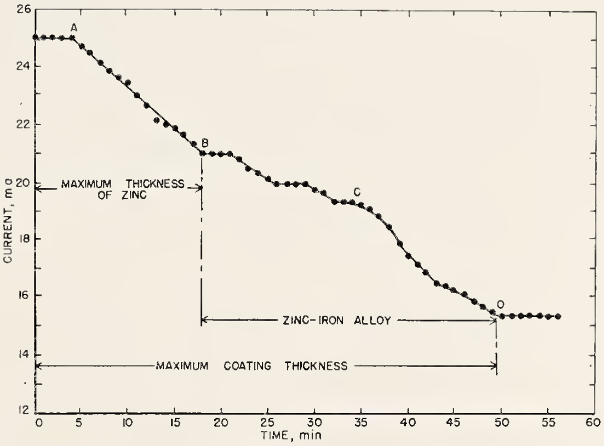

Figure 51. *Thickness of the outer zinc coating and of the zinc-iron alloy.*

b. Results of Field Tests on Galvanized Coatings

In 1924, an underground exposure test was initiated on a series of five different base metals (Bessemer steel, wrought iron, plain and copper-bearing steel, and open-hearth iron) to which a series of zinc coatings were applied by the hot-dip process. This test was terminated after 10-years exposure (table 65). An analysis of these data showed that in most of the soils, zinc coatings of 2 oz or less were destroyed during the 10-year exposure period, and pitting of the underlying steel occurred. However, the test showed that the 3-oz coatings were intact on at least half of the specimens, and in only one (soil 23) of the 47 soils was there any measurable development of pits in the steel. Although the galvanized specimens differed somewhat in coating weight and uniformity of thickness, the results of the tests [115] show in the case of the five alloys tested, that the base metal is not a factor in the corrosion rate.

These results indicated a desirability of a further development of data for the 3-oz coatings, not only, in some of the 1924 soils but in additional soils that had been shown by subsequent tests to be corrosive to both zinc and iron. In view of this, specimens of 1½-in. steel pipe with a 3.08-oz zinc coating were buried in 1937, together with representative control specimens (table 66, fig. 52).

TABLE 65. *Corrosion of galvanized pipe and 16-gage steel sheet buried in 1924*

(The numbers in parentheses are the weights (oz/ft²) of the coatings.)

Z = Zinc continuous over specimen.
A = Blue or black alloy layer exposed over at least a portion of specimen.
R = Rusted or bare steel exposed.
M = Shallow metal attack; no pits as great as 10 mils—total depth.

Soil		Duration of test	Loss in weight (oz/ft²)						Condition or maximum pit depth (in mils)				
No.	Type		Pipe	Sheet				Bare[b]	Pipe[c]	Pipe	Sheet		
			A (2.82)[a]	A3 (0.99)	B (0.81)	Y3 (1.07)	Average		B (1.81)	A	A3	B	Y3
		Years											
1	Allis silt loam	10.66	2.92	4.62	4.79	4.46	4.62	10.20	27	R	28	28	30
2	Bell clay	9.92	.35	.44	.58	.29	.44	------	M	Z	A	R	Z
3	Cecil clay loam	10.09	.41	.48	.72	.62	.61	3.96	M	Z	R	10	R
4	Chester loam	10.62	1.94	1.85	1.76	2.05	1.89	------	R	R	23	17	14
5	Dublin clay adobe	10.17	1.82	2.50	3.03	2.45	2.66	------	------	R	12	22	12
6	Everett gravelly sandy loam	10.16	.12	.27	.25	.09	.20	------	------	Z	A	A	Z
7	Maddox silt loam	10.48	2.62	2.69	2.36	3.04	2.70	------	R	R	17	17	22
8	Fargo clay loam	10.63	.78	.65	.56	.39	.53	5.55	R	Z	A	R	A
9	Genesee silt loam	9.48	1.10	.87	.78	1.08	.91	------	R	A	29	19	23
10	Gloucester sandy loam[d]	10.62	1.29	1.74	1.71	1.75	1.73	------	A	R	16	24	12
11	Hagerstown loam	10.55	.90	.42	.91	1.15	.83	1.79	------	A	16	21	13
12	Hanford fine sandy loam	10.17	------	.33	.96	.26	.52	------	A	------	A	M	A
13	Hanford very fine sandy loam	10.16	[e].87	2.23	.37	1.37	1.32	------	------	R	15	R	8
14	Hempstead silt loam	10.64	.26	.33	.34	.68	.45	5.00	A	Z	A	A	R
15	Houston black clay	10.06	.35	.29	.60	.21	.37	------	------	Z	Z	A	Z
16	Kalmia fine sandy loam	10.04	.99	1.46	2.04	1.78	1.76	6.44	Z	M	20	15	18
17	Keyport loam	10.57	3.64	5.90	3.92	3.89	4.57	------	R	R	22	27	19
19	Lindley silt loam	10.51	.68	.82	1.16	1.04	.67	3.30	A	Z	27	20	22
20	Mahoning silt loam	10.67	1.22	2.10	2.40	1.56	2.02	5.01	R	R	17	21	13
22	Memphis silt loam	9.93	1.19	2.04	2.28	2.37	2.23	7.16	------	R	56	32	29
23	Merced silt loam	10.16	9.60	3.64	2.64	6.38	4.22	25.66	------	68	37	21	41
24	Merrimac gravelly sandy loam	10.63	[e].26	.13	.17	.04	.11	------	Z	Z	A	A	Z
25	Miami clay loam	10.65	.36	1.09	1.03	.92	1.01	------	------	Z	10	R	R
26	Miami silt loam	10.48	.71	.78	1.09	.80	.89	------	A	A	10	6	8
27	Miller clay	10.08	.92	1.49	1.37	.84	.93	------	------	A	12	10	9
28	Montezuma clay adobe	9.60	[e]1.96	4.73	6.41	2.22	4.45	16.32	------	R	33	63	22
29	Muck	10.08	[e]5.98	5.19	4.48	4.24	4.64	14.79	30	R	32	26	28
30	Muscatine silt loam	10.51	.47	1.58	1.42	1.48	1.49	------	12	A	20	13	11
31	Norfolk fine sand	10.04	[e].16	.05	.17	.05	.09	------	------	Z	Z	A	Z
32	Ontario loam	10.71	[e].60	.61	.62	.72	.65	3.04	R	R	A	R	A
33	Peat	10.65	1.83	2.00	4.27	1.58	2.62	11.96	------	R	17	29	14
35	Ramona loam	10.16	.30	.70	1.07	.43	.73	------	A	A	A	R	A
36	Ruston sandy loam	10.05	.23	.14	.43	.34	.30	------	------	Z	A	4	A
37	St. John's fine sand	10.04	2.03	3.15	3.06	3.02	3.08	8.54	------	R	20	17	14
38	Sassafras gravelly sandy loam	10.62	[e].21	.16	.22	.12	.17	------	------	Z	A	A	A
40	Sharkey clay	10.08	.93	2.20	2.22	2.14	2.19	7.48	R	R	47	48	38
41	Summit silt loam	10.52	.54	.27	.38	.27	.31	------	M	A	A	A	A
42	Susquehanna clay	10.05	.71	.86	------	.74	.80	10.64	------	R	21	------	23
43	Tidal marsh	10.73	[e]1.38	1.09	6.27	.69	2.68	12.72	25	A	R	63	R
44	Wabash silt loam	10.52	------	.22	.75	.43	.47	------	------	------	A	A	A
45	Unidentified alkali soil	10.55	[e]1.84	1.01	1.69	1.79	1.50	13.53	38	R	19	5	16
46	Unidentified sandy loam	10.54	.17	.11	.17	.28	.19	4.38	A	Z	Z	Z	Z
47	Unidentified silt loam	10.60	1.06	.70	.83	.69	.74	------	A	A	R	R	R

[a] The weight of coating given here is in ounces per square foot of exposed area. It is the average obtained from at least 10 measurements of thickness by the stripping method.

[b] In the column headed "Bare" are presented the average weight losses of rolled iron and steel specimens buried a similar length of time, i.e., approximately 10 years. These were not available for all soils.

[c] The B pipes were buried 12 years. They were not weighed before burial so weight losses are not known.

[d] In this soil there were 2 specimens. The condition or penetration is for the worse-corroded specimen.

[e] There were 2 specimens of this material. The condition is for the worse of these specimens.

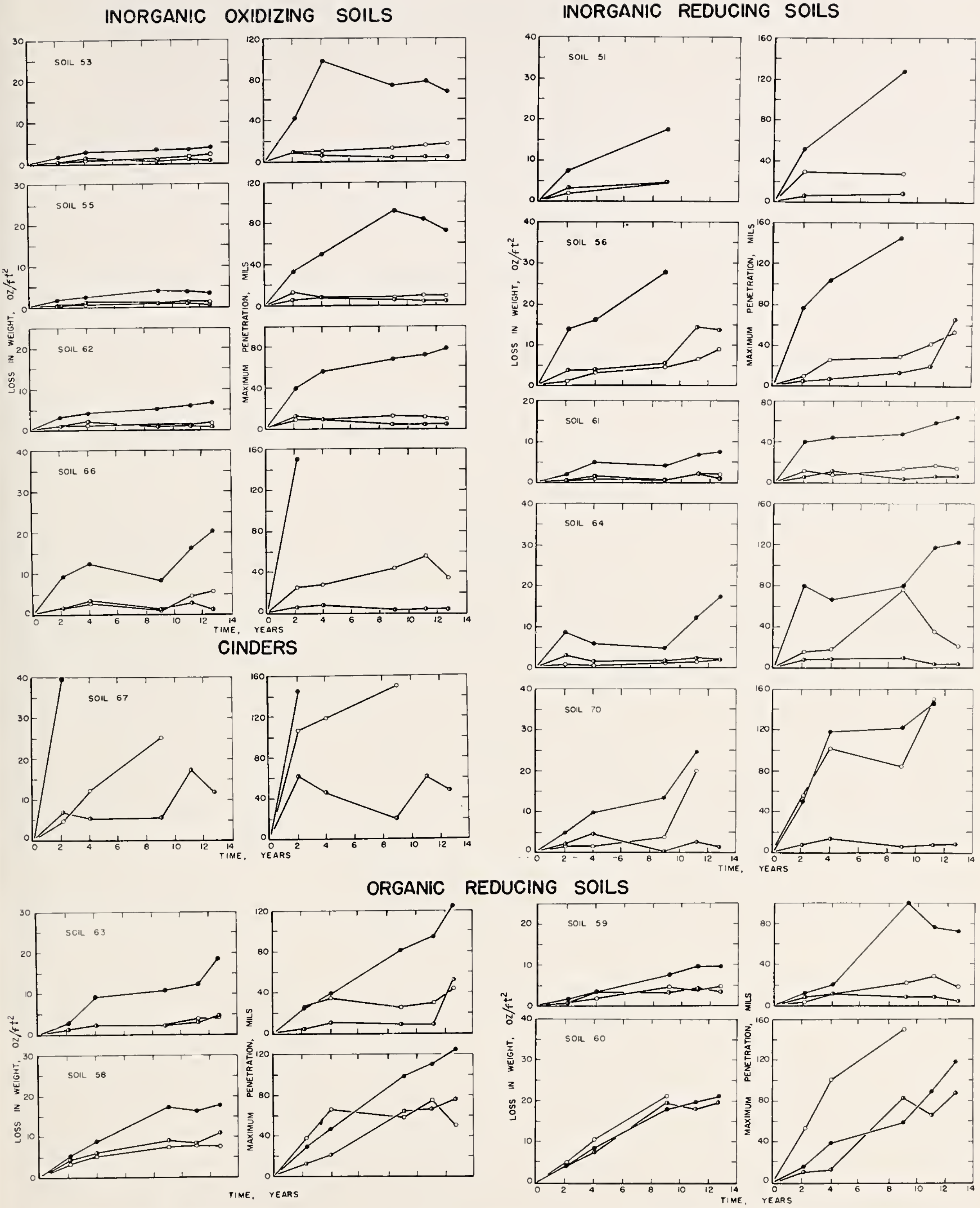

FIGURE 52. *Weight loss and maximum penetration as a function of time for galvanized steel, bare steel, and zinc.*

●, Bare steel; ○, zinc; ◑ galvanized steel.

TABLE 66. *Loss in weight and maximum pit depth of galvanized* [a] *and bare steel pipe and zinc plate buried in 1937*

(Average of 2 specimens)

Soil		Exposure	Galvanized steel						Bare steel		Zinc	
			Condition of surface				Loss in weight	Maximum pit depth	Loss in weight	Maximum pit depth	Loss in weight	Maximum pit depth
No.	Type		Coated with zinc and alloy layer	Coated with zinc	Coated with zinc-iron alloy	Bare steel exposed						
		INORGANIC OXIDIZING-ACID SOILS										
		Years	*Percent*	*Percent*	*Percent*	*Percent*	oz/ft^2	*Mils*	oz/ft^2	*Mils*	oz/ft^2	*Mils*
53	Cecil clay loam	2.1	85 to 100	60 to 100	0 to 40	0	0.3	9	1.8	42	0.2	10
		4.0	100	20 to 40	60 to 80	0	1.4	6	2.9	98	.6	10
		8.9	100	20 to 40	60 to 80	0	.6	<6	3.4	74	1.1	13
		11.2	100	30	70	0	1.0	<6	3.4	78	1.6	16
		12.7	100	20	80	0	.6	<6	3.9	68	2.2	17
55	Hagerstown loam	1.9	100	60 to 100	0 to 40	0	.3	<6	1.8	33	.4	13
		3.9	100	20 to 40	60 to 80	0	1.2	8	2.6	50	.6	8
		9.0	95	20 to 40	55 to 75	<5	.7	6	4.1	92	.7	8
		11.0	100	70	30	0	1.0	<6	3.9	84	1.3	10
		12.6	100	70	30	0	.6	<6	3.4	73	1.2	9
62	Susquehanna clay	2.1	100	50 to 100	0 to 50	0	1.0	12	3.2	40	.6	9
		4.0	100	20 to 40	60 to 80	0	2.3	9	4.3	56	1.2	9
		8.9	100	0 to 20	80 to 100	0	.9	<6	5.3	68	1.3	12
		11.2	100	80	20	0	1.1	<6	6.0	72	1.3	11
		12.7	100	75	25	0	.8	<6	6.8	79	1.7	9
		INORGANIC OXIDIZING-ALKALINE SOILS										
65	Chino silt loam	2.1	100	20 to 40	60 to 80	0	1.1	<6	4.3	50	.5	30
		4.0	100	0 to 20	80 to 100	0	2.3	6	4.6	59	.8	36
		9.0	95	50 to 75	25 to 50	<5	1.6	<6	7.0	65	1.4	56
		11.2	95	0	95	<5	1.7	<6	6.2	84	1.1	40
		12.7	100	0	100	0	1.1	<6	7.2	98	1.8	56
66	Mohave fine gravelly loam	2.1	100	60 to 100	0 to 40	0	1.6	6	9.2	[d]145+	1.7	25
		4.0	100	20 to 40	60 to 80	0	3.3	8	12.3	145+	[b]2.6	28
		9.0	95	20 to 40	60 to 80	5	1.1	<6	8.1	78	.9	44
		11.2	95	0	95	5	2.7	<6	16.3	145+	4.4	56
		12.7	100	0	100	0	1.1	<6	[b]20.3	145+	5.5	34
		INORGANIC REDUCING-ACID SOILS										
61	Sharkey clay	2.1	100	60 to 100	0 to 40	0	.6	6	2.2	40	.5	12
		4.0	100	20 to 40	60 to 80	0	1.5	12	5.0	45	1.0	8
		8.9	95	75 to 95	5 to 20	<5	.7	<6	4.2	48	1.1	14
		11.2	95	0	95	<5	2.2	6	6.9	58	2.1	17
		12.7	100	0	100	0	1.1	6	7.5	64	2.0	14
51	Acadia clay	2.1	15	0	15	85	3.3	6	7.5	52	2.0	30
		[c]9.0	<5	0	<5	95	4.8	8	17.4	128+	4.8	28
		INORGANIC REDUCING-ALKALINE SOILS										
64	Docas clay	2.1	100	0 to 20	80 to 100	0	3.2	8	8.7	80	.7	16
		4.0	100	20 to 50	50 to 100	0	1.6	9	6.0	67	.6	18
		9.0	95	75 to 95	5 to 20	<5	1.6	10	4.7	80	1.4	79
		11.2	95	0	95	5	2.4	<6	12.4	118	1.6	35
		12.8	95	0	95	<5	1.6	<6	[b]17.2	122	2.0	[b]21
70	Merced silt loam	2.1	100	60 to 100	0 to 40	0	2.1	8	4.9	50	1.7	56
		4.0	100	0 to 20	80 to 100	0	4.5	12	[b]9.7	118+	[c]1.6	102+
		9.0	100	20 to 40	60 to 80	0	.1	6	13.4	122	3.6	84
		11.2	85	0	85	15	2.6	8	24.5	145+	D	150+
		12.8	90	0	90	10	1.3	8	21.3	145+	D	150+
56	Lake Charles clay	2.1	5 to 15	0	5 to 15	85 to 95	3.7	5	13.8	77	1.1	10
		4.0	5 to 15	0	5 to 15	85 to 95	3.9	7	16.0	104	3.4	26
		8.9	<5	0	<5	95	5.5	13	27.8	145+	4.5	29
		11.1	<5	0	<5	95	14.3	26	[f]D	145+	6.6	42
		12.7	<5	0	<5	95	13.8	66	D	145+	[b]9.0	[b]53

TABLE 66. *Loss in weight and maximum pit depth of galvanized [a] and bare steel pipe and zinc plate buried in 1937*—Continued

(Average of 2 specimens)

Soil		Exposure	Galvanized steel						Bare steel		Zinc	
			Condition of surface				Loss in weight	Maximum pit depth	Loss in weight	Maximum pit depth	Loss in weight	Maximum pit depth
No.	Type		Coated with zinc and alloy layer	Coated with zinc	Coated with zinc-iron alloy	Bare steel exposed						
ORGANIC REDUCING-ACID SOILS												
		Years	*Percent*	*Percent*	*Percent*	*Percent*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*
59	Carlisle muck	2.1	30 to 50	0	0	50 to 70	1.2	8	1.5	12	0.7	66
		4.0	30 to 50	0	0	50 to 70	3.4	11	3.3	20	1.7	10
		9.1	50	0	20 to 50	50	3.0	8	7.5	101	4.6	22
		11.1	50	0	50	50	4.0	8	9.6	76	3.9	28
		12.7	40	0	40	60	3.4	<6.	9.6	72	4.6	18
63	Tidal marsh	2.1	100	50 to 100	0 to 50	0	1.2	<6	2.7	24	1.2	26
		4.0	100	50 to 100	0 to 50	0	2.1	10	9.2	38	[b]2.3	34
		8.9	95	0	95	5	2.0	8	10.7	80	[g]2.0	25
		11.2	75	0	75	25	2.9	8	12.2	94	3.8	30
		12.6	60	0	60	40	[b]4.8	[b]52	18.5	126	4.1	43
58	Muck	2.1	5 to 15	0	5 to 15	85 to 95	4.3	13	5.1	29	3.3	38
		4.0	0	0	0	100	5.4	[b]21	8.8	46	5.1	66
		9.1	0	0	0	100	9.0	64	17.3	98	7.4	58
		11.1	0	0	0	100	8.3	66	16.3	110	7.6	75
		12.7	0	0	0	100	10.7	76	17.6	124	7.5	50
60	Rifle peat	2.1	0	0	0	100	4.3	10	4.0	15	4.6	53
		4.0	0	0	0	100	7.2	12	8.1	[b]38	10.4	100
		9.1	0	0	0	100	19.8	83+	17.6	58	D	150+
		11.1	0	0	0	100	17.9	66	19.6	89	D	150+
		12.7	0	0	0	100	19.5	88	21.0	118	D	150+
CINDERS												
67	Cinders	2.1	0	0	0	100	6.7	62	40.5	145+	[e]4.6	107+
		4.0	0	0	0	100	5.4	45	[e]37.0	145+	[e]12.2	118+
		9.0	<5	0	<5	95	5.6	21	31.7	145+	D	150+
		11.1	0	0	0	100	17.2	62	D	145+	12.0	78
		12.7	<5	0	<5	95	[b]11.9	[b]48	D	145+	D	150+

[a] Nominal weight of coating, 3.08 oz/ft².

[b] Data for the individual specimens differed from the average by more than 50 percent.

[c] Data for 8 specimens.

[d] The plus sign indicates that 1 or more specimens contained holes because of corrosion.

[e] Data for 1 specimen. The other specimens were destroyed by corrosion.

[f] D, both specimens destroyed by corrosion.

[g] Data for 1 specimen. The other specimen was missing.

The results of this test showed that the heavier zinc coatings remained virtually intact for 13 years in 8 of the 10 inorganic soils (soils 53, 55, 61, 62, 64, 65, 66, and 70). Although the coating was almost completely removed from the specimens during the first few years of exposure to the two highly reducing inorganic soils (51 and 56), the subsequent base metal attack was relatively slow as compared with that of the control specimens. Even in the highly corrosive cinders, soil 67, in which the zinc coating was destroyed within the first 2 years, the weight loss and pitting of the base metal was considerably less than that observed for the control specimens.

A greater attack occurred on the zinc control specimens than on the steel control specimens in only 1 (soil 60) of the 4 organic reducing soils (58, 59, 60, and 63). Comparison of the galvanized specimens and the control specimens after 13-years exposure in three of the more corrosive soils (56, 66, and 70) shows the beneficial effects of the zinc coating. The control specimens were severely pitted and generally corroded, whereas the surfaces of the coated specimens were in relatively good condition (fig. 53).

Typical curves representative of the degree of protection provided by the galvanized coatings considered were derived from the underground corrosion data (fig. 52). The curves show the corrosion characteristics of the soil under observation, as an example, in the case of soil 56 the uniform slope of the initial portion of the curve shows a gradual solution of the zinc and is indicative of the fact that the coating provided mechanical protection. However, when the steel was exposed at a break in the coating the protection shifts from mechanical to electrochemical, as indicated by the shift in the slope of the curve and a reduction in the rate of weight loss. So long as the minimum current density required to protect steel could be maintained, pitting of the steel was arrested. However, when the zinc coating was substantially removed, as indicated by the abrupt increase in the slope of the weight loss curve after 9-years exposure, pitting of the exposed steel proceeded at the same rate on the coated pipe as it did on the bare steel. In this or any other environment in which the protection of steel depends entirely on the sacrificial corrosion of the zinc coating, a galvanized coating could provide only temporary protection of a service pipe at best.

Unlike the galvanized specimens in soil 56, the protection afforded to the coated specimens in soils 64, 65, 66, and 70 cannot be accounted for solely by sacrificial corrosion of the zinc coating. Since

Figure 53. *Condition of bare and galvanized steel exposed to three corrosive soils for 13 years.*

Table 67. *Condition or maximum pit depth of galvanized pipe and 16-gage steel sheet exposed for 10 or 13 years*

(Maximum pit depth in mils)

Z, Zinc continuous over specimen; A, zinc-iron alloy exposed over at least a part of the specimen; R, rusted; M, shallow metal attack.

Soil number	Coating weight (oz/ft²) on—					
	Sheet [a]			Pipe		
	0.81	0.99	1.07	1.81	2.82	3.08 [b]
INORGANIC OXIDIZING—ACID SOILS						
3	R	R	Z	M	Z	
53						A
4	16	22	13	R	R	
6	A	A	Z		Z	
10	24	16	12	A	R	
11	21	16	13		A	
55						A
12	M	A	A	A		
16	15	20	18	Z	M	
19	20	27	22	A	Z	
22	32	56	29		R	
24	A	A	Z	Z	Z	
25	R	10	R		Z	
26	6	11	8	A	A	
31	A	Z	Z		Z	
32	R	A	A	R	R	
35	R	A	A	A	A	
36	4	A	A		Z	
38	A	A	A		Z	
41	A	A	A	M	A	
42		21	23		R	
62						A
46	Z	Z	Z	A	Z	
INORGANIC OXIDIZING—ALKALINE SOILS						
13	R	15	8		R	
65						A
66						A
INORGANIC REDUCING—ACID SOILS						
1	30	30	33	29	R	
2	R	A	Z	M	Z	
5	22	12	12		R	
7	17	17	22	R	R	
9	19	29	23	R	A	
14	A	A	R	A	Z	
17	27	22	19	R	R	
27	10	12	9		A	
28	63	33	22		R	
30	13	20	11	12	A	
37	17	20	14		R	
40	48	47	38	R	R	
61						M
44	A	A	A			
51						15
INORGANIC REDUCING—ALKALINE SOILS						
8	R	A	A	R	Z	
15	A	Z	Z		Z	
20	21	17	13	R	R	
23	21	37	41			7
45	5	19	16	38	R	
47	R	R	R	A	A	
56						17
64						7
ORGANIC REDUCING—ACID SOILS						
29	26	32	28	30	R	
58						65
33	29	17	14		R	
43	63	R	R	25	A	
63						8
59						8
60						75
CINDERS						
67						40

[a] Weights of the coating on one side. This is half the nominal weight of the coating on sheets.

[b] Exposed 13 years.

destruction of the zinc coating in these soils is not reflected by increased weight loss or pitting of the galvanized specimens, it follows that some factor other than sacrificial corrosion of the zinc, such as the formation of a protective film, must determine the behavior of galvanized steel in these soils. As a result, the life of galvanized pipe in these soils may be considerably greater than the period covered by the field tests.

Since the life of a service pipe is determined by the time required for perforation of the wall by pitting, a correlation of the maximum pit depths in the galvanized specimens exposed to the different environments, with the weight of coating would have practical significance. A comparison of the maximum depth of pits or condition of the galvanized coatings, after 10- to 13-years exposure, in the different soil environments (table 67) show that a nominal 2-oz coating would be adequate in inorganic oxidizing soils for at least 10 years. It was also shown (table 67) that a 3-oz coating provided adequate protection for 10 to 13 years in all the inorganic reducing soils except in soils 51 and 56, which are strongly reducing soils containing high concentrations of soluble salts.

A 3-oz galvanized coating is not sufficient to protect the underlying steel in either the highly reducing organic and inorganic soils or in cinders, and hence additional means of protection is required. Such supplementary coatings as the bituminous type have been proposed and the beneficial effect of such coatings was shown by Burns [70] to be effective as demonstrated by the long life observed for galvanized steel armor wires coated with asphalt and jute which were used to support submarine cables. These observations showed that the long life was due not only to the reinforced bituminous coating, but also to the presence of the underlying zinc coating. Burns demonstrated this by restraining the free circulation of water, and observing that the stagnant solution near the surface of the wires became saturated with the corrosion products of zinc.

c. Electrochemical Behavior of Corrosion of Galvanized Steel

Potentials of Zinc, Steel, and Zinc-Iron Alloy in Soils. Many investigations have been conducted on coatings of zinc and zinc-iron alloy in atmospheric and submerged conditions, but due to the many different factors operative in the underground environments this data cannot be directly applied to underground corrosion. The published information up to the present as applied to soil corrosion has been limited to such inferences as have been drawn from the results of the controlled underground exposure tests. In contrast to this, recent extensive controlled laboratory investigations at the Bureau have added considerably to our knowledge of the kinetics of these reactions and as these data have not been published, it will be dealt with in considerable detail in the subsequent section.

The electrochemical behavior of bare steel, zinc, and zinc-iron alloy in aqueous solutions have been investigated by Burns [70], Britton [169], and Kenworthy and Smith [192]. Burns reported that the potential of zinc-iron alloy is intermediate between the potentials of zinc and steel, and so might be expected to provide some protection to steel. However, Britton and Kenworthy and Smith reported that zinc-iron alloy, exposed by removing the outer zinc coating from galvanized iron, provided negligible protection to iron in certain types of waters. The work of Britton showed that iron was protected cathodically for a limited period by connecting pieces of iron and zinc-iron alloy and immersing the couple in water, but after an initial period the potential reversed and corrosion of the iron commenced. Similar reversals of potential were observed by Schwerdtfeger (fig. 31) in a 0.2 percent potassium chloride solution.

In order to evaluate the effectiveness of the alloy layer in cathodically protecting the steel in soils, the potentials of zinc,[9] zinc-iron alloy and steel[10] were measured in 12 air-free soils by the method described by Schwerdtfeger and McDorman [136]. Specimens having a zinc-iron alloy surface were prepared by two methods: (1) surface A, by electrolytic removal of the outer zinc coating from sections of commercial galvanized steel sheet, according to a modification of the method of Britton [193]; and (2) surface B, by cutting sections of 1.75-in. in length from 1.5-in. galvanized-steel pipe from which the outer zinc coating had been removed by 13-years exposure to corrosion in the field tests. An insulated copper wire was soldered to the inside of the pipe section, the ends of which were closed with rubber stoppers with the wire passing through a hole in one of the stoppers. The exposed edges of the pipe were coated with bitumen and the specimens placed in individual 1-pt jars. The jars were filled with water-saturated and mechanically worked soil from the field test sites. Air was excluded from the cell by covering the surface with a layer of paraffin. Contact with the reference electrode was made through a hole in the paraffin layer, which was sealed with a rubber stopper except when potential measurements were being made.

The results of these tests showed that the solution potential of zinc was more negative (anodic) than the protective potential of steel, namely, −0.77 v [136], and indicate that a zinc coating would protect steel cathodically in all of the 12 soils, providing the potential of the coating was not affected unduly by anodic polarization. The field studies of Denison and Romanoff [135] indicate that this effect is unlikely to occur except in some soils containing high concentrations of sodium carbonate.

The potentials (table 68) of the electrodes of

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[9] Composition of zinc in percent: 0.009 Fe, 0.095 Pb, 0.0038 Cd.

[10] Composition of steel in percent: 0.23 C, 0.58 Mn, 0.008 P, 0.025 S, 0.095 Si, 0.077 Cu.

TABLE 68. *Potentials of zinc-iron alloy, zinc, and steel in "air-free" soils*

Soil	Potential (saturated calomel scale)—volts					
	Zinc-iron alloy				Zinc	Steel
	Outer zinc coating removed electrolytically (surface A)		Outer zinc coating removed by corrosion (surface B)			
	Initial	Steady	Initial [a]	Steady [a]		
51	−0.96	−0.62	----------	----------	−1.02	−0.71
55	−.86	−.60	----------	----------	−1.02	−.75
56	−.91	−.61	----------	----------	−1.04	−.73
58	−.87	−.63	----------	----------	−1.04	−.74
60	−.96	−.64	----------	----------	−1.02	−.68
61	−.92	−.66	−0.96	−.103	−1.02	−.72
62	−.90	−.54	----------	----------	−.92	−.72
63	−.92	−.65	----------	----------	−.94	−.64
64	−.97	−.61	−.90	−.75	−1.08	−.73
65	−.95	−.64	−.99	−.96	−1.01	−.71
66	−.80	−.61	−.85	−.84	−.94	−.72
70	−.95	−.60	−.98	−.88	−.99	−.76

[a] Outer zinc coating over part of surface or steel exposed, where values are not given.

zinc-iron alloy prepared by electrolytic stripping (surface A) exhibited a more pronounced drift in the cathodic direction with time than did the potentials of specimens from the field tests (surface B). These alloy electrodes acquired a steady potential in approximately 1 week.

The steady potentials of the electrolytically stripped electrodes of zinc-iron alloys (surface A) were cathodic to steel, with one exception (soil 63), in all of the 12 soils. Consequently, the results of this test indicate that the underlying steel exposed by a break in the zinc-iron alloy surface would not be protected cathodically in any of these soils. This is in agreement with the observations previously cited of Britton [169], Gilbert [170], and Kenworthy and Smith [192].

The corrosion rates of the zinc-iron alloy electrodes were measured in five "air-free" soils by Pearson's method [194], as adapted to soil corrosion measurements by Schwerdtfeger and McDorman [142]. This method involves the anodic and cathodic polarization of the reacting surfaces, and evaluating from characteristic discontinuities in the polarization curves, the currents, I_p and I_q in the following equation:

$$i_0=\frac{I_p \times I_q}{I_p+I_q}$$

where i_0 = corrosion current; I_p and I_q = current required to polarize the metal to the average open circuit potential of the local anodes and cathodes, respectively.

The polarizing characteristics of the electrodes of zinc-iron alloy surfaces in soil 66 are illustrated in figure 54. The flat polarization curves for the alloy layer exposed electrolytically (surface A) probably are caused by local corrosion currents due to normal corrosion on the reacting metal. In fact, it is not until the applied currents are in excess of I_p and I_q that the local currents are eliminated. By contrast, the very large changes in potential, of the zinc-iron alloy exposed by corrosion in the field (surface B), produced by small increments of current indicate the virtual absence of local corrosion circuits and hence a relatively low rate of corrosion.

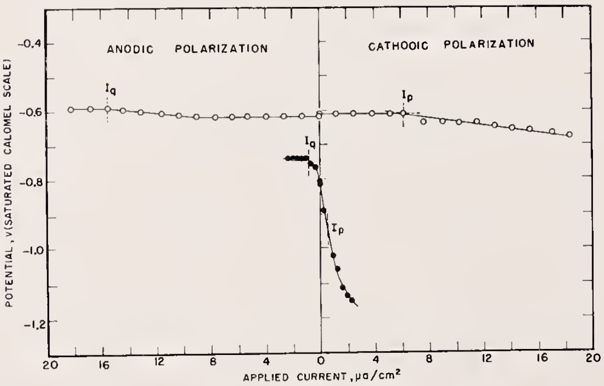

FIGURE 54. *Anodic and cathodic polarization curves of zinc-iron alloy exposed by corrosion in the field and electrolytic stripping in the laboratory in an "air-free" (soil 66).*

○, Outer zinc coating removed by electrolytic stripping (surface A); ●, outer zinc coating removed by corrosion in the field (surface B).

By evaluating the constants I_p and I_q in both curves, the corrosion current of both metal specimens were calculated according to the equation previously given. In the absence of a break in the cathodic polarization curve for surface B, I_p was taken as the current corresponding to the potential of zinc in soil 66, namely, −0.94 v. However, because of the steepness of the curve, the actual value of potential at which I_p is measured has little effect on the calculated current. The values of the corrosion current for the test pieces in the five soils studied are given in table 69.

TABLE 69. *Currents associated with the corrosion of zinc-iron alloy in "air-free" soils*

Soil	Outer zinc coating removed by —	
	Electrolytic stripping (surface A)	Corrosion in the field (surface B)
	μa/cm²	μa/cm²
61	1.2	0.1
64	6.8	.2
65	3.0	.6
66	4.5	.3
70	1.7	.4

A possible explanation for the very low rates of corrosion of surface B, as compared with surface A is that the former was covered with a protective film or coating of high resistance which was deposited cathodically by galvanic action between the outer zinc coating and the alloy layer during the normal corrosion process. The probable composition of such a film will be discussed in a subsequent section (see page 117).

Corrosion of Steel, Galvanized Steel, and Zinc-Iron Alloy. From a comparison of the potentials of zinc-iron alloy layer with those of steel in air-free soils, it was concluded that the alloy layer could provide little, if any, electrochemical protection to steel in those soils. Therefore, any protection provided by the alloy layer must be mechanical. If the protective value of zinc-iron alloy is actually due to a deposited film, specimens of galvanized steel from which the outer zinc coating had been removed by corrosion would be expected to corrode much more slowly than similar specimens from which the coating had been removed by electrolytic stripping.

To test this postulate, test pieces (1.75-in. lengths of 1.5-in. diameter pipe) of bare steel and of hot-dipped galvanized steel (nominal weight of coating, 3 oz/ft^2) from which the outer zinc coating had been removed by both electrolytic stripping (surface A) and field exposure (surface B) procedures were prepared. Zinc-iron alloy specimens (surface C) were also prepared in the laboratory by exposing pieces of new galvanized pipe to a very corrosive soil for 60 days. Each of these specimens was then exposed to samples of soils 56 and 70 for 60 days, in individual crystallizing dishes covered to prevent loss of moisture.

The results of these tests (table 70) show that the weight losses of the specimens from which the outer zinc coating had been previously removed by soil corrosion in the laboratory (surface C) and in the field (surface B) are negligible as compared with the specimens of zinc-iron alloy exposed by electrolytic stripping (surface A). The high resistance to corrosion of zinc-iron alloy surface C is also shown by the polarization curves for this material (fig. 55) which show similar marked changes in potentials as was observed for alloy surface B (fig. 54). The data (table 70) further indicate that the rates of corrosion of zinc, steel, and zinc-iron alloy, exposed by electrolytic stripping (surface A) are all of the same order of magnitude in these soils.

Table 70. *Corrosion of zinc-iron alloy, galvanized steel, and bare steel in aerated soils—exposure 60 days*

Soil	Weight loss				
	Zinc-iron alloy			Galvanized steel[a]	Bare steel
	Outer zinc coating removed electrolytically in the laboratory (surface A)	Outer zinc coating removed by soil corrosion			
		in the field (surface B)	in the laboratory (surface C)		
	g	g	g	g	g
56	2.231	0	0.166	3.234	2.255
70	1.444	0	.045	2.431	2.030

[a] Weight loss in removing outer zinc coatings by exposure to soils in the laboratory.

The high resistance to corrosion shown by specimens of galvanized steel from which the outer zinc coating had been removed by soil corrosion has been attributed to an unidentified protective film formed by galvanic action between the zinc coating and the underlying zinc-iron alloy or bare steel. To determine whether such a protective film could be deposited on zinc-iron alloy, or on steel, by connecting it to a zinc anode and exposing the couple to galvanic corrosion, weighed electrodes of steel and of zinc-iron alloy prepared by electrolytic stripping were separately connected to zinc anodes in soil corrosion cells with samples of soil 70 as the electrolyte. The corrosion cells were similar to those described in appendix 5 except that the overall length of the cell was reduced by one-half and a perforated zinc anode was placed midway between the top and bottom of the cell. After standing on closed circuit for 30 days, the cells were placed on open circuit for 60 days, when they were disassembled and the cathodes cleaned and reweighed. The results of the weight loss measurements (table 71) showed that the steel and zinc-iron alloy was made passive by the couple and virtually immune to corrosion, in a highly corrosive soil after the couple had been broken.

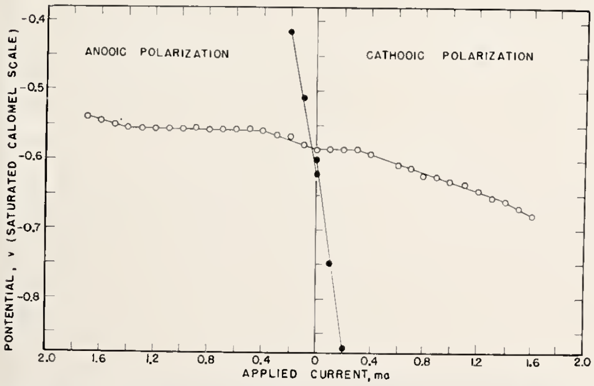

Figure 55. *Anodic and cathodic polarization curves of zinc-iron alloy exposed by electrolytic stripping and by corrosion in an aerated (soil 56).*

Exposure 23 days.
O, Outer zinc coating removed by electrolytic stripping (surface A); ●, outer zinc coating removed by exposure to soil in laboratory (surface C).

Table 71. *Comparison of weight losses of control specimens of zinc-iron alloy and bare steel with that of the same materials protected cathodically by zinc anodes for 30 days and then placed on open circuit for 60 days*[a]

Specimen	Zinc-iron alloy		Bare steel	
	Protected	Unprotected (control)	Protected	Unprotected (control)
	g	g	g	g
A	0.004	0.200	0.041	0.355
B	.006	.232	.004	.358

[a] Exposed to soil 70 in the laboratory.

Subsequently, these results were substantiated by proving the presence of a passive film on bare steel that was galvanically coupled with zinc. A steel drill rod (½-in. by 9-in.) was galvanically coupled to a concentric cylinder of sheet zinc and both were immersed in a tap water solution containing 3 percent of sodium chloride. Periodic measurements were made of the galvanic current and of the cathode potential. The current decreased rapidly and the cathode potential increased proportionately during the initial hour of exposure. That this represented the initial stages of formation of a cathode film became evident when after 3 weeks of exposure, a white deposit became visible on the lower half of the steel rod and the current measured about 0.3 ma. After 6 months of exposure, the cathode was entirely coated with the white glossy deposit and the galvanic current had decreased to 0.05 ma. After 1 year of exposure, no further reduction in current was observed, but the thickness of the white coating had increased to 0.002 or 0.003 in. The test was terminated at the end of 1 year and the coating removed for analysis. The underlying steel surface was found to be bright and unaffected by corrosion. X-ray analysis of the white coating, by the powder-pattern method, indicated that it consisted primarily of zinc silicate. White coatings similar in appearance to this one had been observed on specimens exposed at various field test sites.

16.3. Lead-Coated Steel

The high resistance of lead to corrosion by chloride, sulfate, and carbonate ions, which severely corrode iron and steel, suggested that a lead coating might provide good protection to ferrous metals in many soils. It was known that the corrosion of lead-coated steel follows a different type of pattern than that of galvanized steel due to the fact that lead is cathodic to iron. Also, the insolubility of lead salts afford greater protection to lead than is observed in the case of zinc.

Pipe specimens, lead coated by the hot-dip process, together with steel control specimens were buried in 41 soils in 1924 and in 15 additional soils in 1932. The maximum and minimum thickness of lead on the 1924 specimens were 0.00250 and 0.00030 in., respectively, with an average of 0.00105 in.; the corresponding values for the 1932 specimens were 0.00297 and 0.00050 in., respectively, with an average of 0.00144 in. [115]. Table 72 shows the data for the pipe buried in 1924, and the data for the specimens buried in 1932 are given in table 73. The results show that in a few soils a substantial part of the coating remained intact during the entire exposure period, but in many of the soils large areas of the coatings were removed by corrosion after relatively short periods of exposure.

The progress of corrosion of the bare and coated specimens with time is illustrated in figure 56. In cinders, soil 67, and in the poorly drained soils 56 and 58, the rate of corrosion of lead was so high that the coating was virtually completely removed during the early periods of exposure and thus the coating had no effect in the subsequent corrosion rate of the steel pipe.

In the poorly aerated organic soils, 59, 60, and 63, some protection was evidently provided by the coating for variable lengths of time after which the coated and uncoated specimens corroded at approximately the same rates, as indicated by the similarity in the slopes of the weight loss-time curves (fig. 56). Under conditions of poor aeration, the nature of the cathode, whether lead or steel, would be expected to have a negligible effect on the cathode reaction and hence on the rate of corrosion [195, 196]. The rate of pitting of the exposed areas of the bare metal was greater for the coated pipe than for the uncoated control specimens because when there was a break in the lead coating the steel was anodic. This was confirmed by the pit depth-time curves for the coated and uncoated steel specimens in soils 59, 60, and 63.

Unlike the soils having deficient aeration, the better aerated soils, 53, 55, 62, 64, 65, and 66 did not show accelerated pitting with time. In fact, the pit depth-time curves for these soils indicate that the lead coating, although discontinuous, reduced the pitting of the underlying steel, probably because in these soils lead is more readily polarized cathodically than steel. This was substantiated by Denison [134] in studies based on the polarizing characteristics of different metals in soils, from which he observed that the cathodic polarization of lead was greater than that of steel.

TABLE 72. *Loss in weight and maximum pit depth of 1½-in. lead-coated and Bessemer steel pipe buried in 1924 and exposed 10 or 16 years* [a]

Soil		Lead-coated steel		Uncoated Bessemer steel	
No.	Type	Loss in weight	Maximum depth	Loss in weight	Maximum pit depth
		oz/ft²	*Mils*	*oz/ft²*	*Mils*
1	Allis silt loam	5.3	119	9.3	68
2	Bell clay	1.0	40	5.9	80
3	Cecil clay loam	.7	36	5.1	55
4	Chester loam	2.4	71	6.2	83
5 [b]	Dublin clay adobe	8.9	104	[c] 7.1	[c] 50
6 [b]	Everett gravelly sandy loam	.4	14	2.0	18
7 [b]	Maddox silt loam	4.4	145+	5.8	50
9 [b]	Genesee silt loam	[d] 1.6	[d] 60	5.8	64
10	Gloucester sandy loam	1.6	65	4.4	39
11	Hagerstown loam	.7	34	1.9	58
12 [b]	Hanford fine sandy loam	[e] 1.3	[e] 28	6.0	72
13	Hanford very fine sandy loam	.7	56	------	------
14	Hempstead silt loam	.4	42	4.5	84
15	Houston black clay	.5	32	7.8	54
17 [b]	Keyport loam	7.0	49	9.5	41
18	Knox silt loam	.5	46	2.6	39
20	Mahoning silt loam	2.3	54	6.0	65
22	Memphis silt loan	1.9	73	7.1	78
24 [b]	Merrimac gravelly sandy loam	.8	28	1.8	16
26 [b]	Miami silt loam	1.5	48	4.3	42
27 [b]	Miller clay	4.1	47	10.1	69
28	Montezuma clay adobe	3.1	78	11.8	145+
29	Muck	6.9	64	19.4	145+
31 [b]	Norfolk sand	.5	28	3.7	43
32	Ontario loam	.7	52	3.7	50
33	Peat	5.4	77	14.2	105
35 [b]	Ramona loam	[c] .2	[c] 10	1.5	8
36 [b]	Ruston sandy loam	1.3	24	4.1	55
37	St. Johns fine sand	2.0	64	7.0	68
38 [b]	Sassafras gravelly sandy loam	2.2	34	2.3	28
40	Sharkey clay	1.9	63	6.8	83
41 [b]	Summit silt loam	1.3	80	6.9	92
42	Susquehanna clay	.9	46	11.4	88
43	Tidal marsh	7.3	188	17.6	105
45	Unidentified alkali soil	2.0	92	9.3	82
46	Unidentified sandy loam	.3	45	4.4	104
47	Unidentified silt loam	1.8	61	2.8	31

[a] Average of 2 specimens unless indicated otherwise.

[b] Specimens were exposed to these soils for approximately 16 years. In the other soils the specimens were exposed for approximately 10 years.

[c] Data for 1 specimen.

[d] Average of 3 specimens.

[e] Average of 4 specimens.

Polarization of the cathode of the lead-steel couple would be expected to be especially pronounced in soils in which a protective film forms on lead as a result of normal corrosion. For example, silicate ions passivate lead because of the very low solubility of lead silicate [178]. Silicate ions precipitated as lead silicate on the lead cathode produce

TABLE 73. *Condition of lead coating, weight losses, and maximum pit depth of lead-coated steel pipe*[a] *buried in 1937*

Soil			Exposure	Loss in weight	Maximum pit depth	Approximate area of pipe coated
No.	Type	Aeration				
			Years	*oz/ft²*	*Mils*	*Percent*
51	Acadia clay	Poor	2.0	5.4	54	<10
			5.4	8.6	[b]145+	<10
			7.4	9.2	104	<10
			14.3	15.4	125+	<10
53	Cecil clay loam	Good	2.0	.8	36	85
			5.4	1.0	37	65
			7.4	1.6	44	40
			9.3	1.1	41	40
			14.3	1.0	80	65
55	Hagerstown loam	do	2.0	.5	22	>95
			5.4	.7	26	85
			7.4	1.1	44	85
			9.3	.8	44	85
			14.3	1.0	62	85
56	Lake Charles clay	Very poor	2.0	1.1	57	40
			5.4	5.9	56	<10
			7.4	10.2	140+	<10
			9.3	20.7	145+	<10
			14.3	[c]D	145+	0
57	Merced clay adobe	Poor	2.0	.5	23	85
			5.4	1.1	50	60
58	Muck	do	2.0	1.7	30	40
			5.4	6.2	62	<10
			7.4	11.8	90	<10
			9.3	14.8	91	<10
			14.3	18.1	134+	<10
59	Carlisle muck	Very poor	5.4	.1	0	100
			7.4	.4	7	>95
			9.3	1.1	21	85
			14.3	1.8	46	85
60	Rifle peat	Poor	2.0	3.0	40	40
			5.4	3.4	38	40
			7.4	2.4	50	60
			9.3	7.1	50	<10
			14.3	16.7	79	<10
61	Sharkey clay	do	1.0	.4	20	85
			5.4	2.7	44	40
			7.4	3.3	70	40
			9.3	3.9	50	40
			14.3	6.5	108	40
62	Susquehanna clay	Fair	2.0	.8	35	85
			5.4	1.4	54	85
			7.4	2.1	47	60
			9.3	3.6	59	40
			14.3	1.6	54	85
63	Tidal marsh	Very poor	2.0	.02	16	>95
			5.4	.1	0	100
			7.4	.4	<6	65
			9.3	3.5	145+	40
			14.3	2.8	145+	65
64	Docas clay	Fair	2.0	.4	36	85
			5.4	.8	43	65
			7.4	1.6	56	40
			9.3	2.1	73	40
			14.3	3.7	118	60
65	Chino silt loam	Good	2.0	.4	28	85
			5.4	2.6	60	40
			7.4	3.8	53	40
			9.3	3.2	72	40
			14.3	2.9	94	65
66	Mohave fine gravelly loam	Fair	2.0	.8	36	85
			5.4	3.4	73	40
			7.4	4.4	61	40
			9.3	3.4	57	40
			14.3	5.4	119+	60
67	Cinders	Very poor	2.0	33.6	145+	<10
			5.4	D	145+	<10
			7.4	D	145+	<10
			9.3	D	145+	0
			14.3	D	145+	0

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[a] The coating was 0.00144 in. thick and contained 1 percent of tin

[b] +, one or more specimens contained holes because of corrosion.

[c] D, specimens destroyed by corrosion.

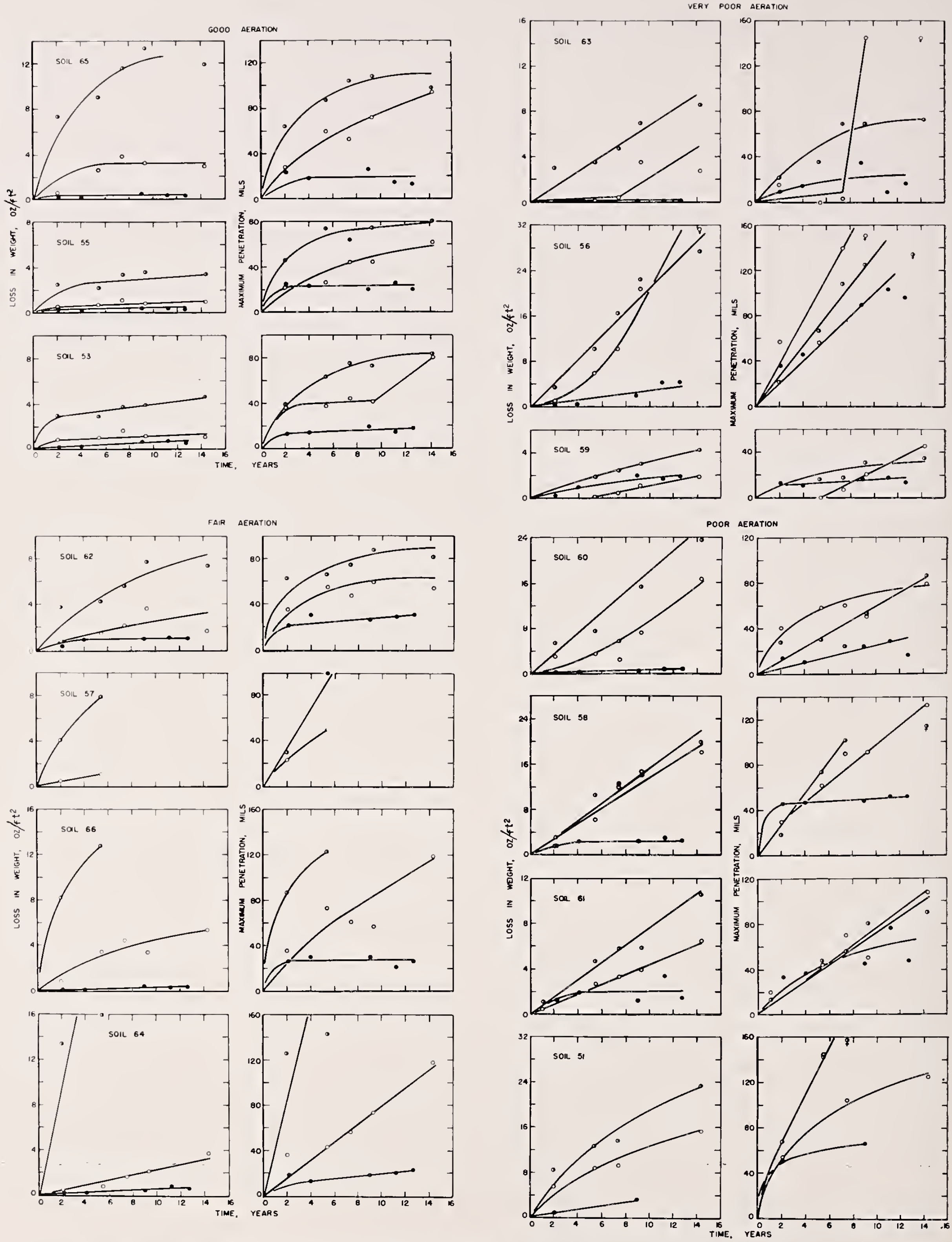

FIGURE 56. *Weight-loss and pit-depth–time curves of lead-coated steel, bare iron and steel, and lead.*
●, Lead; ○, lead-coated steel; ◑, bare iron and steel.

cathodic polarization and a consequent shift of corrosion to other areas with a subsequent deposition of the silicate film generally over the surface. Under these conditions lead provides mechanical protection and the rate of pitting of the coated steel is maintained at low values relative to uncoated steel.

It was previously cited in the section on lead that sulfates, chlorides, and carbonates, although probably less effective than silicates in polarizing lead, are likewise inhibitors of the corrosion of lead. For example, the rate of corrosion of lead is very low in soil 63, which is high in chloride and sulfate ions. However, due to the fact that pitting of the coated steel specimens in this soil was accelerated (table 73), it is believed that the films of lead chloride and sulfate did not extend over the areas of exposed steel, that otherwise would have polarized when the steel was exposed.

Any consideration of the use of lead coatings for the protection of steel in soils obviously must have regard for reduction in thickness of the coating by normal corrosion. Estimates of the reduction in the thickness of the coating by exposure to the soils at the field test sites can be made by converting the weight losses of lead (tables 53 and 54) to the average thickness of lead (average penetration)[11]. Such calculations show that in soils 51, 56, 58, 59, 61, 62, and 67, the average penetrations of lead in 14 years are equal or greater than the thickness of lead coatings generally applied to steel. Even after suitable allowance has been made for the average penetration of lead in such soils, the possibility of accelerated pitting arising from perforation of the coating cannot be neglected.

16.4. Aluminum-Coated (Calorized) Steel

Calorized coatings which are alloys of aluminum with the base metals [190] were developed primarily for the purpose of preventing scaling when the metal is subjected to high temperature. There are two methods of calorizing, one known as the powder process; the other as the dip process. Bare aluminum is anodic to iron in many corrosive media but the oxide film that forms naturally on aluminum is much more noble than aluminum itself [43] and is likely to be cathodic to iron.

Specimens of pipe prepared by each process were buried in seven test sites in 1924. The average thickness of the powder-calorized coating was 0.002 in. and that of the dip-calorized was 0.011 in.

With one exception, the calorized specimens lost less weight and were less pitted than the unprotected pipe in the same soils after 10 years of exposure (table 74). In 5 of the 6 soils, the powder-calorized pipe was less pitted than the dip-calorized pipe, whereas in the same soils the dip-calorized pipe lost less weight than the powder-calorized pipe. In general, calorizing made the pipe more resistant to corrosion but did not eliminate pitting. The rate of pitting and loss in weight of the specimens were highest in poorly drained, corrosive soils.

Table 74. *Corrosion of calorized steel pipe exposed for approximately 10 years*

Soil		Rates of loss in weight[a] (oz/ft ^{2}/yr)			Rates of maximum pit depth[a] (mils/yr)		
No.	Type	Dry calorized	Wet calorized	Bare steel[b]	Dry calorized	Wet calorized	Bare steel[b]
13	Hanford very fine sandy loam	0.137	0.087	1.24	3.4	4.4	13.0
24	Merrimac gravelly, sandy loam	.019	.013	.12	2.4	3.2	2.1
28	Montezuma clay adobe	.437	-------	1.75	5.5	-------	15.1
29	Muck	.250	.458	1.39	3.4	7.8	9.2
42	Susquehanna clay	.452	.088	1.25	7.0	4.2	9.2
43	Tidal marsh	.861	.434	1.72	3.1	3.4	7.4
45	Alkali soil (Casper, Wyo.)	.712	.184	1.23	3.4	4.4	11.9

[a] Average of 2 specimens.
[b] Rates for unprotected Bessemer steel specimens of similar area which were exposed, except in the case of soil 13, for a similar period. The data presented for bare steel in soil 13 are for specimens exposed only 6 years, there being no data available for a longer period.

16.5 Tin-Coated Copper

Copper has been shown to be highly resistant to corrosion in most soils, but some protection of copper is desirable in soils high in sulfides and in highly reducing soils. Although tin is too soft to be used by itself as pipe material, the high resistance of tin to corrosion in a variety of aqueous solutions [197] suggested that tin might provide a beneficial protective coating for copper underground. In addition to mechanical protection, there was a possibility that tin might provide cathodic protection to local areas of exposed copper.

The specimens of tin-coated copper which were exposed at the field test sites in 1937 were 12-in. lengths of 1.5 in. copper tubing with a wall thickness of 0.060 in. and an average coating thickness of 0.00089 in. of tin. The results of this test (table 75) were compared with those of previous exposure tests of bare copper in the same sites. The most significant feature of these results was that the tin coating was appreciably susceptible to corrosive attack in most of the soils, and especially so in cinders (67) and in poorly aerated organic soils (60 and 63). The coatings used in these tests were penetrated by normal corrosion except in the well-aerated soils in which no protection of copper is required.

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[11] The factor used to convert weight losses in ounces per square foot to average penetration in soils is:

$$\text{Factor} = \frac{12 \times 1{,}000}{\text{Wt of 1 ft}^3\text{ of metal (lb)} \times 16} = \frac{750}{\text{density (lb/ft}^3\text{)}}.$$

The factor which applies to the lead specimens in these tests is 1.069.

TABLE 75. *Condition of the tin coating on copper tubing, and weight losses and maximum pit depth of coated and uncoated copper*

Soil			Tinned-copper tube[a]				Deoxidized copper pipe		
No.	Type	Aeration	Exposure	Loss in weight	Maximum pit depth	Approximate area coated	Exposure	Loss in weight	Maximum pit depth
			Years	*oz/ft²*	*Mils*	*Percent*	*Years*	*oz/ft²*	*Mils*
55	Hagerstown loam	Good	2.1	0.06	0	100	2.0	0.14	<6
			4.0	.11	0	100	5.4	.14	<6
			9.0	.04	0	100	7.4	.15	<6
			11.2	.02	0	100	9.3	.18	<6
			12.7	.11	0	100	14.3	.16	<6
53	Cecil clay loam	do	2.1	.06	<6	99	2.0	.12	<6
			4.0	.09	7	99	5.4	.15	7
			9.0	.07	<6	99	7.4	.20	10
			11.2	.08	0	100	9.3	.22	<6
			12.7	.08	0	100	14.3	.24	8
62	Susquehanna clay	do	2.1	.03	<6	99	2.0	.16	<6
			4.0	.08	<6	99	5.4	.26	9
			9.0	.06	0	100	7.4	.38	14
			11.2	.12	<6	99	9.3	.48	8
			12.7	.09	0	100	14.3	.52	10
65	Chino silt loam	do	2.1	.07	<6	>95	2.0	1.71	<6
			4.0	.12	<6	85	5.4	1.02	10
			9.0	.08	8	85	7.4	2.37	18
			11.2	.05	<6	85	9.3	.24	<6
			12.7	.07	<6	85	14.3	1.07	9
58	Muck	Poor	2.1	.37	25	40	2.0	.16	<6
			4.0	.64	39	40	5.4	1.56	12
			9.0	.42	6	90	7.4	1.72	10
			11.2	.70	11	80	9.3	2.10	14
			12.7	1.00	15	80	14.3	2.39	19
70	Merced silt loam	Fair	2.1	.03	<6	85	---	---	---
			4.0	.07	6	85	3.9	.13	<6
			9.0	.06	6	65	8.0	1.07	10
			11.2	.04	<6	65	---	---	---
			12.7	.49	6	25	---	---	---
59	Carlisle muck	Poor	2.1	.04	<6	90	2.0	---	---
			4.0	.23	<6	85	5.4	.12	<6
			9.0	.09	<6	40	7.4	.11	<6
			11.2	.25	<6	40	9.3	.11	<6
			12.7	.35	<6	30	14.3	.21	6
61	Sharkey clay	do	2.1	.20	[b]38+	85	2.0	.06	<6
			4.0	.32	18	40	5.4	.35	23
			9.0	.16	6	85	7.4	.38	8
			11.2	.44	13	40	9.3	.35	8
			12.7	.53	12	40	14.3	.66	24
64	Docas clay	Fair	2.1	.18	<6	85	2.0	1.41	<6
			4.0	.22	6	40	5.4	2.22	9
			9.0	.51	20	40	7.4	3.00	<6
			11.2	.97	22	40	9.3	5.32	16
			12.7	.49	18	40	14.3	5.17	10
66	Mohave fine gravelly loam	do	2.1	.32	6	40	2.0	.28	6
			4.0	.23	<6	40	5.4	.75	7
			9.0	.04	6	85	7.4	1.32	8
			11.2	.03	<6	40	9.3	.62	10
			12.7	.73	6	30	14.3	.54	10
51	Acadia clay	Very poor	2.1	.18	<6	25	2.0	.40	<6
			4.0	---	---	---	5.4	1.01	<6
			9.0	.48	7	25	7.4	.40	<6
			11.2	---	---	---	9.3	---	---
			12.7	---	---	---	14.3	.60	<6
63	Tidal marsh	do	2.1	.44	6	85	2.0	1.13	<6
			4.0	2.19	14	5	5.4	2.45	<6
			9.0	3.25	16	5	7.4	4.25	8
			11.2	3.82	22	5	9.3	4.22	10
			12.7	4.48	16	10	14.3	6.57	10
56	Lake Charles clay	do	2.1	.03	10	5	2.0	.10	<6
			4.0	.36	11	5	5.4	.51	<6
			9.0	.80	8	5	7.4	.80	<6
			11.2	.52	<6	5	9.3	.78	<6
			12.7	1.58	12	5	14.3	.89	<6
60	Rifle peat	do	2.1	1.75	28	5	2.0	1.47	7
			4.0	4.54	42	5	5.4	3.82	28
			9.0	10.92	60+	5	7.4	1.10	8
			11.2	11.50	60+	5	9.3	5.01	38
			12.7	12.62	60+	5	14.3	11.97	48
67	Cinders	do	2.1	12.03	60+	5	2.0	3.98	38
			4.0	20.37	60+	5	5.4	9.33	54
			9.0	[c]D	60+	0	7.4	4.89	44
			11.2	D	60+	0	9.3	11.50	88
			12.7	D	60+	0	14.3	13.77	64

[a] The coating had an average thickness of 0.00089 in.

+, one or more specimens contained holes because of corrosion.

[c] D, specimens destroyed by corrosion.

16.6. Parkway Cable

Parkway cable consists of one or more conductors so insulated and protected that the cable can be laid in a trench without further protection against moisture or mechanical injury. The specimens of cable buried in 1924 consisted of a single rubber covered copper conductor with a lead sheath. Over the sheath was a wrapping of fiber treated to prevent rotting. This was surrounded by two spiral wrappings of zinc-coated steel tape. The final wrapping over the tape consisted of a jute or similar material impregnated with a bitumen. Table 76 shows the condition of the several parts of the cable buried from 10 to 17 years. In no case was there any evidence of corrosive attack or deterioration of the copper conductor.

Table 76. *Condition of parkway cable exposed 10 to 17 years*

G = good.
F = fair.
B = bad.
D = destroyed
M = metal attack.
P = pitted.
R = rusted.
SR = slightly rusted.
H = 1 or more holes.
TW = thin white corrosion product on lead sheet.
W = white corrosion product on lead sheet.

(All steel is zinc-coated)

Soil	Duration of test	Outer fabric	Inner fabric	Outer steel	Inner steel	Lead sheath
	Years					
1	11.6	F	G	R	G	G
2	15.5	----	G	M	M	TW
3	10.0	D	F	P	R	G
5	15.5	G	G	P	SR	TW
6	15.5	F	G	P	M	TW
7	16.9	G	G	P	SR	P
9	15.9	B	G	M	R	W
10	11.9	D	G	P	R	TW
12	15.6	----	G	M	M	W
16	12.0	D	G	P	SR	TW
17	15.8	F	G	M	M	TW
18	11.7	B	G	R	SR	TW
19	11.6	F	G	R	G	TW
24	11.9	F	G	G	G	G
25	11.7	F	G	SR	G	TW
26	15.9	F	G	M	SR	TW
28	9.6	D	G	P	P	TW
29	10.1	B	F	P	G	TW
30	17.0	F	G	M	SR	TW
31	15.7	B	G	P	M	TW
32	11.7	D	G	R	G	TW
34	12.0	F	G	SR	SR	TW
35	10.2	F	G	P	G	TW
36	15.7	F	G	M	M	TW
37	12.0	B	G	SR	SR	TW
38	15.8	F	G	PH	R	TW
39	12.0	F	G	SR	G	TW
41	17.4	B	G	P	SR	TW
43	12.0	B	G	R	SR	G
45	11.7	B	F	R	R	G
46	12.0	D	G	R	R	TW
47	17.4	G	G	M	SR	W

17. Field Tests on Nonbituminous, Nonmetallic, and Miscellaneous Coatings

A number of specimens of nonbituminous, nonmetallic coatings were buried by the National Bureau of Standards in 1932, 1937, and 1939. These tests should be regarded as preliminary or elimination tests since the materials were newly developed at the time of burial and relatively few of some of the specimens were available for test. It was recognized that many of the coatings tested may be too expensive for general use in underground service, but it was felt that the cost was a minor factor in coatings applied in local repair operations or for local protection, for example, of fittings or of joints in the line.

17.1. Organic Coatings Applied to Steel

a. Phenolic

The varieties of phenolic coatings that were exposed at the test sites are described below. Unless stated otherwise all organic coatings were applied to 1½-in. steel pipe 12 in. in length.

Coating L. The first coat of a phenolic resin A was applied by spraying onto sand-blasted pipe. This coating was air-dried for 20 min. and baked for 10 min. at 300°F. A second coat of the same resin and the first coat of another resin B were then applied and each air-dried and baked in the same manner. Finally a second coat of resin B was applied, air-dried for 20 min. and baked for 20 min. at 325°F. The total coating thickness was 7 mils.

Coating M_1. Two coats of a phenolic primer containing zinc chromate were applied to sand-blasted pipe sections by spraying, each coat being allowed to dry overnight. This priming operation was followed by the application of two coats of aluminum pigment in a phenolic resin vehicle with air-drying overnight between coats. The total thickness of coating was 4 mils.

Coating M_2. The same coating M_1 was applied to 12 in. by 2.5 in. by 0.25 in. cold rolled steel plates, which were degreased before the coating was applied. The thickness of this coating was 3 mils.

Coating N. This coating consisted of asbestos tape impregnated with a phenolic varnish. A double layer was applied spirally to sand-blasted pipe, the second layer overlapping the first. Adhesion of the tape to the pipe and of one layer to the other was obtained by a hot-melt application of a phenolic varnish containing zinc chromate. A final coat of aluminum paint was sprayed over the taped pipe. The total thickness of the coating was 32 mils.

The condition of the phenolic coatings after exposure for 13 years is indicated by symbols in table 77. The marked superiority of the baked resin over the air-dried varieties is evident. In all of the soils the baked coating remained continuous for the maximum period of exposure, and in only the highly alkaline soil 70 was there evidence of loss of adherence between the coating and the pipe.

TABLE 77. *Condition of baked and air-dried phenolic coatings after exposure for 13 years* [a]

Soil	Aeration	Baked resin, L	Air-dried aluminum paint applied to		Treated asbestos tape N
			Pipe, M_1	Plate, M_2	
53	Good	G ○ ◬	G ○ ◬	G ○ ◬	G ○ □
55	do	G ○ ◬	G ○ ◬	G ○ ◬	G ○ □
62	do	g ○ ▲	G ○ ◬	G ○ △	G ○ □
65	do	G ○ ◬	G ○ ◬	P ⊙ ▲	G ○ □
64	Fair	G ○ ◬	P ○ ▲	P ○ ▲	F ○ □
66	do	g ○ ▲	P ○ ▲	P ○ ▲	F ○ □
70	do	P ○ ◬	P ○ ▲	P ⊙ ◬	F ○ □
58	Poor	G ○ ◬	F ⊙ ▲	P ⊙ ▲	P ○ ■
60	do	G ○ ◬	F ⊙ ▲	F ⊙ ▲	P ○ □
61	do	G ○ ◬	G ○ ◬	G ○ ◬	G ○ □
51	Very poor	G ○ ◬	P ⊙ ▲	F ⊙ ▲	P ○ ■
56	do	G ○ ▲	P ⊙ ▲	P ⊙ ▲	P ○ ■
59	do	G ○ ◬	G ○ ◬	g ○ ▲	G ○ □
63	do	G ○ ◬	g ⊙ ▲	P ⊙ ▲	P ○ ■
67	do	G ○ ◬	P ● ▲	P ⊙ ▲	P ○ ⊡

[a] Characteristics do not apply to the coatings for which symbols are omitted.

Adhesion of coating to pipe: G, Good; g, good, except under an occasional blister; F, fair; P, poor.

Continuity of coating: ○, Continuous over the entire surface; ⊙, continuous except for ruptured blisters; ●, large areas of coating removed.

Extent of blisters on coating: △, None; ◬, minute blisters distributed generally over the surface; ▲, occasional small blisters.

Condition of fabric coating: □, Unaffected; ⊡, slightly hardened; ■, brittle, partly deteriorated.

In all of the soils, the specimens coated with the baked resin developed discolored areas which were distributed generally over the specimens. These areas were usually very small, but on a few specimens were as large as 0.25 in.^{2} In some cases the discolored areas contained small blisters in which the corrosion and pitting were confined.

The condition of the metal coated with the various phenolic coatings after the different periods of exposure is indicated in table 78. The superiority of the baked phenolic coating over the air-dried systems in preventing corrosion is pronounced. However, the pits which developed under the air-dried coatings showed little tendency to increase in depth with time, from about 4 to 13 years, even in a number of "highly corrosive" soils, as for example, soils 58, 60, 64, 66, and 70. This tendency for the rate of pitting to decrease with time is probably a result of the inhibiting action of zinc chromate.

b. Rubber and Rubberlike Coatings

The following rubber and rubberlike coatings were included in the field tests:

Coating D. This is an isomerized or cyclicized rubber coating prepared by treating rubber with chlorostannic acid, H_2SnCl_6. Five percent of the total solids was carbon black. The first coat was an application of a 23-percent solution and the fourth coat a 20-percent solution of the phenolic resin in a mixture of turpentine and mineral spirits. The final thickness of coating was 10 mils.

Coating G. A hard-rubber compound, containing sulfur and an accelerator, was molded to the pipe and cured to a bone-hard condition. The thickness was 90 mils.

Coating H. A highly-loaded hard-rubber stock, containing 30 percent of magnesium carbonate and 15 percent of "white substitute" was molded to the pipe to a thickness of 100 mils.

Coating P. Cloth tape, coated on the underside with highly plasticized polyvinyl chloride, was wrapped spirally under tension around the pipe. Two coats of a solution of polyvinyl chloride were then applied hot. The thickness of the coating was 33 mils.

Coating K. A paint consisting of highly chlorinated rubber, pigments and quartz flour or carborundum in a solvent with drying oils, was applied to pipe 1-in. in diameter to a thickness of 6 mils.

Coating T. An organic polysulfide rubber was applied by spraying to a thickness of 35 mils.

The condition of the rubber and rubberlike coatings after exposures of 10 to 14 years is shown in table 79. The condition of the steel under the coatings is shown in table 80. The protection afforded by these rubber and rubberlike coatings appeared to be more dependent on the thickness of the coating than on its composition. The rubber coatings which provided virtually complete protection to the steel (coating G, 90 mils; H, 100 mils) were considerably thicker than the coatings which did not provide adequate protection (coating K, 6 mils; D, 10 mils; T, 35 mils; and P, 33 mils). Figure 57A illustrates the characteristic pattern of corrosion that occurred under coating P. It would appear from the spiral pattern that corrosion was concentrated in overlaps in the spirally-wrapped layer of fabric.

Specimens coated with soft rubber were not specifically included in the field exposure tests. However, examination of the condition of the ends of the specimens covered by soft rubber caps to exclude moisture from the interior of the specimens provided some information on the behavior of soft rubber as a protective coating for steel in soils. In attaching the caps, a coating of thinned spar varnish was applied to the inner cylindrical surface of the caps. After the varnish had become tacky, the caps were slipped over the ends of the specimens and forced into position by impact on a hard surface. The wall thickness of the rubber caps was 0.25 in., more than twice as thick as the thickest coating. The excellent protection which was provided by the rubber caps is illustrated in figure 58, in which are shown sections of protected and unprotected specimens exposed nearly 11 years in eight soils.

TABLE 78. *Depth of pits in steel to which phenolic coatings were applied*

(Values are the averages of the maximum pits on two specimens, in mils)

U, Unaffected by corrosion.
R, pipe rusted.
M, metal attack; pipe roughened by corrosion.
P, definite pitting but no pits greater than 6 mils.
+, pipe punctured by corrosion. The wall thickness of the pipe (145 mils) is recorded as the maximum pit.

Soil			Exposure	Coating[a]				
No.	Type	Aeration		Baked resin, L	Air-dried aluminum paint applied to pipe, M_1	Air-dried aluminum paint applied to plates, M_2	Treated asbestos-tape, N	Uncoated steel pipe, S
			Years					
53	Cecil clay loam	Good	2.1	[b] 6	R	R	U	42
			4.0	R	R	M	R	98
			9.0	[c] U	[c] P	P	[c] R	74
			11.1	R	P	6	P	78
			12.7	U	12	10	P	68
55	Hagerstown loam	do	2.1	U	R	R	U	33
			4.0	[b] 9	P	M	R	50
			9.0	U	P	P	R	92
			11.1	U	P	P	P	84
			12.7	U	P	P	6	73
62	Susquehanna clay	do	2.1	U	R	M	R	40
			4.0	U	M	M	R	56
			9.0	U	M	6	R	68
			11.1	R	P	[b] 9	P	72
			12.7	[b] 25	R	[b] 19	6	79
65	Chino silt loam	do	2.1	U	R	R	R	50
			4.0	R	R	[c] 8	M	59
			9.0	M	P	17	7	65
			11.1	R	P	[b] 12	[b] 8	84
			12.7	M	[b] 6	20	18	98
64	Docas clay	Fair	2.1	U	U	M	R	80
			4.0	R	U	P	R	67
			9.0	R	P	13	6	80
			11.1	R	R	[b] 9	[b] 7	118
			12.7	R	U	[b] 10	8	122
66	Mohave fine gravelly loam	do	2.1	U	R	M	R	145+
			4.0	[b] 12	P	20	P	145+
			9.0	R	[b] 9	13	P	78
			11.1	M	P	13	P	145+
			12.7	[b] 15	P	16	13	145+
70	Merced silt loam	do	2.1	U	M	M	R	50
			4.0	R	R	[b] 10	P	118+
			9.0	M	P	14	[b] 8	122
			11.1	M	P	14	11	145+
			12.7	M	M	19	10	145+
58	Muck	Poor	2.1	U	R	[b] 9	U	29
			4.0	[b] b	[b] 9	[b] 14	P	46
			9.0	[b] 19	[b] 21	44	[c] 9	98
			11.1	U	[b] 13	31	29	110
			12.7	U	29	[c] 26	37	124
60	Rifle peat	do	2.1	U	[b] 14	M	R	15
			4.0	R	[b] 8	[b] 29	M	38
			9.0	R	14	22	[b] 8	58
			11.1	R	18	21	[b] 9	89
			12.7	U	24	31	15	118
61	Sharkey clay	do	2.1	U	U	R	U	40
			4.0	[b] 9	[b] 14	22	R	45
			9.0	R	M	18	P	48
			11.1	U	P	17	[b] 7	58
			12.7	U	P	20	[b] 7	64
51	Acadia clay	Very poor	2.1	U	R	6	[b] 8	52
			4.0	--------	--------	--------	--------	--------
			9.0	(e)	[d] 34	21	[d] 15	128+
			11.1	--------	--------	--------	--------	--------
			12.7	--------	--------	--------	--------	--------
56	Lake Charles clay	do	2.1	U	[b] 7	[b] 9	[b] 8	77
			4.0	R	P	[b] 30	P	104
			9.0	R	P	17	11	145+
			11.1	R	P	23	19	145+
			12.7	[b] 7	[b] 35	[c] 60	38	145+
59	Carlisle muck	do	2.1	U	R	6	U	12
			4.0	[b] 20	24	[b] 17	[b] 8	20
			9.0	U	P	M	M	101
			11.1	U	P	P	[b] 11	76
			12.7	U	U	R	[b] 16	72
63	Tidal marsh	do	2.1	U	R	M	R	24
			4.0	R	M	M	12	38
			9.0	P	P	7	16	80
			11.1	R	[b] 8	[b] 10	24	94
			12.7	R	[c] 10	[c] 30	[c] 32	126

See footnotes at end of table.

FIGURE 78. *Depth of pits in steel to which phenolic coatings were applied*—Continued

Soil			Exposure	Coating[a]				
No.	Type	Aeration		Baked resin, L	Air-dried aluminum paint applied to pipe, M_1	Air-dried aluminum paint applied to plates, M_2	Treated asbestos-tape, N	Uncoated steel pipe, S
			Years					
67	Cinders	Very poor	2.1	U	68	31	R	145+
			4.0	R	114	49	32	145+
			9.0	[b] 26	79	23	24	145+
			11.1	R	115	52	50	145+
			12.7	R	141+	72	54	145+

[a] See text for description of coatings. [b] Data for the individual specimens differed from the average by more than 50 percent. [c] Data for 1 specimen only. [d] Average of 8 specimens. [e] Condition of 8 specimens removed: 1 specimen perforated by corrosion, 3 specimens contained rust under blisters, 4 specimens unaffected.

TABLE 79. *Condition of rubber and rubber-like coatings after maximum periods of exposure* [a]

Average exposure		14.3 years				12.7 years	10.6 years	
Soil	Aeration	Isomerized rubber, D	Hard rubber, G	Loaded hard rubber, H	Chlorinated rubber paint, K	Polyvinyl chloride, P	Soft rubber caps	Organic polysulfide rubber, T
53	Good	P ○ △ ▼	--------	--------	F ○ ◬ ⛛	--------	G ○ □ ▽	--------
55	do	P ○ △ ▼	--------	--------	--------	--------	G ○ □ ▽	--------
62	do	P ○ △ ▼	--------	--------	--------	P ● [b] ▼	G ○ □ ▽	G ○ ⊡ ▽
65	do	P ○ ▲ ▼	P ○ □ ▽	G ○ □ ▽	--------	--------	G ○ □ ▽	--------
64	Fair	P ○ △ ▼	P ○ □ ▽	G ○ □ ▽	P ● ▲ ▼	--------	G ○ □ ▽	G ○ ⊡ ▽
66	do	P ○ ▲ ▼	P ○ □ ▽	G ○ □ ▽	--------	P ○ ▼	G ○ □ ▽	--------
70	do	--------	--------	--------	--------	--------	G ○ □ ▽	--------
58	Poor	P ○ △ ▼	--------	--------	--------	--------	G ○ □ ▽	G ○ ⊡ ▽
60	do	P ○ △ ▼	P ○ □ ▽	G ○ □ ▽	--------	--------	G ○ □ ▽	--------
61	do	P ○ △ ▼	--------	--------	--------	--------	G ○ □ ▽	G ○ ⊡ ▽
57 [c]	do	P ○ ◬ ▼	--------	--------	P ● ▲ ▼	--------	--------	--------
51	Very poor	P ○ △ ▼	--------	--------	--------	--------	G ○ □ ▽	--------
56	do	P ○ ▲ ▼	--------	--------	--------	--------	G ○ □ ▽	--------
59	do	P ○ △ ▼	P ○ □ ▽	G ○ □ ▽	--------	P ○ ▼	G ○ □ ▽	--------
63	do	P ○ ▲ ▼	--------	--------	--------	--------	G ○ □ ▽	--------
67	do	P ● △ ▼	P ○ ■ ⛛	G ○ □ ⛛	P ● ▲ ▼	P ○ ▼	G ○ □ ▽	--------

[a] Characteristics do not apply to the coatings for which symbols are omitted.

[b] Holes in coating, apparently due to rodents or some other form of animal life, distributed over the surface of the coating.

[c] Exposed 5.4 years.

Adhesion of coating to pipe: G, good; F, fair; P, poor.

Continuity of coating: ○, continuous over entire surface; ⊙, continuous except in a few small areas; ●, large areas of coating removed.

Extent of blisters on coating: △, None; ◬, coating blistered in one or a few places; ▲, coating blistered in many places.

Extent of cracks in coating: □, None; ⊡, coating generally cracked in many places, but cracks are not wide enough to expose bare metal; ■, coating cracked in one or more places, bare metal exposed.

Brittleness of coating: ▽, Unaffected; ⛛, slightly hardened and brittle; ▼, brittle hardened considerably, with other indications of deterioration (paints are flaky and peel easily).

TABLE 80. *Depth of pits in steel coated with rubber and rubberlike coatings* [a]

(Average of two specimens unless otherwise indicated. Figures are depths of maximum pits, in mils)
+, one or both specimens punctured by corrosion. Wall thickness =145 mils.
R, pipe rusted.
M, metal attack—pipe surface roughened by corrosion.
U, unaffected by corrosion.
E, uncoated ends of pipe corroded.

Soil			Average exposure	Isomerized rubber D	Hard rubber G	Loaded hard rubber H	Chlorinated rubber K	Uncoated steel	Average exposure	Polyvinyl chloride, fabric-reinforced P	Average exposure	Soft rubber caps	Organic polysulfide rubber T
No.	Type	Aeration											
			Years						*Years*		*Years*		
53	Cecil clay loam	Good	2.0	R	--------	--------	16	37	--------	--------	2.1	U	--------
			5.4	R	--------	--------	13	50	--------	--------	7.0	U	--------
			7.4	M	--------	--------	--------	54	--------	--------	9.0	U	--------
			9.3	[b] 6	--------	--------	M	59	--------	--------	10.6	U	--------
			14.3	6	--------	--------	M	84	--------	--------	--------	--------	--------
55	Hagerstown loam	do	2.0	R	--------	--------	--------	41	--------	--------	2.1	U	--------
			5.4	R	--------	--------	--------	57	--------	--------	7.0	U	--------
			7.4	M	--------	--------	--------	57	--------	--------	9.0	U	--------
			9.3	M	--------	--------	--------	59	--------	--------	10.6	U	--------
			14.3	10	--------	--------	--------	65	--------	--------	--------	--------	--------
62	Susquehanna clay	do	2.0	R	--------	--------	--------	68	2.1	[b] 12	2.1	U	R
			5.4	R	--------	--------	--------	66	4.0	15	7.0	U	R
			7.4	R	--------	--------	--------	71	9.0	20	9.0	U	R
			9.3	[b] 12	--------	--------	--------	[b] 87	11.2	27	10.6	U	R
			14.3	M	--------	--------	--------	101	12.7	40	--------	--------	--------

TABLE 80. *Depth of pits in steel coated with rubber and rubberlike coatings* [a]—Continued

Soil			Average exposure	Isomerized rubber D	Hard rubber G	Loaded hard rubber H	Chlorinated rubber K	Uncoated steel	Average exposure	Polyvinyl chloride, fabric-reinforced P	Average exposure	Soft rubber caps	Organic polysulfide rubber T
No.	Type	Aeration											
			Years						*Years*		*Years*		
65	Chino silt loam	do	2.0	M	U	U	--------	40	--------	--------	2.1	U	--------
			5.4	M	R	U	--------	74	--------	--------	7.0	U	--------
			7.4	[b]11	U	UE	--------	83	--------	--------	9.0	U	--------
			9.3	12	UE	U	--------	112	--------	--------	10.6	U	--------
			14.3	[b]26	R	R	--------	86	--------	--------	--------	--------	--------
64	Docas clay	Fair	2.0	63	R	U	M	130	--------	--------	2.1	U	R
			5.4	66	U	U	--------	154+	--------	--------	7.0	U	R
			7.4	[b]31	U	U	32	154+	--------	--------	9.0	U	R
			9.3	42	UE	M	124	154+	--------	--------	10.6	U	R
			14.3	109	UE	U	53	154+	--------	--------	--------	--------	--------
66	Mohave fine gravelly loam	do	2.0	M	U	U	--------	71	2.1	R	2.1	U	--------
			5.4	42	U	U	--------	154+	4.0	[b]8	7.0	U	--------
			7.4	24	U	U	--------	154+	9.0	[b]9	9.0	U	--------
			9.3	22	UE	UE	--------	154+	11.2	8	10.6	U	--------
			14.3	41	RE	M	--------	154+	12.7	P	--------	--------	--------
70	Merced silt loam	do	--------	--------	--------	--------	--------	50	--------	--------	2.1	U	--------
			--------	--------	--------	--------	--------	118+	--------	--------	7.0	U	--------
			--------	--------	--------	--------	--------	122	--------	--------	9.0	U	--------
			--------	--------	--------	--------	--------	145+	--------	--------	10.6	U	--------
			--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
58	Muck	Poor	2.0	M	--------	--------	--------	18	--------	--------	2.1	U	R
			5.4	M	--------	--------	--------	103	--------	--------	7.0	U	R
			7.4	63	--------	--------	--------	110	--------	--------	9.0	U	R
			9.3	52	--------	--------	--------	110	--------	--------	10.6	U	R
			14.3	46	--------	--------	--------	154+	--------	--------	--------	--------	--------
60	Rifle peat	do	2.0	45	U	U	--------	37	--------	--------	2.1	U	--------
			5.4	64	U	U	--------	24	--------	--------	7.0	U	--------
			7.4	[b]30	U	U	--------	17	--------	--------	9.0	U	--------
			9.3	[b]30	U	U	--------	[b]27	--------	--------	10.6	U	--------
			14.3	56	R	U	--------	82	--------	--------	--------	--------	--------
61	Sharkey clay	do	1.0	U	--------	--------	--------	10	--------	--------	2.1	U	R
			5.4	U	--------	--------	--------	[b]54	--------	--------	7.0	U	R
			7.4	R	--------	--------	--------	63	--------	--------	9.0	U	R
			9.3	R	--------	--------	--------	[b]96	--------	--------	10.6	U	R
			14.3	35	--------	--------	--------	88	--------	--------	--------	--------	--------
57	Merced clay adobe	do	2.0	M	U	U	M	34	--------	--------	--------	--------	--------
			5.4	[c]28	U	U	[c]24	[c]100	--------	--------	--------	--------	--------
51	Acadia clay	Very poor	2.0	20	--------	--------	--------	82	--------	--------	2.1	--------	--------
			5.4	80	--------	--------	--------	154+	--------	--------	7.0	[c]U	[b, c]64+
			7.4	[b]60	--------	--------	--------	135+	--------	--------	9.0	--------	--------
			9.3	--------	--------	--------	--------	--------	--------	--------	10.6	--------	--------
			14.3	[b][d]71+	--------	--------	--------	[d]146+	--------	--------	--------	--------	--------
56	Lake Charles clay	do	2.0	40	--------	--------	--------	20	--------	--------	2.1	U	--------
			5.4	33	--------	--------	--------	71	--------	--------	7.0	U	--------
			7.4	26	--------	--------	--------	125+	--------	--------	9.0	U	--------
			9.3	44	--------	--------	--------	154+	--------	--------	10.6	U	--------
			14.3	44	--------	--------	--------	135+	--------	--------	--------	--------	--------
59	Carlisle muck	do	2.0	--------	--------	--------	--------	--------	2.1	M	2.1	U	--------
			5.4	R	U	U	--------	20	4.0	[b]6	7.0	U	--------
			7.4	[b]8	U	U	--------	30	9.0	[b]11	9.0	U	--------
			9.3	[b]11	U	U	--------	[b]40	11.2	14	10.6	U	--------
			14.3	[d]6	[d]R	[d]U	--------	[d]34	12.7	18	--------	--------	--------
63	Tidal marsh	Very poor	2.0	M	--------	--------	--------	15	--------	--------	2.1	U	--------
			5.4	U	--------	--------	--------	36	--------	--------	7.0	U	--------
			7.4	[b]12	--------	--------	--------	70	--------	--------	9.0	U	--------
			9.3	M	--------	--------	--------	54	--------	--------	10.6	U	--------
			14.3	23E	--------	--------	--------	61	--------	--------	--------	--------	--------
67	Cinders	do	2.0	76	U	--------	21	154+	2.1	16	2.1	U	--------
			5.4	60	U	U	78	119+	4.0	48	7.0	U	--------
			7.4	[b]74+	U	U	M	127+	9.0	42	9.0	U	--------
			9.3	111+	U	U	145+	154+	11.2	44	10.6	U	--------
			14.3	122+	U	U	145+	154+	12.7	38	--------	--------	--------

[a] See text for description of coatings. [b] Individual specimens differed from the average by more than 50 percent. [c] Average of 8 specimens. [d] Average of 4 specimens.

The deterioration of natural rubber by microorganisms in some soils has been reported by Blake, Kitchin, and Pratt [198], but examination of the rubber coatings in the NBS tests after exposure revealed no evidence of microbiological deterioration. Rodents or other animal life caused some destruction of coatings in soil 62 as illustrated in figure 57B.

c. Miscellaneous

Manufacturer's descriptions of several miscellaneous coatings which were included in the field tests are given below:

Coating F. A semiplastic compound, consisting of 4½ parts of treated cashew nut oil, 3 parts of asbestos fiber, and 3½ parts of mineral turpentine substitute was applied cold with a brush until the thickness, after drying, was 60 mils.

FIGURE 57. *Condition of polyvinyl-chloride-treated fabric coating and the underlying steel pipe after exposure for approximately 13 years.*

A, Specimen exposed to soil 59. Note the concentration of pitting where the spirally-wrapped layer of fabric overlapped. B, Specimen exposed to soil 62. The holes in the coating were caused by rodents or other form of animal life.

Coating W. An experimental coating prepared as follows: The pipe was primed with a chinawood oil varnish containing zinc chromate and baked at 200°F for ½ hr. A top coat of dehydrated chinawood oil, containing powdered mica and a catalyst, was molded to the pipe and heated at 200°F for 3 hr. The thickness of coating was 170 mils.

Coating R. Two coats of a paint consisting of a mixture of blue basic lead sulfate in raw linseed oil, lampblack in raw linseed oil, and a chinawood oil phenolic resin varnish were applied to a total thickness of 6 mils.

Coating S. A plastic made with a pure vegetable gum base, containing nondrying oils and asbestos fiber was applied cold. The coating was then shielded with a spiral wrap of cotton fabric impregnated with this plastic. Thickness of coating was 4 mils, including shield 44 mils.

The condition of the coatings after 14-years exposure is shown in table 81. The condition of the pipe under the coatings is shown by letter symbols or by the depths of the deepest pits in table 82. Although all of the coatings suffered more or less general deterioration, the steel underlying the heavier coatings, F and W, was not appreciably affected by corrosion, even in the more corrosive soils. On the other hand, deterioration of the thinner coatings, R and S, was accompanied by deep pitting of the metal in several of the soils, and the depths of the pits showed a definite tendency to increase with time as on unprotected metal.

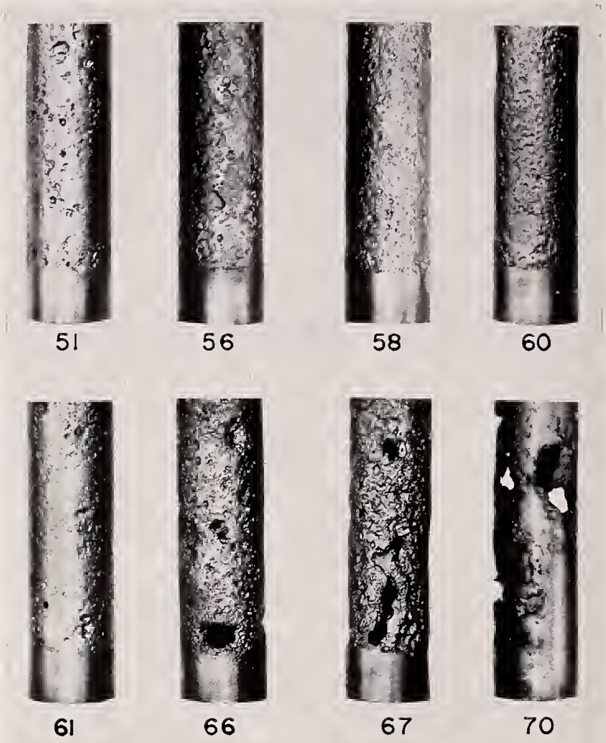

FIGURE 58. *Condition of steel protected by soft rubber caps and bare steel exposed to different soils for 11 years.*

The uncorroded end part of the specimens was covered with a rubber cap. [See table 6 for description and properties of soils.]

TABLE 81. *Condition of miscellaneous coatings after the maximum periods of exposure* [a]

Average exposure		14.3 years		10.6 years	
Soil	Aeration	Cashew-nut oil with asbestos fiber, F	China-wood oil-mica compound, W	Blue lead phenolic resin varnish, R	Vegetable-gum with asbestos fibers shielded with fabric, S
53	Good	F ⊙ ▲ ⊡	P ○ □	F ○ ▲ ⊡	P ○ ■
55	do	F ○ ▲ ⊡	P ● ⊡	P ○ ▲ ■	P ○ ■
62	do	F ○ ▲ ⊡	P ⊙ ⊡	P ○ ▲ ■	P ⊙ ■
65	do	P ○ ▲ ■	P ● ⊡	P ○ ◬ ■	P ⊙ ■
64	Fair	P ⊙ ▲ ■	P ● ■	F ⊙ ▲ ⊡	F ⊙ ■
66	do	P ⊙ ▲ ■	P ● ■	F ⊙ ◬ ⊡	P ○ ■
70	do			P ● ▲ ■	P ● ■
58	Poor	F ○ ▲ ■	P ● ■	P ⊙ ▲ ■	P ⊙ ■
60	do	P ○ ▲ ■	P ● ⊡	P ● ▲ ■	P ● ■
61	do	P ○ ▲ ■	P ● ⊡	F ○ ◬ ■	F ⊙ ■
51	Very poor	P ⊙ ▲ ■	P ● ■		
56	do	F ○ ▲ ■	P ● ■	F ⊙ ▲ ■	P ● ■
59	do	F ⊙ ▲ ⊡	P ● ⊡	F ⊙ ▲ ⊡	P ⊙ ■
63	do	P ○ ▲ ⊡	P ● ■	P ● ◬ ■	P ○ ■
67	do	P ● ▲ ■	P ⊙ ■	F ⊙ ◬ ■	P ● ■

[a] Characteristics do not apply to the coating for which symbols are omitted.

Adhesion of coating to pipe: G, good; F, fair; P, poor.

Continuity of coating: ○, Continuous over the entire surface; ⊙, continuous except for ruptured blisters; ●, large areas of coating removed.

Extent of blisters on coating: △, None; ◬, minute blisters distributed generally over the surface; ▲, occasional small blisters.

Condition of fabric coating: □, Unaffected; ⊡, slightly hardened; ■, brittle, partly deteriorated.

TABLE 82. *Depth of pits in steel to which miscellaneous organic coatings were applied* [a]

(Figures are the average depth of the deepest pits on two specimens, in mils)

+, One or both specimens punctured by corrosion;
U, unaffected by corrosion;
R, pipe rusted;
M, metal attack—pipe surface roughened by corrosion.

Soil No.	Soil Type	Soil Aeration	Exposure	Cashew nut oil with asbestos fibers, F	China-wood oil-mica compound, W	Uncoated steel	Exposure	Blue lead-phenolic resin varnish, R	Vegetable gum plastic with asbestos fiber—shielded with fabric, S
			Years				*Years*		
53	Cecil clay loam	Good	2.0	R	U	37	2.1	M	<6
			5.4	R	R	50	7.0	10	12
			7.4	R	[b]10	54	9.0	<6	24
			9.3	M	M	59	10.6	<6	27
			14.3	R	R	84	-------	-------	-------
55	Hagerstown loam	do	2.0	R	R	41	2.1	M	<6
			5.4	R	M	57	7.0	10	14
			7.4	R	R	57	9.0	[b]8	34
			9.3	R	M	59	10.6	<6	29
			14.3	R	[b]6	65	-------	-------	-------
62	Susquehanna clay	do	2.0	R	R	68	2.1	M	10
			5.4	R	R	66	7.0	[b]7	25
			7.4	R	M	71	9.0	<6	36
			9.3	[b]15	M	[b] 87	10.6	<6	27
			14.3	[b]6	M	101	-------	-------	-------
65	Chino silt loam	do	2.0	R	U	40	2.1	M	P
			5.4	R	R	74	7.0	7	48
			7.4	[b]6	R	83	9.0	8	33
			9.3	<6	M	112	10.6	<6	47
			14.3	[b]7	R	86	-------	-------	-------
64	Docas clay	Fair	2.0	R	U	130	2.1	M	[b]12
			5.4	M	R	154+	7.0	<6	25
			7.4	[b]11	M	154+	9.0	14	37
			9.3	M	M	154+	10.6	17	29
			14.3	22	M	154+	-------	-------	-------
66	Mohave fine gravelly loam	do	2.0	R	R	71	2.1	[b]29	10
			5.4	M	R	154+	7.0	32	19
			7.4	<6	R	154+	9.0	24	29
			9.3	[b]18	M	154+	10.6	16	25
			14.3	14	R	154+	-------	-------	-------
70	Merced silt loam	do	-------	-------	-------	50	2.1	14	8
			-------	-------	-------	118+	7.0	20	[b]25
			-------	-------	-------	122	9.0	74	36
			-------	-------	-------	145+	10.6	132+	63
58	Muck	Poor	2.0	R	R	18	2.1	M	<6
			5.4	R	R	103	7.0	[b]48	18
			7.4	53	[b]30	110	9.0	22	31
			9.3	[b]32	M	110	10.6	15	38
			14.3	[b]14	M	154+	-------	-------	-------
60	Rifle peat	do	2.0	R	U	37	2.1	R	M
			5.4	R	M	24	7.0	[b]26	19
			7.4	M	R	17	9.0	47	43
			9.3	[b]16	M	[b]27	10.6	66	72
			14.3	24	R	82	-------	-------	-------
61	Sharkey clay	do	1.0	R	U	10	2.1	M	M
			5.4	U	R	[b]54	7.0	44	15
			7.4	R	R	63	9.0	18	21
			9.3	R	M	[b]96	10.6	<6	28
			14.3	27	<6	88	-------	-------	-------
57	Merced clay adobe	do	2.0	R	U	34	-------	-------	-------
			5.4	[c]M	[c]R	[c]100	-------	-------	-------
51	Acadia clay	Very poor	2.0	R	R	82	2.1	-------	-------
			5.4	M	R	154+	7.0	[b] [e]20	110+
			7.4	R	M	135+	9.0	-------	-------
			9.3	-------	-------	-------	10.6	-------	-------
			14.3	[b] [d]40	[b] [d]8	[d]146+	-------	-------	-------
56	Lake Charles clay	do	2.0	R	R	20	2.1	[b]7	22
			5.4	M	R	71	7.0	11	37
			7.4	M	M	125+	9.0	18	28
			9.3	M	M	154+	10.6	16	32
			14.3	25	R	135+	-------	-------	-------
59	Carlisle muck	do	2.0	-------	-------	-------	2.1	M	M
			5.4	U	R	20	7.0	<6	[b]23
			7.4	U	R	30	9.0	<6	30
			9.3	M	M	[b]40	10.6	<6	51
			14.3	[d]U	[d]R	[d]34	-------	-------	-------

See footnotes at end of table.

TABLE 82. *Depth of pits in steel to which miscellaneous organic coatings were applied* [a]—Continued

Soil									
No.	Type	Aeration	Exposure	Cashew nut oil with asbestos fibers, F	China-wood oil-mica compound, W	Uncoated steel	Exposure	Blue lead-phenolic resin varnish, R	Vegetable gum plastic with asbestos fiber—shielded with fabric, S
			Years				*Years*		
63	Tidal marsh	Very poor	2.0	M	M	15	2.1	M	28
			5.4	M	M	36	7.0	36	44
			7.4	[b]36	M	70	9.0	38	41
			9.3	<6	--------	54	10.6	61	52
			14.3	15	10	61	--------	--------	--------
67	Cinders	do	2.0	R	[b]21	154+	2.1	[b]15	28
			5.4	[b]41	U	119+	7.0	28	51
			7.4	[b]12	R	127+	9.0	39	49
			9.3	[b]10	M	154+	10.6	54	95
			14.3	33	[b]9	154+	--------	--------	--------

[a] See text for description of coatings.
[b] Individual specimens differed from the average by more than 50 percent.
[c] Average of 8 specimens.
[d] Average of 4 specimens.
[e] Average of 10 specimens.

17.2. Porcelain Enamel

The terms porcelain or vitreous enamel refer to a thin glass-like layer fused into the surface of the metal. Vitreous enamels are made by melting together such materials as feldspar, borax, quartz, soda ash, fluorides, color oxides, and opacifiers to produce a molten glass. The molten glass is then poured into a stream of water which shatters the glass into fragments to which the term frit is applied. The frit is ground in a ball mill, suspended in a slurry and applied to the metal. The coated ware is then heated in a furnace to produce a continuous layer of glass. The composition of porcelain enamels is varied over a wide range depending on the specific environmental condition to which the ware is to be subjected.

The preparation of the specimens for the field tests, according to the manufacturer, was as follows: The ground coats were frits containing the usual cobalt-nickel combinations for adherence to steel. Over these a coating of acid-resisting sheet iron enamel was applied. The sheet iron enamel was of the high-silica, low-alumina, low-titanium type, without antimony or other opacifying agents. Tests for continuity of the coating before exposure, by means of a high frequency spark tester, revealed occasional pinholes and other slight defects in the coating on some of the specimens.

After removal from the test sites and thorough cleaning, the surfaces of specimens were carefully examined for loss of gloss or etching and for the development of rust. All specimens, even those exposed for 14 years, maintained their original gloss, indicating that the various soils had no deteriorating action on the coating. However, one or more small ruptures in the coating were observed on a number of the specimens with accompanying highly localized rusting.

The condition of the pipe specimens coated with vitreous enamel after five periods of exposure is indicated in table 83. The frequency of pitting and the depth of pits in the pipe are apparently not related to the corrosivity of the soil as measured by the maximum pits on specimens of uncoated steel. Hence, the occurrence of pitting would seem to be determined by the original condition of the coating on the individual specimens, that is, to the presence of defects, such as imperfect bonding of the coating to the pipe.

17.3. Concrete

Concrete and cement-mortar coatings have been used by certain pipeline companies when corrosion is very severe. The earlier cement coatings were applied after the pipes were in the trenches, by placing boards 1 to 2 in. from the pipe and filling with mortar. One company developed a metal form which is put around the pipe, filled with cement mortar and removed after the mortar has set [199]. This method makes it possible to use a relatively thin coating, thus reducing the cost. Concrete applied to pipe by means of steel forms was tested at site 205 of the NBS–API coating tests (see page 138). When steel thus coated was examined after 10 years, it was found that the maximum pit depth in the steel was 42 mils and the average pit depth was 5 mils. The maximum pit depth on bare pipe was 50 mils and the average 38 mils.

TABLE 83. *Condition of steel coated with vitreous enamel*

(Figures are the depths of the deepest pits, in mils)

U, unaffected by corrosion;
R, metal rusted;
M, metal attack—pipe surface roughened by corrosion.

Soil		Exposure	Condition of steel under the coating		Maximum pit depths of uncoated steel (Average of 2 specimens)
No.	Aeration		Specimen 1	Specimen 2	
		Years			*Mils*
53	Good	2.0	U	U	37
		5.4	U	U	50
		7.4	U	U	54
		9.3	U	U	59
		14.3	U		84
55	do	2.0	U	U	41
		5.4	U	U	57
		7.4	M	R	57
		9.3	R	U	59
		14.3	U	15	65
62	do	2.0	U	U	62
		5.4	U	U	66
		7.4	R	U	71
		9.3	U	U	87
		14.3	U	U	101
65	do	2.0	U	U	40
		5.4			74
		7.4	U	M	83
		9.3	U	U	112
		14.3	U	U	86
64	Fair	2.0	U	U	130
		5.4	U	U	154+
		7.4	U	U	154+
		9.3	R	U	154+
		14.3	U	100	154+
66	do	2.0	U	U	66
		5.4	31	U	154+
		7.4	U	U	154+
		9.3	U	U	154+
		14.3	U	U	154+
58	Poor	2.0			18
		5.4	13	U	102
		7.4	41	52	110
		9.3	54	R	110
		14.3	U	U	154+
60	do	2.0	U	U	37
		5.4	U	U	24
		7.4	U	U	17
		9.3	U	U	27
		14.3	38	35	82
61	do	1.0	U	U	10
		5.4	U	U	54
		7.4	U	U	63
		9.3	U	U	96
		14.3	U	U	88
57	do	2.0	U	U	33
		[a] 5.4	19	U	
			U	U	
			U	U	100
			U	8	
51	Very poor	2.0	28	U	82
		5.4	U	U	154+
		7.4	55	U	135+
		[b] 14.3	U	U	146+
			U	U	
56	do	2.0	U	U	20
		5.4	U	U	70
		7.4	U	U	125+
		9.3	U	M	154+
		14.3	U	U	135+
59	do	5.4	U	U	20
		7.4	U	U	30
		9.3	U	U	40
		[b] 14.3	U	U	34
			U	U	
63	do	2.0	U	U	15
		5.4	U	U	36
		7.4	U	U	70
		9.3	U	U	54
		14.3	U	U	61
67	do	2.0	U	U	154+
		5.4	U	U	119+
		7.4	U	U	127+
		9.3	U	43	154+
		14.3	U	30	154+

[a] Eight specimens removed at this period.

[b] Four specimens removed at this period.

18. Bituminous Coatings

18.1. General

Although the available data on bituminous coatings are the product of tests of such types of coating as were commercially available in the early 1930's, the present general use of these coatings in pipelines makes it imperative that a rather extensive analysis be made of this test data to determine such general rules of procedure as may be adapted to the present day problems.

In 1943, Kelly [200] conducted a survey of the major pipeline operators to determine the extent of the applicability of coatings in pipelines, the results of which showed that approximately half of the steel pipe in underground service was protected by some form of coating, 80 percent of which was a coal-tar base coating. An A.P.I. statistical survey [201] on 63,500 miles of pipelines revealed that much more emphasis was given to the use of coated pipe during the years between 1940 and 1950 than in the preceding 10-year period, and that from 1950 to 1955 about 95 percent of the pipelines (4 through 26 in. diameter), carrying crude oil and refined products, were coated with a bituminous coating. Except for the asphalt or coal-tar dip coatings that are applied to nearly all cast-iron water mains, currently, the most commonly used coating is a coal-tar enamel made by adding finely divided inert material to coal-tar pitch.

Bituminous coatings can be divided into two general groups, asphalt base and coal-tar base, both having certain favorable and unfavorable characteristics. Within each group, the materials vary so greatly that it cannot be said that one base material is superior to the other. In general, the asphalt-base materials are less susceptible to shock and changes in temperature, but they tend to be more permeable to moisture than the coal-tar-base materials. The so-called plasticised coal-tar enamels are more nearly comparable to the asphalts in their response to changes in temperature, but the range of temperatures within which they can be successfully used is smaller than that of the asphalt enamels.

The principal causes of failures in bituminous coatings result from faulty application, pinholes, mechanical injuries during installation and backfilling operations, settling of the backfill after burial of the pipe, decay, penetration by roots, flowing or cracking of the bitumen due to temperature changes, and distortion from soil stress. The latter effect is caused by the adherence of the soil to the coating material and to expansion or contraction with changes in moisture content [202].

18.2. Requirements of Bituminous Coatings

The fundamental requirements of a satisfactory bituminous coating are permanence, continuity and resistance to water absorption (as indicated by low-electrical conductance [12]). Permanence is a function of the type of bitumen and will vary with the method of application. Continuity depends mostly on the care with which the coating is applied to the pipe, but ultimately will be effected by the resistance of the coating to cracking and cold flow under pressure. Water absorption is a function of the character of the bitumen; all bituminous materials tend to absorb more or less water. Thin coatings and those containing imperfections due to faulty application have a tendency to be less resistant to water absorption. Those bitumens which absorb small amounts of water generally retain their original strength; whereas, those bitumens which absorb appreciable quantities of water may become spongy, or may crack or wrinkle, causing the material to lose its protective qualities.

Another important characteristic of bituminous materials is the hardness or softening point that should be as high as is consistent with freedom from cracking and satisfactory application. Many bituminous coatings have high coefficients of expansion and should be protected against extreme temperature cycles. Conductance is an important function of the coated pipe as an indication of its insulating properties; a coated pipe having as low a conductance, or as high a resistance, as possible would be expected to be free from pinholes. Measurement of electrical resistance after exposure in wet environments is an indication of the coating conductance.

Adhesion of the coating to the pipe is of importance as water spreading beneath the coating will cause the pipe to corrode and as a result the corrosion products may lift the coating and expose still more pipe to produce a progressive corrosive action. Further, such conditions cause concentration cells which tend to accelerate pitting over that of uncoated pipe.

Experience has shown that the best way to secure continuity and long life for a bituminous coating is to use multiple applications. This is comparable to paint coatings in which multiple-coat systems have been found to be consistently better than single-coat systems. If a reinforcement is used to obtain thickness, it should be of inorganic material because organic fabrics exposed to moisture usually rot. A stiff permanent wrapper of this type, such as asbestos-felt, will distribute the pressure on the coating and reduce distortion. A light bitumen-saturated asbestos-felt wrapper, such as used in the past, is not sufficiently rigid to prevent distortion of soft bituminous coatings and may be penetrated by grass roots, examples of which are shown in figure 59. These illustrations indicate that sufficient moisture to sustain plant growth had been absorbed by the bitumen-saturated wrappers. Figure 60 shows a cotton-fabric-reinforced-asphalt coating that cracked badly, and a coal-tar-pitch coating that flowed from the top of the pipe and resulted in localized corrosion that was much more severe than on nearby uncoated pipe.

Figure 59. *Coatings injured by roots.*

A, Root beneath a tar-felt-reinforced asphalt coating; B, grass roots in and beneath a 10-year-old asbestos-felt shielded coal-tar enamel coating on a pipeline.

In the installation of bituminous coated pipelines the bottom of the trench should be free from stones and foreign material and such material should not be allowed to come in contact with the coating

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[12] Information concerning water absorption may be obtained by measurement of the electrical conductance or resistance of pipe coatings over a period of time. The general form of the conductance-time curve is characteristic of the coatings, which gradually and continuously absorb moisture, until they become saturated and show no further increase in conductance.

FIGURE 60. *Examples of failure of pipe coatings in a tidal marsh soil.*

A, Cotton-fabric-reinforced asphalt coating—note cracks; B, a coal-tar coated pipe from which the coating flowed because it was too soft.

when the trench is backfilled. Precautions should also be taken to prevent injury to the coating by skids, chains, or other tools used in laying the pipe, as such injuries are among the most common causes of pipe coating failures.

Since the completion of the tests reported herein the American Water Works Association, American Society for Testing Materials, and the Asphalt Institute have revised their specifications for asphalt and coal-tar enamels for use under different conditions [203, 204, 205, 206]. The specifications include such properties as the softening point, percentage and fineness of filler, specific gravity, penetration, electrical resistance, tests for cracking at low temperature, flow resistance at high temperature and impact tests. The authoritative treatise by Abraham [207] contains a full discussion of the properties of bituminous materials.

18.3. Inspection of Pipeline Coatings

a. Appearance

The results of the extensive NBS field tests on bituminous coatings started in 1922, showed that some adequate and uniform specification to determine inspection procedures was needed for describing the coatings and recording data relative to the performance of the specimens. The coating manufacturers cooperated with the Bureau in the program which led to the formulation of an extensive code for the visual inspection of coatings. This Tentative Code for the Visual Inspection of Protective Coatings on Buried Pipe, is too voluminous for presentation in this circular. However, it has been published by Ewing as an appendix to his book [71]. This code was intended to yield detailed information as free as possible from any bias of the inspector and it has been followed in the inspections of the National Bureau of Standards field tests.

b. Pattern and Conductance Tests

Ewing [71, 208], Scott [209], and Shepard [210] developed tests for measurement of continuity and resistance of pipeline coatings known as the pattern and conductance tests, which have been proven to be useful for aiding in the inspection of coatings exposed to soils. A detailed description of these tests is given in appendix 6. Recently, a specification has been developed for standardization of procedures for measuring pipe coating conductance by the Unit Committee T–2D of the National Association of Corrosion Engineers [211].

c. Pinhole and Flaw Detectors

The pattern and conductance tests are applicable only to small areas of coatings after they have been exposed to soil or water long enough to permit the moisture to penetrate the pores or defects in the coating. There are other electrical methods for locating defects (holidays) in coatings which can be used on large areas of bituminous coatings. One of these is a high-voltage or spark test intended primarily for the detection of pinholes.

The usual apparatus, figure 61, consists of a high-voltage transformer, or induction coil such as a spark coil, a battery, a current interrupter, and an insulated metal brush. One side of the battery and interrupter are connected across the primary of the coil. As the brush is passed over the surface of the coating a spark which is both audible and visible will jump to the pipe when the brush is over a pinhole or break in the coating (holiday), thus locating the flaws in the coating. This apparatus is described in detail by Clarvoe [212] and Harrell [213]. This type of flaw detector has several faults, but despite

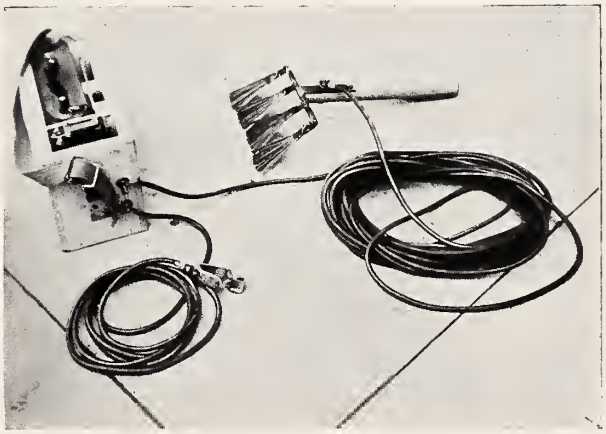

FIGURE 61. *Apparatus for locating pinholes in bituminous coatings.*

It consists of a spark coil, batteries, and a metal brush with an insulated handle.

these faults it has been used extensively and successfully as a continuity test in the development of better coatings. Stearns [212, 215, 216] developed an improved detector that operates in such a manner as to greatly reduce errors in flaw detection. The apparatus eliminates much of the human element by use of a counter, colored lights, and ringing of a bell whenever a flaw is detected. The voltage of the apparatus can be controlled to regulate the intensity of the spark, and after a spark has passed, the high voltage is cut off for a second. This regulation prevents further damage to the coating which can occur if the high voltage is applied too long at one spot.

This type of holiday detector is used on newly coated pipe prior to backfilling the trench. Other detectors have been developed, such as the Pearson apparatus [217], which afford a means of inspecting a coated pipeline for pinholes and other flaws any time after the pipe is laid, without uncovering the pipeline. Subsequent inspections by the same method will determine the progress of the coating deterioration. The Pearson detector [217] consists essentially of a 1,000-cps battery-driven hummer which is connected between the coated pipe and a rod driven into the ground 100 ft away. Because most of the current that passes from the pipe to the ground rod must flow through defects in the coating, an increase in IR drop in the soil adjacent to the defects occurs. The disturbed earth potential is located by two men 20 ft apart, one of whom carries an amplifier and indicating meter, the other man providing the ground connection. Each man has steel cleats on his shoes, connected in the first case to the amplifier shielding and in the second case to the amplifier input by means of a shielded cable. They walk along the pipeline as nearly over its center as possible. When either man passes over a defect in the coating there is an increase in the deflection of the indicating meter and in the sound in the earphones in parallel with the meter. In addition to giving details concerning the design and use of the apparatus, Pearson [217] also describes a method for measuring the resistance of a coating on a pipeline without uncovering the line.

18.4. Accelerated Laboratory Tests

The object of the laboratory tests developed at the Bureau was to secure information on the resistance of bituminous coatings to soil stress, moisture absorption, impact, and low temperature. The information obtained from these tests permits the evaluation of newly developed coatings and of available commercial coatings by comparison of the different coatings under similar conditions. The accelerated laboratory tests developed and used at the Bureau are: (1) the outdoor soil box; (2) moisture absorption and conductance tests; (3) impact test; (4) low-temperature tests; and (5) tests of coating wrappers (reinforcements and shields).

a. Outdoor Soil Box

The NBS soil box developed by Ewing [71] affords a method of comparing the ability of different coatings to withstand soil stress under conditions which simulate the stress developed in soils. The specimens under investigation were first subjected to the pattern and conductance tests and then buried in the box so that there was about 6 in. of dry soil above the specimens. The outdoor soil box, shown in figure 62, provides a means for rapid evaporation and thereby induces rapid shrinking of the soil with changes in its moisture content. The box, about 1 ft deep, is constructed of porous bricks and is built above the ground to provide maximum surface for evaporation. Tests of permeability to water showed that the bricks were more uniform and more permeable than the most porous concrete available.

Since the available soil did not have a sufficient volume shrinkage between saturation and complete dryness, it was modified by the addition of about 1 percent by weight of sodium carbonate (washing soda) which increased the shrinkage from 28 percent to about 53 percent. By alternately wetting and drying the soil, the coated pipe specimens were subjected to a number of cycles of stress and then examined. Soft coatings were found to be distorted (fig. 63), but not so much as some specimens observed in field tests, because in the soil box the soil in shrinking tended to pull away from the sides of the box instead of from the coating.

Since 1950, laboratory tests on protective coatings and wrappings (reinforcements and shields) have been conducted by the Bureau of Reclamation of the Department of Interior [218, 219]. Coated pipe specimens have been subjected to as many as 25 cycles of disruptive wetting and drying actions of clay soils in a modification of the NBS soil box.

Figure 62. *Outdoor soil box.*

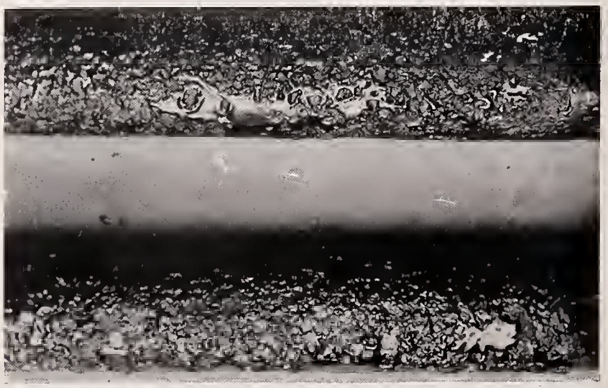

Figure 63. *Appearance of an originally smooth coal-tar enamel coating after exposure in the soil box for 1 year.*

Coatings in these tests consist of coal-tar and asphalt enamels with and without various types of shield and reinforcement wrappings, including asbestos felt, glass mat, and plastic tapes.

b. Moisture Absorption and Conductance Tests

The NBS moisture absorption test [220] consists of following the change of electrical conductance of coated pipe on exposure to a salt solution in tap water (resistivity of 500 ohm-cm). For most accurate results the test should extend over a period of 6 months during which periodic conductance measurements are made. The shape of the conductance-time curve is of as much importance as the initial and final measurements. These curves show a gradual increase in conductance with increased moisture absorption by the coating until saturation is reached, which is indicated by no further increase in conductance.

c. Impact Test

Whenever a coated pipe is laid, precautions should be taken to insure that the coating is not injured, or if injured, that the coating is properly patched before the line is covered. The more vulnerable the coating, the greater the necessary precautions, trouble, and added expense. Since any coating can be ruptured with a sufficient impact, and since the construction engineer would prefer to take no precautions whatever in handling the pipe, it is evident that it would be difficult to set up a minimum impact or abrasion requirement which would be universally applicable. However, other things being equal, the coating with the greater impact resistance would be the preferable coating.

With this view in mind, the NBS impact test developed by Ewing [220], used a trial and error method to evaluate impact failure on a coated pipe, by dropping a steel ball weighing 1.65 lb from various heights. With heavier coatings failure was usually apparent from visual inspection. With thin coatings, such as paint coatings, failure was determined by an electrical test.

A similar test developed by the Bureau of Reclamation [218, 219] consisted of an indentation test which is designed to measure relative resistance to puncture by rocks in backfill operations. In this test, a constant load of 6.48 lb is applied to the flat end of a ¼-in. steel rod which is imposed on the coating at 73.5°F and maintained until movement of the rod ceases. The extent of indentation is then measured and tested to determine whether or not damaging perforation of the coating has occurred. The total applied load is equivalent to the weight of a rock approximately 5 in. in diameter.

d. Low-Temperature Test

A low-temperature test consists of placing coated pipe specimens in a mechanical refrigerator for study of their resistance to cracking or spalling at low temperature. A test temperature is selected that is below the minimum to which the coated pipe is likely to be exposed. The reaction of the coating is a function of both the cooling cycle and the minimum temperature.

e. Tests of Coating Reinforcements and Shields

To reduce distortion of bituminous coatings by clod pressure, pipe movement, and soil stress, the bitumen used in the NBS tests was reinforced by a spiral wrapping of fabric, which may be an open-mesh woven cotton fabric, burlap or bitumen-saturated rag, or asbestos felt. This wrapping may be covered with bitumen, in which case it is called a reinforcement, or it may be left exposed directly to the soil, in which case it is called a shield.

To determine the effect of soil, or of soil bacteria, on these materials, Scott and Ewing [221] exposed 26 varieties of these materials to a dark brown clay loam soil containing considerable organic matter. Strips of the material were placed vertically in boxes which were filled with the water-saturated soil. Water was added at intervals of 1 month so that the soil was always moist in the bottom half of the box. The materials were exposed directly to the soil. Some of these were not impregnated with bitumen or treated to resist rot. In service, they might be saturated and covered by a fairly thick layer of bitumen. Table 84 shows the character of the materials tested and their strengths, in terms of the original strength, after exposure for 301 days. The results show that the uncoated and untreated fabrics had lost practically all of their strength, and that saturation of the cotton fabrics with asphalt or coal tar had a slight effect in delaying deterioration.

TABLE 84. *Effect of soil exposure on strength of pipeline fabric materials*

No.	Description of material	Weight	Thickness	Ratio of strength of bottom half of specimens after exposure of 301 days to original strength [1]
		$lb/100\ ft^2$	*Mils*	
1	14-lb asbestos felt, asphalt-saturated	13.9	26.7	0.88
2	15-lb asbestos felt, asphalt-saturated	17.0	28.1	.87
3	15-lb asbestos felt, tar-saturated	14.6	29.5	.49
4	14-lb asbestos felt, tar-saturated	13.7	27.4	.745
5	Same as 1 with bakelite resin saturant	12.4	25.9	.48
6	15-lb asbestos felt, tar-saturated	15.1	28.7	.93
7	15-lb asbestos felt, grease-saturated	15.8	28.6	.445
8	15-lb rag felt, asphalt-saturated	17.3	41.6	.21
9	30-lb rag felt, asphalt-saturated	32.3	69.8	.22
10	30-lb coated rag felt, asphalt-saturated	30.2	55.2	.25
11	40-lb coated rag felt, asphalt-saturated	47.4	96.8	.26
12	15-lb rag felt, tar-saturated	15.5	40.4	.00
13	30-lb rag felt, tar-saturated	26.8	65.2	.07
14	Polymerized resin shield	5.5	10.5	.12
15	Polymerized resin shield, paper-backed	9.3	19.7	.105
16	Cotton fabric with rot inhibitor, grease-saturated	8.7	21.0	.11
17	Cotton fabric without rot inhibitor, grease-saturated	8.0	18.5	.00
18	Woven asbestos fabric, open weave, tar-saturated	21.5	73.0	1.37
19	Cotton fabric, asphalt-saturated	8.05	32.7	.00
20	Cotton fabric, tar-saturated	8.25	33.7	.00
21	Coir fiber, close weave	22.0	97.7	.00
22	Burlap	7.8	26.0	.00
23	Manila fiber	------	------	.00
24	Manila fiber, creosote-treated	25.4	111.1	.16
25	Hemp	46.5	188.1	.00
26	Sisal	48.6	214.7	.00

[1] Based on average strength after soaking.

After the removal of coated specimens which were exposed to 15 different soils for 9 months, Ewing [222] desaturated the fabrics and determined their strength, concluding that: (1) asbestos felts were practically unaffected under all soil conditions even though on several coatings the fabric was exposed to the direct action of the soil; (2) the coal tar saturated fabrics were practically unaffected under all soil conditions; (3) the rag felts and cotton fabrics deteriorated by rotting when they were near the surface of asphalt coatings exposed in organic soils, particularly in muck soils; and (4) rotting of the organic fabrics decreased with an increase in thickness of the asphalt coating over the fabric.

18.5. Field Tests on Bituminous Coatings

a. NBS Coating Tests

The National Bureau of Standards first investigated pipe coatings as a means of preventing electrolysis about 1912 [5] and included several types of bituminous coatings in its field tests between 1922 and 1928. The results indicated that these coatings were unsatisfactory as a means of preventing electrolysis. When they failed, as most of those tested did within a short time, the current discharge was concentrated in the small exposed anodic areas and corrosion was consequently accelerated at these points. In the early field tests [116] only one bituminous coating, a cotton fabric impregnated with coal-tar pitch, appeared to be reasonably satisfactory, and the later development of better coatings makes superfluous any detailed report on these tests. The results of the Bureau's soil-corrosion investigation and the corrosion losses suffered in pipeline operations led the American Gas Association (AGA) and the American Petroleum Institute (API) to cooperate with the National Bureau of Standards in extensive field tests of pipe coatings. Coatings applied to sections of pipe or pipelines located in selected soils were examined from time to time to determine whether they were effective in protecting the pipe from corrosion. Four criteria of the performance of the coating were used: (1) Appearance of the coating with respect to adhesion, cracking, distortion, and other physical changes; (2) the pattern test; (3) the conductance or resistance of the coating; and (4) the extent of the corrosion of the metal underlying the coating.

b. NBS-AGA Field Tests

The National Bureau of Standards with the cooperation of the American Gas Association and independent coating manufacturers undertook field tests of coatings applied to short lengths of pipe. Forty-two proprietary bituminous coatings were applied by the manufacturers of the coatings to 20-ft lengths of sandblasted 2-in. steel pipe. The pipe was then cut into 2-ft. lengths, and the ends were closed by tin cans filled with the bitumen coating. The cans served to keep water out of the pipe, protect the cut ends of the coatings, and support the specimen during shipment. Four specimens of each coating were buried in each of 15 soils (table 8). Three inspections were made, the last one in 1934 after the coatings had been exposed for about 5.5 years.

Ewing [223] (fig. 64) summarized the results of the final inspection of these coatings. As a result of the tests, it was concluded (1) that none of the coatings prevented corrosion entirely at all test sites, (2) that coal-tar base materials were more stable and waterproof than asphalt-base materials, (3) that machine-applied coatings were superior to hand-applied coatings and particularly to hand-applications in the field, and (4) that any organic reinforcement in a coating is a weakness, especially if the coating is asphalt.

c. NBS-API Tests

Sites and Coatings. The tests conducted by the National Bureau of Standards with the cooperation of the American Gas Association were primarily demonstrations of the relative behavior of certain proprietary coatings. In 1930, the Bureau and the American Petroleum Institute [118, 209] undertook a cooperative test to establish the engineering principles that govern the design and selection of pipeline coatings. Further, the tests were designed to investigate the applicability of corrosion tests on short sections of coated pipe, such as the National Bureau of Standards was conducting, to the performance of coatings on pipelines.

Arrangements were made with each of 16 cooperating pipeline operators to furnish 1,000 ft of new or substantially new operating line, together with labor for taking up the pipe, applying the coatings, and installing sections of newly coated pipe. In general, sites were selected that were known to be corrosive. However, accessibility of the line and the characteristics of the soil were also considered.

The installation procedure consisted of: After the pipe had been carefully cleaned, a coating was applied to 30 ft of the line by or under the supervision of the manufacturer. Another coating was applied to the next 30 ft of the line while the next 20 ft-section was left uncoated as a control. This sequence was repeated until half of the new pipe had been used. The other half was then treated similarly so that in each site there were two 30-ft sections of line coated with each coating, and each coated section was in contact with a section of bare pipe.

The resistivity of the soil near each coating was recorded and the thickness of each coating was measured at a number of places to determine its uniformity. Before the coated pipe was returned to the trench, the coatings were carefully inspected and all imperfections were repaired. To avoid injuries to the coating, great care was exercised in returning the pipe and in backfilling the trench.

To compare the results of tests of coatings on operating lines and on isolated short sections of small-diameter pipe, all the coatings in the test (tables 85, 86, and 87) were applied to 2-ft sections of 3-in. steel pipe, three of which were buried in a

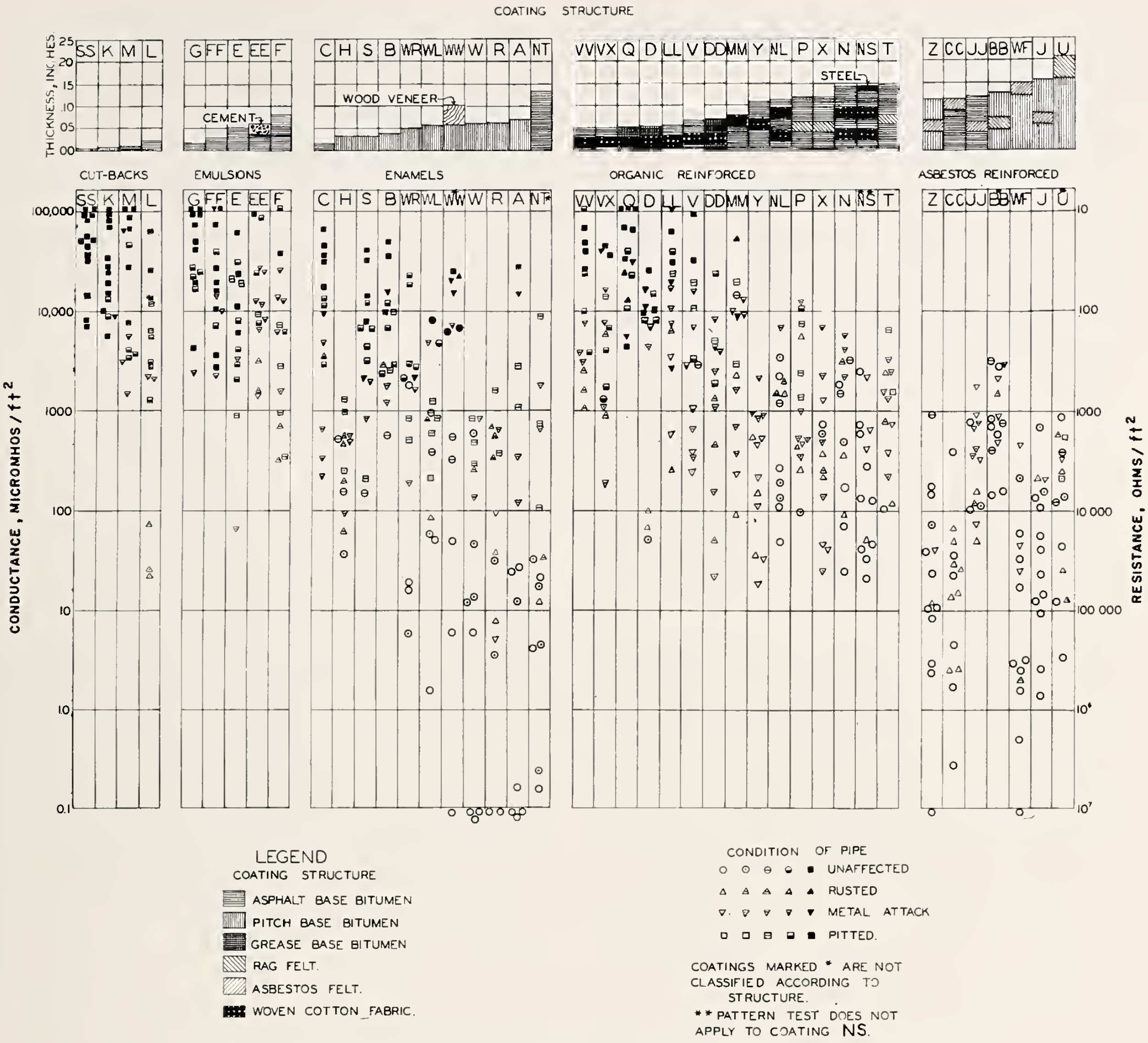

FIGURE 64. *Results of inspections of NBS-AGA coatings after exposure for 5.5 years.*

separate trench parallel to each of the operating lines. To supplement the bare control sections of the pipelines, and to study the relative rates of corrosion of working lines and small sections of pipe, uncoated specimens were buried in the pipeline trench adjacent to the bare and coated sections of the line.

The final report [118] presented a comparison of the coatings with regard to the uniformity of test conditions and to the relative merits of different criteria of coating performance; only the latter will be dealt with herein.

Results of Tests of Coatings Applied to Operating Lines and on Isolated Small Pipe. The averages of the maximum pit depths, after 10 years of exposure, on the coated and uncoated sections line pipe and on the 3-inch control pipes are shown in table 88. As an indication of the uniformity of soil conditions, the resistivity of the soil opposite each section of the line is also given. The scope of the test did not permit the exposure of all types of coatings to all the soils, and therefore the investigation was designed to expose selected coatings in the soils to which they appeared best suited, that is, the heavier coatings were placed in what prior data indicated to be the more destructive soils. In many cases the same basic coating was used in two ways, for example, with and without a reinforcement or shield.

Data (table 88) based on the averages of the pit depths beneath each foot of coating, tend to minimize the seriousness of corrosion associated with the coatings. A subsequent analysis was made to show the deepest pit associated with 20 ft of the coatings. Correlation of these analyses (tables 89 and 90) illustrate the pit depth-area relation and the extremes of corrosion that may occur under nominally the same condition. The latter approach (table 89) shows how difficult it is to produce continuous coatings on a 20-ft length of pipe that will prevent corrosion completely for 10 years, even when soil conditions are as mild as they were at most of the test sites involved in the tests, as indicated by the shallow pit depths (table 88) on the unprotected pipe.

The results of the tests on the 46 coatings applied to the short pipe sections (table 90) furnish data that supplement the data from the NBS–AGA tests.

Effect of Time on Rate of Corrosion of Coated Pipe. It is evident from the data presented that the commercial production of a few feet of coating on pipe that would retain its continuity for a 10-year period had not been accomplished. A combination of protective coating with cathodic protection might be more economical and more effective than an attempt to obtain a permanently nonporous coating. In the latter case, the current required for cathodic protection is determined to a considerable extent by the conductivity or the permeability of the coating. The conductivities of the coatings measured on the sections of operating pipelines (table 91) depend on the conductance of the electrolyte, the pores and flaws in the coating and on the coating thickness.

The fact that the maximum rate of pitting of bare ferrous pipes exposed in soils generally decrease with the duration of exposure has been observed from the NBS field tests as early as 1928 (see section 8). However, up to the conclusion of the NBS–API tests on bituminous coatings, no specific attempt has been made to analyze the pit depth-time relation for pipes with protective coatings. The data obtained from these field tests were utilized by Logan [224] to compare the performance of the same coatings in different soils, as well as of the different coatings in the same soils, by a series of pit depth-time curves. This comparison showed that many coatings that have failed in spots permitted the development of pits on the coated pipe that increased in depth at rates which, for the latter part of the 10-year period of exposure, were higher than the rates of pitting for unprotected pipe exposed to the same soil conditions. Further, a comparison of the pit depths on the coated and uncoated sections of the operating pipe lines with that on the short sections of isolated pipe specimens indicated that the rate of pitting on the coated sections were not affected galvanically by the interaction of the adjacent uncoated sections of the pipeline.

Conclusions Based on the NBS–API Tests. The implication of the data [224] raises a serious question as to the ultimate usefulness of bituminous coatings when they are imperfectly applied, contain pinholes, or other flaws because of pipe movements, soil stress, penetration by roots, or deterioration of the coating. However, it should be borne in mind that even an accelerated rate of pitting on coated pipes, which are not completely protected, does not imply that the coating will not prolong the useful life of the pipe, as occasional leaks may be repaired at no great cost.

The data on the conductance of the coatings (table 93) lack uniformity because frequently one section of a coating showed many times the conductance of another section of the same coating at the same test site. Based on the data available, it is difficult or impossible to determine whether this lack of consistency is the result of lack of uniformity in the thickness or composition of the coating, poor application, or of nonuniform soil conditions. The same statements are applicable to maximum pit depths. The important fact is that the amount of protection afforded by many coatings was not uniform even under comparable conditions.

There was a general increase in the conductance of the coatings at the 10-year inspection period over that observed at the 4-year inspection period indicating that the usefulness of the coatings is limited with respect to time of the test.

As a class, the coatings that were applied cold and were not reinforced or shielded showed more cases of exposed pipe than did the thicker coatings of the wrapped type.

Zinc chromate and baked-on red and blue lead appear to be satisfactory as undercoats under the conditions to which they were subjected. The bond between the undercoats and the pipe was stronger than that between the undercoats and the coatings applied over them; this is a characteristic of a poor coating. Coatings so built up seem to have reduced corrosion, but did not afford complete protection to pipe in corrosive soils.

The number of coated pipe reacting to the pattern test was greater after 10 years of exposure than after 4 years of exposure. The results of the pattern tests showed a continued decrease with time in the effectiveness of most coatings.

The soils at only four test sites were severely corrosive, as indicated by the depths of the pits on unprotected sections of pipe (table 90). The majority of the test sites were, therefore, favorable to the coatings, if pit depths are used as criteria for the effectiveness of the coatings. The steel under a larger percentage of the coatings was pitted and had greater pit depths after 10 years of exposure than after 4 years of exposure. There is no consistent difference between the depths of the deepest pits on uncoated sections of line pipe and on the uncoated short pipe sections. In general, there were fewer pits under thick coatings than under thin coatings.

Because the coatings in the NBS–API tests differ in many ways from those in the NBS–AGA tests, it is impossible to determine positively, by the test results whether the machine-applied coatings were superior to those applied by hand or to determine the relative merits of coal tar and asphalt as protective coatings. Likewise, the data do not show clearly whether impregnated asbestos felt was superior to organic materials as a reinforcement. However, as a shield, asbestos felt did not deteriorate as did the organic materials. A layer of cement-sand mortar over an emulsion coating was insufficient to prevent serious pitting in a corrosive soil.

All the coatings reduced the number of pits per unit area of surface, and most of the coated sections of pipe showed shallower maximum pit depths than occurred on the corresponding unprotected pipe. Several of the coatings afforded nearly complete protection for the duration of the test to most of the sections of pipe to which they were applied, but no coating completely protected all sections.

The primary purpose of the test was to establish engineering principles related to the manufacture and use of protective coatings for pipe lines. The following are some of the facts established by the test.

1. Many of these coatings will greatly reduce corrosion during at least 10 years (the period of this test), although complete protection from all corrosion has not been realized in corrosive and destructive soils.
2. The effectiveness of all coatings tested decreased throughout the period of the test. This in most cases is the result of continued soil pressure and the absorption of water. There appears to be little change in the coating materials other than that in the organic fabrics used as reinforcements or shields.
3. Shields and reinforcements should be permanent and sufficiently rigid to distribute soil stress and pressure due to the weight of the pipe over enough area to prevent the flow of the bituminous or other material in the coating.
4. In these particular tests, the thicker coatings appeared to provide better protection.
5. A coating should be sufficiently rigid to withstand pressures over long periods and elastic enough to withstand stresses resulting from pipe movement and sudden changes in temperature. These requirements are difficult to obtain in any one coating.
6. A coating that develops flaws at one or more points may cause deeper pits at those points than would have occurred on uncoated pipe in the same location.
7. In mildly corrosive soils, no protective coating is required unless the cost of a leak would be abnormally high.
8. These tests show that comparable results are obtained from exposures of isolated short sections of coated pipe and from long sections of pipelines.
9. The presence of uncoated or bare sections in a coated pipeline did not appreciably affect the pit depth-time relation for the adjacent coated sections.

TABLE 85. *Characteristics of the bitumens used in the NBS-API coatings*

Designation of material	Specific gravity	Ring-and-ball softening point	Penetration (Dow) at 115° F in 5 sec (50 g)	Ductility (Dow) at 115° F	Consistometer hardness (Abraham) at 115° F	Insoluble in CS_2 [a]	Ash [a]
		° F		*cm*		*Percent*	*Percent*
E	1.028	186	20	14.0	14.7	2.1	0.98
G, N	1.420	202	3	.7	67.1	42.9	26.5
H, L	1.628	205	2	3.9	54.8	55.4	37.8
K, U	1.266	192	16	16.0	23.5	29.1	18.9
M	1.418	145	83	60.0	44.5	37.4	22.9
S	.996	194	-------	3.2	10.9	1.0	.4
T	1.350	191	-------	4.1	63.5	34.1	14.4
X, Z	.997	238	16	2.5	17.1	.7	.13
a	1.300	241	-------	2.7	34.5	42.8	10.9
d, dd	1.360	190	-------	3.6	56.5	32.7	13.2
g, zz, zzz	1.610	205	2	3.8	61.3	55.6	35.3
h	1.685	189	21	10.3	13.0	61.6	61.3
k, kk	1.259	192	27	62.0	9.1	21.9	5.6
n	1.032	190	14	12.6	16.9	4.6	2.4
q, qq	1.006	232	33	2.5	16.0	.8	.4
s, ss	1.421	195	2	2.8	63.0	40.6	26.9
t	1.420	158	25	58.2	10.0	39.3	21.4
vv	1.050	320+	-------	0.0	36.7	17.0	13.4
w, ww	1.470	163	30	7.2	8.8	42.2	39.9
y, yy, yyy	1.011	189	-------	3.2	10.9	1.1	.5
z	1.638	222	0	1.7	65.4	57.6	40.2

[a] When differences between the insoluble in CS_2 and ash are greater than 4 percent, the difference is apparently due to free carbon (a constituent of coal tar).

TABLE 86. *Coatings in the NBS-API line tests*

Symbol	Thickness	Description
	Inch	
A	0.0647	Two coats of asphalt emulsion.
B	.1072	One coat of grease, spiral wrap of grease-saturated fabric (Osnaburg type), and outer coat of heavier-consistency grease.
C	.0206	Two coats of filled cutback coal tar.
E	.1506	Asphalt primer, followed by sling coat of asphalt compound, spiral wrap of coal-tar-saturated Osnaburg fabric, outer coat of asphalt and kraft paper.
F	.4185	Two coats of asphalt emulsion, followed by rigid shield of sand and cement mortar.
G	.0625	Coal-tar primer, followed by coal-tar-asphalt enamel, and unbonded wrap of asbestos pipe-line felt.
H	.0807	Coal-tar primer, followed by coal-tar enamel, and unbonded wrap of wood veneer.
K	.0685	Coal-tar primer, followed by coal-tar-asphalt enamel.
L	.0798	Coal-tar primer, followed by coal-tar enamel.
M	.0576	Do.
N	.0596	Coal-tar primer, followed by coal-tar-asphalt enamel.
O	.5186	Asphalt primer, followed by a hot coat of priming asphalt, and spiral wrap of asphalt mastic carried on pipe with tissue and sheathing paper (machine-applied).
R	.1427	Asphalt primer, followed by two coats of asphalt enamel; spiral application of asbestos pipe-line felt; flood coat of enamel, and kraft paper (machine applied).
S	.1502	Asphalt primer, followed by two coats of asphalt; spiral application of rag-base pipeline felt; flood coat of asphalt, and kraft paper (machine-applied).
T	.3507	Coal-tar primer, followed by two straight-away rag-base pipe-line felt applications on the inner faces of which coal-tar enamel mopped on; sling coat of coal-tar enamel, and whitewash.
U	.1709	Coal-tar primer, followed by two coats of coal-tar-asphalt enamel; spiral application of asbestos pipe-line felt; flood coat of enamel, and kraft paper (machine-applied).
X	.2302	Hot asphalt primer, followed by double-spiral wrap of unsaturated fabric (Osnaburg type) drawn through molten asphalt, and spiral-butt wrap of 26-gage strip steel.
Y	.0287	Asphalt primer, followed by one coat of asphalt cutback; one coat of asphalt adhesive, and machine-wrap of aluminum foil.
Z	.2062	Hot asphalt primer, followed by double-spiral wrap of unsaturated fabric (Osnaburg type) drawn through molten asphalt, and kraft paper (machine-applied).

TABLE 87. *Coatings on the NBS-API short pipe sections*

Symbol	Sponsor	Average thickness	Description
		Inch	
a	American Tar Products Co.	0.054	Pyrmax Primer, followed by one coat of Komac P. C. enamel (coal tar).
b	Arco Co.	.020	Two coats of filled Arco Q. D. Savaline (cutback coal tar).
bb	do	.034	One coat of filled Arco Q. D. Savaline; spiral wrap of saturated fabric (Osnaburg type); and final coat of Savaline.
c	Barber Asphalt Co.	.072	Asphalt primer, followed by two spiral wraps of saturated fabric (Osnaburg type), and kraft paper—Genasco pipe-coating type 1—(fabric and kraft paper machine-applied.)
cc	do	.045	Two coats of cutback asphalt—Genasco pipe-coating type 2.
d	The Barrett Co.	.342	Barrett coal-tar primer, followed by two coats of rag-base roofing felt to the inside face of which hot Barrett pipeline enamel (coal tar) was mopped on, and an outer coat of enamel followed by whitewash.
dd	do	.050	Barrett coal-tar primer, followed by Barrett pipeline enamel (coal tar) and whitewash.
ddd	do	[a] .050	Barrett coal tar primer, followed by Barrett pipeline enamel (coal tar) and unbonded polymerized resin shield.
e	Dearborn Chemical Co.	.026	One coat of No-Ox-Id G special, spiral wrap of grease-saturated fabric (Osnaburg type), and outer coat of service coat (heavier-consistency grease).
ee	do	.022	Same as e excepting impregnated asbestos-base roofing felt used in place of woven fabric.
f	E. I. duPont de Nemours and Flintkote Co.	.149	Two coats of asphalt-chromate emulsion, spiral-butt wrap of asbestos pipe-line felt, outer coat of A.C.E. and whitewash.
ff	do	.190	Two coats of asphalt-chromate emulsion followed by a coat of sand and cement mortar.
fff	do	.037	Two coats of asphalt-chromate emulsion (whitewashed).
g	Eagle Picher Lead Co.	.069	Under coat of sublimed blue lead followed by bitumastic primer (coal tar) and bitumastic XXH (coal-tar enamel). See coating zzz.
h	Benjamin Foster Co.	.069	Asphalt primer followed by one sling coat of I. B. M. bituminous pipe coating No. 4 (asphalt mastic).
j	Headley Emulsified Products Co.	.015	Three coats of Headley No. 11 asphalt emulsion.
k	Hill, Hubbell and Co.	.075	Biturine primer, followed by sling coat of biturine No. 212 enamel (coal-tar–asphalt).
kk	do	.165	Biturine primer followed by two coats of biturine No. 212 enamel (coal-tar–asphalt), spiral wrap of J.M. 15-lb asbestos pipe-line felt, flood coat of enamel, and kraft paper (machine-applied).
l	Inertol Co.	.081	Inertol No. 49 primer followed by two coats of seal coat (cutback asphalt) and kraft paper (kraft paper machine-applied).
m	Andrew McLean Co.	.089	Priming coat of zinc chromate, followed by McLean's asphalt emulsion and wrapped with asphalt-saturated burlap and kraft paper (burlap and kraft machine-applied).
n	Everlast, Inc.	.158	McEverlast penetration followed by a coat of hot blended compound (asphalt), spiral wrap of coal-tar-saturated Osnaburg fabric, outer coat of H.B.C. and kraft paper (fabric and kraft paper machine-applied).
nn	do	.337	Asphalt primer, followed by hot coat of priming asphalt and spiral wrap of Somastic (asphalt mastic) carried on pipe with tissue and sheathing paper (machine-applied).
p	Lead Industries Assn.	.071	One coat of red-lead paint, followed by bitumastic primer and bitumastic XXH (coal-tar enamel). See coating zzz.
pp	do	.138	One coat of red-lead paint followed by coating q.
ppp	do	.015	Priming coat of red-lead paint followed by two coats of Headley No. 11 (asphalt emulsion).
q	National Tube Co.	.155	Hot Robertson asphalt, followed by double-spiral wrap of unsaturated fabric (Osnaburg type) drawn through molten Robertson asphalt and kraft paper (machine-applied).
qq	do	.216	Same as coating q, excepting 26-gage strip steel substituted for kraft paper.
qqq	do	.183	Hot Robertson asphalt, followed by extruded National mastic (asphalt).
r	Fish-Schurman Corp.	.105	One coat of grease, followed by spiral-wrap of Denso-Tek protective tape (grease-saturated Osnaburg-type fabric), and outer coat of asphalt-saturated burlap.
s	Resistcor Engineering Corp.	.041	Resistcor primer (coal tar) followed by sling coat of Resistcor enamel (coal-tar–asphalt).
ss	do	[a] .041	Resistcor primer (coal-tar–asphalt) followed by sling coat of Resistcor enamel (coal tar) and unbonded wrap of J.M. 15-lb asbestos pipe-line felt.
t	Sherwin-Williams Co.	.052	Lynkote primer (coal tar), followed by sling coat of Lynkote enamel (coal tar).
u	James B. Sipe and Co.	.047	Impervobond No. 411-083 (asphalt primer), followed by cutback-asphalt compound sprayed on.
v	Standard Oil Co. of California	.337	Same as nn, using asphalt-mastic pipe coating.
vv	do	.079	Asphalt primer, followed by Sonamel (asphalt-enamel) tissue paper, and kraft.
w	Standard Oil Co. of New Jersey	.092	Asphalt primer and two coats of Standard pipe coating (asphalt-enamel).
ww	Johns-Manville Corp. and Standard Oil Co. of New Jersey	.170	Asphalt primer, followed by one coat of Standard pipe coating (asphalt-enamel), spiral application of J.M. 15-lb asbestos pipe-line felt; flood coat of enamel, and kraft paper (fabric machine-aplied).
x	Technical Products Co., Inc., Aluminum Co. of America	.018	Tec-Pro primer (asphalt), followed by one coat of Tec-Pro black line No. 45 (asphalt cutback) and Tec-Pro adhesive (asphalt) and machine-wrap of aluminum foil.
y	The Texas Co.	.144	Texaco primer (asphalt), followed by two coats of Texaco No. 30 asphalt pipe coating, spiral wrap of Texaco pipe-line felt (asphalt-saturated rag-base); flood coat of asphalt and kraft paper (machine-applied).
yy	do	.199	Texaco primer (asphalt), followed by two coats of Texaco No. 30 asphalt pipe coating, spiral wrap of Texaco pipe-line felt; coat of asphalt, second ply of felt and kraft paper (machine-applied).
yyy	do	.259	Same as coating yy, excepting a flood coat of Texaco No. 30 asphalt pipe coating over second ply of felt. Outer wrap of kraft paper.
yx	Udylite Process Co.	.0004	Electrodeposited cadmium-udylite. Cadmium.
z	Wailes Dove-Hermiston Corp.	.072	Bitumastic primer, followed by sling coat of bitumastic XH enamel (coal tar) and whitewash.
zz	Wailes Dove-Hermiston Corp. Merchants Basket and Box Co.	[a] .077	Bitumastic primer (coal tar) followed by sling coat of bitumastic XXH enamel (coal tar) and unbonded wrap of Becker's sewed wood veneer.
zzz	Wailes Dove-Hermiston Corp.	.077	Bitumastic primer. followed by sling coat of bitumastic XXH enamel and whitewash.
zx	do	.012	Two coats of bitumastic No. 4 (cutback coal tar).

[a] Without shield, felt, or wood veneer.

TABLE 88. *Averages*[1] *of maximum pit depths on coated and corresponding bare pipes with soil resistivities (exposure 10 years)*

Coating [2]				Sites [3]																	
				201 Temple, Tex.						202 Arkansas City, Kans.						203 Beaumont, Tex.					
				Pit depths (*mils*)				Resistivity (ohm-cm)		Pit depths (*mils*)				Resistivity (ohm-cm)		Pit depths (*mils*)				Resistivity (ohm-cm)	
				Line		Control				Line		Control				Line		Control			
Symbol	Thickness (*mils*)	Associated coating	Character	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare
1. COLD APPLICATIONS: CUTBACKS, C; AND EMULSIONS, A																					
C	21	Y	Cutback coal tar	3.6	22	50	49	490	525							208	185	H	H	590	480
A	65	F	Asphalt emulsion	35	29	49	49	475	525	51	50	61	43	1,200	875	233	187	H	H	500	530
2. ENAMELS																					
N	60	G	Coal-tar–asphalt enamel							8.3	59	48	39	1,000	715	73	209	H	H	480	490
K	69	U	do							30	59	57	39	1,025	715	109	175	H	H	480	415
M	58		Coal-tar enamel	29	29	69	49	455	480	33	53	39	52	2,325	900	188	151	H		545	585
L	80	H	do							10	53	49	52	3,275	900	231	175	H	H	525	415
3. MASTIC																					
O	519		Asphalt mastic	1.5	21	58	61	500	700	0.25	48	52	46	1,800	1,025	0	151	H		360	585
4. SHIELDED COATINGS: CUTBACKS, C; EMULSIONS, A; AND ENAMELS																					
Y	29	C	Cutback asphalt	5.8	20	53	48	525	495												
F	419	A	Asphalt emulsion	1.2	22	56	49	530	525												
G	63	N	Coal-tar–asphalt enamel							1.1	48	60	56	1,225	850	14	185	H	H	500	480
H	81	L	Coal-tar enamel													87	209	H	H	660	490
5. REINFORCED COATINGS																					
B	107		Grease	6.0	29	48	49	500	480	20	48	53	56	950	850						
S	150		Asphalt	29	39	51		725	535	22	59	71	65	3,265	3,240						
E	151		do	2.4	20	48	48	640	495	5.7	48	55	46	1,525	1,025						
Z	201	X	do	4.8	23	53	46	465	555	19	47	50	78	2,825	1,325	44	100	H	H	355	305
R	143		Asphalt enamel	13	21	62	61	625	700	20	59	59	65	965	3,240	15	130	H	159	450	440
U	171	K	Coal-tar–asphalt enamel	7.6	35	66	49	2,740	615	6.1	58	60	53	1,025	690	4.0	130	H	159	475	440
T	351		Coal-tar enamel	3.2	39	56		825	535												
6. SHIELDED AND REINFORCED																					
X	230	Z	Asphalt	3.5	23	51	46	570	555	5.8	47	56	78	1,700	1,325	10	100	H	H	305	305

See footnotes at end of table.

TABLE 88. *Averages*[1] *of maximum pit depths on coated and corresponding bare pipes with soil resistivities (exposure 10 years)*—Continued

Coating[2]				Sites [3]																	
				204 League City, Tex.						205 Preble, Ind.						206 Council Hill, Okla.					
				Pit depths (*mils*)				Resistivity (ohm-cm)		Pit depths (*mils*)				Resistivity (ohm-cm)		Pit depths (*mils*)				Resistivity (ohm-cm)	
				Line		Control				Line		Control				Line		Control			
Symbol	Thickness (*mils*)	Associated coating	Character	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare
			1. COLD APPLICATIONS: CUTBACKS, C; AND EMULSIONS, A																		
C	21	Y	Cutback coal tar	40	64	76	69	1,400	1,750	46	35	50	42	2,000	3,000	25	41	59	44	3,200	3,100
A	65	F	Asphalt emulsion	42	33	71	51	1,300	1,450	61	41	57	37	2,200	2,900	38	40	45	44	2,400	2,450
			2. ENAMELS																		
N	60	G	Coal-tar-asphalt enamel	------	------	------	------	------	------	------	------	------	------	------	------	36	41	56	65	4,100	5,100
K	69	U	do	------	------	------	------	------	------	12	35	62	60	2,900	3,000	28	46	60	57	3,150	3,250
M	58	------	Coal-tar enamel	------	------	------	------	------	------	------	------	------	------	------	------	38	36	48	44	2,450	2,600
L	80	H	do	------	------	------	------	------	------	------	------	------	------	------	------	50	44	54	62	1,650	4,750
			3. MASTIC																		
O	519	------	Asphalt mastic	0.2	51	90	95	1,350	1,900	0.05	35	49	60	5,500	3,000	------	------	------	------	------	------
			4. SHIELDED COATINGS: CUTBACKS, C; EMULSIONS, A; AND ENAMELS																		
Y	29	C	Cutback asphalt	19	52	68	84	1,650	1,500	------	------	------	------	------	------	43	41	49	48	3,900	2,350
F	419	A	Asphalt emulsion	------	------	------	------	------	------	1.7	34	51	38	2,250	3,900	21	41	46	48	3,750	2,350
G	63	N	Coal-tar-asphalt enamel	------	------	------	------	------	------	7.4	34	50	64	3,500	2,250	14	45	60	62	5,000	5,500
H	81	L	Coal-tar enamel	8	53	84	108	1,400	1,750	2.8	34	48	64	2,500	2,250	31	40	54	65	2,600	4,100
			5. REINFORCED COATINGS																		
B	107	------	Grease	11	33	61	51	1,750	1,450	14	34	46	38	5,300	3,900	25	40	50	44	2,175	2,450
S	150	------	Asphalt	32	40	71	83	1,100	1,150	12	39	46	39	1,950	2,800	------	------	------	------	------	------
E	151	------	do	3.7	24	82	51	1,650	1,000	8.6	35	46	46	2,750	3,000	26	47	57	62	4,650	4,000
Z	201	X	do	6.2	29	76	71	900	900	6.5	45	59	36	4,250	4,000	------	------	------	------	------	------
R	143	------	Asphalt enamel	12	37	80	84	1,350	1,450	9.9	39	42	39	2,900	2,800	------	------	------	------	------	------
U	171	K	Coal-tar-asphalt enamel	2.6	29	77	71	900	650	------	------	------	------	------	------	------	------	------	------	------	------
T	351	------	Coal-tar enamel	25	37	75	69	1,000	900	------	------	------	------	------	------	27	42	72	50	2,750	3,900
			6. SHIELDED AND REINFORCED																		
X	230	Z	Asphalt	2.1	53	65	58	3,000	1,350	3.8	45	46	36	1,800	4,000	------	------	------	------	------	------

See footnotes at end of table.

TABLE 88. *Averages*[1] *of maximum pit depths on coated and corresponding bare pipes with soil resistivities (exposure 10 years)*—Continued

Coating[2]				Sites[3]																	
				207 Caney, Kans.						208 Spindletop Gully, Tex.						209 Long Beach, Calif.					
				Pit depths (*mils*)				Resistivity (ohm-cm)		Pit depths (*mils*)				Resistivity (ohm-cm)		Pit depths (*mils*)				Resistivity (ohm-cm)	
				Line		Control				Line		Control				Line		Control			
Symbol	Thickness (*mils*)	Associated coating	Character	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare
1. COLD APPLICATIONS: CUTBACKS, C; AND EMULSIONS, A																					
C	21	Y	Cutback coal tar	27	40	54	52	1,700	1,700	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
A	65	F	Asphalt emulsion	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
2. ENAMELS																					
N	60	G	Coal-tar–asphalt enamel	30	60	68	83	1,400	1,500	74	79	H	-------	455	460	0.4	81	80	109	1,500	1,015
K	69	U	do	19	73	40	48	1,400	1,150	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
M	58	------	Coal-tar enamel	35	60	63	83	1,525	1,500	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
L	80	H	do	25	73	78	48	1,350	1,150	111	89	89	-------	385	345	0.06	62	74	77	1,815	1,090
3. MASTIC																					
O	519	------	Asphalt mastic	1.2	45	45	50	1,500	1,075	6	89	H	-------	370	345	0.0	94	89	72	1,020	975
4. SHIELDED COATINGS: CUTBACKS, C; EMULSIONS, A; AND ENAMELS																					
Y	29	C	Cutback asphalt	-------	-------	-------	-------	-------	-------	85	120	74	-------	355	375	44	106	101	112	1,265	605
F	419	A	Asphalt emulsion	-------	-------	-------	-------	-------	-------	37	93	77	-------	360	360	1.3	93	H	70	1,180	580
G	63	N	Coal-tar–asphalt enamel	1.3	40	69	52	1,600	1,700	6.8	90	H	-------	445	430	0.65	72	87	85	800	925
H	81	L	Coal-tar enamel	-------	-------	-------	-------	-------	-------	129	79	69	-------	310	460	0.05	82	106	86	875	810
5. REINFORCED COATINGS																					
B	107	------	Grease	19	40	52	44	1,550	1,400	-------	-------	-------	-------	-------	-------	15	90	99	70	1,025	675
S	150	------	Asphalt	27	48	62	57	1,500	1,200	92	104	85	-------	390	370	-------	-------	-------	-------	-------	-------
E	151	------	do	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
Z	201	X	do	5.6	70	75	56	1,100	1,125	75	113	H	-------	355	350	13	99	46	72	2,325	845
R	143	------	Asphalt enamel	21	45	70	50	1,350	1,075	96	104	H	-------	290	390	0.0	99	86	72	1,025	845
U	171	K	Coal-tar–asphalt enamel	20	100	67	62	900	975	43	135	H	-------	415	385	0.0	58	43	78	1,600	1,345
T	351	------	Coal-tar enamel	11	48	66	57	1,400	1,250	12	135	103	-------	385	385	5.2	80	184	107	1,925	810
6. SHIELDED AND REINFORCED																					
X	230	Z	Asphalt	-------	-------	-------	-------	-------	-------	13	125	79	-------	335	415	2.4	58	77	78	1,240	1,345

See footnotes at end of table.

TABLE 88. *Averages*[1] *of maximum pit depths on coated and corresponding bare pipes with soil resistivities (exposure 10 years)*—Continued

Coating [2]				Sites[3]																	
				210 Mt. Auburn, Ill.						211 Skiatook, Okla.						213 Bunkie, La.					
				Pit depths (*mils*)				Resistivity (ohm-cm)		Pit depths (*mils*)				Resistivity (ohm-cm)		Pit depths (*mils*)				Resistivity (ohm-cm)	
				Line		Control				Line		Control				Line		Control			
Symbol	Thickness (*mils*)	Associated coating	Character	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare
1. COLD APPLICATIONS: CUTBACKS, C; AND EMULSIONS, A																					
C	21	Y	Cutback coal tar	23	35	57	58	2,250	1,200							81	99	62	44	440	875
A	65	F	Asphalt emulsion	48	41	70	58	2,600	1,650							106	70	49	39	440	375
2. ENAMELS																					
N	60	G	Coal-tar–asphalt enamel	33	55	75	69	1,800	1,300	36	64	51	40	265	315						
K	69	U	do	16	45	68	60	2,050	1,050	16	107	85	55	525	540	31	74	71	43	425	375
M	58		Coal-tar enamel	44	55	60	69	3,000	1,300	102	87	51	44	265	425						
L	80	H	do	23	24	65	50	1,200	1,500	73	87	41	44	590	425						
3. MASTIC																					
O	519		Asphalt mastic							2.8	64	52	40	1,000	315	0.0	92	46	41	440	465
4. SHIELDED COATINGS: CUTBACKS, C; EMULSIONS, A; AND ENAMELS																					
Y	29	C	Cutback asphalt	11	56	77		2,000	1,550							78	56	41	41	375	450
F	419	A	Asphalt emulsion	24	46	66	55	1,600	1,450							6.6	52	37	44	375	390
G	63	N	Coal-tar–asphalt enamel	21	35	60	58	1,550	1,200							9.0	56	41	41	400	450
H	81	L	Coal-tar enamel	5.1	45	57	60	1,200	1,050							116	74	49	43	450	375
5. REINFORCED COATINGS																					
B	107		Grease	17	46	65	55	2,300	1,450	37	102	88	90	365	210						
S	150		Asphalt													127	92	54	41	390	465
E	151		do	19	24	72	50	1,150	1,500	46	79	79	101	265	335	120	52	42	44	415	390
Z	201	X	Asphalt							17	107	66	55	875	540	22	53	41	35	440	450
R	143		Asphalt enamel							29	71	55	48	715	700						
U	171	K	Coal-tar–asphalt enamel							27	56	49	46	775	375	27	99	63	44	390	375
T	351		Coal-tar enamel	10	56	85		1,500	1,550	3.4	71	59	48	525	700						
6. SHIELDED AND REINFORCED																					
X	230	Z	Asphalt							8.6	79	62	101	440	335	2.6	53	40	35	390	450

See footnotes at end of table.

Table 88. *Averages*[1] *of maximum pit depths on coated and corresponding bare pipes with soil resistivities (exposure 10 years)*—Continued

Coating[2]				Sites[3]											
				214 Chambersburg, Pa.						215 Cholame Flats, Calif.					
				Pit depths (*mils*)				Resistivity (ohm-cm)		Pit depths (*mils*)				Resistivity (ohm-cm)	
				Line		Control				Line		Control			
Symbol	Thickness (*mils*)	Associated coating	Character	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare
1. COLD APPLICATIONS: CUTBACKS, C; AND EMULSIONS, A															
C	21	Y	Cutback coal tar												
A	65	F	Asphalt emulsion	26	31	59	50								
2. ENAMELS															
N	60	G	Coal-tar–asphalt enamel												
K	69	U	do	2.5	36	56	50								
M	58		Coal-tar enamel	21	36	48	50								
L	80	H	do							60		H		140	
3. MASTIC															
O	519		Asphalt mastic							0.39		H		315	
4. SHIELDED COATINGS: CUTBACKS, C; EMULSIONS, A; AND ENAMELS															
Y	29	C	Cutback asphalt	2.9	32	54	42								
F	419	A	Asphalt emulsion	3.9	28	48	51			40		H		140	
G	63	N	Coal-tar–asphalt enamel							81		H		225	
H	81	L	Coal-tar enamel	2.9	33	62	53								
5. REINFORCED COATINGS															
B	107		Grease	3.5	28	45	51								
S	150		Asphalt	9.7	35	41	46								
E	151		do	3.3	33	48	53			51		153		210	
Z	201	X	do							21		H		190	
R	143		Asphalt enamel	1.8	35	59	46								
U	171	K	Coal-tar–asphalt enamel	0.08	32	55	49			20		H		240	
T	351		Coal-tar enamel							1.4		H		180	
6. SHIELDED AND REINFORCED															
X	230	Z	Asphalt	2.4	32	48	49			33		H		235	

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[1] Averages are based on 20 one-foot sections of coated pipe; 14 one-foot sections bare lines; and the equivalent of 2 three-foot sections of 3-inch bare control pipe. In some cases the pipes have been punctured by corrosion. The holes in the line pipe were small, and the thickness of the pipe wall has been taken as the depth of the pit. The holes in the control pipes were sometimes numerous and large, and no attempt to obtain an average pit depth for punctured control specimens was made. This condition is indicated by the letter "H."

[2] See tables 85 and 86 for description of coatings.

[3] See appendix 4 and table 8 for description of soils.

TABLE 89. *Single deepest pit on 20 feet of coated line pipe after 10 years of exposure*

(In mils)

U = Unaffected.
R = Rusted.
M = Metal attack.
+ = Hole.

Coating symbol	Test sites [a]													
	201	202	203	204	205	206	207	208	209	210	211	213	214	215
1. COLD APPLICATIONS														
C	20	--------	322+	67	137	39	47	--------	--------	51	--------	242	--------	--------
A	91	86	322+	87	107	37	--------	--------	--------	105	--------	128	54	--------
2. ENAMELS														
M	43	69	231	--------	--------	76	57	--------	--------	60	148	--------	45	--------
K	--------	60	195	--------	89	52	84	--------	--------	70	36	166	16	--------
N	--------	45	264	--------	--------	89	65	170	R	61	58	--------	--------	--------
L	--------	52	322+	--------	--------	97	60	148	R	76	151	--------	--------	63
3. MASTIC														
O	R	M	U	U	U	--------	R	38	U	--------	R	U	--------	R
4. SHIELDED COATINGS														
Y	40	--------	--------	73	--------	97	--------	126	80	45	--------	120	M	--------
F	M	--------	--------	--------	M	40	--------	107	M	68	--------	38	M	103
G	--------	R	118	--------	90	29	R	45	10	35	--------	46	--------	322+
H	--------	--------	211	30	20	45	--------	220	R	35	--------	240	53	--------
5. REINFORCED COATINGS														
B	12	38	--------	39	52	50	37	--------	36	89	54	--------	23	--------
S	100	55	--------	77	40	--------	61	290	--------	--------	--------	202	30	--------
E	12	19	--------	10	45	40	--------	--------	--------	26	117	197	21	103
Z	22	50	183	36	21	--------	18	144	30	--------	69	132	--------	80
R	51	51	61	59	59	--------	67	197	U	--------	56	--------	23	--------
U	61	39	40	40	--------	--------	123	120	U	--------	126	70	R	70
T	16	--------	--------	58	--------	40	27	32	32	38	27	--------	--------	17
6. SHIELDED REINFORCED COATINGS														
X	15	17	22	M	24	--------	--------	121	M	--------	31	M	11	124

[a] See table 8 for location and properties of soils.

TABLE 90. *Depth of the deepest pit on short pipe sections*

(In mils)

U, Pipe unaffected by corrosion;
M, Definite pitting but no pits greater than 10 mils in depth;
R, Pipe rusted, no appreciable pit depths;
H, Pipe punctured by corrosion. The number preceding an "H" indicates the number of holes in the specimen.

Coating[1]				Test sites[2]														
Symbol	Thickness (mils)	Associated coating[3]	Character	201 Temple, Tex.	202 Arkansas City, Kans.	203 Beaumont, Tex.	204 League City, Tex.	205 Preble, Ind.	206 Council Hill, Okla.	207 Caney, Kans.	208 Spindletop Gully, Tex.	209 Long Beach, Calif.	210 Mt. Auburn, Ill.	211 Skiatook, Okla.	212 Mendota, Calif.	213 Bunkie, La.	214 Chambersburg, Pa.	215 Cholame Flats, Calif.
1. COLD APPLICATIONS																		
cc	45	c	Cutback asphalt	R	R	104	M	M	12	16	88	M	M	38	R	M	R	M
u	47		do	R	32	112	26	M	12	21	43	67	R	M	U	H	R	M
l	81		do	R	32	108	M	M	23	13	35	51	M	M	U	23	M	M
zx	12		do	M	28	10H	26	22	26	32	55	32	R	25	78	H	M	54
b	20	bb	do	M	17	H	14	41	29	35	67	M	23	M	U	14	M	35
j	15	ppp	Asphalt emulsion	41	27	15H	31	37	32	38	58	77	M	31	31	4H	10	78
ppp	15	j	do	R	12	5H	32	22	29	24	H	32	R	75	59	H	M	94
fff	37	f, ff	do	14	24	5H	54	36	29	50	51	21	M	21	35	129	21	48
2. ENAMELS																		
vv	79		Asphalt	R	M	62	22	M	R	M	23	24	M	M	24	25	M	27
w	92	ww	do	10	80	2H	38	55	27	31	65	M	M	M	17	107	M	65
s	41	ss	Coal-tar asphalt	U	U	U	R	U	16	U	23	22	M	M	U	M	U	24
k	75	kk	do	R	10	U	U	M	14	R	M	M	U	M	32	M	U	M
t	52		Coal tar	14	22	10H	24	25	31	37	43	24	M	25	R	H	38	77
dd	50	d, ddd	do	14	M	H	41	U	23	38	45	R	M	56	58	154	M	29
a	54		do	R	24	114	M	16	23	31	63	76	U	U	U	M	U	M
g	69	p, zz, zzz	do	R		32	M	U	M	17	18	R	U	U	U	M	U	U
z	72		do	R	U	H	32	U	12	R	33	U	U	U	U	R	M	U
zzz	77	p, g, zz	do	M	M	108	22	U	18	15	48	U	U	U	U	U	U	47
p		zz, zzz, g	do	R	U	51	M	U	20	U	50	U	R	R	R	H	U	U
3. MASTIC																		
h	69		Asphalt	28	M	3H	61	29	25	45	64	44	R	M	U	2H	U	57
qqq	183		do	14	M	H	U	M	13	11	32	36	M	M	U	109	U	70
nn	337		do	U	R	30	U	U	U	R	M	R	M	M	U	U	U	U
v	337		do	U	M	M	U	U	U	U	U	R	U	M	U	U	R	U
4. SHIELDED COATINGS																		
x	18		Cutback asphalt	R	M	122	M	M	M	M	39	71	R	14	55	M	U	H
ff	190	f, fff	Asphalt emulsion	U	M	63	M	U	M	R	20	M	M	M	R	23	M	38
ss	[4]41	s	Coal-tar-asphalt enamel	R	U	U	U	U	M	U	U	U	M	21	U	U	U	U
ddd	[4]50	d, dd	Coal-tar enamel	U	U	U	M	U	U	U	M	U	R	U	U	U	U	U
zz	[4]77	g, p, zzz	do	R	U	U	U	U	M	U	M	U	U	U	U	U	U	U
5. REINFORCED COATINGS																		
c	72	cc	Cutback asphalt	33	23	112	32	M	15	31	67	R	M	M	M	41	23	M
bb	34	b	Cutback coal tar	12	12	5H	38	30	33	24	37	12	M	M	R	81	R	55
m	89		Asphalt emulsion	M	M	90	M	M	11	M	50	21	M	22	M	37	M	M
f	149	ff, fff	do	M	M	M	R	M	M	M	M	M	M	M	U	19	M	R
ee	22	e	Grease	14	25	H	M		19	M	21	M		19	47	29	M	28
e	26	ee	do	M	11	5H	M	M	R	12	17	M	M	14	31	88	20	18
y	144	yy, yyy	Asphalt	R	M	42	M	M	28	24	33	24	M	M	R	H	M	43
pp	138	q, g	do	M	U		R	M	M	M	20	M	M	M	U	15	M	
q	155	pp, qq	do	M	14	62	M	M	M	M	13	M	M	16	M	22	M	17
n	158		do	M	M	141	22	R	M	M	19	M	M	10	U	H	U	22
yyy	259	y, yy	do	U	M	29	M	M	M	M	21	M	M	M	M	M	M	20
ww	170	w	Asphalt enamel	14	M	34	M	M	M	15	20	U	M	M	U	20	U	M
kk	165	k	Coal-tar-asphalt enamel	R	R	H	M	M	M	R	28	M	U	U	M	12	U	20
d	342	dd, ddd	Coal-tar enamel	M	R	R	M	R	R	M	M	M	U	U	U	M	R	U
6. SHIELDED, REINFORCED COATINGS																		
r	105		Grease	M	M	54	14	M	M	M	20	M	R	10	R	17	M	M
yy	199		Asphalt	M	18	35	14	M	M	M	25	M	M	13	U	13	11	28
qq	216	q	do	R	M	38	M	M	M	M	15	M	M	U	U	U	U	M
yx	0.4		Metal coating	22	27	2H	46	23	42	34	37	100+	39	42	65	33	15	H

[1] See tables 85 and 87 for a description of the coatings.
[2] See appendix 4 and table 8 for a description of the soils.
[3] The associated coating is similar to the coating on the same specimen except for a change in priming coat, reinforcement or shield.
[4] Without shield.

TABLE 91. *Maximum conductance*[1] *of coatings on operating pipelines*

Coating[2]				Test sites[3]														
Symbol	Thickness (mils)	Associated coating	Character	Section	201. Temple, Tex.	202. Arkansas City, Kans.	203. Beaumont, Tex.	204. League City, Tex.	205. Preble, Ind.	206. Council Hill, Okla.	207. Caney, Kans.	208 Spindletop Gully, Tex.	209. Long Beach, Calif.	210. Mt. Auburn, Ill.	211. Skiatook, Okla.	213. Bunkie, La.	214. Chambersburg, Pa.	215. Cholame Flats, Calif.
1. COLD APPLICATIONS: CUTBACK C; EMULSION A																		
C	21	Y	Cutback coal tar	a	2,510	--------	[4] E	2,700	E	E	4,800	--------	--------	E	--------	E	--------	--------
				b	E	--------	E	1,600	E	4,300	3,200	--------	--------	E	--------	E	--------	--------
A	65	F	Asphalt emulsion	a	E	E	E	4,000	E	930	--------	--------	--------	E	--------	E	E	--------
				b	E	E	E	4,800	E	E	--------	--------	--------	270	--------	12,000	570	--------
2. ENAMELS																		
N	60	G	Coal-tar-asphalt enamel	a	--------	3.5	138	--------	--------	E	240	E	23	D	4,700	--------	--------	--------
				b	--------	98	E	--------	--------	24	1,600	E	98	--------	1,400	--------	--------	--------
K	69	U	do	a	--------	E	124	--------	E	270	120	--------	--------	E	3,500	E	E	--------
				b	--------	E	E	--------	67	E	E	--------	--------	0.25	1,000	E	130	--------
M	58	--------	Coal-tar enamel	a	E	E	E	--------	--------	28	E	--------	--------	E	17,000	--------	--------	--------
				b	[5] D	E	E	--------	--------	1,200	E	--------	--------	E	10,000	--------	E	--------
L	80	H	do	a	--------	580	576	--------	--------	E	1,100	E	8,700	66	4,700	--------	--------	--------
				b	--------	E	E	--------	--------	E	18	E	51	440	3,400	--------	--------	22,000
3. MASTIC																		
O	519	--------	Asphalt mastic	a	5.4	10	11	12	13	--------	30	55	0.23	--------	32	13	--------	330
				b	110	16	2	21	12	--------	8	620	52	--------	290	8.9	--------	67
4. SHIELDED COATINGS: CUTBACK Y; EMULSION F; AND ENAMELS																		
Y	29	C	Cutback asphalt	a	E	--------	--------	8,900	--------	E	--------	E	E	E	--------	E	D	--------
				b	E	--------	--------	31,000	--------	27,000	--------	E	E	E	--------	13,300	D	--------
F	419	A	Asphalt emulsion	a	220	--------	--------	--------	1,200	3,600	--------	E	810	1,700	--------	1,200	1,200	E
				b	720	--------	--------	--------	2,800	650	--------	3,100	1,300	2,000	--------	800	750	1,600
G	63	N	Coal-tar-asphalt enamel	a	--------	4.5	200	--------	0.08	2.3	0.005	190	60	8.9	--------	360	--------	E
				b	--------	98	29	--------	9.0	470	0.004	260	460	D	--------	1,900	--------	E
H	81	L	Coal-tar enamel	a	--------	--------	800	1,800	0.15	E	--------	E	0.87	0.016	--------	E	12	--------
				b	--------	--------	220	2,300	0.001	330	--------	E	1.9	4.6	--------	E	0.00	--------
5. REINFORCED COATINGS																		
B	107	--------	Grease	a	E	670	--------	E	E	E	36	--------	2,800	E	D	--------	E	--------
				b	E	710	--------	E	110	12	110	--------	38,000	E	2,700	--------	D	--------
S	150	--------	Asphalt	a	E	530	--------	D	71	--------	33	E	--------	--------	--------	E	380	--------
				b	E	E	--------	250	230	--------	E	1,700	--------	--------	--------	1,400	--------	--------
E	151	--------	do	a	360	150	--------	240	75	E	--------	--------	--------	E	6,800	17,000	50	18,000
				b	D	240	--------	620	55	E	--------	--------	--------	E	5,500	5,800	11	1,300
Z	201	X	do	a	220	E	800	51	E	--------	440	E	620	--------	3,500	2,900	--------	440
				b	E	E	580	14	E	--------	E	E	2,300	--------	2,200	E	--------	1,100
R	143	--------	Asphalt enamel	a	E	2,000	1,300	1,300	570	--------	16	E	12	--------	1,300	--------	67	--------
				b	E	E	130	440	38	--------	2,400	E	20	--------	2,000	--------	E	--------
U	171	K	Coal-tar-asphalt enamel	a	650	29	80	14	--------	--------	220	2,500	--------	--------	6,600	360	0.24	220
				b	320	67	31	1,200	--------	--------	2,100	E	17	--------	1,600	800	0.64	360
T	351	--------	Coal-tar enamel	a	90	--------	--------	190	--------	150	120	310	45	110	810	--------	--------	2,000
				b	540	--------	--------	160	--------	190	130	620	170	--------	120	--------	--------	180
6. SHIELDED, REINFORCED ASPHALT																		
X	230	Z	Asphalt	a	13	40	E	11	7.1	--------	--------	530	10,000	--------	680	530	6.9	E
				b	3.6	210	580	42	20	--------	--------	14,000	5,200	--------	68	4,000	32	--------

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[1] In micro-mhos per square foot.

[2] A description of these coatings is given in tables 85 and 86.

[3] The coating in column 1 and the related coating in column 3 contain, with the exception of coatings C and Y, the same bituminous material.

[4] E = pipe exposed.

[5] Coating damaged by tools.

18.6. Performance of Bituminous Coatings in Service

Little information is available on the effectiveness of the more recently developed coatings, because corrosion in most soils does not become serious, even on poorly coated pipe, until after a decade or so of exposure. Subsequent to the Bureau's field tests, marked improvements have been made in commercial pipe coatings. It is of interest, therefore, to consider the type of coatings used on some of the large pipelines, since results of the Bureau's tests were made available.

The War Emergency Pipeline [225], built by an organization composed of prominent pipeline operators, was coated over most of the line with a coal-tar primer followed by a coal-tar enamel and a wrapper or shield of asbestos felt. The coating was machine applied in the field and had an average thickness of 3/32 in. The choice of this type of coating may have been largely influenced by the exigencies of the situation, availability of materials and machines, ease of application, etc. The Products Line [226] constructed by the same organization, was similarly protected, but was triple-coated and in addition wrapped at river crossings. In the wet corrosive soils of the Gulf Coast area, some of the feeder lines were coated with an asphalt mastic similar to coating "O" in the NBS–API tests but applied by a different machine, which extruded the mastic around the pipe without seams.

Another installation was reported by Sterling [227] of a pipeline which was coated with a petroleum asphalt (3/32-in. thick) applied in the field by machine and shielded by a spiral wrap of asbestos felt. This line was found to be in excellent condition after 13 years, whereas unwrapped sections of the same pipeline were almost beyond recovery, many joints having from 15 to 18 punctures.

Other investigations have shown that pipeline enamel sheathed in a concrete coating, cast in place after the line had been coated and lowered in the trench, prevented corrosion entirely for 6 years in poorly drained soils [228].

Data on new enamel coatings reported by Rogers [229] and Hadley [230] showed somewhat similar experiences with electrical resistance measurements on the coatings shielded by wrappers of asbestos felt. In each of the installations cited, a large drop in coating resistance was observed within the first year or two after installation of the line, the change being of a much lesser extent thereafter. From other electrical measurements made with the Pearson flaw detector, Hugo [231] reported that an inspection of about 150 miles of an asphalt mastic coating, most of which was about 1 year old but with 11 miles of 3⅔-year-old coating, disclosed 80 electrical imperfections. Eleven of these were examined and five obvious coating injuries were found. At six points no imperfections were visible. A similar test of 45 miles of asbestos-felt-shielded coal-tar-enamel coating of about the same age revealed 36 electrical leaks, 3 of which were examined. One defect was a large flaw beneath the wrapping; the second was a puncture of the coating by a ring from the pipe left in the trench; the third was a defective patch with the water beneath it. It will be noted that all of these failures were the result of poor installation rather than of poor coating materials.

Records of repairs to pipe, wrapped with coal-tar enamel and asbestos felt, of the Southern Counties Gas Company of California [232] show that coatings which were carefully installed and inspected gave no indication of deterioration over a 15-year period.

As no one type of coating is superior to all others under all conditions, it is usually best to choose the type that can be most easily applied under the circumstances, because poor installation is the chief cause of unsatisfactory performance. As a result of a survey of various control methods used on pipelines, Sharpe [233] concluded that (1) even the best pipeline enamel coatings are not free from imperfections and require supplementary cathodic protection, either by applied emf or sacrifical anodes, to fully protect the pipe, and (2) the cost of cathodic protection on reasonably well-coated lines is so small that the large expense and effort required to secure more than reasonably good coating jobs are difficult to justify. A recent statistical survey [201] on power costs for cathodic protection revealed that the protection costs on bare lines are about 10 times as much as those on coated lines.

19. Accelerated Methods for Determining Corrosivity of Soils

Paralleling the field-exposure tests that have been discussed in this Circular, there were many attempts made, by the Bureau and by other organizations, to find a simple, reliable, and rapid test procedure that could be used either in the field or in the laboratory in place of the long term burial tests. Considerable thought was given to the possibility that the corrosive characteristics of a soil could be so well correlated with either the type of the soil, or its composition and content of soluble salts, that a simple soil survey would suffice to predict the probable life of a pipeline or to identify areas where corrosion would be most severe.

19.1. Identification of Soil Types

The U.S. Department of Agriculture has mapped most of the soils of the United States, classified them as to soil type, and described the characteristics of each soil type and of each soil horizon, usually to a depth of 6 ft, as was discussed in section 3 of this Circular. As the same soil types are recurrent in many areas, a soil survey along a right-of-way should be helpful in subdividing the territory with respect to its corrosivity. However, the corrosiveness of only a small percentage of the soil types or series has been actually determined, and, in general, the corrosiveness of a soil series must be inferred from its chemical and physical characteristics and by association of the characteristics of soils of unknown corrosivity with that of soils of known corrosivity. The procedure usually followed consists in testing the soil at arbitrarily selected intervals along a right-of-way to determine those areas in which corrosion will be severe and hence, where protection of the metal structure will be required. Instead of testing the soil in place, samples of soil so obtained may be examined in the laboratory. Once the soil profile of the proposed right-of-way has been established, the extent of corrosion that probably would be encountered in a pipeline can be estimated from known data available on the soil types traversed.

To determine whether the corrosiveness of certain soil types is sufficiently well defined to be of practical use in corrosion surveys, Denison and Ewing [105] made a survey along 200 miles of pipeline right-of-way, in Northern Ohio, which contained five parallel pipelines ranging in age from 26 to 44 years and traversed 35 different soil types. The soils were mapped and the corrosiveness of each type was estimated from records of repairs made on the pipelines which were available from the time of their installation.

The survey showed that although there was some variation in the amount of pipe replaced in various isolated areas of the same soil type, there were consistent differences in the corrosiveness between the various types. Inconsistencies in the corrosivity of the same soil types generally occurred at the boundaries of different soil types, or were attributed to stray-current electrolysis. In some cases where sections of the pipelines closely paralleled railroads, the accumulation of cinders on the surface of the soils appeared to be responsible for accelerated corrosion of the pipelines.

In considering further the relation between the various soils and their corrosiveness, Denison and Ewing compared the corrosiveness of the soils with the measurements of total acidity and resistivity (table 4) and with the degree of development of the horizons within the soil profile (fig. 65). In table 92, the typical upland soils of northeastern Ohio, which have developed from sandstone and shale, are grouped according to the degree of development shown by their profiles. Within each vertical column the soils are arranged according to the texture of the B horizon. In table 93 a similar arrangement is shown for the glacial soils of northwestern Ohio, which have been derived from limestone. The results show that the corrosiveness of the soils is related to their stage of development, the least developed soils being the most corrosive. Thus the Trumbull soils, which are mottled throughout the profile and show very little differentiation into horizons, are seen to be corrosive, whereas the Wooster soils, which are well developed, are noncorrosive. It will also be observed that within the vertical columns corrosiveness increases as the subsoil becomes heavier in texture.

The relationship between the stage of development and texture of the soils and their corrosiveness can be largely explained on the basis of average acidity and resistivity. Because of the slight weathering that has occurred in the case of the poorly developed soils, such as those of the Trumbull series, there has been but little tendency for soluble materials to be removed, with the result that the average resistivity of these soils is relatively low. Similarly, the very heavy texture of poorly drained soils accounts largely for their high acidity, the acidity of a soil being affected by its content of colloidal material. Conversely, the high stage of development of the noncorrosive Wooster soils has resulted from the thorough removal of soluble salts, as indicated by their high average resistivity. Aside from the effects of acidity and resistivity, however, it is highly probable that those physical characteristics of the soils that determine their drainage and aeration have an important bearing on the observed relations.

The correlation of corrosiveness with soil types is helpful to supplement the information available in the U.S. Department of Agriculture soil survey reports. It might be possible, however, to make a simpler correlation by the use of soil series as a criterion for corrosion instead of soil types, as usually the different types in a soil series differ only in the texture of the uppermost layer, or A horizon. That is, the subsoils are usually the same for most of the soils belonging to the same soil series. To investigate the possibilities of such a correlation, data were taken from NBS field tests for specimens of open-hearth iron, wrought iron, steel, and cast iron that had been buried, in different test sites, in two or more soil types in each of 10 soil series (table 94). As the duration of the exposure in different soil types of the same series differed somewhat, the corrosion losses and pit depths have been reduced to values per square foot per year. The table is satisfactory for comparing materials exposed for comparable lengths of time in the same soil series, but as has been emphasized previously in the text, extrapolation to other periods of time requires complete information about the time-corrosion curve.

If allowance is made for the probable spread of data attributed to uncontrolled factors, it will be seen that the rate of corrosion within each soil series investigated is reasonably constant. An exception is the Norfolk series where the corrosion in Norfolk sandy loam is different from that in Norfolk sand because the subsoils of these types are not comparable. This serves as a warning that before assuming that corrosion throughout a soil series is the same, one should ascertain the effect of the subsoils.

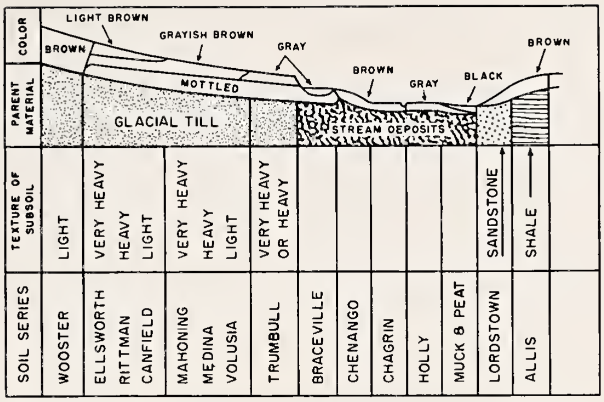

FIGURE 65. *Characteristics of soils in the region of glaciated sandstones and shales [105].*

TABLE 92. *Relation between the degree of development of the glacial soils of northeastern Ohio and their corrosiveness [105]*

	Degree of development							
	1		2		3		4	
Color of surface soil	Gray		Gray brown		Light brown		Brown.	
Mottling of A_1 horizon	Mottled		Mottled		No mottling		No mottling.	
Mottling of B horizon	do		do		Mottled		do	
Mottling of C horizon	do		do		do		do	
	Series	Repairs	Series	Repairs	Series	Repairs	Series	Repairs
		Percent		*Percent*		*Percent*		*Percent*
Light B horizon			Volusia	13.6	Canfield	6.2	Wooster	6.0
Heavy B horizon	Trumbull	20.0						
Very heavy B horizon			Mahoning	20.9	Ellsworth	16.1		

TABLE 93. *Relation between the degree of development of the glacial soils of northwestern Ohio and their corrosiveness [105]*

	Degree of development					
	1		2		3	
Color of surface soil	Grayish black		Dark gray		Gray brown.	
Color of subsoil	Mottled bluish gray		Mottled bluish gray and yellowish brown		Mottled yellowish brown and yellowish gray.	
	Series	Repairs	Series	Repairs	Series	Repairs
		Percent		*Percent*		*Percent*
Light B horizon					Miami	22.8
Heavy B horizon	Clyde	46.2	Brookston	34.1	Crosby	30.8
Very heavy B horizon					Nappanee	57.0

TABLE 94. *Relation of soil series to rates of loss in weight and to weighted rates of maximum penetration of ferrous specimens*

(Average of 2 specimens, except for the pit cast (A and L), the data for which cover 1 specimen only)

Soil		Location	Duration of test	Rates of loss, in ounces per square foot per year							Weighted rates of maximum penetration, in mils per year						
No.	Type			Open-hearth iron,	Hand-puddled wrought iron,	Bessemer steel,	Southern cast iron,	Northern cast iron,	Monocast centrifugal cast iron,	Average for six specimens	Open-hearth iron,	Hand-puddled wrought iron,	Bessemer steel,	Southern cast iron,	Northern cast iron,	Monocast centrifugal cast iron,	Average for six specimens
				A	B, D	N	A or Z	L	I		A	B, D	N	A or Z	L	I	
			Years														
101	Billings silt loam (low alkali).	Grand Junction, Colo	9.27	1.13	1.01	0.99	1.10	1.18	0.87	1.05	13.7	9.7	8.8	12.3	20.6	14.8	13.3
102	Billings silt loam (moderate alkali).	do	9.27	1.98	1.74	1.90	2.77	2.76	2.49	2.27	12.8	9.8	10.0	29.2	29.9	22.4	19.0
103	Billings silt loam (high alkali).	do	9.27	2.02	2.30	1.92	6.33	4.57	4.88	3.67	19.1	13.9	19.9	43.4	36.6	20.5	25.6
	Average			1.71	1.68	1.60	3.40	2.84	2.75	2.33	15.2	11.1	12.9	28.3	29.0	19.2	19.3
104	Cecil clay	Charlotte, N. C.	11.71	.61	.62	.65	.58	.45	.50	.57	7.3	7.6	9.4	7.3	7.6	8.4	7.9
3	Cecil clay loam	Atlanta, Ga.	12.10	.35	.39	.36	.35	.32	--------	.35	5.0	5.3	5.7	12.1	9.9	--------	7.6
105	do	Macon, Ga.	11.66	.41	.31	.42	.39	.39	.35	.38	4.7	4.1	4.4	8.8	11.6	9.3	7.2
106	do	Salisbury, N. C.	11.70	.62	.74	.76	.68	.74	.66	.70	8.0	5.9	6.2	10.1	20.4	13.2	10.6
107	Cecil fine sandy loam	Raleigh, N. C.	11.70	.46	.47	.48	.27	.30	.30	.38	8.1	7.5	9.4	7.2	6.3	8.5	7.8
108	Cecil gravelly loam	Atlanta, Ga.	11.66	.41	.38	.50	.38	.47	.42	.43	6.6	5.9	7.6	17.9	20.2	12.8	11.8
	Average			.48	.49	.53	.44	.45	.45	.47	6.6	6.1	7.1	10.6	12.7	10.4	8.9
109	Fresno fine sandy loam (low alkali).	Fresno, Calif.	9.24	1.26	1.28	1.22	3.25	1.86	2.26	1.86	11.9	10.4	10.9	26.6	21.7	19.7	16.9
110	Fresno fine sandy loam (moderate alkali).	do	9.24	2.01	1.71	2.19	1.94	1.84	2.08	1.96	14.7	12.5	16.0	22.9	25.1	25.7	19.5
111	Fresno fine sandy loam (high alkali).	Kernell, Calif.	8.90	1.98	2.12	2.18	3.00	2.57	2.74	2.43	[a]17.1+	18.0	12.7	28.7	18.1	16.2	18.5
	Average			1.75	1.70	1.86	2.73	2.09	2.36	2.08	14.6	13.6	13.2	26.1	21.6	20.5	18.3
112	Imperial clay (moderate alkali).	Niland, Calif.	5.93	3.34	2.85	3.17	4.13	5.28	[b]D	3.66	38.4+	26.5+	37.5+	45.4	43.4	46.4	39.6
113	Imperial clay (high alkali).	do	5.93	4.34	3.68	3.98	D	4.82	[c]5.75+	4.21	38.1+	29.2	38.1+	54.7	38.1	37.4	39.3
	Average			3.84	3.27	3.58	--------	5.05	--------	3.94	38.3	27.9	37.8	50.1	40.8	41.9	39.5
22	Memphis silt loam	Memphis, Tenn.	11.65	.60	.68	.67	--------	.72	--------	.67	4.6	4.8	5.4	--------	13.4	--------	7.1
115	do	Vicksburg, Miss.	11.69	.28	.30	.33	.20	.20	.17	.28	6.7	4.1	5.4	9.6	7.0	6.3	5.8
	Average			.44	.49	.50	--------	.46	--------	.47	5.7	4.5	5.4	--------	10.2	--------	6.5
23	Merced silt loam	Buttonwillow, Calif.	10.18	1.94	1.94	2.13	6.11	2.78	--------	2.98	14.7	13.1	13.1	31.5	20.7	--------	18.6
116	Merced clay	Los Banos, Calif.	9.27	2.33	2.06	2.10	4.74	4.00	3.59	3.05	12.8	17.2	9.4	28.9	23.1	22.4	18.3
117	Merced clay loam adobe	Tranquillity, Calif.	9.27	2.26	2.14	2.24	1.90	2.29	1.64	2.16	19.1	13.2	14.8	17.7	17.3	15.9	16.4
	Average			2.18	2.05	2.15	4.25	3.02	--------	2.73	15.5	14.5	12.4	26.0	20.4	--------	17.8
119	Norfolk sandy loam	Macon, Ga.	11.66	.70	.75	.76	.50	.60	.50	.66	8.2	5.7	6.2	12.2	11.8	8.4	8.8
120	Norfolk sand	Pensacola, Fla.	11.65	.16	.15	.18	.066	.037	.092	.12	2.9	2.3	2.1	2.6	1.5	3.9	2.3
121	do	Tampa, Fla.	11.71	.12	.12	.13	.028	.014	.10	.082	2.2	2.0	1.7	1.8	2.2	4.4	2.0
31	Norfolk fine sand	Jacksonville, Fla.	12.04	.24	.23	.23	.31	.19	--------	.24	3.2	3.1	3.0	5.2	1.5	--------	3.2
	Average			.31	.31	.33	.23	.21	--------	.28	4.1	3.3	3.3	5.5	4.3	--------	4.1

TABLE 94. *Relation of soil series to rates of loss in weight and to weighted rates of maximum penetration of ferrous specimens*—Continued

(Average of 2 specimens, except for the pit cast (A and L), the data for which cover 1 specimen only)

Soil		Location	Duration of test	Rates of loss, in ounces per square foot per year							Weighted rates of maximum penetration, in mils per year						
No.	Type			Open-hearth iron,	Hand-puddled wrought iron,	Bessemer steel,	Southern cast iron,	Northern cast iron,	Monocast centrifugal cast iron,	Average for six specimens	Open-hearth iron,	Hand-puddled wrought iron,	Bessemer steel,	Southern cast iron,	Northern cast iron,	Monocast centrifugal cast iron,	Average for six specimens
				A	B, D	N	A or Z	L	I		A	B, D	N	A or Z	L	I	
			Years														
42	Susquehanna clay	Meridian, Miss.	12.03	0.93	0.74	0.92	2.53	1.48		1.32	10.3	6.7	7.2	22.8	16.0		12.6
123	do	Shreveport, La.	11.68	.89	.94	.94	.75	.83	.85	.87	3.8	4.9	5.1	18.0	15.4	11.0	9.4
124	Susquehanna silt loam	Troup, Tex.	10.50	.71	.74	.74	.54	.63	.58	.67	6.6	6.7	6.6	5.0	6.6	11.0	6.3
125	Susquehanna fine sandy loam.	Shreveport, La.	11.85	.59	.67	.72	.74	.72	.84	.69	5.5	5.7	6.1	7.3	7.3	7.8	6.4
	Average			.78	.77	.83	1.14	.93		.89	6.6	6.0	6.3	13.3	11.3		8.7
12	Hanford fine sandy loam	Los Angeles, Calif.	6.17	.45	.54	.44	.37	.35		.45	9.0	10.4	9.8	9.3	3.5		9.6
13	Hanford very fine sandy loam.	Bakersfield, Calif.	5.89	1.04	.94	1.33	2.16			1.37	8.0	9.6	8.4	30.0			14.0
	Average			.75	.74	.89	1.27			.91	8.5	10.0	9.1	19.7			11.8
25	Miami clay loam	Milwaukee, Wis.	16.99	.19	.16	.16	.15	.14		.16	3.2	3.0	3.1	5.7	5.8		4.2
26	Miami silt loam	Springfield, Ohio	16.93	.24	.28	.28	.23	.19		.24	3.4	2.4	3.2	8.2	4.5		4.3
	Average			.22	.22	.22	.19	.17		.20	3.3	2.7	3.2	7.0	5.2		4.3

[a] +indicates 1 or more punctures due to corrosion. [b] D = Destroyed by corrosion. [c] Data for 1 specimen only. The other was destroyed by corrosion.

19.2. Chemical Tests

a. Soluble Salts

It has been observed that corrosion of metals in soils is affected by the chemical composition and the soluble salts of the soil. However, chemical compositions have not been used to any great extent for determining the corrosiveness of soils because of the variations that exist between sampling points and because of inconsistencies shown to exist in the rates of corrosion at locations where the chemical compositions of the soils are not markedly different. It is apparent that other factors must be taken into consideration along with the chemical composition of soils for determination of the degree of corrosiveness. Under the assumption that consideration of soil composition in conjunction with topographical factors might be a suitable method for predicting relative corrosive action, Smith and Richards [234, 235] analyzed data obtained from soil samples taken along the right-of-way of the 340-mile Amarillo-Denver Natural Gas Pipeline to determine this relationship. An attempt to rate the soils from chemical composition alone revealed many inconsistencies. A more reliable rating was obtained by considering both the chemical composition and the following topographical factors: (1) slope; (2) direction of exposure; (3) apparent moisture; (4) present and probable use of the surface; (5) vegetation; (6) surface drainage; (7) physical character and compactness of soil; (8) evidences of any probable abrupt changes in character of soils; and (9) average annual precipitation.

A survey of the Denver-Amarillo pipeline 2 years after it was laid [236] indicated that the corrosion ratings made by Smith and Richards [234, 235] were approximately 75 percent correct. However, electrical resistivity measurements taken at the identical sampling points appeared to be just as reliable as the more complicated ratings derived from chemical analysis and other considerations.

b. Hydrogen-Ion Concentration

The methods generally used for the determination of the hydrogen-ion concentration of soils are either colorimetric or electrometric [237]. The colorimetric method is used to a large extent in the field because the equipment is simple, compact, and portable. However, the determination of *p*H by the colorimetric method is often inaccurate because it is necessary to make a solution or suspension of the soil in water, and the solution is often turbid which interferes with the accurate determination of the colorimetric end-point.

Laboratory determinations of *p*H are generally made by electrometric methods, and the subsequent development of portable equipment has made field application practical. The cell that is universally used employs glass and calomel electrodes, and many commercial varieties of this instrument are available. Many of the portable variations of this instrument have accessory electrodes which are sufficiently rugged for field use and are made with shielded leads so that the electrodes may be used external to the meter.

In laboratory determinations of hydrogen-ion concentrations, the soil samples generally are air dried and then remoistened to bring the soil to a uniform moisture content. Addition of a volume of water equal to that of the air-dried soil is used, except for soils high in organic content, for which a soil to water ratio of 1 to 5 is used. These laboratory determinations are in good agreement with those obtained on the soil in its natural field condition except in the case of some poorly aerated soils, specifically soils having appreciable quantities of soluble sulfur compounds. Such soils undergo radical changes in hydrogen-ion concentration in passing from the natural field condition to the air-dried state, due to the fact that in drying the sulfides in the soil are oxidized to sulfates. For example, Romanoff [87] showed that a change from the moist field condition to the air dried condition in soils of this type was accompanied by reductions in the *p*H values (more acid) by as much as 3.5 units. It was concluded that the *p*H of most soils may be determined by the air-dried-and-remoistened procedure, but for determinations of the actual *p*H under all soil conditions, the *p*H must be obtained from soil samples in their natural field condition.

The latter recommended procedure of measuring *p*H of soils in their field condition raises the question of reproducibility because it has been shown [238, 239] that the *p*H of soils varies with changes in climate and other factors. However, although some degree of reproducibility will be sacrificed, the extent of these variations in hydrogen-ion concentration are insignificant as far as a correlation between *p*H and soil corrosivity is concerned.

c. Total Acidity

Shipley and his coworkers [55, 56] observed that corrosion of iron in soils is roughly related to the soil acidity. Holler [240] studied the rate of hydrogen evolution from iron filings in contact with soil in the absence of oxygen, and found a logarithmic relation between the total acidity of the soils at the Bureau test sites and the volume of hydrogen evolved. Because of the very slight dissociation of soil acids, the *p*H value of a soil may offer no indication of the capacity of the acidic material to prevent the formation of a protective layer of hydroxides that tends to form as a result of initial corrosion. However, it has been noted [240] that with a definite oxygen concentration the rate of corrosion is determined by the total quantity of hydrogen-ions that comes into contact with the metal surface, rather than by the hydrogen-ion concentration of the corrosive medium. In order to determine the effect of soil acidity on corrosion in aerated soil, Denison and Hobbs [107] tested a series of synthetic soils having different controlled total acidities. They concluded that, under the conditions of their test, the rate of corrosion was roughly proportional to the total acidity of the soils. A somewhat less definite relationship was found between the rate of pitting and the acidity of soils at the Bureau test sites.

Although the corrosivity of most soils is influenced by several characteristics, some of which are not closely related, Denison and Ewing [105] showed that, for the northern Ohio soils discussed in section 19.1, corrosivity could be roughly expressed by the equation $P=7500(A-5)/R$, in which P is the percentage of pipe repaired, A is the total acidity in milliequivalents of hydrogen per 100 cm ^{3} of soil, and R is the soil resistivity in ohm-centimeters. The methods of determination of total acidity of soils are described in appendix 7 and the relation of the total acidity of the soil to its corrosivity was indicated by table 4.

19.3. Oxidation-Reduction Potential

Corrosion of iron and steel in many areas in the eastern part of the United States, in England, in Holland, and quite likely elsewhere, is partly due to the depolarizing effects of anaerobic bacteria, as was discussed in section 4.2. Sulfate-reducing organisms are anaerobic, and grow under strongly reducing conditions. Starkey and Wight [92] concluded that soils having *p*H values of less than 5.5 were unfavorable for anaerobic corrosion and that anaerobic corrosion is most severe in wet, poorly drained soils having hydrogen-ion concentrations close to neutrality (*p*H 7.0). The corrosion products resulting from sulfur-reducing bacteria are soft, porous, and loosely adherent to the metal surface. Under these conditions, when the corrosion products are removed, the metal surface is bright and pitted. A characteristic of the products of anaerobic corrosion is the presence of sulfide, which on treatment with a dilute solution of hydrochloric acid, is readily detected by the odor of hydrogen sulfide. A positive test for sulfides is that lead acetate paper will turn black when exposed to the evolved gas.

Starkey and Wight [92] claimed that the most significant soil factor, indicative of anaerobic bacterial corrosion, is the oxidation-reduction potential, otherwise known as the redox potential. This is a potential measured at an inert metal surface, such as platinum, using either a hydrogen or a calomel reference electrode. To establish the feasibility of the use of the soil redox potential as an index of corrosivity of a soil, Starkey and Wight measured the redox potentials in many soils along pipeline distribution systems. These results were correlated with severity of corrosion on the pipes and the resulting corrosion criteria were derived:

Range of soil redox potential	*Classification of corrosiveness*
Below 100 mv	Severe
100 to 200 mv	Moderate
200 to 400 mv	Slight
Above 400 mv	Noncorrosive

The apparatus devised by Starkey and Wight [92] for measuring soil *p*H and redox potentials in the field, to depths of 3 to 4 ft, consisted of a long insulated cylinder that housed glass, platinum, and calomel electrodes. The instrument is best adapted for use in wet soils, such as swamps, marshes, and beds of streams, rather than in dry or moist soils. This apparatus is not readily portable and requires considerable revision to make it suitable for rapid measurements in the field.

19.4. Soil Resistivity

a. General

The simplest criterion for estimating the corrosivity of a given soil is its resistivity which depends largely upon the nature and amount of dissolved salts in the soil, and is also affected by the temperature and moisture content, compactness of the soil and presence of inert materials, such as stones and gravel. Obviously, the resistance of the electrolyte is one of the factors that affect the flow of the current associated with corrosion. If other factors are constant, there is a relation between soil resistivity and corrosion, as was shown in table 4.

The precise measurement of soil resistivity requires carefully designed apparatus and carefully planned procedures. If direct current is used, polarization of the electrodes will affect the results; if alternating currents are employed, the apparatus must compensate for inductive and capacitive effects. However, as two samples of soil are seldom identical, and as the factors other than resistivity are rarely constant, an approximate value of resistivity is usually sufficient. The following laboratory and field methods have been used for determining the resistivity of a soil sample.

b. Laboratory Methods of Measurement

In 1915, McCollum and Logan [8] reported results of resistivity measurements made in connection with the NBS study of stray-current electrolysis. Samples of soil were transported to the laboratory and subjected to potential and current density determinations, using 60-cps alternating current. It was shown that the resistivities decreased with increasing pressure reaching a minimum at about 100 lb/in.,^{2} but above this pressure there was little change in resistance with further increase in the pressure applied to the soil. It was also shown that in many cases laboratory determinations under a pressure of 50 lb/in.^{2} approximated determinations made on the soil in situ, but, in general, this procedure was not satisfactory for determining the resistivity of the undisturbed soil in the field. Subsequently it was found that more reproducible measurements could be made, using a Wheatstone bridge and 1,000-cps current, if the soil samples were saturated with water and were not subjected to pressure. In other determinations at the Bureau a cell was used which consisted of a Bakelite frame containing two removable iron electrodes 5 cm^2 in cross section and spaced 5 cm apart. The frame was placed on a glass plate and was packed with saturated soil and measurements were made with an alternating current bridge. For these specific cell dimensions, the resistivity of the soil in ohm-centimeters is equal to the measured resistance; however, if the cell is enlarged so that the electrodes are of 30 cm^2 cross section and are separated 3 cm, the resistivity is 10 times the measured resistance.

It is difficult to correlate the resistivity of water-saturated soils used in the laboratory determination, with the resistivity of the same soils in the varying degrees of saturation that exist in the field. The effect of moisture content on the resistivity of a clay soil is shown in figure 66. When the soil is nearly dry, its resistivity is very high. However, the resistivity decreases rapidly with increases of moisture content until the saturation point is reached, after which further additions of moisture have little or no effect on the resistivity. Other kinds of soils yield similar curves, but the point at which the resistivity reaches the nearly constant value depends on the salt and moisture contents (table 6) of the soil. The effect of temperature on the resistivity of a soil (fig. 67) shows that there is a gradual increase of resistivity with a decrease in temperature until the freezing point of water is reached, but at temperatures below the freezing point, the soil resistivity increases very rapidly. For temperatures between 0° and 25°C the relation between soil resistance and temperature is given by the equation [241]

$$R_{15.5}=\frac{R_t\,(24.5+t)}{40},$$

where $R_{15.5}$ is the resistance at 15.5°C (60°F) and R_t is the observed resistance at temperature t°C.

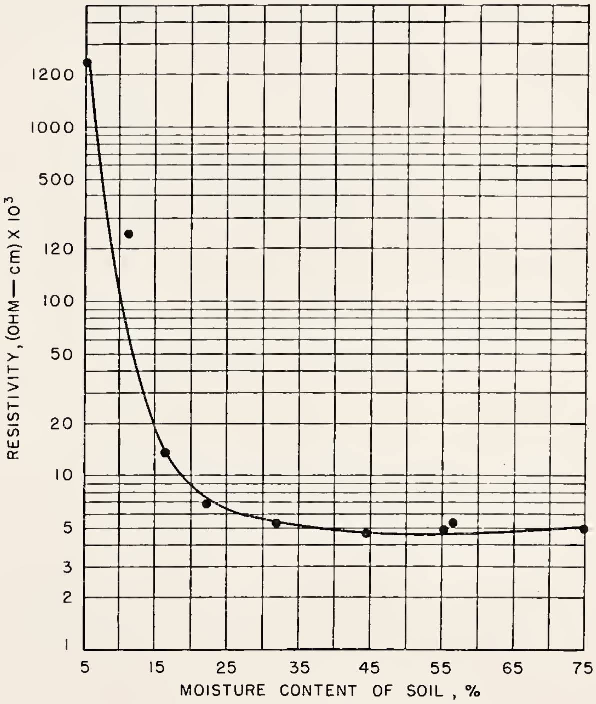

FIGURE 66. *Effect of moisture content on resistivity of a clay soil.*

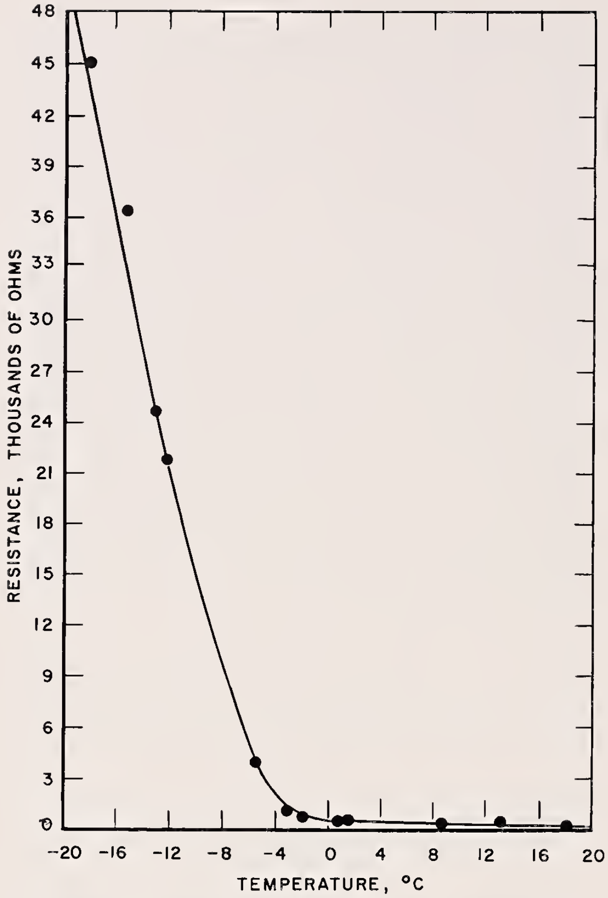

Figure 67. *Effect of temperature on earth resistance* [8].

c. Electrolytic-Bridge Method

The electrolytic bridge (also referred to as the Soil Alkali Bridge) designed by the U. S. Department of Agriculture [63, 242] is a reliable method for measurements of soil resistivity, both in the field and in the laboratory. The instrument (fig. 68), which is used as a null indicator, consists of a Wheatstone bridge which is excited by a vibrator, and a set of earphones. In preparing the soil sample for this determination, foreign materials, such as pebbles, stones, and root fragments, are removed. Sufficient soil sample to fill the cell (50 ml) is placed in a convenient mixing dish and distilled water added slowly while the sample is mixed with a spatula until saturation is reached. The condition of saturation is obtained when the soil paste is no longer capable of absorbing an additional drop of water applied to its surface. Because of the tendency of dry soils of the heavy plastic clay type to absorb water slowly, it is usually necessary to crush the sample to pass a No. 20 (2-mm diameter) U. S. standard sieve prior to saturation. The "Bureau of Soils" cup which contains two electrodes is completely filled to the lip with the saturated soil sample while the cup is tapped gently to release air bubbles. The excess soil is removed with a spatula, leaving the surface smooth. The cell is then placed in the circuit, and the bridge is balanced until the sound in the earphones is reduced to a minimum. The temperature of the saturated soil sample in the cell is recorded after the resistance is measured. The resistivity of the soil in ohm-centimeters is obtained by multiplying the resistance measured between the electrodes of the cell by the constant 3.85. As the resistivity depends upon temperature, the measurements are corrected for a uniform temperature of 60°F by use of the equation previously given, the temperature conversion nomogram (fig. 69) or tables in the Department of Agriculture Soil Survey Manual [63]. By use of other tables and nomograms prepared by the Department of Agriculture [63, 242], the percent of soluble material in a soil can be estimated from the results of the measurements of resistance and temperature.

Figure 68. *Electrolytic bridge for measuring soil resistivity.* Designed by the U. S. Department of Agriculture. Note the Bureau of Soils cup in place [63].

d. Shepard's Soil-Resistivity Apparatus

Shepard [80] has developed an apparatus (fig. 70) which is widely used for determination of soil resistivity in the field. It is portable and inexpensive, and a large number of observations can be made in a few hours either in the walls and bottoms of trenches or in holes driven in the ground. The

EXAMPLE: GIVEN OBSERVED VALUES OF 80 OHMS AND 56°F, CONNECT THESE POINTS ON THE OUTER SCALES WITH A STRAIGHT EDGE OR FINE BLACK THREAD. THE LINE INTERSECTS THE SCALE FOR OHMS AT 60°F, AT 75 OHMS.

FIGURE 69. *Nomogram or conversion chart for reducing soil paste resistance in ohms at a particular temperature, as measured in the Bureau of Soils cup, to resistance at 60°F [63].*

This chart was prepared by Reuben E. Nelson, Division of Soil Survey, based on data given in Bureau of Soils Bulletin 61, and a scale proposed by Forrest H. Coulter, Bureau of Reclamation.

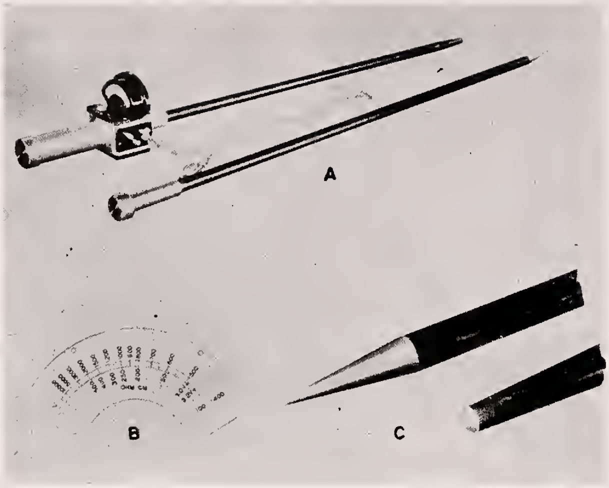

Figure 70. *Shepard soil resistivity meter.*

A, Apparatus assembled for use. Note the top rod houses the meter, switches, and battery; B, scale of milliammeter converted to read directly in ohm-cm; C, enlarged view of the cathode (top) and anode (bottom).

apparatus consists of 2 insulating rods, such as Bakelite, about 3 ft. long, on which are mounted the two iron electrodes which are connected to leads running through the center of the rod. Because polarization of iron electrodes is largely a cathode effect, the amount of polarization can be reduced considerably by making the cathode larger than the anode, thereby decreasing the current density on the cathode. The anode is an iron cone of ½-in. base and a ¼-in. altitude, and the cathode has a ¾-in. base and an altitude of 2⅝-in. The point of the cathode is turned to a 1/16-in. radius. The circuit is energized by a 3-v battery (two flashlight cells) and the positive pole is connected through a switch to the anode. The batteries, indicating meter, and appropriate switches are mounted on one of the rods. The resistivities are registered on a milliammeter having ranges of 25 to 100 ma. The 25-ma range is used for resistivities above 370 ohm-cm, and the 100 ma range is used for resistivities between 400 and 100 ohm-cm. The scale of the meter can be calibrated directly in ohm-centimeters, and a multiplier coil is included in the meter so that the voltage of the battery can be checked from time to time. With this instrument, the soil resistivity, in ohm-centimeters, is equal to approximately three times the measured resistance between the electrodes when they are separated in the earth by 8 in. or more. The apparatus cannot be used in very dry or rocky soil.

Several readings are required to measure the average resistivity of the soil throughout the test area because the apparatus measures the resistivity of only a small volume of soil.

e. Wenner's Four-Terminal Method

The average resistivity of a large volume of earth can be obtained from the surface of the ground by a method developed by Wenner [243]. These measurements can be made by either the McCollum earth current meter [20], the Megger apparatus [244] which was designed by Biddle and employs Wenner's method, or by a combination setup employing a voltmeter, ammeter, and battery. Four contact points are placed in the earth spaced at equal distances a in a straight line. An alternating or periodically reversed direct current is caused to flow between the outer electrodes, and the resulting differences of potential between the inner electrodes is observed. If the depth to which the electrodes are inserted in the ground is small compared with the distance a, (best results are obtained when the depth is less than 5 percent of the distance between electrodes) the effective resistance between the potential electrodes equals $r/2\pi a$, where r is the resistivity of a unit volume of soil in terms of the unit in which a is measured. For example, when the distance between electrodes a is expressed in centimeters and the resistance in ohms, the resistivity is in ohms per centimeter cube (ohm-cm). The resistance measured is equivalent to that of a half cylinder of length a and radius $2a$. The four-terminal method has been used for studying the changes in soil resistivity with depth and, hence, for determining the desirable length of vertical anodes or the depth at which they should be placed.

f. Radio Balance

Huddleston [245] described a comparatively rapid method for measuring soil resistivity, based on the radio balance that was originally intended for use in locating pipelines or other buried metal. Huddleston's assembly weighed about 30 lb and consisted of a six-tube, portable, impedence-coupled radio receiver and a two-tube oscillator. Both of these instruments are housed in wooden cases with built-in loops and batteries, and are mounted at the ends of wooden rods, between which the operator walks. The apparatus operates on the principle that conducting materials act as a shield to the propagation of high-frequency waves, and consequently, the presence of conducting materials can be detected by properly designed apparatus. The instrument may be calibrated by making successive determinations of a number of soils of known resistivity. The deflection of the receiving set is proportional to the conductivity of the soil to a depth of about 4 ft. The equipment has the advantages that it requires no excavations and will give a continuous reading along the pipeline. The apparatus is especially useful in approximately locating the boundaries of low-resistance soils, which are usually corrosive. Huddleston reported that 10 miles of right-of-way can be covered in a day. However, it is generally felt that the results obtained are less accurate than those obtained from the other instruments and procedures described.

19.5. Methods Involving Current and Potential Measurements

a. Columbia Rod

The currents that are associated with corrosion depend not only on the resistivity of the soil but also on the potential of the metal with respect to

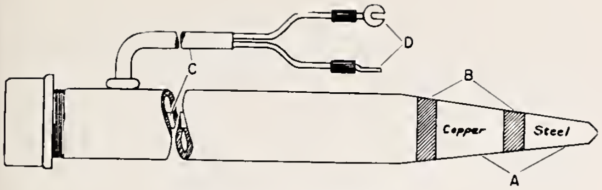

FIGURE 71. *Columbia rod.*
A, Dissimilar metal electrodes; B, insulating material between electrodes; C, lead connections to electrodes; D, lead terminals to milliammeter.

the adjacent electrolyte and on the suppression of the corrosion currents by polarization films and corrosion products. Several attempts have been made to design soil-testing apparatus that would take account of one or more of these factors. The Columbia rod (fig. 71) developed by Legg [246, 247] for this purpose consists of a 1½-in. diameter insulated rod, one end of which is in the form of a cone housing a steel electrode and another electrode of some more noble metal, such as copper. The two electrodes are insulated from each other and are connected to a sensitive milliammeter, which indicates the current flowing when the two electrodes are in contact with the soil. The cell formed by the dissimilar metal electrodes and the soil electrolyte, in which the rod is inserted, constitutes the only source of current. The changes in the current between the electrodes are indicative of film formation, and the amount flowing depends on the effective areas of the electrodes as well as on other and more constant factors. The instrument is calibrated by readings taken in soils of known resistivity.

The apparatus is satisfactory only for some soil conditions. It could be made with the electrodes on separate rods, as in the Shepard apparatus, and an external battery could be used, but this would mask the galvanic effect and the polarization would depend on the applied voltage. Some tests indicate that the readings of the rod are affected more by the resistance of the soil than by the potential of the metal [248].

b. Putman's Decomposition Potential Tests

Putman [249] developed a laboratory test that has been used extensively in the West and constituted one of the earliest attempts to determine soil corrosivity and to associate corrosion with the electrical condition of the corroding metal. A subsequent modification [250, 251] takes account of the resistivity and acidity of the soil and of polarization.

The test determines the resistivity and *p*H of the soil in the field condition and a current value may be derived which Putman calls the "potential corrosivity" of the soil. The modified circuit for determining "potential corrosivity" is shown in figure 72. This circuit consists of two polished-steel electrodes having faces 1 in. square, held in a Bakelite case (not shown) spaced 1 in. apart to form a cubical cell 1 in. on a side. The soil to be tested is compacted in this cell under a pressure of 500 lb/in.^{2} The resistance of the soil cube is determined by measuring the resistance between the electrodes with an alternating current Wheatstone bridge. A potential difference of 1.4 v is then impressed upon the steel electrodes by means of a battery and potential divider as shown. After the current has reached a steady value, usually after about 5 min., its value, C, is read. The equation $C=(1.4-Ed)/R$ gives the value of current, C, in terms of the impressed voltage (1.4 v), the decomposition potential, Ed, and the resistance, R, of the soil cube. The value of C in milliamperes is called the "potential corrosivity." Values of *p*H are determined colorimetrically in a neutral 5-percent potassium chloride solution. By correlating these values with the National Bureau of Standards soil-corrosion data, Putman derived several empirical relationships for determining such quantities as the loss of metal per square foot, the average maximum pit depths, and the total number of leaks per mile in a given time. Putman [251] obtained fairly accurate results, by this method, in determining the corrosivity of many soils that differ widely in resistivity and *p*H.

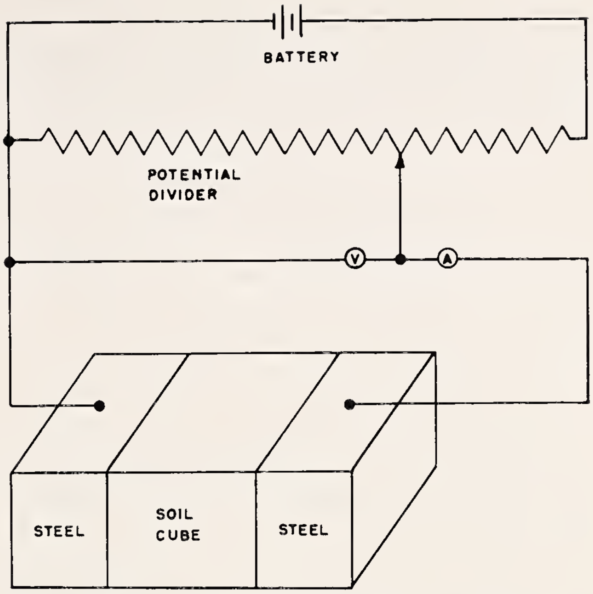

FIGURE 72. *Modified Putman apparatus for testing for "potential corrosivity"* [*251*].

c. Williams-Corfield or Nipple-and-Can Test

A more frequently used and simpler test, but one that has less theoretical background than Putman's test, is the Williams-Corfield [252, 253] or nipple-and-can test. A 4-in. length of ¾-in. sand-blasted iron pipe is carefully weighed, and a rubber stopper is inserted in one end so that it protrudes ½ in. The pipe section is then placed in the center of a pint friction-top can, with the stopper resting on the bottom, and the space between the pipe and the can is filled with a water-saturated sample of the soil to be tested. The pipe is connected to the positive side of a 6-v storage battery, and the circuit is completed by connecting the negative pole of the battery to the can. After 24 hr. the pipe is removed, cleaned, and reweighed. The corrosivity of the soil is indicated by a "corrosion index" as determined by the loss in weight (table 95).

Table 95. *Corfield corrosivity index*

Corrosion index (weight loss of specimen)	Corrosiveness of soil
3 g or over	Very severe.
2 to 2.99 g	Severe.
1 to 1.99 g	Moderate.
Less than 1 g	Good.

Corfield tested about 8,000 samples of soil from Los Angeles, Calif., and vicinity by this method and used the results to make a soil-corrosivity map of that area. The method has been used extensively by others and appears to be reasonably satisfactory for soils such as occur in California. Repeated tests have shown that although this method gives an accurate estimate of the typical soils in the Western part of the United States, it is not readily adaptable to the more generally acid soils of the East.

19.6. Denison Electrolytic Corrosion Cell

a. Experimental Methods

Description of the Corrosion Cell. Denison and his associates [129,130,133,134] developed a corrosion cell for the study of corrosion phenomena in the laboratory. This cell has the advantage that the behavior of different soils and metals can be investigated under uniform conditions of moisture and aeration, and the current through the cell can be regulated at will.

The cell consists essentially of two electrodes, a cathode in the form of a metal screen or perforated disk and an anode in the form of a solid disk of the same metal, separated by a layer of moist soil that constitutes the electrolyte. The cell is assembled in such a manner that the perforated cathode is more accessible to air than the solid metal anode. Therefore, an electromotive force is developed in the cell by means of differential aeration between the two electrodes. The maximum current measured between the electrodes over a 2-week period was used as an index of soil corrosivity. A fair correlation was obtained between laboratory and field data except for soils of relatively high resistivity. In such soils, because of local action, the anode weight losses were more significant than the cell currents as an index of soil corrosivity.

In order to obtain a cell that would give better reproducibility and which would remain operative for a longer period of time, Schwerdtfeger [143] modified the original Denison cell. In the modified cell, more reproducible results were obtained and the cells operate over a longer period of time which brings out the effect of time on the rate of corrosion, thus permitting more accurate correlations between the laboratory test data with field data. This was accomplished by increasing the distance between the electrodes, obtaining better control of aeration at the cathode, by adjusting the moisture content of the soil, and restricting access of air to the anode by mechanically working the layer of soil in contact with it. Details concerning the preparation of the modified cell are given in appendix 5.

Use of the Corrosion Cell. In using the original Denison cell for investigating corrosion phenomena, the principal measurements made were of open-circuit potentials, short-circuit currents, and simultaneous values of current and potential under various conditions. Open-circuit potentials are measured with a potentiometer-voltmeter, which has the advantage that it draws no current from the circuit under test. Individual potentials of the anode and cathode are determined by using an auxiliary saturated calomel electrode connected through an agar-KCl bridge placed in contact with the soil through a hole in the cell. Short-circuit currents are measured by means of a "zero-resistance" milliameter in which the resistance of the instrument is compensated for by opposing the voltage drop in the instrument by an equal applied voltage. The original cell is subject to errors due to unknown and variable *IR* drops which were practically eliminated by using a method developed by Hickling [254] and adapted to the Denison cell by Darnielle [132]. By this modification, the current is periodically interrupted for very short intervals of time, and the potentials are measured during the period of interruption. If the interval of interruption is too long, the potential of a polarized electrode will change during the measurement, so that the observed value will not correspond to the potential existing while the current is flowing. The advantage of the Hickling method is that the time during which the current is interrupted can be made very short (of the order of 10^{-5} sec), so that errors due to depolarization are very small. Details of the modified Hickling circuit are given in appendix 8.

The rate of corrosion of steel in soils is controlled by the amount of polarization that occurs at the anode or cathode, and is influenced by the formation of protective films or of insoluble products resulting from the corrosion reaction. Because polarization is predominant on the electrode that has a film, if a more or less protective film develops on the anode, the rate of corrosion tends to be controlled by the reaction at the anode, and the corrosion reaction is said to be under anodic control. On the other hand, if the protective film develops on the cathode, the progress of corrosion in soils is determined by the rate of the cathode reaction. Under such conditions, the corrosion reaction is said to be under cathodic control. The type of control that proceeds, that is, whether anodic or cathodic has been shown by Bannister and Evans [255], Burns [256], and Brown and Mears [257] to be indicated by the relation between the current (or current density) and the potentials of the anode and cathode of a corroding specimen. The current density-potential curves in figure 73 were obtained

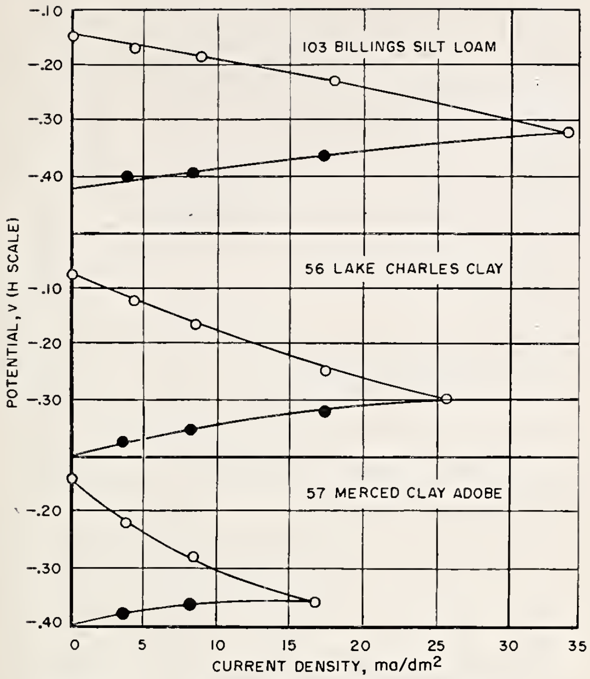

FIGURE 73. *Current density-potential curves* [*133*].
●, Anode; ○, cathode.

by use of the unmodified Denison cell and are typical of electrodes predominantly under cathodic control. The curves show that the change in the cathode potential with increasing current density is much greater than the corresponding change in anode potential. This is particularly well illustrated by the curve for soil 57 in which an increase in current density up to 17 ma/dm^2 raised the potential of the anode by only 0.05 v, whereas the potential of the cathode was lowered by 0.20 v. Curves for metals corroding predominantly under anodic control show that the change in potential with increasing current density is greater for the anode than for the cathode.

If it were not for the high internal resistance of the cell that limits the value of the current on short circuit, the rate of corrosion could be determined simply by measuring the short-circuit current at a suitable stage of corrosion. It is possible, however, to eliminate the effect of resistance by making use of the current density-potential curves. As the current density is increased, the potentials of the anode and cathode approach the same value. At the point where the two curves intersect, the cell is completely polarized, the internal potential difference is zero and the applied electromotive force just balances the internal *IR* drop. The potential of the electrodes at this point is known as a corrosion potential. The associated current density is the limiting value for the particular combination of soil and electrodes and corresponds to the current for the maximum rate of corrosion. The interpretation of current density-potential curves as indicative of the rate of corrosion has been discussed by Evans [258], Evans and Hoar [259], Burns [256], and others.

b. Behavior of Different Metals in Various Soils

Denison and Darnielle [133] used the corrosion cell to investigate the behavior of steel under cathodic control in various soils. Measurements of the corrosion potential were made at intervals over a 2-week period during which the temperature (25°C) and the moisture content were maintained at constant values.

The corrosion potential-time curves (fig. 74) show that after the first few days the corrosion potential usually became practically constant. However, in a few soils, a slight regular electropositive increase in the corrosion potential continued throughout the test period. In all the soils studied, the corrosion potential was more positive than the open-circuit potential of the anode. Brown and Mears [257] pointed out that the potential of a galvanic couple can be identical with the open-circuit potential of the anode only if there is no anodic polarization. The fact that, in many soils, the polarization curves for the cathode is very flat causes the potential of the short-circuited electrodes to become more cathodic.

Typical results of measurements of open-circuit potentials of the anode and cathode of a test cell after having also been on closed circuit for a period of 2 weeks, are shown in figure 75. The potential of the cathode becomes more positive and approaches the potential of the oxygen electrode in the particular environment, but the latter potential is not reached because of imperfections in the protective oxide film that expose the underlying metal and thereby set up local couples.

In addition to the measurement of potential, daily measurements of the short-circuit current of the cells were made. The maximum current de-

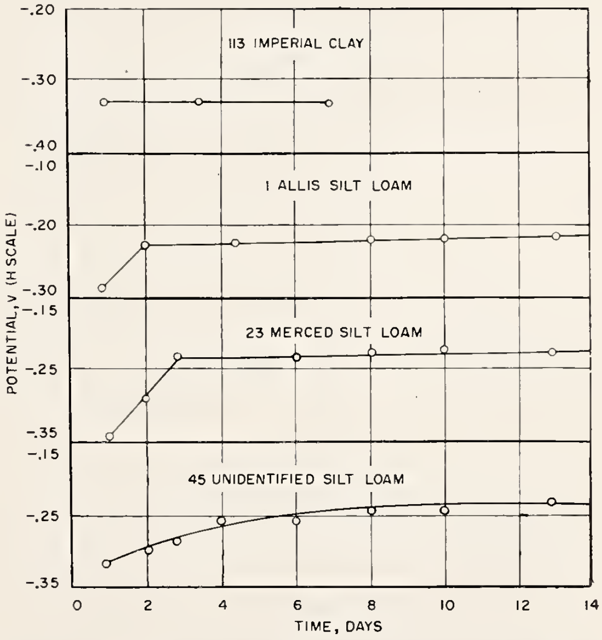

FIGURE 74. *Relation between corrosion potential and time* [*133*].

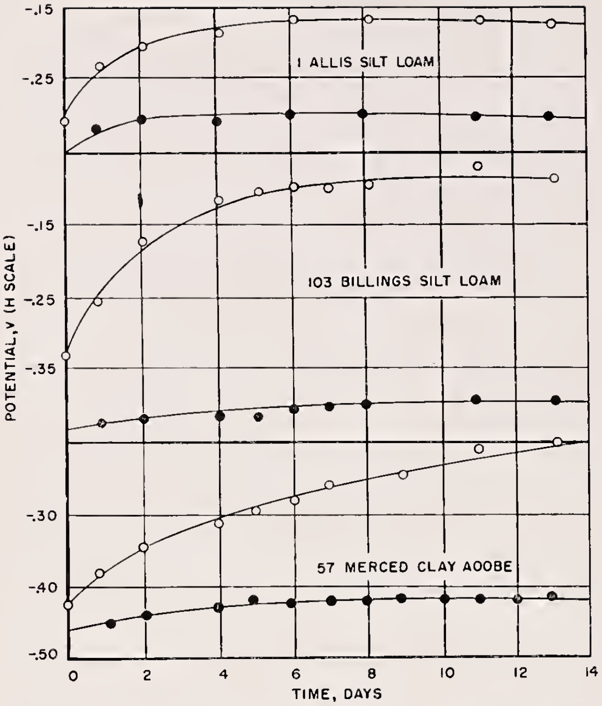

FIGURE 75. *Potential-time curves for the anode and cathode [133].* ●, Anode; ○, cathode.

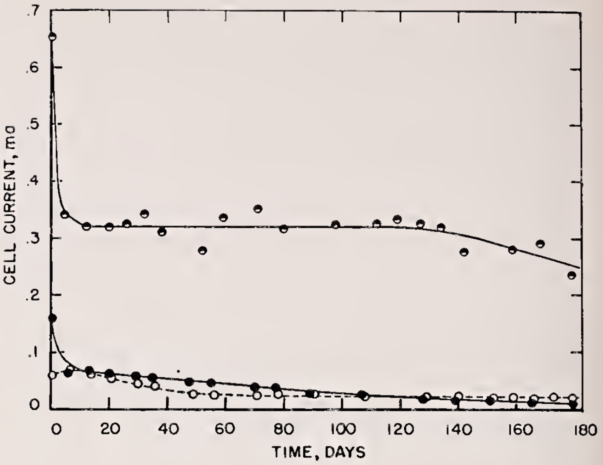

FIGURE 76. *Effect of exposure time on the corrosion of steel in soils [143].*

Symbol	Soil	Resistivity	Cell current[a]	Weight loss of cell electrodes[b]	Corrosivity of soil[c]
		Ohm-cm	*ma*	*oz/ft²*	
◓	64	62	0.280	2.53	Most.
○	62	6,922	.030	1.05	Intermediate.
●	26	2,980	.035	0.56	Least.

[a] Calculated from the area under a line through the points. [b] Combined weight loss of the anode and cathode exposed for 180 days. [c] Order shown by the field-exposure tests.

veloped usually within 18 to 24 hr, although in a few cells the current increased gradually for a week or longer.

In order to correlate the results of the various electrical measurements with the corrosion, the loss in weight of the anodes was determined at the conclusion of the 2-week test period. The results, summarized in table 96, show that there is a rather definite correlation between the loss in weight and either the current at corrosion potential or the maximum short-circuit current. The ratio between these two currents is fairly constant in soils of low resistivity, and tends to increase in soils of higher resistivity.

TABLE 96. *Corrosiveness of soils as indicated by electrical measurements and loss in weight of the anodes*

Soil No.	Soil Type	Resistivity at 60° F	Maximum open circuit voltage [a]	Corrosion potential [b]	Current at corrosion potential	Maximum short-circuit current	Loss of weight [c]
		Ohm-cm	*v*	*v*	*ma*	*ma*	*(mg/cm²)/yr*
64	Docas clay	62	0.31	0.34	2.72	2.19	1,475
103	Billings silt loam	81	.30	.32	3.86	2.85	1,230
45	Unidentified alkali soil	263	.38	.29	2.55	2.20	1,230
56	Lake Charles clay	406	.37	.29	2.92	1.64	1,150
113	Imperial clay	102	.38	.31	2.90	1.70	1,130
57	Merced clay adobe	128	.30	.35	2.00	1.70	1,040
23	Merced silt loam	278	.34	.22	1.88	1.05	722
51	Acadia clay	190	.12	.31	1.20	.80	708
8	Fargo clay loam	350	.12	.37	.78	.55	580
111	Fresno fine sandy loam	51	.16	.21	1.20	.60	534
2	Bell clay	684	.14	.33	.90	.54	504
7	Unidentified soil	2,120	.14	.24	.50	.42	370
1	Allis silt loam	1,215	.14	.22	.60	.23	244
41	Summit silt loam	1,320	07	.26	.40	.20	214
20	Mahoning silt loam	2,870	.20	.30	.67	.32	202
25	Miami clay loam	1,780	.01	.32	.005	.003	16

[a] Potential (H scale) between anode and cathode of corrosion cell on open circuit.
[b] Potential (H scale) at intersection of current-density–potential curves.
[c] Calculated from results in a 2-week run.

Data (fig. 76) obtained by Schwerdtfeger [143], with the modified corrosion cell, illustrates the effect of longer periods of time on corrosion of iron or steel. The cell currents were measured with a zero-resistance milliameter without permitting the cells to be on open circuit. It will be noted from the table in the legend of the figure that the electrode weight losses indicate the actual order of corrosivity of the soils, whereas the average cell currents in soils 62 and 26 are in reverse order because of the soil resistivities. However, based on field data (tables 13 and 21) the curves do reflect the effect of time on the rate of corrosion of ferrous materials in the three soils. The field data reveal a fairly constant rate of corrosion of wrought materials exposed to soils 64 and 62 over a period of 14 years and a stifling effect in well-aerated soils similar to soil 26. It will be noted, figure 76, that in soil 26 the cell current gradually decreases, whereas in soils 64 and 62 after the initial decrease the currents are relatively steady.

As a result of these and other experiments, it appears that 6 months is the minimum time required to determine soil corrosion by means of the modified Denison cell. The laboratory results at the conclusion of the tests are based on the weight losses of the cell electrodes. However, periodic measurements of the current indicates the proper performance of a cell; for example, if incorrect polarity, as indicated by a reversal of cathode and anode, or relatively low current is observed in a cell 2 weeks after assembly time, that cell should be replaced. Six months after assembly the corrosion cells are taken apart and the electrodes cleaned. The average combined loss of metal on the anodes and cathodes is used as the corrosion index.

In view of the extensive use underground of such alloys as stainless steel, copper, brass, lead, and zinc, Denison [134] investigated the behavior of these alloys in his cell. As these alloys tend to form protective oxide films in soils, they develop only small potential differences and, as the Denison cell has a high resistance, only a negligible current flow between the electrodes. Under these conditions, the corrosion is due almost entirely to local cell currents and obviously the short-circuit current would not be sufficient to account for the observed corrosion. The type of control for the various metals in different soils was determined by inspection of the current-potential curves of the separate electrodes (figs. 77 and 78) that show corrosion under cathodic and anodic control. Since the corrosion cells produce their own emf, the closed-circuit potentials of the anode and cathode are represented by points in the current-potential curves for the respective electrodes, the exact location of the points depending on the resistance of the cell. To obtain potentials corresponding to currents less than the cell current, a suitable resistance was introduced into the current circuit. For potentials corresponding to higher currents, an external emf was applied.

The type of control is sometimes determined by the character of the soil as is indicated by the behavior of lead in organic soils such as muck (soil 58) and Rifle peat (soil 60). Consideration of the soluble material in these soils (table 6) shows that both soils are very acid and that soil 60 is extremely high in sulfates. The slight anodic polarization shown by lead in soil 58 (fig. 77) is consistent with the known corrosive action on lead of organic acids, produced in the decomposition of wood and other organic matter, which maintain a low concentration of lead ions at the anode. The corrosion of lead in soil 60 was inhibited by the marked polarizing action of sulfate ions as is shown by the curve for the anode (fig. 78).

The curves for stainless steels in soils 43 and 13 represent the behavior of this alloy in the active state (fig. 77) and in the passive state (fig. 78). While the anode is in the passive state, even a slight flow of current is seen to have a marked effect on its potential, whereas in the active state, the anode exhibits the characteristic behavior of ordinary carbon steel. The shift from the passive to the active condition in soil 43 (fig. 77) results from the inability of the oxide film to maintain a state of repair in a reducing environment high in chlorides and sulfates. Reactions of this type were discussed by Hoar [260].

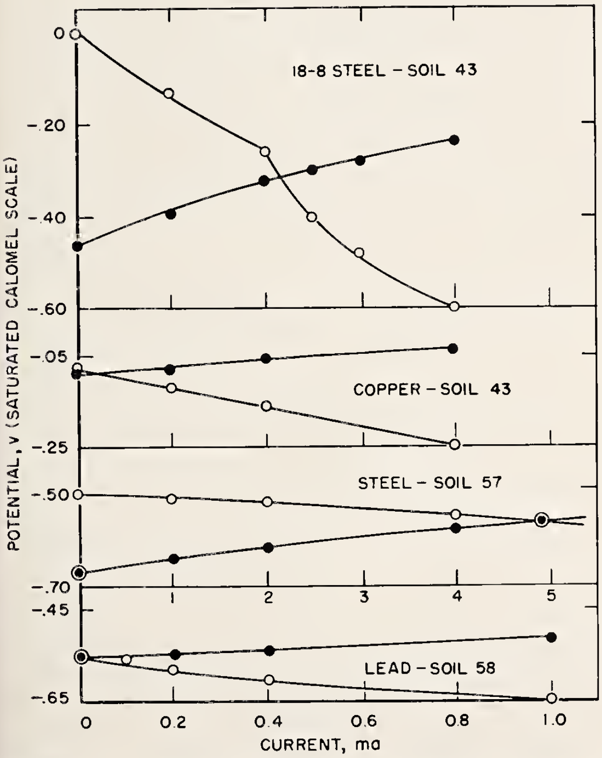

Figure 77. *Current-potential curves illustrating corrosion under cathodic control [134].*

●, Anode; ○, cathode.

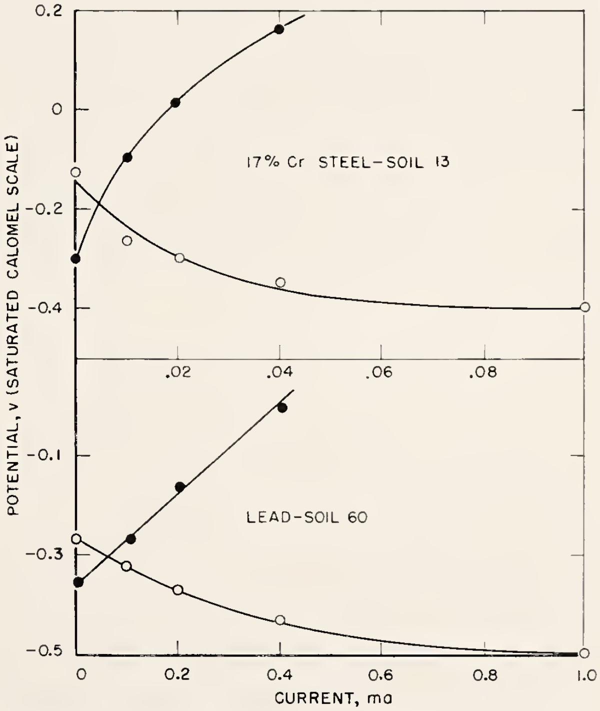

Figure 78. *Current-potential curves illustrating corrosion under anodic control [134].*

●, Anode; ○, cathode.

TABLE 97. *Control of the corrosion rate of metals in different soil environments* [*134*]

Material	Environment							
	Alkali carbonate		Chloride	Sulfate	Chloride and sulfate	Reducing, with organic acids	Reducing, with organic acids and sulfate	Reducing with organic acids chloride and sulfate
	Good aeration	Poor aeration						
	Soil							
	13	23 [a]	64	57	56	58	60	43
Low-carbon steel	Cathodic [b]	Cathodic	Cathodic	Cathodic	Cathodic	Cathodic	Cathodic	Cathodic
Steel with 17% Cr	Anodic	Anodic	Anodic	Anodic	Anodic	Anodic	Anodic	Do
18-8 steel	do	do	do	do	do	do	do	Do
Copper	do	do	do	do	do	Cathodic	Cathodic	Do
Brass (60-40)	do	do	do	do	do	do	do	Do
Zinc	Cathodic	Cathodic	Cathodic	Cathodic	Cathodic	do	do	Do
Lead	Anodic	Anodic	Anodic	Anodic	Anodic	do	Anodic	Anodic

[a] Sulfates also present.
[b] Anodic with exceptionally good aeration.

Table 97 shows the type of control under which the materials corrode in the different soil environments. The corrosion reaction of zinc and plain-carbon steel is under cathodic control in all of the soils. In an environment containing chloride, sulfate, carbonate, and bicarbonate ions, and deficient in oxygen, the primary reaction products of steel and zinc are soluble and consequently are readily removed from the anode surface by diffusion. Under these conditions, a fairly large negative potential may be maintained at the anode, even at relatively high-current densities. Conversely, in very porous soils which are either strongly alkaline or are deficient in soluble salts, the type of control in the case of steel and zinc shifts from cathodic to anodic. The fact that the corrosion of zinc is generally under cathodic control naturally has an important bearing on its use as a protective coating for steel and as an anode in cathodic protection installations.

c. Correlation Between Results from 6 Months in the Corrosion Cell and 10 Years in Field Exposures

Certain factors that are controlled in the laboratory cannot be controlled in the field, and, consequently, an exact correlation between the results of laboratory and field exposure tests can not be expected. However, a laboratory test should give a general indication as to whether, under roughly comparable field conditions, corrosion will be severe, moderate or negligible. To evaluate the laboratory corrosion test as a measure of the relative corrosiveness of soils, Schwerdtfeger [143] compared the weight losses of steel after exposure for 6 months in the modified Denison cell and for 10 years in the same soils in the field. Four cells were set up, according to the procedure described in appendix 5, for each of the soils tested which were selected to cover the range of corrosiveness of all soils in the NBS field tests. Duplicate determinations were made in the laboratories of the Waterways Experiment Station, Corps of Engineers, U. S. Army, for 9 of the 10 soils used by the Bureau and determinations of 5 other soil types.

The data show that a good correlation exists between the NBS laboratory data and the actual field weight losses. An equally good correlation exists between The Waterways Experiment Station data and the field data with the exception of the laboratory data for soil 64. The soil sample from this site, although supplied by the Bureau, was apparently not typical of the soil at the field test site. All the other laboratory data when averaged showed a good correlation with the field data. This correlation was used by Schwerdtfeger in setting up an equation of best fit [148], between the laboratory and field weight losses, which appeared to be applicable to all soils, whatever their degree of corrosivity. The calculated weight losses shown in table 98 were obtained by the use of the equation.

Following a statistical procedure based on the test of Croxton and Cowden [261], Schwerdtfeger also found that a fair correlation exists between the weight losses and maximum pit depths of wrought ferrous metals buried in 58 different test sites for 10 years. By making use of this correlation, it was shown that the laboratory weight losses obtained with the modified Denison cell can be used to estimate probable maximum pit depths (table 98) on ferrous metals after field exposure for 10 years.

TABLE 98. *Correlation between combined laboratory and NBS field data*

Soil		Location of site	pH	Resistivity at 60° F	Aeration[b]	Weight loss of steel electrodes after 6 months of laboratory exposure			Weight loss of wrought ferrous specimens after 10 years of field exposure		Maximum pit depth on wrought ferrous specimens after 10 years of field exposure	
No.[a]	Type					National Bureau of Standards	Waterways Exp. Station	Average[c] w	Actual	Calculated[c] W_{10}	Actual	Calculated[d] P_{10}
				Ohm-cm		*oz/ft²*	*oz/ft²*	*oz/ft²*	*oz/ft²*	*oz/ft²*	*Mils*	*Mils*
4	Chester loam	Jenkintown, Pa	5.6	6,670	G	0.61	0.91	0.76	6.4	5.3	75	63
5	Dublin clay adobe	Oakland, Calif	7.0	1,346	P	1.97	1.41	1.69	6.4	13.2	50	104
8	Fargo clay loam	Fargo, N. Dak	7.6	350	P	.89	--------	.89	5.5	6.4	79	69
15	Houston black clay	San Antonio, Tex	7.5	489	P	--------	1.27	1.27	7.0	9.7	63	86
25	Miami clay loam	Milwaukee, Wis	7.2	1,780	F	.20	.86	.53	2.6	3.4	49	53
26	Miami silt loam	Springfield, Ohio	7.3	2,980	G	.56	.48	.52	2.5	3.3	59	53
32	Ontario loam	Rochester, N. Y	7.3	5,700	G	.37	.56	.46	3.1	2.8	55	50
41	Summit silt loam	Kansas City, Mo	5.5	1,320	F	--------	.32	.32	6.1	1.6	64	44
43	Tidal marsh	Elizabeth, N. J	3.1	60	VP	1.36	2.18	1.77	12.6	13.9	112	108
55	Hagerstown loam	Lock Raven, Md	5.8	5,213	G	--------	.43	.43	3.2	2.5	75	49
56	Lake Charles clay	El Vista, Tex	7.1	406	VP	2.17	3.23	2.70	21.2	21.7	132	148
61	Sharkey clay	New Orleans, La	5.9	943	P	--------	1.69	1.69	7.1	13.2	72	104
62	Susquehanna clay	Meridian, Miss	4.1	6,922	F	1.05	.91	.98	6.2	7.2	78	73
64	Docas clay	Cholame, Calif	8.3	62	F	2.53	1.49	2.53	30.0	20.3	145	141
65	Chino silt loam	Wilmington, Calif	7.2	148	F	--------	1.03	1.03	11.9	7.6	100	75

[a] See table 6 for properties of the soils. [b] Aeration of soils: G, good; F, fair; P, poor; VP, very poor. [c] $W_{10} = 8.45w - 1.1$, where W_{10} is the anticipated weight loss of wrought ferrous specimens after 10 years of field exposure, expressed in ounces per square foot; w is the mean combined weight loss in 6 months of the anode and cathode of 4 corrosion cells, expressed in ounces per square foot.

[d] $P_{10} = 43.9w + 30$, where P_{10} is the probable maximum pit depth in mils on an exposed area of 0.4 ft.²; w is as expressed in footnote (c).

It was realized that the practical value of tests made with the laboratory corrosion cell would be greatly enhanced if it were possible to extend the estimate of weight loss and pitting to be expected in the field for longer periods of exposure and on larger exposed areas. Several investigators (see section 8.6) derived exponential formulas based on limited field data to show such relationships. Some exponents used in these equations were derived for individual soils, and some were approximated from average values of a large number of soils. By utilizing the equations developed at the Bureau [106, 147] and by suggesting values for the exponents based on different soil properties, Schwerdtfeger [143] set up equations whereby weight losses and maximum pit depths as indicated by the laboratory corrosion cell could be extrapolated to any desired area of specimen and period of exposure within reasonable limits.

In order to detect differences in the corrodibility of commonly used plain ferrous materials, corrosion cells [143] were assembled with both steel and cast iron electrodes in the same soils. These laboratory results correlated favorably with comparable 12-year field exposures results (see section 8.4).

19.7. Value of Soil-Corrosivity Tests

The need for field tests of long duration was recognized early in the NBS program. This led to attempts by many investigators to develop determinations, in the laboratory or in the field, of individual properties of the soils that could replace the time-consuming field exposures as indices of soil corrosivity. A comprehensive evaluation of all the test procedures proposed up to that time was published in 1939 by Logan and Koenig [262], as described in the ensuing paragraphs.

In 1937, the Magnolia Pipeline Company uncovered 25 miles of 8-in. asphalt-coated steel line that had been buried for 16 years in southeastern Texas. As a measure of the corrosive action, Logan and Koenig recorded the depths of the three deepest pits, and the number of punctures if any, in each 20-ft length of pipe. They used the Shepard resistivity apparatus to determine soil resistivity at pipe depth, at 200-ft intervals along the right-of-way. The soils were identified according to the U. S. Department of Agriculture classification system, and soil samples taken at pipe depth were sent to the laboratories of the National Bureau of Standards for determinations of hydrogen-ion concentration, total acidity, resistivity at normal moisture content, Columbia Rod test (modified for laboratory use), Putman test, nipple-and-can test, and the original Denison electrolytic cell test.

In attempting to correlate these data with the known corrosivity, as indicated by pit-depth measurements, Logan and Koenig concluded that correlation on a spot basis, i.e., for a single length of pipe or an individual soil sample location, was impossible. However, when the pipeline area was divided into five arbitrary zones, according to corrosivity or pit depths, it was found that all of the methods used show, in a general way, the corrosiveness of the soils, but that no test correctly determined the corrosivity of every soil series and some correctly classified only two of the soils. The

Denison cell test was the most accurate in ranking the soil zones in their order to corrosiveness. For the highly regarded resistivity determinations, the data showed a wide range of pit depths associated with each value of resistivity, probably because of local or seasonal variations in pitting attack that was not indicated by a single or average resistivity determination. Within these limits, resistivities determined in the field, with Shepard's apparatus, and in the laboratory were equally satisfactory. Some of the data on which Logan and Koenig based their conclusions are shown in figure 79 and tables 99 and 100.

As a result of these studies, Logan and Koenig concluded that: (a) the soil types of a series usually do not differ greatly in corrosiveness; (b) some degree of correlation with corrosivity can be established for single property determinations of selected soils; (c) no single property determination can be correlated with corrosiveness of all the soil types encountered in the United States; (d) the Denison cell test has the best potentialities for correlation with soils in general, because it is, in effect, an accelerated corrosion test rather than a determination of a single property of the soil; and (e) correlations can be established better on the basis of an area or zone than on a particular spot. As pointed out by Logan and Koenig, the last conclusion is in accord with the general practice of pipeline engineers, who separate the soils or areas traversed by their line into 4 or 5 groups, with respect to corrosion, because it is impractical to provide more than that number of degrees or kinds of protection.

Other comparisons of soil resistivity with pit depths on pipelines have been reported by Weidner and Davis [263], Fitzgerald [264], Gill and Rogers [83], and Ewing [265]. Putman [158], Denison and Darnielle [131, 134], and Schwerdtfeger [143] have made correlations between the results of their soil-testing methods and the loss in weight and pit depths of the National Bureau of Standards field specimens.

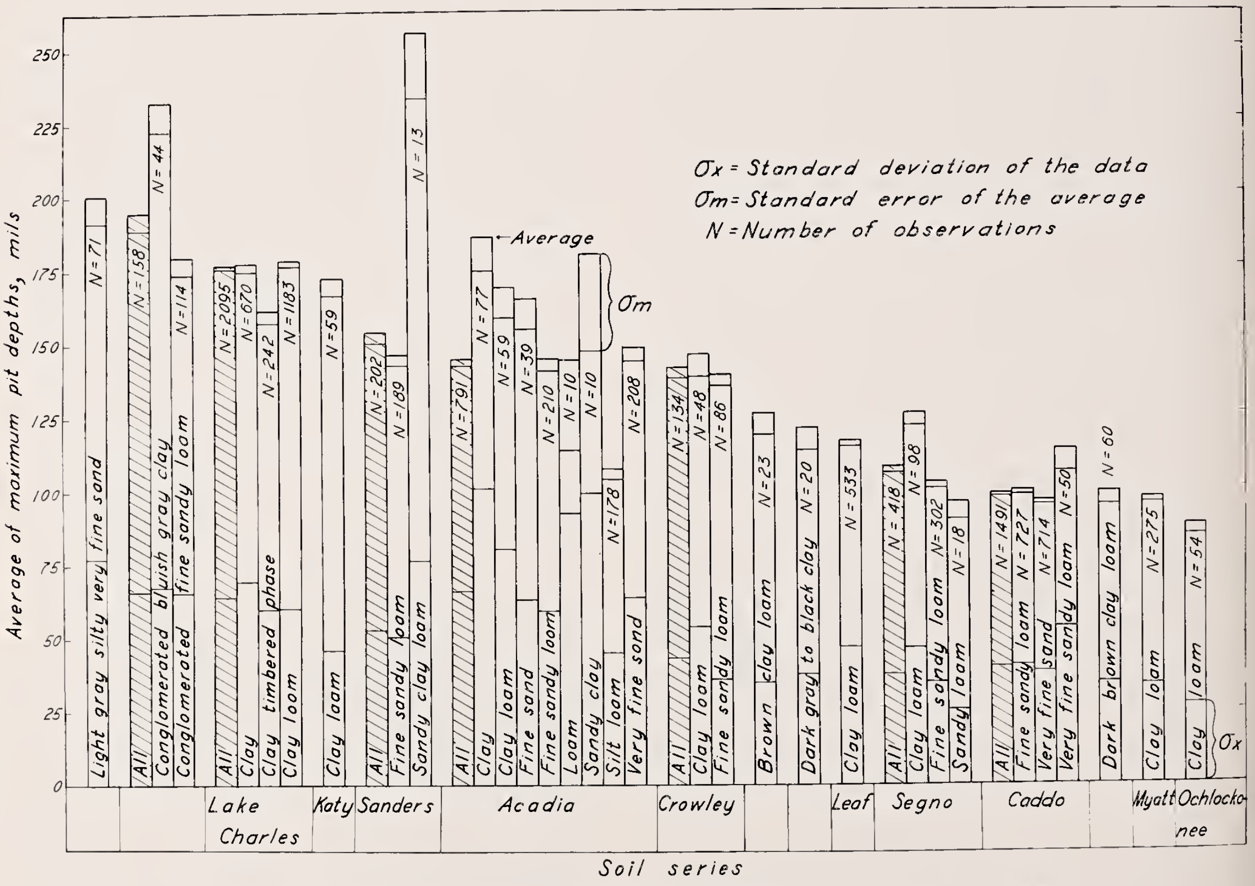

FIGURE 79. *Maximum pit depths on sections of pipes exposed to different soil types [262].*

TABLE 99. *Arbitrary ranges of values of corrosion data for grouping of soils with respect to their corrosivity*

Soil corrosivity group	Pit depth	Shepard resistivity meter	Resistivity at moisture equivalent	Total acidity	Modified Columbia rod test	Putman test	Nipple-and-can test	Denison electrolytic cell
	Mils	*Ohm-cm*	*Ohm-cm*	*mg-eq/100 g soil*	*ma*	*ma*	*g*	*ma/dm²*
1	<100	>5,000	>10,000	<4.0	<1.75	<3.75	<0.30	<3.0
2	101 to 125	2,000 to 4,999	5,000 to 9,999	4.1 to 8.0	1.76 to 2.50	3.76 to 5.00	0.31 to 0.35	3.1 to 6.0
3	126 to 150	1,000 to 1,999	2,000 to 4,999	8.1 to 12.0	2.51 to 3.00	5.01 to 10.00	.36 to 0.40	6.1 to 9.0
4	151 to 200	700 to 999	1,000 to 1,999	12.1 to 16.0	3.01 to 4.00	10.01 to 15.00	.41 to 0.80	9.1 to 15.0
5	>200	<700	<1,000	>16.0	>4.00	>15.00	>0.80	>15.0

TABLE 100. *Comparison of methods of testing soils on basis of correct arrangement of soils in the rank, or order, of corrosiveness [262]*

Soil series	Soil rank, or order, of corrosiveness		Shepard resistivity meter			Resistivity at moisture equivalent			Total acidity			Modified Columbia rod test			Putman test			Nipple-and-can test			Denison electrolytic cell		
				Deviation			Deviation			Deviation			Deviation			Deviation			Deviation			Deviation	
	By adjacent maximum pit depth	By average maximum pit depth	Assigned rank	By adjacent maximum pit depth	By average maximum pit depth	Assigned rank	By adjacent maximum pit depth	By average maximum pit depth	Assigned rank	By adjacent maximum pit depth	By average maximum pit depth	Assigned rank	By adjacent maximum pit depth	By average maximum pit depth	Assigned rank	By adjacent maximum pit depth	By average maximum pit depth	Assigned rank	By adjacent maximum pit depth	By average maximum pit depth	Assigned rank	By adjacent maximum pit depth	By average maximum pit depth
Acadia	11	9	9	−2	0	5	−6	−4	10	−1	+1	10	−1	+1	8	−3	−1	10	−1	+1	9	−2	0
Brown	8	7	11	+3	+4	11	+3	+4	4	−4	−3	9	+1	+2	11	+3	+4	9	+1	+2	6	−2	−1
Caddo	4	3 and 4	1	−3	−2	1	−3	−2	6	+2	+2	1	−3	−2	1	−3	−2	1	−3	−2	3	−1	0
Conglomerate	9	11	7	−2	−4	8	−1	−3	1 and 2	−7	−9	3	−6	−8	7	−2	−4	11	+2	0	11	+2	0
Crowley	7	8	4	−3	−4	7	0	−1	9	+2	+1	8	+1	0	4	−3	−4	2	−5	−6	8	+1	0
Dark brown	1	3 and 4	2	−1	−1	4	+3	0	1 and 2	0	−1	5	+4	+1	3	+2	0	5	+4	+1	1	0	−2
Lake Charles	10	10	8	−2	−2	9	−1	−1	8	−2	−2	11	+1	+1	10	0	0	7	−3	−3	10	0	0
Leaf	6	6	6	0	0	6	0	0	12	+4	+4	6	0	0	6	0	0	6	0	0	4	−2	−2
Light gray	12	12	12	0	0	12	0	0	3	−9	−9	12	0	0	12	0	0	12	0	0	12	0	0
Myatt	2	2	10	+8	+8	10	+8	+8	5	+3	+3	7	+5	+5	9	+7	+7	3	+1	+1	7	+5	+5
Ochlockonee	3	1	3	0	+2	2	−1	+1	11	+8	+10	2	−1	+1	2	−1	+1	4	+1	+3	2	−1	+1
Segno	5	5	5	0	0	3	−2	−2	7	+2	+2	4	−1	−1	5	0	0	8	+3	+3	5	0	0
Σ				24	27		28	26		44	47		24	22		24	23		24	22		16	11
Rank, or order, of effectiveness of test method				2	6		6	5		8	8		2	2		2	4		2	2		1	1

20. Determination of the Condition of a Pipeline

20.1. Location of Corroding Areas on Pipelines

Soil tests such as those described in the preceding sections are used to locate places along a right-of-way where corrosion may be expected due to soil characteristics. However, it has previously been pointed out that the effects of the soil are modified by the way in which a trench is backfilled, by the interaction of different adjacent soil types, by electric currents picked up by the pipeline, and by other factors previously discussed. Therefore, after a pipeline has been laid, it is advisable to determine not only if it lies in potentially corrosive soil, but also to follow the progress of corrosion. Several methods based on the association of corrosion with differences of potential and a flow of electrical current have been devised for this purpose.

a. Measurement of Potentials and Currents

Investigations by the Bureau [80, 266] showed that measurable electric currents exist on pipelines and that there is a relation between such currents and corrosion. Abrupt changes in magnitude of these currents indicated that the currents originate, largely from galvanic effects, and disappear at the pipe surface. On some sections of pipelines current was found to flow from both directions, in which case maximum corrosion usually occurred. Moreover, these currents remained substantially constant day after day, except for the fluctuations referred to. Soil resistivity measurements along the lines investigated showed that invariably the abrupt discharges of current from pipe sections were in soils of low resistivity, while the sections in which current collected or remained unchanged were in soils of moderate or high resistivity. Because destructive corrosion of pipelines is largely confined to local areas of comparatively small extent, measurements of line currents and of soil resistivity afford a means of locating the most corrosive areas on existing pipelines.

If the conductivity of a pipe material is known, the current in the pipe can be calculated, by the potential-drop method, from the difference of potential measured on the pipe between two points a known distance apart. The measurement of the current in a line from point to point provides data that indicate whether the line is collecting or discharging current. A discharging section, indicated by more negative potentials, is indicative of an anodic area or active corrosion attack, and is a potential point of failure. In using the potential-drop method for locating corrosive areas, measurements should be made at definite intervals, such as ⅛ to ¼ mile, and when one of these sections shows a pronounced loss of current it should be further subdivided until the exact point where the current is discharging into earth is located. Earth resistivity measurements can then be made to ascertain the extent of the corrosive soil area.

The greatest problem involved in measuring pipeline currents by the potential-drop method is that of making good electrical contact with pipe because any resistance, such as a rust film, introduced into the circuit at the point of contact with the pipe will affect the accuracy of the measurements. Unless the pipe is uncovered, this is best accomplished by driving a bar into the earth down to the top of the pipe and then inserting in the hole a hardened steel point or drill which is turned until good contact is made with the pipe. Further, because the potential differences to be measured are usually less than 1 mv, it is necessary to use a meter of high sensitivity, and care must be taken to avoid spurious potentials caused by thermal and other effects.

Measurements of pipeline currents by the potential-drop method have been described by several investigators [80, 266, 267, 268, 269]. Mudd [81, 270] successfully detected corrosion on pipelines with a combination of current and potential measurements. Schlumberger and Leonardon [271] described a method of locating corrosion by observations at the surface of the earth and developed apparatus for this purpose. Current flowing to or from pipes can be measured directly by apparatus devised by Pearson [272], and by the earth-current meter developed by McCollum and Logan [20]. All these methods and apparatus, except the last one, measure the current discharged from a considerable area of pipe and disclose only the average current density in the length of pipe considered. Such techniques, therefore, give data for computing the average rate of loss in weight or penetration but do not show directly the maximum rates. For small areas, such as that of a few feet of small diameter pipe, exposed to approximately uniform conditions, the ratio of the maximum to the average penetration is in the order of 10 to 1. However, for large areas, such as that of a 20-ft length of 8-in. pipe, the ratio may be much larger. In a pipe with a bituminous coating, the current may be discharged from a very small area where the coating has been injured.

b. Coupons

Coupons are small iron or steel plates buried at arbitrary intervals near a pipeline and at pipe depth to determine the rate of corrosion to be expected on the structure. The corrosion occurring on coupons that are not electrically connected to the pipe is attributed to the corrosive action of the soil only. If the coupon is electrically connected to the pipe, the corrosion may be due to stray and long line currents in the soil, as well as to the soil. In the latter case, coupons may be used to indicate whether the pipeline is discharging or collecting current at certain points. Schneider [273] cited a number of cases of close agreement between pipe life and predictions based on the use of coupons.

20.2. Inspection as a Means of Determining the Condition of a Pipeline

As it is usually impractical to examine an entire pipeline periodically, the problem arises of the number and extent of the examinations necessary to furnish representative data. In 1923, Gill [274] concluded from statistical considerations, that a line should be inspected at equally spaced points, and that 2,000 ft was the greatest permissible distance between inspection points necessary to estimate the average condition of the line. In 1939, Logan and Koenig [275] made statistical studies of pit depths on several hundred miles of oil pipelines, including one 200-mile length, and reported the effect of the different factors on the results of inspections, including the space interval between the sections inspected, the number of inspection points, the location of the starting point from which equally spaced inspections were made, and the effect of the size of the area inspected on the observed average maximum pit depth.

To bring out possible correlations between the various measurements, the deepest pit on each 20-ft joint along 25 miles of a 26-year-old steel line (8-in. diameter) was measured and averaged to represent the actual condition of the pipeline. This true average value is shown in table 101 along with the estimated averages of the maximum pit depths on the joints of pipe separated by equal distances of ⅛, ¼, ½, and 1 mile, respectively. The data show that a reduction in the number of inspection points from 6,384 to 25 along the line did not appreciably affect the average pit depth data, and that the standard error of the average increases as the number of inspection points is decreased. For these data, the true average pit depth lies within the estimated averages plus or minus their standard error regardless of the number of inspection points. Statistical considerations show that the probability is about 0.95 that the average obtained by the complete inspection is within the estimated average plus or minus twice its standard error. It will also be noted that the standard deviation of the data, which is an indication of their dispersion, is nearly the same for all inspection frequencies, i.e., for the line under consideration the 25 inspections 1 mile apart gave a good approximation of conditions on the line.

TABLE 101. *Effect of the number of inspection points on the average of the observed maximum pit depths on 20-ft sections of a 25-mile pipeline (8-in. diameter)*

Distance between inspection points	Number of inspections	Average for the deepest pits on each 20-ft joint	Standard deviation of the average	Standard error of the average
ft		*Mils*	*Mils*	*Mils*
20	6,384	139	65	0.8
660	200	137	63	4.5
1,320	100	143	70	7
2,640	50	143	70	10
5,280	25	138	66	13

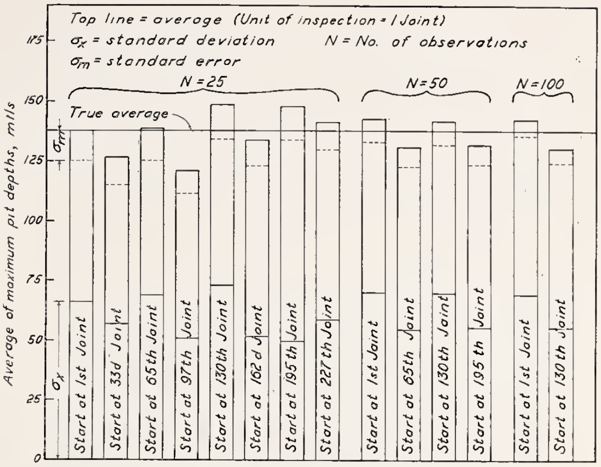

FIGURE 80. *Effect of the starting point and the number of inspections on the observed average of maximum pit depths on sections of a pipeline [275.]*

A comparison of the maximum pit depths for different starting points of equally spaced observations on the 25-mile pipeline is shown in figure 80. Each of the first eight columns represents the average of the depths of the deepest pit on each of 25 joints (20-ft lengths) of pipe spaced at 1-mile intervals. The different columns represent the data for eight different starting points separated by ⅛ mile intervals. The next four columns show the results of four sets of 50 inspections each on the same line, spaced at ½-mile intervals. The last two columns show the results of inspections made at ¼-mile intervals, using two starting points. The horizontal line crossing the figure indicates the average of the deepest pit on each 20-ft joint along the entire line. It is seen that in all cases the estimated averages of the deepest pits differed from the true average by less than twice their standard errors. Hence, the probability of there being a significant difference in the averages is small, and the data show that the average was independent of the starting point.

Measurements of the deepest pit on each joint of pipe along 200 miles of a pipeline and at space intervals of 1, 2, 3, and 5 miles, using eight different starting points, showed that the reliability of the average, as indicated by the standard error, decreases appreciably with inspection intervals greater than 1 mile.

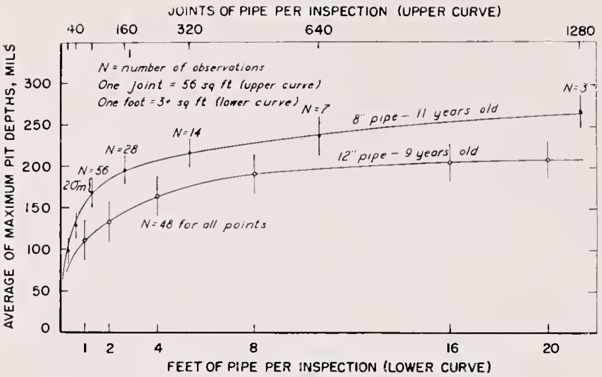

FIGURE 81. *Relation of area of pipe inspected to the maximum pit depths on each area [275].*

The data in figure 81 show that the relation between the size of the area inspected, the depth of the deepest pit and the effect of the area on the reproducibility of the data are important considerations in determining how much pipe should be exposed at each inspection point and the frequency of inspection intervals. The lower curve, based on data from a 9-year-old 12-in. steel line exposed to a heavy clay soil, shows the average maximum pit depths on similar areas from inspections at 48 different points on the line. First, 1 ft of pipe was uncovered and the depth of the deepest pit was measured. The trench was then extended 1 ft and the depth of the deepest pit on the 2-ft section was measured. Similarly, the depth of the deepest pits on greater lengths up to one joint of pipe (20 ft) was measured. The curve indicates that the average depths of the deepest pits increase as the area inspected is increased, but that when a large number of observations (48) is made, the standard error of the average remains practically constant. The average of the values obtained by a large number of inspections of 1-ft lengths is almost as representative as the averages of the values obtained on entire joints of pipe. This conclusion would not hold if only a few inspections of 1-ft lengths of pipe were made, as the pit depth on a length of pipe varies greatly from foot to foot. The upper curve, based on data from an 11-year-old 8-inch steel pipeline exposed to a sandy loam soil, shows that each inspection point would have to include a large number of lengths of pipe before the value of the average maximum pit depth would become substantially constant. The curve also indicates that when this area is reached, the number of observations required for a specified degree of reproducibility decreases as the area examined is increased. Similar studies on a number of pipelines under a wide range of soil conditions show no exception to this relation.

From these studies Logan and Koenig [275] concluded that: (1) the simplest way to determine the condition of a pipeline is to inspect it at equally spaced intervals; (2) the number of inspections to be made depends on the required precision of the data; (3) if a number of observations are made within 1-mile intervals, starting the observations at different points on the line does not produce appreciable differences in the results; (4) if the number of inspections is sufficiently large (at least one 20-ft pipe joint per mile) for an accurate determination of the condition of the line, the size of the area inspected is unimportant, but to maintain a specified degree of precision the number of inspections required increases as the area inspected decreases.

Logan and Koenig also suggested that, as corrosion appears to be characteristic of the type of soil to which the pipe is exposed, a point previously discussed, and as the same type may occur in several places along a pipeline, the number of inspections necessary for determining the condition of the line might be reduced by first identifying the soils traversed by the line and then making only a sufficient number of inspections in each soil to establish its corrosiveness. This procedure is especially helpful in determining the boundaries of the severely corroded sections of the line.

In order to maintain a pipeline in repair some inspection method is required. Conclusions on the experimental data discussed in the previous paragraphs has shown that pipe should be inspected at equally spaced distances or with regard to soil types to maintain a serviceable condition of the line. A practical application of routine inspection maintenance of pipelines in controlling leaks is demonstrated in the practice described by Van de Water [276]. From 7 to 10 feet of pipe are exposed for inspection at places where abnormal corrosion is likely, based on the soil profile of the pipeline right-of-way, such as at low spots, bogs, swamps, highway and railroad crossings, and locations where a leak would be particularly dangerous. As a result of such inspection procedures 10 percent of a line extending through Pennsylvania and Ohio has been protected by boxing the pipe and filling the box with asphalt, the protected sections ranging from 20 to several hundred feet in length.

However, the American Petroleum Institute and the Interstate Commerce Commission [277] did not consider the inspection method essential for the purpose of determining the condition of a line for rate-making purposes, and proposed an empirical standard for determining pipeline life based on the experience of the engineers and the age of the line. The decision was reached partly because the cost of an adequate number of inspections would be excessive, and partly because for rate-making purposes age was considered to be the controlling factor. In the case of one pipeline [277], an agreement was reached that the life of new wrought iron and steel pipe would be considered to be 33⅓ years and that the life would be increased 3 to 7 years by bituminous protective coatings, depending on the number of reinforcing layers. Obviously, this was an arbitrary approach for determining the physical condition of a pipeline that did not consider reconditioning, protection, or repairs.

21. Stray-Current Electrolysis

Electrolysis is the term used to describe the results of the passage of an electric current from one electrode to the other through an electrolyte. When the electrodes are insoluble, i.e., non-ionizable, the current is carried by ions derived from the electrolyte, for example, in an aqueous electrolyte the current is carried primarily by hydrogen and hydroxyl ions, which are derived from the water and are discharged, respectively, by the passage of the current, at the surface of the insoluble cathode and anode. If the electrodes are soluble in the electrolyte, as in the case in most corrosive reactions, metallic ions are liberated from the anode to assist the hydrogen ions (from the water) in carrying positive charges to the cathode. This loss of metallic ions from the anode, with its accompanying loss of weight or development of pits, is the principal damage resulting from electrolysis, although the process is complicated by side reactions with other ions that may produce chemical or electrochemical effects that stimulate or retard reactions at both the anode and cathode.

At the initiation of the National Bureau of Standards program it was thought that the presence of stray currents, for example, from the grounding of street-car systems or leakage from street-car tracks and power lines, was the principal or sole cause of corrosion of pipelines, cable sheaths, street-car rails, and other structures underground or in contact with the ground. It was soon evident that serious corrosion of metals in contact with soils could and did occur in the absence of any stray currents, because of electrochemical reactions of local couples at the surface of a piece of metal or of chemical reactions with the dissolved acids, salts, or alkalis of the soil. When stray currents are present they intensify and localize the corrosive effects.

Interest in the effects of stray currents was intense when the Bureau's studies were initiated in 1910, and during the period of development and expansion of the electric street-railway industry in this country. Interest in stray-current electrolysis subsequently declined, owing to a better understanding of the problems by the utility engineers, but in the past 30 years there has been a revival of interest in the subject as a result of such factors as the growth of cross-country pipelines, transmission of electric power and electrification of railroad systems. Although the Bureau's investigations were confined to street and suburban railway systems, the principles are applicable to electrified railroad systems that use considerably higher electrical power for their operation, even though alternating currents are used on many of the more recent installations. Because of the revived interest in the subject, it seems advisable to review and summarize the 17 published papers [5 through 21] that recorded results of the Bureau's studies of stray-current electrolysis. These papers are now out of print and, consequently, are available only in bound volumes in technical libraries. However, the 1921 Report of the American Committee on Electrolysis [23] is still available, at $1.00 per copy, from the American Institute of Electrical Engineers, 33 W. 39th Street, New York, N. Y.

21.1. Surface Insulation of Pipes as a Means of Preventing Electrolysis

McCollum and Peters [5] conducted tests on paints, bitumens, dips, and fabricated wrappings to determine their protective value as pipe coatings when subjected to the action of stray-current electrolysis. Painted specimens were submerged in water and in dilute acid. Some were subjected to a positive and some to a negative potential of 4 v, while others were not subjected to any electrical stress. Periodic measurements of the electrical resistance of each specimen were made, and the time of failure, as indicated by the first appearance of current flow, was noted. Bituminous and other coating compounds were tested alone and in combination with various wrapping materials, by submerging them in water and subjecting the coatings to positive and negative potentials of from 4 to 15 v. Failure was indicated by the first appearance of current flow. A number of wrapped specimens were buried in the soil and tested in the same manner as were those submerged in water. The authors concluded that all of the pipe paints, dips, and wrappings that were investigated were of no value whatever for protecting pipes from electrolysis when applied in positive areas, where the current leaves the underground metallic structure to return to the power houses. If, however, they are applied in negative areas, they may be of considerable temporary value in reducing the current picked up by the pipe, and in that way indirectly may reduce damage in positive areas.

These tests are not to be considered as an evaluation of the coatings for protecting metals from ordinary soil corrosion, as the tests were designed solely for the purpose of evaluating these coatings as protection against stray currents.

21.2. Electrolysis in Concrete

As a result of extensive experiments to investigate the damage caused by stray currents to structures embedded in or reinforced with concrete, Rosa, McCollum, and Peters [6] concluded:

(1) Aside from slight heating, which is usually negligible, the only effect which an electric current has on unreinforced concrete is to cause a migration of the water soluble elements. Consequently, the ultimate effect of current flow on the physical properties of the concrete is similar to that of slow seepage, which also removes the water-soluble elements. Nonreinforced concrete buildings are therefore immune from trouble due to stray earth currents. They might, however, be injured by the grounding of power wires within the structure, since these or the inclosing conduits would then act as electrodes.

(2) Insoluble anodes and metals that form soluble corrosion products never caused cracking of concrete as a result of the passage of an electric current.

(3) The passage of current under high potential gradients (100 to 240 v/ft) from an iron anode embedded in wet concrete caused cracking of the surrounding concrete within 24 to 96 hr. No cracking of the concrete was observed in similar specimens, over a period of 7½ months, when the potential gradient was about 60 v/ft.

(4) The cracking of reinforced concrete due to the passage of electric current was attributed to oxidation of the iron anode following electrolytic corrosion. The oxides formed occupy 2.2 times as great a volume as the original iron, and the mechanical pressure resulting from this has been found to reach values as high as 4,700 lb/in.^{2}, more than sufficient to cause the concrete to crack open.

(5) Corrosion of iron anodes, even in wet cured concrete, was very slight at temperatures below 45°C (113°F) because of the inhibiting effect of the calcium hydroxide and possibly other alkalies in the concrete.

(6) The rapid destruction of the anode specimens in moist concrete at potential gradients above 100 v/ft was attributed to the heating effect of the current, which raised the temperature above 45°C. If the specimen was artificially cooled no appreciable corrosion of the anode occurred, and no cracking of the concrete resulted.

(7) Because the passivity of iron in concrete was due chiefly to the calcium hydroxide present it appeared probable that old structures in which the calcium hydroxide had been largely converted into calcium carbonate would be more susceptible to the effects of electric currents than comparatively new concrete with which the experiments were made.

(8) The addition of a small amount of sodium chloride (a fraction of 1 percent) to concrete (as is frequently done to prevent freezing while setting) has a twofold effect; it greatly increases the initial conductivity of the wet concrete, and it destroys the passive condition of the iron at ordinary temperatures, thus greatly increasing the rate of corrosion and consequent tendency of the concrete to crack. Hence, salt should never be used in structures that may be exposed to electrolytic action. Further, reinforced concrete structures built in contact with sea water, or in salt marshes, are more susceptible to electrolysis troubles than structures not subjected to such influences.

(9) Specimens of wet concrete carrying currents show a hundredfold or more decrease in conductivity in the course of a few weeks due to a number of causes including the precipitation of calcium carbonate within the pores of the concrete thus plugging them up. A slight amount of salt tends to prevent this precipitation and interferes with the decrease of conductivity. This further emphasizes the detrimental effect of salt.

(10) There was a definite softening of the concrete near the cathodes, when reinforcing iron was made cathodic, resulting in practically complete destruction of the bond between the reinforcing iron and the concrete. This softening is due to the gradual concentration of sodium and potassium ions near the cathode, by the passage of electric current. In time the alkali becomes so strong as to attack the cement. The softening at the cathode can be reduced by diminishing the sodium and potassium content of the cement, at least below 10 percent of the total salts.

(11) The softening of the concrete begins at the cathode surface and slowly spreads outward, in extreme cases as far as ¼ in. or more. However, the main body of the concrete remains sound as indicated by tests which showed conclusively that the crushing strength of the main body of the concrete is not appreciably reduced, even when the potential gradient is maintained at 175 v/ft for over 1 year.

(12) In general, the cathode effect occurs under conditions that are frequently encountered in practice. Unlike the anode effect that becomes serious in normal concrete only on comparatively high voltages, the cathode effect develops at all voltages used in the experiments, the rate being roughly proportional to the voltage in a given specimen.

(13) Because of the cathode effect noted above, reinforced structures cannot be protected by maintaining the reinforcing material cathodic because such practice would be more dangerous than no protection at all.[13]

(14) If reinforced concrete could be thoroughly waterproofed, it would greatly increase its resistance and diminish accordingly the danger from either the anode or cathode effects. It should be emphasized, however, that waterproofing to prevent electrolysis is a much more difficult matter than waterproofing to maintain a moderate degree of dryness.

(15) Copper-clad steel or aluminum appeared to be impracticable as reinforcing materials, as both copper and aluminum are attacked by the alkali in the concrete.

(16) All direct-current electric power circuits within a concrete building should be kept free from grounds. If the power supply comes from a central station the local circuits should be periodically disconnected and tested for grounds and defects in the insulation. In the case of isolated plants, ground detectors should be installed and the system kept free from grounds at all times.

(17) All pipelines entering concrete buildings should, if possible, be provided with insulating joints outside the building. If a pipeline passes through a building and continues beyond, one or more insulating joints should be placed on each side of the building. If the potential drop around the isolated section is large, about 8 v or more, the isolated portion should be shunted by means of a copper cable.

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[13] Tests performed by the Corps of Engineers, U. S. Army [278], in 1954, showed that current densities as low as 20 ma/ft^2 of cathode (concrete-embedded steel) caused appreciable damage to the bond in a 1-year period. These current densities were considerably smaller than any used by Rosa, McCollum, and Peters.

(18) Lead-covered cables entering such buildings should be isolated from the concrete. Wooden or other nonmetallic supports that prevent actual contact between the cable and the concrete will give sufficient isolation for this purpose. Such isolation of the lead-covered cable is desirable for the protection of the cable as well as the building.

(19) The interconnection of all metal work within a building is an advantage where practicable, provided that all pipelines entering the building are equipped with insulating joints and lead cables are taken care of as indicated in the preceding paragraph, but the grounding of such interconnected metal work or any part of it to ground plates or to pipelines outside of the insulating joints is to be avoided.

(20) In diagnosing the cause of damage in any particular case, the fact that a fairly large voltage reading may be obtained somewhere about the structure should not be taken as sufficient evidence, that the trouble is due to electrolysis. The distance between the points, and particularly the character of the intervening medium are of much greater importance than the mere magnitude of the voltage reading. As a precautionary measure, however, all potential readings about a reinforced-concrete structure should be kept as low as practicable.

21.3 Earth Resistance and Its Relation to Electrolysis of Underground Structures

The resistivity of the soil was shown by McCollum and Logan [8] to be of importance with respect to electrolysis of underground metallic structures. The results of measurements on soil samples from widely separated points in the United States showed large variations in soil resistivity and indicated the desirability of a study of local soil conditions in connection with any complete electrolysis survey.

The relation of soil resistivity to electrolysis was considered from the standpoint of leakage from street railway lines using the track for return current. Good rail bonding and well-drained roadbed were shown to be important factors in reducing current leakage from tracks. Stray currents are increased by imperfectly bonded track joints.[14]

The relations of the various factors that affect leakage resistance, i.e., character of the soil, pressure, moisture, temperature, polarization, and surface films, to the electrolysis problem were discussed by McCollum and Logan. It was shown that the moisture and temperature of the soil materially affect the amount of current escaping from the grounded track used as a return circuit, and that these factors should be given due consideration in the interpretation of data obtained during an electrolysis survey.

21.4. Electrolysis and Its Mitigation

Investigations that were confined principally to the study of methods for the prevention of electrolysis in metallic structures, including gas and water systems and lead-covered cables, were discussed by Rosa and McCollum [12], as follows:

(1) By far the greatest portion of damage due to electrolysis is that arising from corrosion of underground pipes and cables. In general, those remedial measures that are applicable to pipe systems should be regarded as a secondary means of mitigation of electrolysis trouble, with the principal reliance on proper construction and maintenance of the railway return circuit. In special cases mitigative measures may be applied to the undergound structures.

(2) The protection of pipes from electrolysis by the use of chemicals, such as lime or other soluble hydroxides which tend to render iron passive when it is anodic, has been found to be of only temporary value. Because of diffusion into the surrounding earth and the infiltration of earth salts, which may have a counteracting influence, the protection afforded by this means is generally too short lived to justify its application.

(3) Conducting coatings, as a means of preventing electrolysis, were impractical. All noncorrodible metals available for this purpose were too expensive for commercial application, and nonmetallic coatings, such as black oxide or particles of coke in combination with a binder, invariably have been harmful in their effects because of their tendency to produce a greatly increased amount of local or galvanic action.

(4) Electric screens have been used in some cases to reduce electrolysis on pipes in close proximity to street-railway tracks or other underground structures to which they tend to discharge current. The most common and effective type of screen is a large pipe inclosing the pipe to be protected. The protected pipe, being electrically connected to the screen, is shielded at the expense of the latter and if the outer pipe is of heavy material, it will afford indefinite protection.

(5) Insulating joints in piping systems have found rather extensive use as a means of interrupting the current flow in pipes and thereby reducing electrolysis. The value of insulating joints as a means of mitigating electrolysis depends upon a large number of factors, including kind of joints, distribution of joints, nature and extent of piping system, and the frequency of metallic connections with other underground systems. Cement joints have a high electrical resistance when compared with lead joints and when properly used will afford satisfactory protection against stray currents. Lead joints cannot be depended upon to remain permanently insulating. A sufficient number of insulating joints should be installed to limit the potential drop across an individual joint to between 0.1 and 0.4 v for cast-iron mains while in wrought iron or steel pipes a voltage not exceeding about one-third of these values should be allowed. The minimum

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[14] The difficulties and uncertainties attending the proper maintenance of rail joints and bonds have been eliminated to a large degree by the modern practice of welding rail joints. Most types of welded joints have a conductivity equal or greater than the continuous rail and are less subject to failure than any other form of rail bond [23].

values apply to pipes in low-resistance soils and to joints having a short leakage path, and the maximum values to pipes in relatively high-resistance soils and to joints having a long leakage path. Insulating joints are particularly effective in excluding current from isolated pipelines that cross under street-railway tracks or from one system which contacts with another at relatively few points.

(6) As a means of preventing electrolysis, electrical drainage had a wider application than any other mitigative measure. A drainage system is one in which wires or cables are run from a negative return circuit of an electric railway and attached to the underground pipes, cable sheaths or other underground metallic structures that tend to become positive to the earth, so as to conduct current from such structures to the power station, thereby tending to reduce the flow of current from such structures to earth. In most cases this system, as well as insulating joints, should be restricted to use as an auxiliary means of protection, after reasonable precautions have been taken to reduce potential drops in the tracks to as low values as possible.

(7) The most important methods applicable to street-railways were the adequate maintenance of track bonding, the use of a proper number and location of power houses or substations, and, where the carrying capacity of the rails is not sufficient to return current to stations without excessive drop, the installation of supplementary return or feeder lines.

(8) Experience has shown that regulations limiting voltage drops in the negative return are necessary to a satisfactory solution of the problem. In defining the voltage limitations the all-day average value is preferable, as it affords the best criterion of the actual danger involved.

(9) In fixing voltage limitations some plan analogous to the zone system should be adopted, the voltage limits prescribed for the various zones being determined largely by the degree of development of the underground utilities in the zones. The voltage drops either in the tracks or in the pipes and earth may be used as the basis for fixing limitation, but, in general, the latter is to be preferred.

(10) Under most conditions the potential gradients in street-railway tracks should be restricted to about 0.3 or 0.4 v/1,000 ft, these figures being all-day average values, or to corresponding values based on averages for a period of not less than ½ hour. Potential drops on pipe systems should be, roughly, half of these figures.

(11) In order that ready determination of voltage drops can be made at any time, potential wires should be installed running from a central point to selected points on the railway or pipe networks. The selected points should include the points of approximately highest and lowest potential, and preferably also some intermediate points.

(15) Any regulations concerning electrolysis mitigation should not only apply to the railway system, but should also define the responsibilities of the owners of the underground utilities as the latter can often contribute materially to the diminution of the trouble at a practically negligible cost.

21.5. Studies of Electrolysis Conditions on Typical Street-Railway Systems

In cooperation with several utilities, the Bureau, prior to 1920, undertook a series of tests to study electrolysis conditions on street-railway systems in Springfield, Ohio [9,13], St. Louis, Missouri [11], Elyria, Ohio [14], and Washington, D. C. [18]. In an investigation typical of this series, Rosa, McCollum, and Logan [11] measured potential gradients and over-all voltage drops on tracks, potential differences between water pipes and tracks, and electric current flow on water and gas mains under two systems of negative feeders. Table 102 gives a brief summary of the results of the measurements. The conclusions based on this investigation were as follows:

(1) Under the insulated negative feeder system potential differences between pipes and rails, and over-all potential differences range from one-half to one-seventh of the corresponding values when an uninsulated feeder system is used.

Table 102. *Comparison of electrolysis conditions under uninsulated and insulated negative feeder systems*

Basis of comparison	Uninsulated feeders		Insulated feeders	
	No. of tests	Average voltage or amperage	No. of tests	Average voltage or amperage
Potential gradients on rails	21	0.93 [a] v	26	0.46 v
Over-all voltage drops on rails	22	10.4 v	22	1.8 v
Current flow on gas and water pipes (pipes not drained)	21	13.0 amp	21	3.1 amp
Current flow on gas and water pipes (pipes drained)	21	40.0 amp	21	4.0 amp
Potential differences between pipes and rails (pipes not drained):				
A, potentials originally over 1 v.	14	2.44 v	14	0.33 v
B, potentials originally less than 1 v	14	0.49 v	14	.28 v
C, potentials originally negative	8	−.31 v	8	.56 v

[a] Potential gradients measured in volts on a fixed length of 4 feet of rail.

(2) For substantially the same installation cost much better protection against electrolysis can be secured with insulated negative feeders than with uninsulated feeders.

(3) When the potential differences in the track return are reduced to the low values readily obtainable by means of insulated negative feeders, the tying in of the pipes to the tracks has a much smaller tendency to cause heavy current flow in the pipes.

(4) Where low voltage conditions are maintained in the negative return, the insulated feeder system usually can be installed so as to yield far greater economies both in installation and operation costs than is possible with uninsulated feeders.

(5) In the case of old stations in which there is a large amount of negative copper installed in such a way that it is impracticable to insulate it, the insulated feeder system would still be economical in case it is desired to lower existing potential differences in the negative return.

21.6. Earth-Current Meter

As a result of the development of the earth-current meter, which measures the intensity of discharge of current from a pipeline at any specific location, methods of making electrolysis measurements were modified. McCollum and Logan [20] discussed this instrument, in a paper that is not readily abstracted because it consists of detailed descriptions of the theory of the instrument and methods of using it under different conditions.

Experience with the earth-current meter showed that the older methods of measurements used in electrolysis surveys, under certain conditions, led to erroneous conclusions. McCollum and Logan [21] made a comparison of a number of methods of determining general electrolysis conditions. They discussed methods for studying local conditions, and described procedures for the determination of street-railway track conditions and the interpretation of electrolysis data.

21.7. Effect of Alternating Current on the Electrolytic Corrosion of Iron and Steel

McCollum and Ahlborn [17] reported the results of experiments designed to determine the corrosion of iron and lead in soil with varying frequencies of alternating or reversed current. Frequencies up to 60 cps were used as the highest frequency, and 1 cycle every 2 weeks as the lowest frequency; direct-current tests were made as a check on the methods. The results showed that:

(1) The corrosive effects of alternating currents are much less in magnitude than those produced by direct currents.

(2) The amount of corrosion of iron and lead in soils, when subjected to the action of direct current, was found to be about 90 percent and 25 percent, respectively, of the theoretical value as calculated from Faraday's law.

(3) The corrosion of both iron and lead electrodes increases with decreasing frequencies of alternating currents for frequencies less than 1 per 5 min.; no corrosion occurs at frequencies of 60 cps and the amount of corrosion is negligible at frequencies of 1 cycle per 5 min.

(4) With iron electrodes, reducing the frequencies of alternating current to such low values as 1 cycle per hour, 1 cycle per 2 days, and 1 cycle per 2 weeks resulted in corrosion amounting to about 15, 30, and 60 percent, respectively, of that caused by direct current.

(5) A similar relation exists with respect to lead electrodes when subjected to the same frequencies of alternating current.

(6) The addition of sodium carbonate to the soil reduces electrolytic corrosion in the case of iron and increases it in the case of lead.

(7) The most important conclusion drawn from these investigations is that periodic reversals of polarity in street-railway networks result in considerably less corrosion by electrolysis of the underground pipes than that resulting from direct current.

Subsequent to the publication of the above results, additional experiments on the electrolytic corrosion of lead, under both alternating and direct currents, were made by Shepard [279]. His conclusions agreed generally with those obtained by McCollum and Ahlborn, with the exception that, with direct current, the corrosion of lead in soil was almost 100 percent of the theoretical value. Shepard attributed the 25-percent value reported by McCollum and Ahlborn to a low moisture content of the soil, and to not tamping the earth around the lead electrodes.

21.8. Leakage Resistance of Street-Railway Roadbeds and Its Relation to Electrolysis of Underground Structures

Although much attention had been given to the subject of electrolysis mitigation and methods had been proposed and used for preventing and reducing the escape of electricity from street-railway tracks used as the return circuit, very little thought was given by engineers to the question of insulating the roadbeds, which include the pavement, ties and ballast, or constructing them in such a manner as to offer high resistance to the leakage of currents. The leakage path traversed by stray currents from electric railways varies with different types of roadbed construction. In the case of open track, the current leaves the rails, enters the ties through the spikes and base of the rails, and then passes into the ballast and finally into the adjacent earth from which it finds its way to metallic structures, and eventually to the negative pole of the generator. In paved streets an additional leakage path is offered through direct contact of the rails with the earth, pavement, or other material in which they are embedded. Shepard [19] described several methods of measuring the electrical resistance to leakage of current from electric street-railway roadbeds and gave the results of such measurements under various weather conditions, on a number of experimental roadbeds built on the grounds of the National Bureau of Standards and on several city and interurban lines. Some of his conclusions were:

(1) Roadbeds should be constructed with as high an electrical resistance to earth as possible, special attention being given to keeping them dry, i.e., well drained. Wet roadbeds of any type are several times less resistant to leakage of current to earth than are dry roadbeds.

(2) Roadbeds constructed with a foundation of clean crushed stone under a concrete or pavement

base offer much greater electrical resistance to leakage of current into the earth than roadbeds with a solid concrete ballast under the ties. If earth or street dirt is permitted to filter into ballast of this type, its insulating property is greatly impaired. Also, vegetation tends to maintain the roadbed in a moist condition, and thus increases its conductivity.

(3) Gravel and particularly crushed stone, when used as ballast in open construction, produce the most resistant roadbeds. The resistance to current leakage of earth roadbeds, in which ties are embedded directly in the earth, is comparatively much lower than that of open construction roadbeds.

(4) Zinc chloride and similar chemical preservatives for wood ties, should be avoided because they reduce the insulating properties of the ties. On the other hand, treatment of wood ties with a 3 to 1 mixture of gas oil and creosote greatly improved its insulating properties.

(5) Salt, which is often used to prevent freezing of switches, greatly increases the conductivity of roadbeds and thereby facilitates the escape of current into the earth.

22. Electrical Measurement of Corrosion Rates

22.1. General

The various electrical tests for estimating the tendency of metals to corrode in soils, which were described in section 19, are relative methods because they do not give exact quantitative expressions of the corrosion rate. However, the electrochemical nature of the corrosion of iron has been established by a number of investigators. Experimental proof of this type of corrosion of iron in aqueous media was established by Evans and Hoar [259]. Later, Brown and Mears [280] concluded that, at least for the conditions of their experiment, the corrosion of aluminum was essentially electrochemical. These investigators carried out their experiments with corrosion cells having separated anodes and cathodes and, therefore, were able to show the relation between the potentials of these elements and values of current within the range represented by the local cell current. Muller [281] in discussing the local cell theory of corrosion interpreted polarization in the terms of porosity and film resistance. The interpretation of cathodic and anodic polarization curves characteristic of continuous metallic surfaces in relation to electrochemical corrosion was discussed by several investigators [282 through 287]. Streicher [283] showed that breaks occur in anodic polarization curves when local action ceases. An explanation of the breaks in polarization curves as related to cathodic protection and the type of control was discussed by Mears and Brown [288, 289].

Based on the studies of Muller, Pearson [194] derived an equation for local action current as a function of the external direct currents, applied anodically and cathodically, which are required to reduce the local action current to zero. Holler [137] confirmed the equation by deriving it mathematically. Both investigators established the validity of the equation by measuring local cell currents under conditions that precluded appreciable local action on the separate elements of galvanic couples. Elimination of the measurable currents also was indicated by potential breaks in the anodic and cathodic polarization curves of the couples.

Whether or not the Pearson equation can be applied generally in measuring the corrosion current[15] resulting from the innumerable galvanic couples[16] characteristic of the corrosion of most metals in aqueous environments has not been shown. If all of the couples on a corroding surface can be considered as being statistically equivalent to a single couple, it seems reasonable to expect the known electrical relations to apply. The data obtained by Schwerdtfeger and McDorman [142], and the discussion that follows show that good agreement can be obtained between values of weight loss calculated by Faraday's law from electrical measurements made on corroding surfaces with the observed actual weight losses. Hence, the accuracy of the electrolytic method for measuring corrosion rate in aqueous media and in soils can be determined.

22.2. Theoretical Electrical Relations

The electrical relations existing among the current produced by a galvanic couple, the polarizing characteristics of the anode and the cathode, and the potential of the couple in an aqueous medium of negligible resistance, are illustrated in section A of figure 82. The hypothetical relations between the potential of the couple and external direct current applied anodically and cathodically are shown in section B of figure 82. These relationships are shown to result in the equation for corrosion current originated by Pearson [194] and confirmed by Holler [137]. The purpose of the method of plotting and the derivation of the equation that follows, is to demonstrate the relation between the polarization of the elements of a galvanic couple and the polarization of the couple itself when an external current is applied. The type of control, i.e., the electrode at which the rate of corrosion is controlled, can be deduced from changes in potential of the

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[15] The term "corrosion current" as used in this discussion refers to that current which is equivalent to the sum of all the currents associated with local cell action.

[16] The term "galvanic couple" is used in the general sense and implies the flow of current produced locally by cell action due to the contact of dissimilar metals in a given aqueous environment or because of differences in the environment on the exposed surface of a given metal.

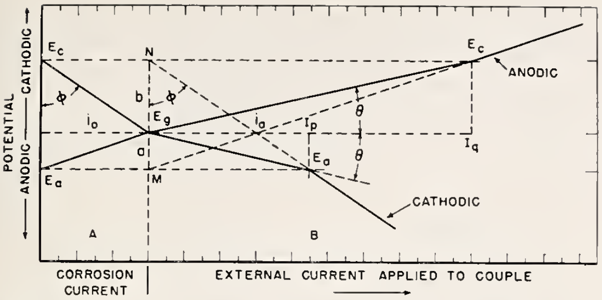

FIGURE 82. *Hypothetical relations between the polarization of the elements of a couple and the polarization of the couple* [*142*].

couple and also from the associated external currents applied anodically and cathodically to the couple which produce such changes. These currents are indicated by definite changes in slope of the polarization curves when the local action current is reduced to zero (fig. 82). For a given environment, the resulting slopes will be shown to be related to the rate of corrosion.

The symbols used are indentified as follows:

E_a = open-circuit potential of the anode.
E_c = open-circuit potential of the cathode.
E_g = potential of the couple.
i_0 = corrosion current.
I_p = external cathodic current applied to the couple when the anode current (corrosion current) becomes zero. This is the minimum current required for cathodic protection.
I_q = external anodic current applied to the couple when the cathode current (cell current) becomes zero.
a = change (ΔE_g) in the potential of the couple from the value at zero applied current to the value at I_p.
b = change (ΔE_g) in the potential of the couple from the value at zero applied current to the value at I_q.

When the elements of a galvanic cell are short-circuited and exposed to an aqueous electrolyte of high conductivity, the anode and the cathode polarize to a potential, E_g, as represented in section A of figure 82. The limiting current corresponding to this potential is the corrosion current, i_0, assuming that the elements are free of local action. If an increasing external current is applied to the couple (section B of figure 82) the potential of the couple will become more cathodic or anodic, depending on the polarity of the applied voltage. Potential breaks which occur at the open-circuit potentials of the anode, E_a, and the cathode, E_c, indicate that the cell current has been reduced to zero. The current, Ip, is determined by the intersection of the ordinate, E_a, and the line drawn from N parallel to the polarization curve of the cathode. The current I_q, is determined by the intersection of the ordinate, E_c, and the line drawn from M parallel to the polarization curve of the anode. For externally applied currents greater than I_p or I_q, the surface of the hypothetical couple becomes either all cathodic or anodic, respectively; for these currents the polarization curves are assumed to follow the extension of the broken line drawn from N and M, respectively.

Polarization of the couple at applied currents smaller than either I_p or I_q is represented by the solid lines connecting points E_a and E_g and points E_c and E_g, respectively. Because it can be shown by geometry that these solid lines are diagonals of similar rectangles, each forms the angle θ with the horizontal line through E_g at zero applied current. It can be shown that the corrosion current can be expressed as a function of the externally applied currents from the equation [142].

$$i_0=\frac{I_p\,I_q}{I_p+I_q}. \tag{8}$$

The type of control of the corrosion rate, that is, the electrode reaction which determines the rate of corrosion, can be expressed by the ratio a/b (fig. 82). As the value of this fraction approaches zero, the corrosion rate tends to be controlled by the cathode reaction exclusively. Conversely, as the fraction approaches infinity, virtually complete control by the anode reaction is indicated.

Diagrams similar to figure 82 are shown in figure 83for hypothetical couples corroding under different types of control. The expression for i_0 given by eq. (8) applies in all cases. For the special condition of strict cathodic control (top of fig. 83) and strict anodic control (bottom of fig. 83) the respective currents, I_q and I_p, are theoretically infinite and, therefore, not indicated on the diagrams. Most corrosion reactions are represented by figure 83 (b), (c), or (d).

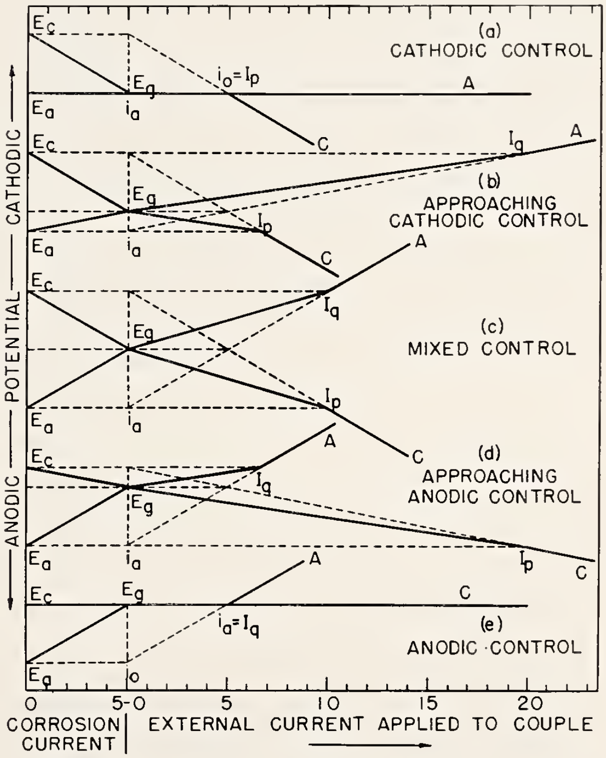

FIGURE 83. *Hypothetical polarization diagrams for various types of control* [*142*].

22.3. Measurement of the Rate of Corrosion of Steel in Soils

Having shown that all the corrosion associated with an iron-copper couple in a potassium chloride solution could be correlated with breaks in the external current polarization curves, Schwerdtfeger and McDorman [142] applied the same technique to steel specimens exposed to five corrosive soils. The accuracy with which the current associated with the natural corrosion of the steel could be measured was determined by comparing the actual weight loss of a specimen after 2 months of exposure with the weight loss calculated by Faraday's law, using average rates of corrosion current as determined by periodic electrical measurements of I_p and I_q.

In view of the fact that soil corrosion cells in which the single steel electrode corrodes by differential aeration, were found to maintain relatively steady corrosion rates for extended periods, it was decided to use such cells for this study. A special advantage of the cell lies in the fact that it is stable, as indicated by the rapid restoration of the electrode potential to the normal value after having been subjected to cathodic and anodic polarization. Because of the normal decrease in the rate of corrosion of steel with time, it was necessary to repeat the polarization measurements at periodic intervals during the 2-month exposure period. The design of the cell was described by Schwerdtfeger and McDorman [136]. Potential measurements were made with the modified Hickling circuit (appendix 8).

The polarization curves (fig. 84) of a steel electrode, after exposure for 2 days in 1 of the five soils used, show breaks in the current-potential curves that are typical of corroding steel in soils. If, as indicated, two breaks occur in the cathodic polarization curve, I_p is represented by the current at the second break because it is known from experience that iron exposed to soils corrodes, as illustrated in figure 83 (b). The horizontal portion of the curve, usually but not always evident, probably represents a depolarizing effect due to oxygen.

The fact that no break having any significance in the calculation of the rate of normal corrosion of iron will occur at a potential more negative than the protective potential (-0.77 v with respect to the calomel reference electrode), serves as a guide in estimating the magnitude of the cathodic polarizing current and, as a consequence, the range of the anodic polarizing current. It can be shown that $(i_0/I_p)=(b/a+b)$, and also $(a/b)=(I_p/I_q)$. These relations are fairly well substantiated by substituting appropriate values from figure 84 into the equations.

Data obtained for steel in five soils over a period of 2 months are tabulated in table 103. The absolute value of the difference between the calculated and the actual weight losses averages approximately 3.9 percent. The good agreement indicates that the innumerable galvanic couples on the corroding steel surface can be considered as being statistically equivalent to a single couple. The polarization of the elements of the statistical couple including resistive components is represented by the triangle connecting points E_a, E_c, and E_g, figure 84. Since $(i_0/I_p)=(b/a+b)$, and the average value of i_0/I_p for each soil ranges between 0.78 and 0.88, the data show that the rate of corrosion of steel in these soils is determined chiefly by the cathode reaction.

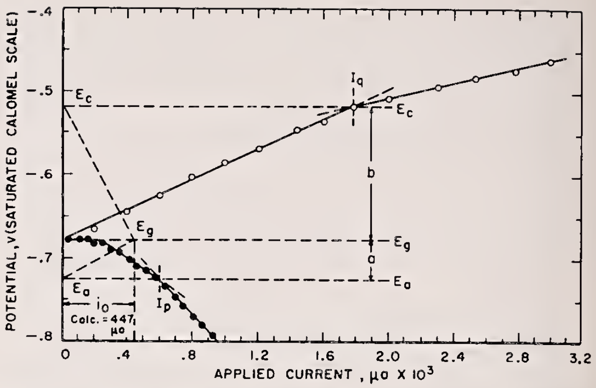

FIGURE 84. *Polarization curves of a steel electrode exposed to soil 60 [142].*

○, Anodic; ●, cathodic.

Further evidence of the direct relation existing between i_0 and I_p is represented in figure 85 for two electrodes that are typical of all the electrodes of table 103. The curves are linear and can be extrapolated back to the origin as shown, thereby demonstrating that the actual absence of a potential break I_p, during cathodic polarization is indicative of relatively little or no corrosion. This was discussed by Schwerdtfeger and McDorman [136] as a criterion of cathodic protection.

Because of the close relation between i_0 and I_p, the corrosion rate in a given environment can be approximately obtained by the use of cathodic polarization data exclusively. This was verified by exposing two specimens of steel to soil 64 for 2 months. The current, I_p, was obtained for both specimens by running periodic cathodic polarization curves and calculating i_0 by applying the factor $(i_0/I_p)=0.87$ (see soil 64, table 103). The average deviation between the actual and calculated weight losses for the two specimens was 4.4 percent.

In addition to the measurements described it has also been shown [142] that the slopes of cathodic polarization curves of a metal of known area, corroding at different rates under cathodic control in a given aqueous environment, are shown to bear an inverse relation to the current required for cathodic protection and consequently to the corrosion current. The potentials were measured by Darnielle's modification of the Hickling-interruption circuit (appendix 8). While null or current-interruption circuits

Table 103. *Corrosion rate and weight loss of steel in soils as calculated from polarization curves—exposure 2 months*

Soil	Electrode number	Exposure time of the electrode	Polarizing current at the potential-break		Corrosion current, i_o[a]	$\frac{i_o}{I_p}$	Weight loss of electrode		
			Cathodic, I_p	Anodic, I_q			Calculated[b]	Actual	Difference based on actual
		Days	μa	μa	μa		*mg*	*mg*	*Percent*
60	3	2	600	1750	447	0.75	22	------	------
		34	380	1250	292	.77	295	------	------
		63	300	1280	243	.81	194	------	------
		63	------	------	------	[c] .78	[d] 511	519	−1.5
13	9	2	770	$\gg I_p$	770	1.0	38	------	------
		17	400	$\gg I_p$	400	1.0	220	------	------
		30	360	800	248	0.69	105	------	------
		45	420	780	273	.65	98	------	------
		63	305	1370	249	.82	117	------	------
		63	------	------	------	[c] .83	[d] 578	575	+0.5
78	20	7	135	$\gg I_p$	135	1.0	24	------	------
		16	107	$\gg I_p$	107	1.0	27	------	------
		27	60	$\gg I_p$	60	1.0	23	------	------
		34	52	185	41	79	9	------	------
		42	55	160	41	.75	8	------	------
		59	70	200	52	.74	20	------	------
		63	------	------	------	------	5	------	------
		63	------	------	------	[c] .88	[d] 116	111	+4.5
79	23	3	352	900	253	.72	19	------	------
		11	150	600	120	.80	37	------	------
		18	220	970	179	.81	26	------	------
		26	355	1600	290	.82	47	------	------
		33	290	1340	239	.82	46	------	------
		41	250	1600	216	.86	45	------	------
		48	200	1200	171	.85	34	------	------
		59	390	2000	326	.84	68		
		61	------	------	------	------	16	------	------
		61	------	------	------	[c] .81	[d] 338	364	−7.1
79	24	3	404	950	283	.70	21	------	------
		11	350	930	254	.73	54	------	------
		18	210	1000	174	.83	37	------	------
		26	220	800	173	.79	35	------	------
		33	200	1290	173	.86	30	------	------
		41	200	2120	183	.91	36	------	------
		48	150	1400	136	.91	28	------	------
		59	300	2700	270	.90	56	------	------
		61	------	------	------	------	14	------	------
		61	------	------	------	[c] .83	[d] 311	342	−9.1
64	29	7	100	400	80	.80	14	------	------
		19	80	1000	74	.92	23	------	------
		29	82	600	72	.88	18	------	------
		42	60	600	55	.91	21	------	------
		53	60	600	55	.92	15	------	------
		62	150	600	120	.80	20	------	------
		63	------	------	------	------	3	------	------
		63	------	------	------	[c] .87	[d] 114	113	+0.9

[a] $i_o = (I_p I_q)/(I_p + I_q)$, equation (8)

[b] Weight loss (grams) $= Kt\ I$, where $K = 2.8938 \times 10^{-4}$ grams per coulomb, $I = i_o =$ average current (amp) for the period (t in seconds) between successive readings. Note: The value of i_o at the instant of exposure and at the end of exposure is taken as the initial and final values, respectively, as calculated.

[c] Average value.

[d] Total value.

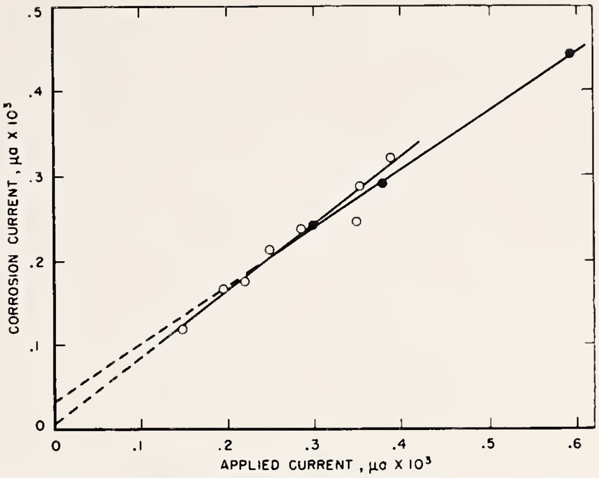

Figure 85. *Relation between the corrosion current and the cathodic polarizing current at the potential break for steel in two soils* [*142*].

●, Soil 60 (electrode 3, table 103); ○, soil 79 (electrode 23, table 103).

are necessary when significance is attached to a potential reading, their use is not essential to observe breaks in polarization curves. Schwerdtfeger [290] showed that, under specified conditions, cathodic polarization curves with *IR* drop included are valuable for measuring corrosion rates. Effects on the corrosion rate of steel of such variables as carbon content, oxygen concentration and heat treatment, are determinable from polarization curves plotted by a two-pen strip chart recorder.

LaQue [291] has shown that there is no correlation between the potentials of metals and their rates of corrosion in sea water. Presumably, this is also true when soil is the electrolyte. Corrosion rate depends on the polarization of the anodic and cathodic areas on the metal surface, which affects the type of control (fig. 83) and the potential E_g of the metal. Recently, May and LaQue [292] made observations of the anodic and cathodic polarization of steel in sea water and related the data to rates of corrosion determined by weight loss measurements.

23. Cathodic Protection

23.1. General

About 25 years ago, the most common method of reducing corrosion underground was by the application of protective coatings. In the interim the principle of cathodic protection was applied to underground structures and is rapidly coming to the forefront as the dominant method for protecting underground structures. Fundamentally, cathodic protection consists in impressing an electromotive force on an underground structure in such a way as to make the entire structure cathodic with respect to the adjacent soil. This may be accomplished by using either auxiliary anodes to impress an emf from an outside source on the structure or by the sacrificial anode principle. In this manner the structure is protected from corrosion at the expense of the anodes, which are easily and economically replaceable.

Cathodic protection was developed for other corrosive environments before it was applied to structures in soils. The use of zinc as a sacrificial anode for the protection of ship hulls, boilers, and similar structures has been practiced for many years. The earliest reference to sacrificial anodes, whereby zinc was used to prevent corrosion of the copper sheathing on the hulls of ships of the British Navy, was made in a series of papers by Sir Humphry Davy published in 1824 and 1825 [293]. A system of cathodic protection known as "pipe drainage" [23, 294] was recommended as early as 1910, to protect underground pipelines from stray currents originating from street-railway systems. The beneficial effects were not fully appreciated, however, until about 1930, when the cathodic effects resulting from electric drainage was observed to have resulted in a marked reduction in corrosion of underground pipeline and cable systems [295, 296]. In 1932, Scherer [297] reported that 26 companies were operating 542 cathodic protection units to protect over 2,000 miles of pipe. Since that time, the number of miles of pipe so protected has considerably increased, for example, according to a survey, made in 1953 by the Corrosion Committee of the American Gas Association [298], of 29 representative gas companies throughout the United States, it was reported that cathodic protection was used on 11,459 miles (16%) of the 69,843 miles of steel pipe controlled by the companies. The report further states that economics is the decisive factor in methods employed to protect new lines, cathodic protection being used on a wider scale in the Gulf States where soils are generally more corrosive.

23.2. Criteria of Cathodic Protection

a. Potential

The theoretical requirements for cathodic protection were demonstrated by Mears and Brown [299] in connection with a study of galvanic couples. Their work established a criterion based on the equalization of surface potentials, accomplished by polarizing the cathodes until their potentials became equal to the open-circuit potentials of the anodes.

In soils, differences in potential exist on the surface of buried steel structures, in effect forming galvanic couples. Therefore, according to the Mears-Brown theory, corrosion would continue on such structures until the potential of the entire surface was equal to that of the most anodic element. An empirical approach, previously established by Kuhn [296] on the basis of experience with piping systems, suggested an optimum protective potential of −0.85 v referred to a copper-copper sulfate electrode. The theoretical aspects of a protective potential for iron were discussed by Holler [138] and the theoretical and experimental justification of the −0.85 v potential in soils was substantiated by Schwerdtfeger and McDorman [136].

b. Current

The relationship between the current required for cathodic protection and the open-circuit potential of the anode can be shown by cathodic polarization curves. In the course of a study of the rate of corrosion of iron in aqueous solutions, Evans, Bannister, and Britton [300] observed that when a cathodic potential is applied to a specimen there is a critical value of current at which the potential of the iron with respect to a reference electrode shifts markedly in the anodic direction and corrosion ceases. The subject has since been studied by Ewing [301], Mears and Brown [288, 289], Pearson [194], Logan [302], Denison and Romanoff [135], Holler [139], and Schwerdtfeger and McDorman [136]. The relationship between corrosion current density and current required for cathodic protection was stated by Pearson, and verified by Holler through an interpretation of polarization curves, and experimental evidence of such a relationship was provided by Schwerdtfeger and McDorman [142].

23.3. Requirements for the Cathodic Protection of Steel in Soils

a. Potential of Steel in Air-Free Soils

To investigate the potential requirement for the cathodic protection of steel in corrosive soils, Schwerdtfeger and McDorman [136] measured the potentials of steel electrodes in 20 air-free soils ranging in pH from 2.9 to 9.6 and in resistivity from 60 to 17,800 ohm-cm. After the soil cells were set up, they were individually confined in a water-saturated atmosphere and removed only for such times as was required for daily potential measurements. The potentials of the cells became relatively steady within 10 days and varied less than 5 mv., indicating that oxygen had been effectively excluded or consumed by corrosion.

The relation between the potentials of the steel electrodes in the different air-free soils and the pH values of the soils are shown in figure 86. Each

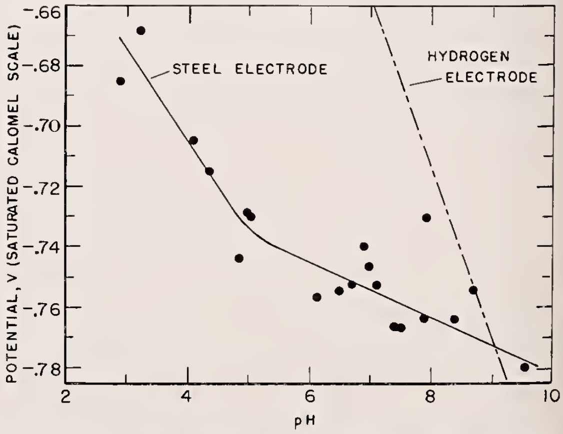

Figure 86. *Relation between the potential of steel in air-free soils and the* pH *values of the soils* [*136*].

point represents the average of potential measurements made daily on 4 consecutive days on each of three cells after stabilization of the electrodes. The rather wide dispersion of the values for soils having approximately the same hydrogen-ion concentration results from the fact that the potential of steel in aqueous electrolytes is determined by the composition of the electrolyte, as well as by its hydrogen-ion concentration.

The curve (fig. 86) is similar to those obtained by Gatty and Spooner [303] to show the effect of hydrogen-ion concentration in different aqueous electrolytes on the potential of iron. In fact, it may be considered as a composite of the potential *p*H curves for different salt solutions reported in the literature.

Corey and Finnegan [304] reported that the hydrogen-ion concentration of waters in which iron is in equilibrum with ferrous hydroxide is between 8.3 and 9.6, depending on the soluble salt content of the waters and other factors. It will be observed (fig. 86) that the potential curve for the standard hydrogen electrode at atmospheric pressure intersects the potential curve for steel at *p*H 9. According to Holler [138] corrosion is reduced to a negligible amount at this point, as there is no difference of potential between the hydrogen and steel electrodes. The potential at this intersection, approximately −0.77 v, with reference to the saturated calomel scale, therefore, is considered as the protective potential. This potential is equivalent to −0.85 v with respect to the copper-copper sulfate electrode.

b. Protection of Steel Using the Potential Criterion

The degree of cathodic protection of five corrosive soils was investigated by Schwerdtfeger and McDorman [136] by setting up differential cells and comparing the weight losses of unprotected steel specimens (controls) with that of similar steel specimens that were protected cathodically by maintaining their potentials at approximately −0.77 v (calomel reference electrode). The weight losses that were attributed to incomplete protection during an initial freely corroding period of 48 hr before cathodic protection became wholly effective (threshold effect) have been deducted from the weight losses of the cathodes (table 104). These data show that the weight losses of the cathodes in all the soils are small compared with that of the unprotected control specimens. The weight losses are lowest and most uniform for those cathodes whose potential departed the least from the critical potential, −0.77 v, and larger weight losses for any given soil are associated with greater positive deviations from the critical potential, taking into consideration the time of departure. Figure 87 shows some of the cathodes and the corresponding controls for which data are included in table 104. The fact that corrosion was not completely prevented in any of the soils in consistent with the results of Mears and Bialosky [305] who reported small residual weight losses for cathodically protected specimens that were attributed to a threshold effect. The differences in weight losses of cathodes 1, 2, and 32 in the same soil (soil 60) but maintained at different

Table 104. *Weight losses of cathodes maintained at approximately −0.77 v (referred to saturated calomel) for 60 days [136]*

Soil [a]	Cathode number	Weight loss of electrodes		Average potential of the cathodes during the period of departure from −0.77 v	
		Cathode	Control	Days of departure	Potential
		mg	*mg*		*v*
13	5	8	431	0	−0.77
64	30	6	196	5	.76
78	19	19	111	3	.75
60	32	40	519	18	.75
60	1	84	519	12	.69
79	16	19	364	7	.74
79	13	28	364	14	.69

[a] See table 6 for properties of the soils.

Figure 87. *Unprotected (control) and protected steel electrodes in soil 60 (pH 2.9) and soil 13 (pH 9.5), exposure 60 days [136].*

Protected cathodes 32 (soil 60) and 5 (soil 13) were maintained at potential −0.77 v (saturated calomel scale) after 48 hours without protection.

Table 105. *Potential changes and weight losses of cathodes receiving current indicated by the break in cathodic polarization curves—exposure 60 days [136]*

Soil number	Cathode number	Weight loss of electrodes		Potential at the break	Average potential of the cathode [a]			
					Less than −0.77 v		Greater than −0.77 v	
		Cathode	Control		Days [b]	Potential	Days	Potential
		mg	*mg*	*v*		*v*		*v*
78	21	5	111	−0.69	3	−0.74	57	[c] −0.77
79	25	14	364	.71	7	.75	53	[c] .77
60	2	27	519	.74	3	.76	57	1.00
13	6	9	431	.72	21	.72	39	1.50
64	22	119	196	.73	60	.68	0	--------

[a] Potential referred to the saturated calomel half-cell.

[b] Time required for the cathodic potentials to drift to the protective value −0.77 v.

[c] Current reduced to maintain potential indicated.

potentials (tables 104 and 105) render further proof that initial corrosion cannot be entirely prevented, and that −0.77 v (saturated calomel) is the approximate optimum protective potential. The potential of cathode 1 was maintained at −0.69 v for 12 days, and this resulted in a much larger weight loss than that shown by cathode 32 which was maintained close to the critical potential. The weight loss of cathode 2 that was maintained at a greatly increased potential was not appreciably different from that for cathode 32. This is in accord with Kuhn's observation [296] that polarizing an iron structure to potentials greater than the critical value (−0.85 v with reference to the copper-copper sulfate electrode) represents wasted electric energy.

c. Interpretation of Cathodic Polarization Curves

Breaks in cathodic polarization curves, based chiefly on theoretical considerations, have been interpreted by Ewing [301], Pearson [306], Logan [307], Denison and Romanoff [135], and Holler [138] in terms of the current density and potential requirements for cathodic protection in soils. The effect of time on chemical polarization, as related to critical current densities, has received scant attention. Under most natural soil conditions, the potential of iron with respect to a standard reference electrode is considerably less negative than the potential of iron in the same environment with air excluded. For such conditions the significance of breaks in cathodic polarization curves with respect to cathodic protection heretofore has not been readily understood.

Two breaks are shown in the typical cathodic polarization curve (fig. 88a), obtained by Schwerdtfeger and McDorman [136] on one of their experimental cells, point A corresponding to the average open-circuit potential of the anode of the cell, and point B corresponding to the beginning of the hydrogen-overvoltage portion of the curve. An approximation of the current indicated by A (fig. 88a) is obtained from the semilogarithmic curve (fig. 88b) by the intersection of the extrapolated straight-line portions of the curve. The straight-line portion of the semilogarithmic curve at currents greater than the extrapolated value represents the hydrogen overvoltage. The beginning of the hydrogen-overvoltage curve does not always appear as a distinct break (B) in the rectangular plot but sometimes appears as a gradual decrease in the polarization rate. Although the current indicated at A (fig. 88a) would not be sufficient initially to eliminate all local corrosion on the surface of an electrode it is reasonable to expect that the drift in potential caused by the continuous application of this current indicated by the break would be sufficient to polarize the surface to the protective potential and thereby to provide cathodic protection.

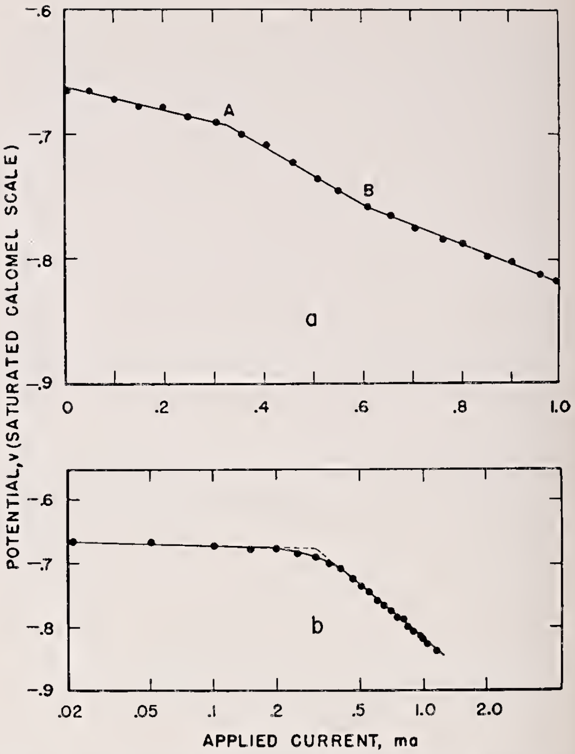

Figure 88. *Cathodic polarization curves of a single steel electrode in a differential-aeration cell.*

(a), Plotted on rectangular coordinates; (b), on semilogarithmic coordinates [136].

In order to determine the effectiveness of the current indicated by A (fig. 88a) as a requirement for cathodic protection, differential aeration corrosion cells [136] were set up and current densities corresponding to the breaks A, in the cathodic polarization curves for the five soils studied, were applied to the steel cathodes. In four of the soils the cathode potentials drifted to the protective value of −0.77 v (calomel reference electrode) in from 3 to 21 days (table 105). The cathodes of two of these cells were allowed to drift to potentials greater than the protective potential, whereas the cathodes of the other two cells were maintained at −0.77 v. A comparison of weight losses of the cathodes with losses of the respective control electrodes shows that the degree of protection is good, except in soil 64. The fact that the potential of cathode 22 (soil 64) did not drift to the protective potential during the period of the test does not indicate that the current corresponding to the break in cathodic polarization curves is insufficient for cathodic protection. The failure of the potential of cathode 22 to reach the protective value is attributed to selecting the applied current before the maximum rate of corrosion developed, this current being insufficient for cathodic protection. Depolarization of the cathode after application of the protective current corresponding to the break in the polarization curve indicates that the protective current should be increased because of an increase in the rate of corrosion, which in soil 64 is attributed to the high concentration of chlorides. Under such conditions, the applied current can be gradually increased until electrical measurements show that the cathode is polarizing. The increase in the corrosion rate of cathode 22 during the course of the test is shown by the fact that the break in the cathodic polarization curve obtained at the conclusion of the test indicated a greater current requirement for polarization than was indicated by the curve at the beginning (fig. 89).

A comparison of the weight losses for the cathodes in soils 13 and 60 (table 104), in which the cathodes of the cells were maintained at −0.77 v (calomel reference electrode) with similar data for the cathodes of the respective soils (table 105), in which the cathodes were maintained at potentials appreciably greater than −0.77 v, show that no additional protection from corrosion is obtained by overprotecting a cathode, i.e., by polarizing the cathode to a potential greater than the protective potential of −0.77 v.

In maintaining the cathodes in the five soils at the protective potential, chemical polarization resulted in a reduction of the current (table 106) with constant emf applied. In four of the soils a steady value of current was reached in from 14 to 21 days after the current was initially applied. The reduction of current in the case of cathode 30 was slight, and continued progressively over the 60-day period. Elimination of local couples by diffusion of alkali over the surface of this cathode progressed slowly because of the preponderance of soluble chloride in soil 64. It is probable that the applied emf could have been reduced even more had the length of the test period been extended.

Table 106. *Current required for cathodic protection—exposure 60 days [136]*

Soil	Cathode number	Weight loss of electrodes		Protective current applied to cathode [a]		Average current calculated from weight loss of control by Faraday's law	Current indicated by departure from relatively constant potential on original cathodic polarization curve of cathode
		Cathode	Control	Initial	Minimum		
		mg	*mg*	*ma*	*ma*	*ma*	*ma*
13	8	12	431	3.90	[b] 0.28	0.29	0.28
60	32	40	519	1.27	[b] .24	.35	.30
78	19	19	111	0.20	[b] .05	.07	.06
79	16	19	364	.88	[b] .24	.24	.16
64	30	6	196	.68	[c] .55	.13	.15

[a] Cathode maintained at −.77 v ±0.015 v (referred to saturated calomel).
[b] Mimimum steady current after 14 to 21 days.
[c] Minimum current after a progressive decrease for 60 days.

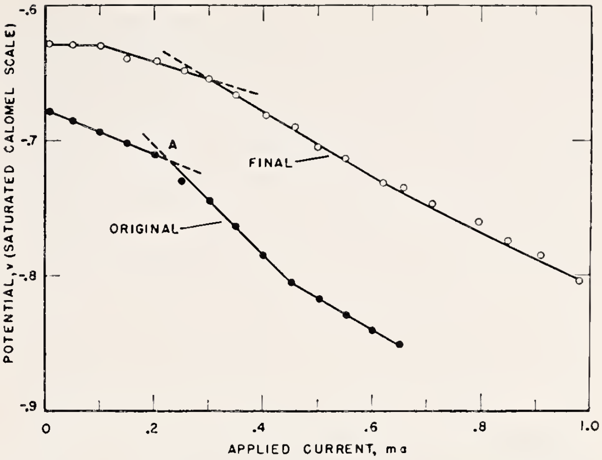

Figure 89. *Cathodic polarization curves of a steel cathode (22) in soil 64 before and after the application of external current A for 60 days [136].*

Protection was incomplete, as indicated by a weight loss of 119 mg and reoccurrence of a break in the final curve. Note: In 4 of the 5 soils tested, the current at A was sufficient to polarize the cathode and provide protection.

The average corrosion currents calculated from the weight losses of the control electrodes by the application of Faraday's law (table 106) indicate in most cases that the minimum current required for cathodic protection is about equal to the average current associated with corrosion. Thus, the high initial currents required for protection are partly attributable to the higher initial corrosion rates. Denison and Romanoff [135] (cf. section 23.5), studied the behavior of zinc-steel couples underground and concluded that the maximum current required for the cathodic protection of steel is that calculated by Faraday's law for loss in weight produced by normal corrosion.

Schwerdtfeger and McDorman [136] showed that at low values of applied current the potential of a corroding electrode is relatively constant (fig. 90). The currents at which the corresponding potentials depart from relatively constant values are given in the last column of table 106. For cathode 8 this value is shown at B in figure 90, which is charac-

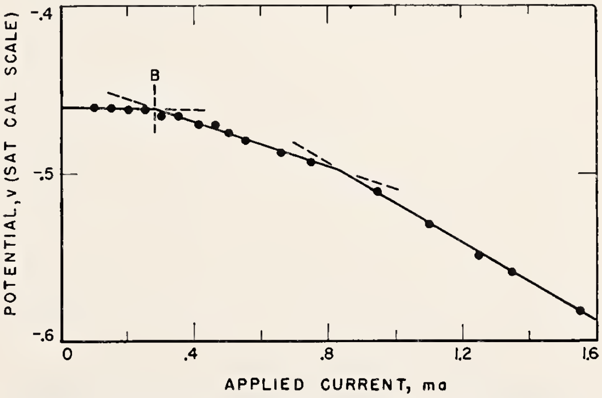

Figure 90. *Cathodic polarization curve of a steel cathode (8) in soil 13 before the application of protective current [136].*

B, Minimum protective current, which maintained a cathode potential of −0.77 v.

teristic of the curves used for obtaining the other values in the last column. There is fair agreement between the minimum current that actually maintained protection and the values in the last column for the four cathodes that had stabilized after 21 days. Apparently the point of departure on the initial cathodic polarization curve of the electrode potential from a relatively stable value, designates the applied current necessary to maintain a balance between the consumed and available oxygen after a cathodically protective alkaline film has been formed on the electrode surface.

The close relation between the current required for protection and that associated with corrosion was probably applicable over the greater part of the 60-day period, therefore suggesting that initially applied currents smaller than those indicated would not have been sufficient for protection. Consequently, the minimum current required for maintaining cathodic protection must not be confused with the current initially required to establish protection. To verify this statement additional cells were assembled with soils 78 and 79 and the respective minimum currents required to maintain cathodic protection, as indicated by the departure of cathode potentials from relatively constant values on the original cathodic polarization curves, were applied to the electrodes for the duration of the 60-day test period. The weight losses of these electrodes were as large as the losses associated with the unprotected controls. Hence it was established that a threshold effect existed, requiring high initial currents to initiate cathodic protection. The potential of the cathode in soil 78 remained substantially unchanged during the test period while the potential of the cathode in soil 79 became less negative. Field investigations with pipe coupons in soils show that polarization is essential for a reduction in corrosion. [308].

At the conclusion of the 60-day test period all cathodes were placed on open circuit and after a threshold period of about 15 hr, required for stabilization of the cathode potentials, a cathodic polarization curve was again derived from data on each electrode. In figure 91 a polarization curve is shown that is typical of the type obtained on the electrodes completely protected from corrosion.

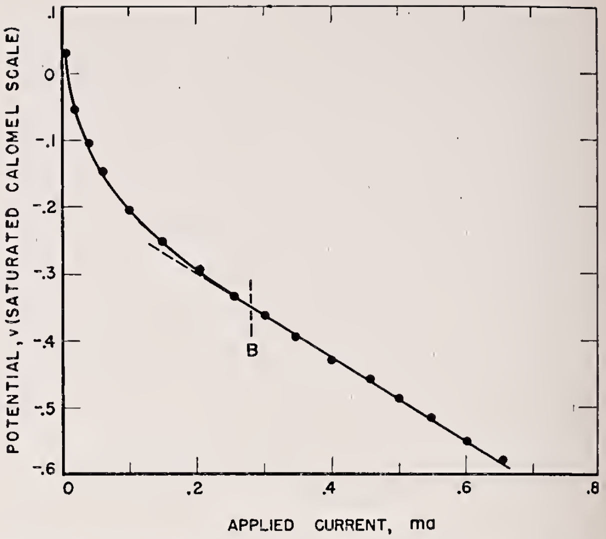

FIGURE 91. *Cathodic polarization curve of cathode 8 in soil 13 (see fig. 90) after the application of protective current for 60 days.* [*136*].

B, Minimum protective current, which maintained a cathode potential of −0.77v. Weight loss, 12 mg.

d. Position of Reference Electrode in Measuring Potentials

When using a potential criterion for the cathodic protection of underground pipelines, particularly on bare lines, the positioning of the reference electrode must be considered because the *IR* drop through the soil resulting from the applied current has a major effect on the potential reading. A 1953 survey conducted by the American Gas Association [309] showed that utility companies, applying the −0.85 v (copper-copper sulfate electrode) criterion to uncoated pipelines, placed the reference electrode at varying distances from their lines, some placing it directly over the line and others from 5 to 400 ft away. Subsequent experiences have shown that these practices are not conducive to either economical protection for the one extreme or effective protection for the other.

Miller [310] buried a system of galvanic couples in a clay soil having a resistivity of approximately 1,000 ohm-cm, and applied current to various combinations of the anodes that were buried in the soil at about 100 ft distant from the pipeline to be protected. The data showed that excessive protection, as indicated by current in the anode circuit of the couple, while using the potential criterion (open-circuit anode), resulted when the reference electrode was placed in the area of the cathode. However, optimum protection was indicated with the reference electrode in the vicinity of the anode or at a remote position. Because electrical measurements in soils are affected by both the soil resistivity and the positioning of the reference electrode the same system of galvanic couples, in a soil of higher resistivity, might have revealed inadequate protection with the reference electrode in the remote position.

In the laboratory, Schwerdtfeger and Denison [311] studied the position of the reference electrode as related to potential criteria in cathodic protection and concluded that geometric factors, in addition to soil resistivity, should be considered. Scott [312] attributed most corrosion occurring on pipelines to local action, such as current leaving the bottom of the pipe where the soil is moist and deficient in oxygen, and entering the top of the line where soil is less moist and better aerated. Based on theoretical reasoning and data obtained on experimental cylindrical couples, Schwerdtfeger and Denison [311] found that the electrical boundary of the couples ranged, for practical purposes, between 4 and 6 diameters of the laboratory model, and, accordingly, suggested that the reference electrode be placed 4 to 6 pipe diameters from the line.

From the results of an investigation, Sudrabin [313] reported that the value of −0.85 v measured against a copper-copper sulfate reference electrode was generally accepted as the protective potential for iron, and that although there is no accepted position for a reference electrode in relation to a pipeline, the following generalizations, when applied to bare pipe, have merit: (1) Long line corrosion currents are controlled when the protective potential, −0.85 v, is measured to a copper-copper sulfate reference electrode in a remote location, i.e., at least 100 ft distant from the pipeline, and intermediate and local cell corrosion currents, measured under the same conditions, are reduced; (2) long line and intermediate corrosion currents are controlled when the protected potential is measured to a reference electrode placed over the pipeline, and local cell corrosion currents are reduced when measured under similar conditions; (3) long line, intermediate, and local cell corrosion currents are controlled when the protective potential is measured close to the pipe surface.

23.4. Circuits for Measurement of Protective Current

The current required for cathodic protection might be defined as the minimum current density required to keep a structure polarized to the protective potential. Based on reports by the National Association of Corrosion Engineers [314] and the American Gas Association [298], the pipe-to-soil potential is the chief criterion for evaluating the adequacy of cathodic protection that is generally accepted as being −0.85 v with reference to the copper-copper sulfate half cell. Thus, all circuits for measuring protective current requirements are in effect a means for determining the minimum current density needed to produce adequate polarization and maintenance of this current.

The current density required for cathodic protection depends on the corrosivity of the soil, and as the corrosion of ferrous metals in soils appears to be cathodically controlled, the ratio of the corrosion current density to the protective current density is relatively constant [142]. Therefore, the relative corrosivity of ferrous metals in various soils, for example, based on field test data, might serve as a guide to the relative current densities required for cathodic protection in those soils. In fact, if applied to uncoated metals, corrosivity in terms of unit weight losses might be converted by use of Faraday's law to protective current densities.

The current-potential curve, obtained by cathodically polarizing a structure, enables one to measure the minimum current density required for cathodic protection. In very corrosive soils, that is, in soils having resistivities less than 1,000 ohm-cm, the breaks in the curves can be observed without the use of special null circuits designed to eliminate *IR* drop from the potential measurements, as was demonstrated by Logan [315] for 80 ft of 6-in. pipe buried in a soil having a resistivity of 230 ohm-cm. However, in soils of high resistivity, it is often difficult to observe the break in the curve because of the preponderance of *IR* drop between the structure and the reference electrode unless the *IR* drop is eliminated by use of a null circuit.

Interruption and null circuits are designed to eliminate the *IR* drop from the potential reading. An electronic interruption method (modified Hickling circuit), designed primarily for laboratory use, was employed for obtaining the data previously discussed in this section. This circuit (appendix 8) measures the electrode potential during a period of interruption which is about 8×10^{-5} sec in duration. Because depolarization is negligible during these short intervals when the current is zero, the measured potential is substantially the true polarized value.

The null method is based on the principle of the Wheatstone bridge and was originally applied to corrosion measurements by Pearson [194] whose circuit includes components for simultaneously applying alternating and direct current to a corroding object, in order to make it possible to measure film resistance. This was shown to be a desirable feature in corrosion studies involving the evaluation of inhibitors [316, 317]. The Pearson null circuit, using direct current only, was utilized for determining the minimum current required for cathodic protection in the field [306, 318]. A discussion of the results of some of the initial trials with Pearson's apparatus was prepared by Logan in collaboration with Pearson, Denison, Hadley, and Smith [307, 319].

Holler [137] developed a null circuit, using direct current only (fig. 92), which measures both the polarized potential and the resistance of a corrosion

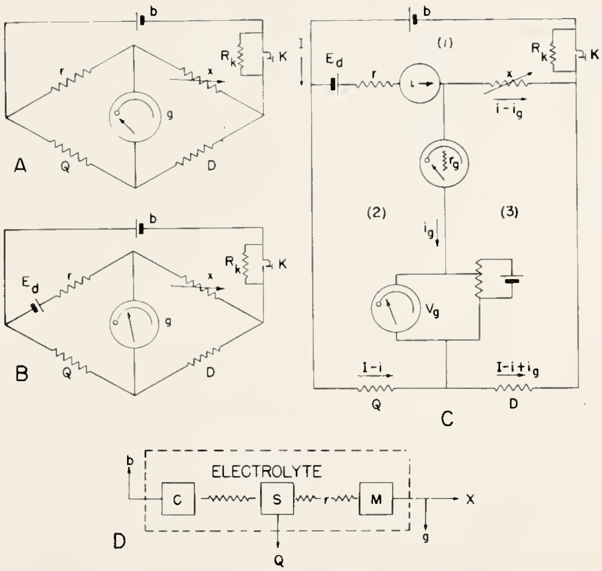

FIGURE 92. *Holler's circuit for measuring potential and internal resistance.*

A, Most elementary Wheatstone bridge; B, elementary Wheatstone bridge with emf in one arm; C, Wheatstone bridge with emf in one arm and an adjustable counter emf in series with galvanometer; D, diagram showing introduction of halfcell, S, into cell under investigation.

cell. If the resistance in the simplest bridge circuit (fig. 92A) have such values that

$$\frac{r}{x}=\frac{Q}{D} \tag{9}$$

then closure of key K in the branch containing the emf b will cause no deflection of galvanometer g. This is the condition of a balanced bridge. A resistance R_k may be used in parallel with the key K to limit the change in voltage applied to the bridge, when the key is closed, and thereby control sensitivity.

By replacing r with a cell having an emf E_d and an internal resistance r, as in figure 92B, where r has the same value as in figure 92A, there is now a deflection of the galvanometer due to E_d. If the value of r changes, the bridge may be rebalanced with respect to the resistive component by varying resistance X until closing or opening the key K causes no change in deflection.

To measure the value of E_d, an adjustable counter emf V_g is put in series with the galvanometer, to give the circuits shown in figure 92C. Then according to Kirchoff's laws, in circuit (2) of figure 92C:

$$E_d-V_g=ir+i_gr_g-(I-i)\ Q, \tag{10}$$

r_g being the galvanometer resistance. In circuit (3) of figure 92C:

$$V_g=(i-i_g)\ X-i_gr_g-(I-i+i_g)D. \tag{11}$$

Now, if $r=X$ and $Q=D$, then when i_g is reduced to zero, by adjusting V_g until the galvanometer reads zero,

$$E_d=2V_g. \tag{12}$$

This is true for any equal values of Q and D.

As Pearson [194] has shown, the adjustable counter emf may be used in the same arm of the bridge containing the emf to be measured, and the latter be read directly as V_g. However, the Holler circuit more readily permits the galvanometer and adjustable counter emf to be replaced by a recording potentiometer for obtaining emf-time curves for the cell through which current is flowing. If r should vary with current, the bridge may be rebalanced by adjustment of X, giving r directly. This may be done as described above, or with alternating current.

For measuring electrode potentials, Holler introduced a carbon anode C, a reference electrode S, and a corrodible metal M, such as iron, as shown in figure 92D. S and M now replace E_d (fig. 92C) and the reisistance r between S and M replaces the internal resistance of cell E_d. The potential between the reference electrode S and the metal M under observation now is equal to $2V_g$ (eq 12) when the bridge is balanced.

Holler used this circuit for laboratory measurements of the current required for cathodic protection [137,139] and, also for determining current distribution in cathodic protection [320]. Logan [315] used the circuit in the field during the course of a study of cathodic protection test methods.

23.5. Field Methods and Application of Cathodic Protection to Pipelines

Basically all that is required for cathodic protection is a source of direct current, and a circuit for applying this current through the electrolyte to the structure to be protected, and back to the source to maintain a potential between the pipe to soil of −0.85 v with reference to the copper-copper sulfate half cell. Cathodic protection engineering consists in determining how much power is required and selecting the most economical means for supply and distribution. In general, two systems of distribution are used, regardless of the source of power. One system introduces the emf into the earth at a single favorable location (point of lowest resistivity), and attempts to protect as much as is practicable. The current density at the surface of the pipe and the potential of the earth with respect to the pipe is greatest near the point where the current is drained from the pipe, which is usually the point on the pipe nearest the anode. The current distribution on the surface of the pipe tends to become more nearly uniform and the protected surface tends to increase with increased separation between anode and pipe up to distances of a few hundred feet. This system requires the minimum amount of wire to transmit the current but might be wasteful of power in the region near the anode. The distributed anode system, patented by Rhodes [321, 322, 323], requires less power but a greater investment in copper and power converters. The Rhodes system is almost essential particularly for city networks, when sacrificial anodes are used as the potential source.

The design of cathodic protection for cross-country lines has been discussed by Rhodes [321], McGary [324], Rogers [325], Thayer [326], Scott [327], Ewing [71, 328], Schneider [329], Olson [330], Pearson [331], and Pope [332]. Three main points are to be considered: (1) An economical source of power including distribution costs and losses; (2) a low-resistance anode, preferably with little polarization and low counter voltage; (3) as extensive a distribution of current from a single source as is consistent with economy, and with no interference with other structures. Some of these requirements will be discussed in detail.

a. Converted Power as Current Source

Rectifiers, gas engine-driven generators, and windmills are used by most engineers as sources of direct current power for cathodic protection. The design of such apparatus has become stabilized to the extent that it is only necessary to select a reliable manufacturer and furnish him information as to the required power output.

Selenium and copper-oxide rectifiers (air-cooled and oil immersed) are the most popular types of converted power supply, due in part to the fact that they usually require little attention other than occasional adjustment of the voltage. At their best, single-phase rectifiers have an efficiency of about 65 percent [333] and the efficiency of a three-phase apparatus is approximately 15 to 20 percent higher than a single-phase unit [334]. The construction and operating characteristics of copper-oxide rectifiers were discussed by Burton and Hamann [335] who also compared their behavior with selenium rectifiers. According to Waelterman [336], for outputs above 6 v, selenium rectifiers have some definite advantages.

Generators driven by gas engines are used where substantial power is required and a power-line supply is not convenient, especially where gas is readily available. The popularity of wind-driven generators as a source of power has decreased because of the need for continuous power and they are now used to better advantage as a source of auxiliary power [337, 338].

b. Use of Anodes with External Power

Resistance to Earth. Anodes are used in cathodic protection installations either as a source of primary power as in the case of sacrificial anodes, or as a means of introducing an applied emf into the earth from an external power source. The important characteristics of anodes are (1) electric contact resistance of anode to earth, (2) polarization, especially with sacrificial anodes, (3) permanence, and (4) cost.

Most of the resistance to the flow of the protective current is at the areas of contact of the anode and cathode with the soil. If the cathode, the pipe to be protected, is bare, the resistance at its surface is usually small and attributable to corrosion products or polarization. Making the resistance between anode and cathode low is one of the major problems of cathodic protection and this depends largely on the size, shape, location, and distribution of the anode system.

Frequently, several anodes are connected together in a line parallel to the pipe to be protected, in which case they are known as distributed anodes, or in a two-dimensional group known as a ground bed. The distributed anodes, usually consist of rods from 1 to 4 in. in diameter and up to 80 in. in length. Eight or more are spaced from 5 to 10 ft apart in a line parallel to and a few feet from the pipe. The resistance to earth of the group is roughly that of the resistances to earth of the individual anodes in parallel, that is, $1/R=1/r_1+1/r_2+\ldots 1/r_n$, where R is the resultant resistance and r_1, r_2, etc., are the individual resistances to earth. The same equation applies to any other arrangement of anodes, if they are sufficiently separated from each other.

The resistance to earth of the individual anodes depends on their diameters and lengths and on the resistivity of the soils in which they are placed. The anodes may be placed vertically or horizontally, the choice depending largely on the depth of relatively low resistance soil. The data on the contact resistance to earth of ground rods for electric systems are applicable to anodes if they are placed in homogeneous soil. This subject was discussed by Peters [339], who showed that the contact resistance to earth of a pipe driven in the earth was represented by the equation $R=\rho/2\pi C$, in which R is the resistance between the pipe and the earth, ρ is the resistivity of the soil, and C is the combined electrostatic capacity in free space of the electrode and its image above the surface of the ground. The value of C can be calculated approximately from the equation $C=2L/2\log_e(4L/d)$, in which L is the length of the pipe and d its diameter. The equation can be used for computing the effect of increasing the diameter or length of the pipe. Figure 93 illustrates the effect of increasing the length of the pipe as determined by the above equation and by experiment in a high resistance soil. The effect of putting two or more vertical rods in parallel is illustrated in figures 94 and 95.

Frequently the resistance of the subsoil or underlying rock is so high that extending a ground rod into it does little good. It is advisable therefore, to determine the resistivity of the soil at various depths by Gish and Rooney's [340] application of the Wenner method and to limit the length of the anodes accordingly.

If the subsoil has a high resistance, it may be advisable to lay the anode horizontally, in which case its resistance to ground will be

$$R=\rho\log_e(2L/d)/\pi L.,$$

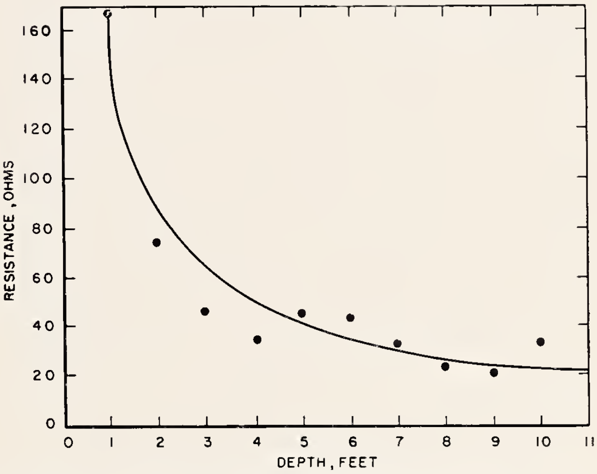

Figure 93. *Effect of the length of a driven-pipe ground on its resistance to earth* [339].

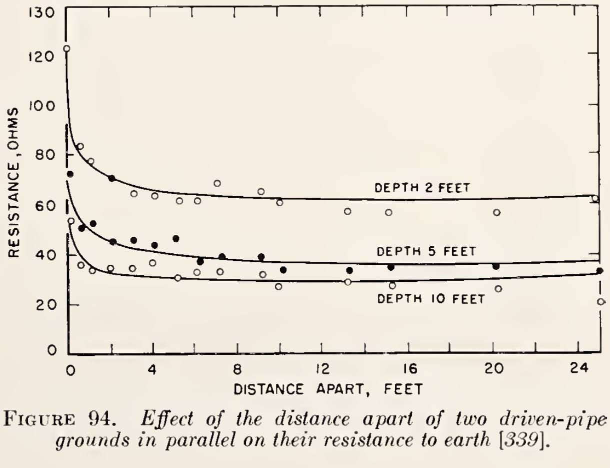

Figure 94. *Effect of the distance apart of two driven-pipe grounds in parallel on their resistance to earth* [339].

in which the symbols have the same significance as in the preceding equation.

If the resistivity of the soil is constant, the resistance to earth of a horizontal ground plate, such as a sheet of metal, decreases as its distance below the surface of the earth increases until, at depths large in comparison with the diameter of the plate, its resistance to earth is half that at the surface of the ground. The effect of the area of a plate near the surface of the earth on its resistance to earth is shown in figure 96.

The resistance to earth of a circular plate at the surface of the ground is $R=r/2d$, in which r is the resistivity of the soil and d is the diameter of the plate. Consequently, to reduce the resistance to earth of a plate to one-half, its area must be made four times as great. It would be more economical to use two plates of the same diameter in parallel and some distance apart. Likewise, a number of small widely separated rods or strips in parallel have a lower resistance to earth than a continuous piece having the same area.

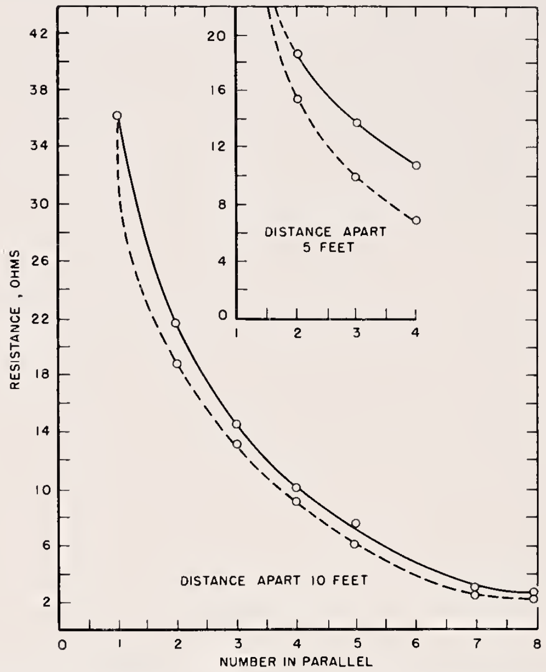

Figure 95. *Effect of the number of 10-foot driven-pipe grounds in parallel on their resistance to earth* [*339*].

———, Observed values; – – –, calculated values.

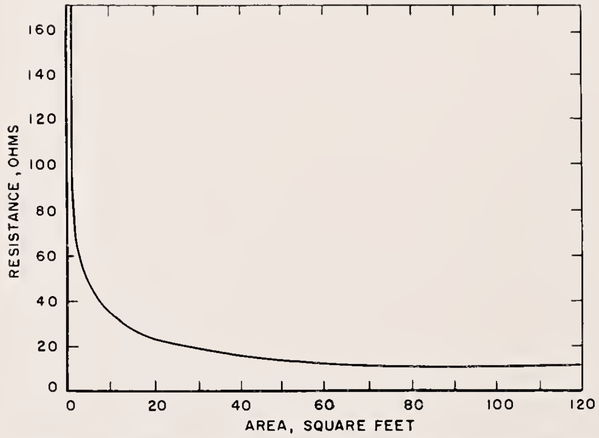

Figure 96. *Effect of the diameter of a buried circular plate on its resistance to ground* [*339*].

Iron. The kind of iron or steel used for anodes is unimportant. Junk iron, usually old pipe, is often used because of its low initial cost, low polarization, and low resistance of the corrosion products. Boilers and parts of old engines and large machines have been used and also old well casings in place. If the current density at the surface of the iron is kept low, the anode will lose about 20 lb/amp-yr plus some loss caused by local corrosion. The latter will depend on the corrosivity of the soil and the homogeneity of the metal. If the current density is high, the rate of loss of metal may be lowered, because part of the current may cause the evolution of oxygen by the electrolysis of water in the soil. Hence, additonal energy will be required to ionize the water and still more to overcome the resistance resulting from the heating and drying of the soil.

The relation of the current density to the corrosion efficiency (the ratio of the actual to the theoretical loss of anode material) was investigated by McCollum and Logan [7], who found that it ranged from 1.40 for a current density of 0.1 ma/cm^2 to about 0.4 for a current density 40 times as great.

Carbon and Graphite. Carbon and graphite anodes have come into use because they are more inert than iron or steel. The theoretical loss of carbon by electrochemical action in soils is about one-tenth that of iron. The corrosion products of carbon are predominantly gaseous (carbon dioxide) and escape without causing an appreciable increase in anode-to-ground resistance, provided sufficient moisture is available to the anodes to maintain a nearly constant resistance. Usually, the anode is surrounded by an artificial environment, such as crushed coke, coal-coke breeze, or loam soil to lower the anode-to-soil resistance. Carbon or graphite anodes have lower mechanical strength than iron anodes and have an electropositive potential with respect to iron, which varies from 0.8 to 1.8 v, depending on polarization. Comparative data pertaining to ground anodes were reported by Holsteyn [341].

High-Silicon Cast Iron. Like carbon and graphite, high-silicon cast iron, which contains about 14.5 percent of silicon, is cathodic to steel and has been used successfully an anodes in the cathodic protection of iron and steel structures in fresh water, salt water, and soil [342]. Field data included in the report of Technical Committee T2-B (see below) show a potential difference between steel and silicon cast iron, measured shortly after opening the anode circuit, as ranging between 1.8 and 2.6 v. At the 1955 convention of the National Association of Corrosion Engineers, Technical Committee T2-B

(Anodes for Impressed Currents) reported low consumption rates for high-silicon cast iron anodes in fresh and salt water. It was also reported that silicon cast iron surrounded by coke breeze in high chloride soils was consumed at rates ranging from nil to 0.23 lb/amp-yr, while the same type anodes installed without this backfill material, in a similar soil were consumed at rates ranging from 2 to 18 lb/amp-yr. This high rate was attributed to gas blocking.

c. Sacrificial Anodes as a Power Source

In sections of the country remote from power lines and in cities where the stringing of wires to supply power would be unsightly, and where anodes must be placed close to the protected structure to avoid endangering neighboring structures, aluminum, magnesium, or zinc may be used as sacrificial anodes to furnish power for cathodic protection. However, the resistance of the soil must be sufficiently low so that the anode system can provide an emf that will be capable of maintaining the critical potential of -0.85 v (with respect to a copper-copper sulfate reference electrode) between the structure to be protected and the soil. Wainwright [343] discussed conditions that justify the use of rectifiers or sacrificial anodes in cathodic protection installations. In some soils, an insulating film is deposited on sacrificial anodes that greatly reduces the efficiency of the metal as an anode. In order to overcome such effects, the anodes are surrounded by backfill material to provide a favorable environment around the anodes and to maintain an active surface for the maximum output of current [187, 344, 345, 346, 347, 348].

Aluminum Anodes. The electrode-potential series indicates that aluminum might be more effective than zinc as a current-generating anode for cathodic protection, the open-circuit potential between iron and aluminum being about 1.1 v. Results reported by Aliter [349] showed that for the protection of steel rods in two Hanford soils, aluminum was more effective than zinc in a soil containing carbonates because zinc reversed its potential with respect to iron. As aluminum is attacked by some alkali soils, its use in such soils might be limited by local corrosion, although the *p*H of the Hanford soils was from 7.7 to 8.1. Investigations carried out by the Aluminum Company of America show that aluminum alloyed with 5 percent of zinc is a better anode especially when used in conjunction with proper backfill materials [350, 351].

Magnesium Anodes. The open-circuit potential between iron and magnesium is of the order of 1 v, which is more than twice that betweem zinc and iron. In a field experiment involving the use of magnesium anodes on a pipeline, Olson [352] observed that some of the anodes became inactive after a few months of exposure, whereas others continued to supply 50 percent or more of the original power. However, the loss in weight of the magnesium anodes was several times that attributable to the current density of the anode. Grebe and McNulty [353] reported extensive experience with magnesium anodes, which show electrolytic corrosion efficiencies up to 30 percent.

Robinson [348, 354, 355, 356] conducted laboratory investigations of the performance characteristics of magnesium anodes to determine the effect of such variables as current density, anode composition, impurities, electrolyte, and *p*H. The general conclusions derived from his extensive investigation are as follows: (1) The potential of the magnesium anode is ample for cathodic protection purposes in most naturally occurring electrolytes, including soils; (2) both anode current efficiency and uniformity of anode consumption improve with increasing current density. Efficiencies of 50 to 60 percent are obtained with magnesium alloy anodes for current densities in excess of 50 to 100 ma/ft^2; (3) the high-purity Mg-Al and Mg-Al-Zn alloys perform much more efficiently than the commercial grade of magnesium at current densities up to 700 ma/ft^2. Of the various compositions tested, a magnesium alloy containing 6-percent aluminum, 3-percent zinc, and 0.2-percent manganese, exhibited the best over-all performance characteristics; (4) of the electrolytes tested, saturated aqueous solutions of either calcium sulfate or magnesium sulfate were the most satisfactory environments for magnesium anodes. An electrolyte *p*H of 9.5 to 10.5 was optimum. Higher *p*H values produced polarization and lower *p*H values reduced current efficiency by stimulating local corrosion.

Experiences on field installations of magnesium anodes were reported by Hart and coworkers [358, 359] and by Peifer [360] who proposed a method of obtaining cathodic protection by use of an expendable anode in the form of magnesium ribbon that is laid parallel to the pipe. The performance of magnesium anodes in sea water was reported by Humble [357].

Zinc Anodes. The open-circuit potential difference between iron and zinc is in the order of 0.4 v, which may be enough to furnish an adequate protective current if the resistances of the soil and anode environment are low. Zinc anodes have been installed in a number of soils with beneficial effects, although in some soils the protection obtained has not been satisfactory. These failures to protect were in part attributable to an insufficient number of anodes and in part to improper installation or maintenance.

Wahlquist [346] described an installation of high-purity cast zinc anodes, attached to a gas line in eastern Colorado in 1935. The rods were 1 or 1⅜ in. in diameter by 4 ft long with a ¼-in. iron core, and weighed 12 to 18 lb each. Usually eight rods, spaced about 10 ft apart, were connected in parallel and alined 5 to 14 ft from the pipeline. Most of the soils contained sulfates and carbonates and had resistivities between 200 and 700 ohm-cm. In general, zinc anodes furnished between 30 and 50 ma/rod for a period of 6 or 8 years, and maintained the pipe-to-soil potential at from -0.6 to

−0.93 v with respect to a remote copper-copper sulfate electrode. Several leaks occurred after the installation of the zinc anodes, but the frequency of their occurrence was greatly reduced by the anodes.

Brockschmidt [344] described an installation in which the current provided by the zinc anodes was less than half of that observed in Walquist's installation, although the size and location of the anodes, and the soil resistivities, were approximately the same. Because the pipe-to-soil potentials were generally greater than the commonly accepted criterion of −0.85 v required for protection, the two installations were equally effective.

Mudd [345] used zinc anodes, rolled from ¼-in. sheet to form cylinders 7 in. in diameter and 3 ft long, which were installed in a vertical position from 4 to 6 ft deep. A backfill consisting of calcium sulfate (gypsum) and crushed rock was packed around the cylinder to insure good soil-to-anode contact. The results showed that this type of installation was most effective when a total anode area of 30 ft^2 was maintained, and when the distance between the nearest anode to the pipeline was more than 100 anode diameters with a spacing of 50 diameters between anodes, conforming to Schneider's [361] recommendations.

The generally accepted backfill material consists of a mixture of clay and powdered gypsum. When zinc anodes are installed without a backfill, the corrosion products that form on the anodes are often of a hard impervious type that cause a large increase in resistance-to-earth; and the impurities in zinc are generally sufficient to cause the zinc to become passive. Both of these effects tend to lower the efficiency of zinc as a sacrificial anode.

Results of investigations with zinc used as sacrificial anodes have been reported by Smith and Marshall [362], Romanoff [363], Denison and Romanoff [135], and Morgan [364]. Rhodes [322], May and coworkers [365], Anderson [366], and a report of the American Zinc Institute [367] show the importance of using high-purity zinc anodes, and of using proper backfill material to promote maximum current efficiency.

d. Behavior of Experimental Zinc-Steel Couples Underground

Experimental Procedure. In order to study the effectiveness of zinc for the cathodic protection of iron and steel in different soils, the National Bureau of Standards in 1941 initiated a series of field tests in cooperation with eight pipeline companies [135, 363]. Specimens were installed at eight test sites selected to represent diverse soil conditions (table 107). The experimental couple was so designed that the data may be applied to practical installations, as it can be shown that if the appropriate dimensions are maintained in a medium of large extent and with the same resistivity, the current densities on the cathodes will be the same for the experimental field and practical installations.

The design of the experimental cathode and the installation of the couple were based on theoretical considerations and on measurements of current distribution as affected by the form of the cathode, horizontal spacing, and depth of the cathode below the surface of the ground. Cathodes for the field tests were constructed by bending a plain carbon steel rod, 0.5 in. in diameter, to form a ring having an external diameter of 10 in. and a surface area of 48 $in.^2$. The cylindrical anodes, 1.75 in. in diameter and 3.75 in. in height, were cast from high-purity zinc and had a base area of 2.4 $in.^2$. By exposing only the base of the anode to the soil, the area of the zinc and hence the zinc-steel area ratio in the couple could be maintained reasonably constant. This was accomplished by coating the cylindrical surface with a bituminous paint to prevent local corrosion and housing each anode in a wide-mouth glass bottle from which the base had been removed. The weight of the anode was sufficient to provide firm contact with the soil and the cylinder was free to move downward as its base corroded. After burial at the test sites, the electric circuit was completed to a copper bus which was placed in a glass bottle to protect the terminals from corrosion. The plan of installation of the couples is shown in figure 97.

Although measurement of the loss in weight of the steel cathodes after a given period of exposure would establish the degree of cathodic protection provided by the zinc anodes in the environments selected, provisions were also made for measurement of galvanic currents and electrode potentials as possible alternative indications of the protection obtained.

Cathodic Protection as Indicated by Corrosion Measurements. The losses in weight and the depths of the deepest pits on the steel cathodes connected to the zinc anodes are shown in table 107, together with similar data for the unconnected steel rings and zinc cylinders. It is evident from these data that over the test periods of from 3 to nearly 6 years, practically complete protection was obtained at 6 of the 8 test sites, namely 71 to 75, inclusive, and 78. Although a zinc-steel area ratio of 1:20 was sufficient for protection at sites 74, 75, and 78, an area ratio of 1:10 was required at sites 71, 72, and 73. The condition of the connected and unconnected steel rings and the bases of the zinc cylinders from sites 75 and 78 is shown in figure 98.

The soil properties that appear to have the most inhibitive effect on the anodes are high resistivity and high alkalinity. The fact that protection was not obtained at site 77 is no doubt caused by the high specific resistance of the soil, 9,370 ohm-cm, at this site. Although the relatively high resistivity of soil 76 (2,650 ohm-cm) was probably an important factor in the poor performance of the zinc anodes at this site, the high concentration of hydroxyl ions in this soil, indicated by the *p*H value of 9.2, probably tended to inhibit the galvanic corrosion of the zinc anodes. With regard to the remaining soils, it would seem that the composition of the water soluble material was unimportant, providing the resistivity of the soil was relatively

TABLE 107. *Weight losses and maximum pit depths on connected and unconnected electrodes* [*135*]

P, Deepest pit less than 6 mils; *M*, shallow metal attack—no definite pits; *S*, uniform corrosion—no reference surface for pit measurements

Site[a]		pH	Resistivity at 60°F	Duration of exposure	State of couple	Number of zinc anodes	Weight loss		Maximum penetration of cathode	Effectiveness of protection[b]
No.	Location						Cathode	Total loss of anodes		
SITES AT WHICH PROTECTION WAS OBTAINED WITH A 1:20 ZINC-STEEL AREA RATIO										
			Ohm-cm	*Years*			*g*	*g*	*Mils*	*Percent*
75	Albuquerque, N. Mex	8.4	379	5.80	Unconnected	1	109.2	0.8	135	----------
					Connected	1	3.2	229.9	P	97
					do	2	2.0	283.6	P	98
					do	3	0.6	309.0	P	99
78	Latex, Tex	4.5	821	3.14	Unconnected	1	67.3	0.8	84	----------
				3.14	Connected	1	1.8	43.1	7	97
				4.26	do	2	0.8	88.3	P	99
				3.14	do	3	1.4	63.6	4	98
74	Rocky Ford, Colo	7.3	436	5.82	Unconnected	1	28.9	0.6	P	----------
					Connected	1	0.6	40.1	P	98
					do	2	[c]25.2	[c]28.7	[c]48	[c]13
					do	3	0.2	29.1	P	99
SITES AT WHICH PROTECTION WAS OBTAINED WITH A 1:10 ZINC-STEEL AREA RATIO										
73	East St. Louis, Ill	6.8	521	5.83	Unconnected	1	235.0	0.2	70	----------
					Connected	1	32.6	184.9	35	86
					do	2	1.7	135.9	P	99
					do	3	5.2	260.4	P	98
71	West Austintown, Ohio	7.1	2,582	5.12	Unconnected	1	57.1	0.0	38	----------
					Connected	1	13.2	25.1	20	77
					do	2	7.6	37.8	16	87
					do	3	7.4	45.0	22	87
72	Deerfield, Ohio	7.2	762	5.18	Unconnected	1	26.8	0.6	11S	----------
					Connected	1	29.0	16.1	42	----------
					do	2	2.9	33.0	M	89
					do	3	2.9	43.1	P	89
SITES AT WHICH INCOMPLETE PROTECTION WAS OBTAINED EVEN WITH A 1:6.7 ZINC-STEEL AREA RATIO										
76	Los Angeles, Calif	9.2	2,650	1.49	Unconnected	1	45.9	0.4	70	----------
					Connected	1	27.3	33.8	78	41
					do	2	17.1	39.1	35	63
					do	3	15.3	72.8	41	67
77	Louisville, Miss	4.3	9,390	5.67	Unconnected	1	58.3	0.7	58	----------
					Connected	1	47.2	8.8	98	19
					do	2	29.1	19.1	84	50
					do	3	28.0	34.6	65	52

[a] See table 6 for soil names and other soil properties.
[b] Based on weight loss of unconnected ring.
[c] Couple on open circuit for an indefinite period.

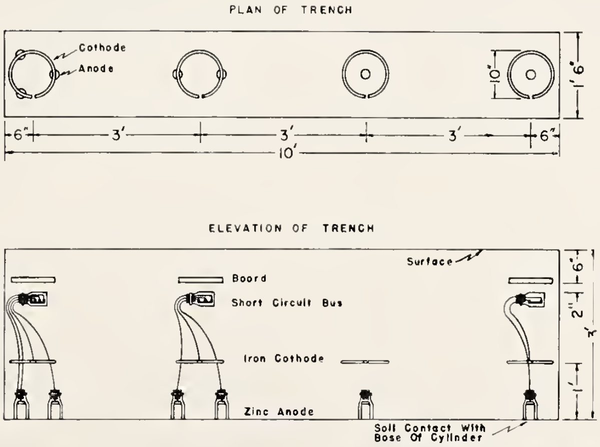

FIGURE 97. *Arrangement of zinc-steel couples at the test sites* [*135*].

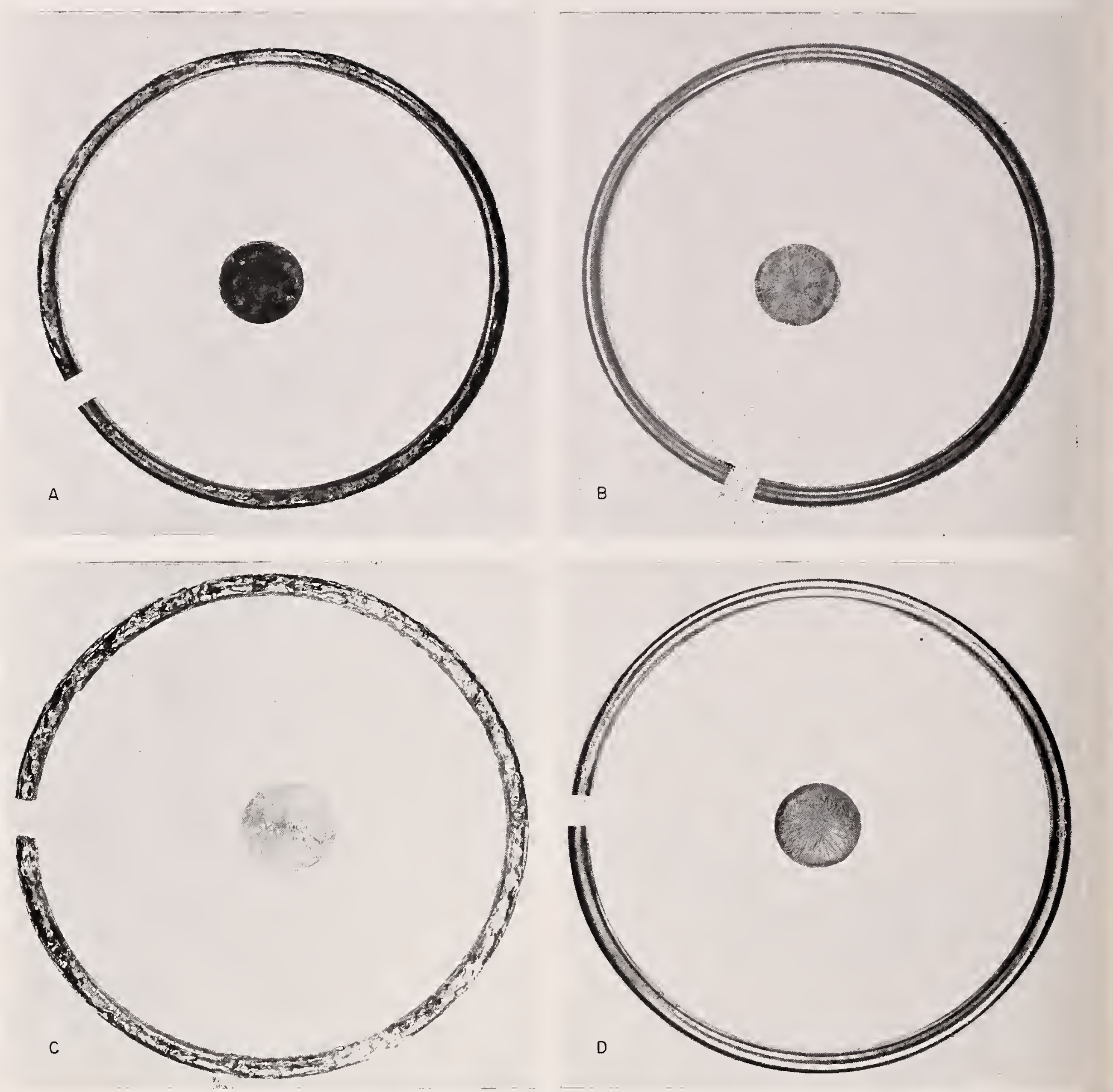

Figure 98. *Condition of connected and unconnected steel cathodes and zinc anodes at two test sites* [*135*].

A, Unprotected steel ring and zinc cylinder exposed at site 78 for 3.1 years; B, ring connected to zinc anode at site 78 for 3.1 years. Zn-Fe area ratio 1:20; C, unprotected steel ring and zinc cylinder exposed at site 75 for 5.8 years; D, ring connected to zinc anode at site 75 for 5.8 years. Zn-Fe area ratio 1:20.

low. Improvement in the performance of zinc anodes in poorly conducting soils and in strongly alkaline soils deficient in chloride and sulfate ions can probably be obtained by surrounding the anodes with proper backfill materials which produce soluble corrosion products of zinc.

The data obtained from site 72 throw light on the somewhat controversial subject of whether cathodic protection is practical in highly reducing environments in which microbiological activity is an important factor in corrosion. In such environments it is assumed that high-resistance oxide films, which normally cover cathodic areas, are converted to sulfide films of relatively low resistance, and that the effect of this conversion is to cause a large proportion of the protective current to be bypassed by the cathodic areas, thereby requiring an abnormally high current for protection. Soil 72 contains a relatively high concentration of sulfate ions and the reducing nature of this soil was shown by the presence of sulfide in the corrosion products of steel at this location and also by measurements of the oxidation-reduction potential. Under these conditions it is noteworthy that adequate protection of the steel cathodes was obtained with a moderate area-ratio of zinc to steel.

Cathodic Protection as Indicated by Electrical Measurements. Table 108 gives the results of electrical measurements, made on the galvanic couples. After measuring the galvanic currents and the closed-circuit potentials of the couples, the circuits were opened for 15 to 20 min, and the open-circuit potentials of the zinc anodes and steel cathodes were measured during this period.

The results show that the sites at which protection of the steel cathodes occurred, as indicated by the weight losses and maximum pit depths (table 107), were the same as those at which the galvanic currents were high early in the exposure period and thereafter diminished as the cathodes polarized (table 108). No exact interpretation can be placed on the degree of protection achieved as related to the open-circuit potentials of the cathodes, as the potentials were not necessarily measured immediately after opening the couple circuit. However, it is evident that protection is related to the degree of polarization. For example, the cathodes at site 71 that received the least protection (table 107) of all the cathodes placed in the protected category, polarized the least of all.

There is little evidence of cathodic polarization at sites 76 and 77, except toward the close of the exposure period at site 76 when it was too late to be reflected in the cathode weight losses. Although the relatively cathodic couple potentials (table 108) at these two sites might infer the occurrence of anodic polarization, this is not shown by the open-circuit potentials of the zinc. The cathodic couple potentials could be caused by the formation of corrosion products on the zinc having relatively high resistance.

TABLE 108. *Potential and current measurements on zinc-steel couples [135]*

Site	Duration of exposure	Potentials									Galvanic currents		
		Steel rings having Zn:Fe area ratio of—			Zinc cylinders having Zn:Fe area ratio of—			Zinc-steel couples having Zn:Fe area ratio of—			Zinc-steel having Zn:Fe area ratios of—		
		1:20	1:10	1:6.7	1:20	1:10	1:6.7	1:20	1:10	1:6.7	1:20	1:10	1:6.7
SITES AT WHICH PROTECTION WAS OBTAINED WITH A 1:20 ZINC-STEEL AREA RATIO													
	Years	*v*	*v*	*v*	*v*	*v*	*v*	*v*	*v*	*v*	*ma*	*ma*	*ma*
75	0	0.71	0.70	0.74	1.11	1.15	1.17	---	---	---	5.9	11.7	15.2
	.53	.80	.82	---	1.08	---	---	0.92	1.00	1.02	4.7	5.4	5.4
	5.80	---	.88	.93	---	1.00	1.10	---	1.03	1.04	---	1.32	1.30
78	0	.59	.58	.58	.91	.92	.92	---	---	---	3.80	5.35	6.80
	.27	.95	.96	.96	1.04	1.06	1.05	1.00	1.00	1.01	.86	2.00	1.61
	.48	.91	.95	.93	1.09	1.10	1.10	1.05	1.05	1.05	.80	1.79	1.41
	.84	.80	.78	.82	1.10	1.10	1.06	1.00	1.05	1.05	2.40	4.90	3.68
	1.17	.76	.83	.74	---	1.14	1.15	.96	.96	1.20	1.50	1.89	1.40
	3.14	---	---	---	---	---	---	.68	.91	.96	2.00	1.62	1.95
	4.26	---	.81	---	---	1.08	---	---	.91	---	---	1.8	---
74	0	.74	---	---	1.18	---	---	---	---	---	7.26	---	---
	.54	---	---	---	---	---	---	1.04	1.08	1.08	.28	.55	.45
	2.23	---	---	---	---	---	---	1.04	1.05	1.08	.58	1.11	.49
	5.82	.90	[a].72	1.03	1.08	[a]1.09	1.10	---	---	1.08	.66	[a]6.00	.38
SITES AT WHICH PROTECTION WAS OBTAINED WITH A 1:10 ZINC-STEEL AREA RATIO													
73	0	---	---	---	---	---	---	---	---	---	2.6	4.6	4.60
	.68	0.94	0.95	0.85	1.10	1.11	1.14	1.01	1.03	1.03	.58	1.00	1.02
	5.83	.68	.84	.68	1.05	1.09	1.06	---	.90	.76	3.45	2.40	5.00
71	0	.59	.58	.60	1.09	1.10	1.10	---	---	---	.44	.48	.66
	.32	.62	.55	.60	1.11	1.12	1.13	.76	.80	.94	.93	1.33	1.30
	.77	---	---	---	---	---	---	.79	.84	.92	.62	1.15	1.48
	3.02	.50	.58	.56	1.04	1.26	1.28	.55	.69	.73	.43	1.12	2.00
	5.12	.63	.74	.93	1.04	1.08	1.11	.76	.86	1.00	.21	.27	.35
72	0	.73	.73	.73	1.14	1.14	1.14	---	---	---	.73	1.46	2.65
	.31	.78	.85	.75	1.02	1.06	1.05	.79	.89	.83	.24	.41	1.14
	.73	.76	.80	.77	1.02	1.07	1.05	.77	.83	.82	.35	.66	1.17
	1.04	.71	.76	.76	1.02	1.06	1.06	.72	.80	.81	.54	.97	1.34
	3.01	.62	.71	.73	.91	1.05	1.06	.64	.72	.77	.52	.84	.08
	3.18	.58	.63	.75	.82	1.08	1.04	.58	.65	.79	.14	.31	.49
SITES AT WHICH INCOMPLETE PROTECTION WAS OBTAINED EVEN WITH A 1:6.7 ZINC-STEEL AREA RATIO													
76	0	0.52	0.49	0.50	0.95	0.93	0.97	0.55	0.50	0.51	0.19	0.58	1.44
	.26	.68	.63	.72	1.07	1.05	1.07	.70	.67	.79	.87	2.30	3.27
	.47	.66	.50	.67	1.05	1.03	1.03	.70	.66	.78	1.39	4.49	3.43
	.80	.47	.54	.56	1.05	1.03	1.04	.57	.63	.71	3.05	1.98	6.15
	1.28	.45	.45	.35	1.03	1.03	1.03	.59	.57	.61	2.25	1.69	4.09
	1.49	.83	.63	.83	1.07	1.02	1.03	.86	.67	.89	1.55	1.42	.62
77	0	.58	.55	.57	1.08	1.09	1.09	---	---	---	.52	.61	.71
	.54	---	---	---	---	---	---	.58	.66	.69	.10	.53	.93
	5.67	.14	.20	[a].25	1.08	1.06	[a]1.07	.16	.22	[a]1.06	.12	.31	[a]1.25

[a] Couple found on open circuit. Circuit was closed to measure the galvanic current.

e. Interference Problems in Cathodic Protection Installations

The installation of cathodic protection to cross-country lines usually involves no interference problems with other underground structures. However, in the underground installations of the larger cities, the current applied to protect a structure may flow onto and off the adjacent structures and damage them. The adjacent structures may also interfere with the desired distribution of current. It is necessary, therefore, to take precautions in applying cathodic protection to the underground pipe or cable systems in congested areas.

The interference problem has been discussed by Smith [368], Pearson [318], Pope [369], Kuhn [370], Schneider [371], Wainwright [372], Simpson [373], and Gorman [374].

The solution to the interference problem recommended by most of these investigators is to protect all structures in a neighborhood by the joint action of all interested parties. This involves an agreement as to the distribution of costs which occasionally is difficult to determine satisfactorily. A tentative plan for such cooperation was proposed by the Cathodic Protection Committee of the Petroleum Industry Electrical Association [375]. An alternative solution is the application of protection to a single structure. If this is done, a current and potential survey of all structures that may be affected should be made both before and after cathodic protection is applied. Anode locations should be selected and bonds or insulating joints properly adjusted so that none of the neighboring structures are endangered. The importance of properly locating the ground bed to avoid interference was discussed by Ringer [376] who described a method, based on the work of Pearson [318], to determine the extent of interference before permanent cathodic protection installations are completed. In most cases, the least interference will probably result from a system, developed by Rhodes [377], of distributed anodes that are placed close to the pipe to be protected.

f. Cathodic Protection of Structures Other than Pipelines

Cathodic protection can be applied to other ferrous structures in soils or aqueous solutions by methods similar in principle to the protection of pipelines. The same criteria for protection are used. The cathodic protection of tanks and various types of farm equipment has been described by Holsteyn [308], Brannon [378], Bond [379], Bialosky [380], Collopy [381], Ewing and Hutchison [382], and Fergus [383]. Cathodic protection applied to the underside of a gas holder was described by Grebstad and Gilbert [384]. The application of cathodic protection to structures submerged in water was reported by Shepard and Graeser [385], Sudrabin [386, 387], Humble [388], and Doremus [389]. Schuldiner [390] and Barnard and coworkers [391, 392] investigated the application of cathodic protection to the hulls of ships in sea water.

g. Status and Economics of Cathodic Protection

In view of the foregoing discussion on cathodic protection, it appears that the methods used for the application of cathodic protection to underground structures and the criteria for judging the effectiveness of the protection are not yet well established. The immediate problem of the corrosion engineer has been to effect a substantial reduction in corrosion of structures presently buried underground. Hence, the applications of cathodic protection during the past decade, and to some extent at present, have been necessarily experimental in character or based largely upon the judgement of corrosion engineers, some engineers having preference for one system and other engineers for other systems. However, from experience gained as a result of trial installations and laboratory experimentation, more definite engineering principles are being established to the extent that today most engineers practice methods that are gaining general acceptance.

The application of principles established by laboratory experiment to field installations is difficult because the conditions encountered in practice are more complex. For example, in the laboratory there is definite control of such factors as aeration, composition, and homogeneity of the electrolyte, including soil samples. On the other hand, the engineer in the field has to contend with variations in these factors that make necessary precise measurements of electric currents and potentials associated with underground metallic structures.

The pipe-to-soil potential measurements are made with a potentiometer or very high resistance voltmeter and a nonpolarizing reference electrode. Copper-copper sulfate reference electrodes are commonly used for the pipe-to-soil potential measurements because they are easily constructed and give reproducible results. Miller [393] describes the instruments generally used by corrosion engineers for electrical measurements pertaining to the field application of cathodic protection.

As has been previously stated, the cheif requirement for cathodic protection is a source of direct current and a uniform distribution of the current to all points on the surface of the structure to be protected. The most common source of current is a low-voltage generator or a rectifier connected between the structure (cathode) and an anode or system of anodes (ground bed) buried remote from the structure. The structure to be protected is connected to the negative side of the power source and the anode is connected to the positive side. This raises the potential of the earth adjacent to the structure and reduces current leaving it, and consequently retards or eliminates corrosion of the structure. The length of a pipeline that can be protected by given installation depends on the capacity of the generator, the resistivity and other characteristics of the soil, and the insulating properties of the pipe coating, if a coating is used. Under some conditions 10 or more miles of pipe can be protected by an anode ground bed; under other conditions it may be practical to protect only a few hundred feet by a similar installation.

In many installations, especially where commercial power is not available, the current for cathodic protection is supplied by galvanic or sacrificial anodes (zinc, aluminum, or magnesium). A sacrificial anode is placed within a few feet of the pipe and a relatively small area is protected by a single or group of anodes, in comparison to that protected by current obtained from a power source, unless the pipe is well coated. Whatever the source of power, the pipe or structure to be protected must be electrically continuous, i.e., all joints except welded joints must be bonded.

The current required for protection differs greatly for different conditions. The average current density required to protect bare pipe is about 3 ma/ft^2 of exposed bare pipe surface which amounts to approximately 36 amp/mile of 8-in. diameter pipe. If a pipe has been coated with a bituminous material, current flows to the pipe only at points where there is a break in the coating. Such breaks occur more or less frequently in most coatings for reasons described in section 18. However, thick bituminous coatings appreciably reduce the current required to protect a pipeline for 10 or more years. As pipe coatings gradually deteriorate, the current required for cathodic protection must be increased with time to maintain the proper emf.

Corrosion engineers in the field and investigators in the laboratory are in agreement that corrosion of underground structures is either prevented or sufficiently retarded if the structure is maintained at a potential of -0.85 v with respect to a copper-copper sulfate reference electrode in contact with the soil. However, the procedure of positioning the reference electrode with respect to the structure to be protected has been a matter of a great deal of controversy. Investigations performed at the National Bureau of Standards (see page 184) show that placing the reference electrode remote from the structure, especially in high resistance soils, give erroneous potential measurements due to the inclusion of large *IR* drops. In low resistivity soils, about 500 ohm-cm or less, errors due to the positioning of the reference electrode are not expected to be serious. Based on the Bureau's studies, it is recommended that the reference electrode be placed approximately 4 to 6 pipe diameters from a pipeline when measuring potentials along the line.

Cathodic polarization curves (see page 181) can be used to determine the amount of current that should be applied initially to effectively protect a structure during the application of cathodic protection, because the current indicated by the break in the polarization curve is sufficient to stop corrosion at the time the measurements are made. Thereafter, adjustments in the applied current to maintain the potential of the structure at -0.85 v with respect to the copper-copper sulfate reference electrode will assure continued protection.

Many factors enter into the cost of cathodic protection and the cost of one installation may be quite different from that of another. The cost for a particular installation is subject to local conditions, including availability of materials and electric power supply, extent of the protected structure, soil resistivity, and the skill, experience and foresight of the engineer in charge of the installation. A combination of a bituminous coating and cathodic protection is now recognized as the most economical method of protecting pipeline systems and other underground structures. An approximation of the costs for an installation may be based on the experience of others. The economics of cathodic protection from experiences based on various installations have been discussed by Wainwright [343, 372, 394], Olson [330], Rhodes [377], Wahlquist [346], Roddey and Shepard [395], Schneider [396, 397], Thayer [398], Stewart [399], Secrest [400], Good [401], Senatoroff [402], and Peabody and Woody [403].

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25. Appendix 1. Cooperators in the National Bureau of Standards Underground Corrosion Investigations

Grateful acknowledgment is extended to the cooperating agencies and individuals who contributed greatly to the National Bureau of Standards investigations of underground corrosion; particularly in the early stages of the program. Contributions included advisory services in planning experiments and evaluating results, supplying and maintaining test sites, supplying test materials and the labor required to install the test specimens and to remove them after exposure. Cooperators in one or more phases of these respects, and in one or more phases of the 40-year program, are listed as follows:

25.1. Advisory Organizations

American Committee on Electrolysis, Research Subcommittee
American Engineering Standards Committee
American Foundrymen's Association
American Gas Association
American Petroleum Institute
American Society for Testing Materials
American Standards Association
American Water Works Association
American Zinc Institute, Inc.
Asphalt Institute
Cast Iron Pipe Research Association
Copper and Brass Research Association
Lead Industries Association
U. S. Department of Agriculture, Bureau of Plant Industry
U. S. Department of Commerce, National Bureau of Standards
U. S. Department of Interior: Bureau of Mines, Geological Survey (Water Resources Branch)
Waterways Experiment Station, Corps of Engineers, U. S. Army

25.2. Suppliers of Materials

a. Ferrous

Allegheny Ludlum Steel Corp.
American Cast Iron Pipe Co.
American Radiator Co.
Armco Steel Co.
H. A. Brassert Co.
A. M. Byers Co.
Carnegie-Illinois Steel Corp.
Carson Cadillac Corp.
The Duriron Co., Inc.
Electric Steel Founders
Electro Metallurgical Co.
Inland Steel Co.
The International Nickel Co., Inc.
Jones and Laughlin Steel Corp.
Lukenheimer Co.
McWane Cast Iron Pipe Co.
Meehanite Metals Co.
National Cast Iron Pipe Co.
National Tube Co.
Nugent Steel Casting Co.
Pittsburgh Valve, Foundry & Construction Co
Reading Iron Co.
Republic Steel Corp.
Sharon Steel Corp.
Sivier Steel Casting Co.
Stockham Pipe and Fittings Co.
Union Carbide & Carbon Research Laboratories
United States Pipe & Foundry Co.
Walworth Co.
Youngstown Sheet & Tube Co.

b. Nonferrous

American Brass Co.
American Smelting & Refining Co.
American Zinc Products Co.
Bell Telephone Laboratories Inc.
Bridgeport Brass Co.
Brown Co.
Chase Brass & Copper Co.
General Cable Corp.
Habirshaw Electric Cable Co.
The Hoyt Metal Co.
V. T. Hungerford Brass & Copper Co.
Illinois Zinc Co.
Johns-Manville Corp.
Keasby & Martison Co.
Lumen Bearing Co.
Mueller Brass Co.
Mueller Co.
National Carbon Co.
National Lead Co.
The New Jersey Zinc Co.
Revere Copper & Brass, Inc.
Scovill Manufacturing Co.
Sharon Steel Hoop Co.
Standard Underground Cable Co.

c. Coatings

Albrecht Pagenstecher
Aluminum Co. of America
American Machine & Foundry Co.
American Tar Products Co.
Arco Co.
The Bakelite Co.
Ball Chemical Co.
Barber Asphalt Co.
The Barrett Co.
Benjamin Foster Co.
Calorizing Co.
Chadeloid Chemical Co.
Consolidated Gas Co. of New York
Dearborn Chemical Co.
E. I. du Pont de Nemours & Co., Inc.
Eagle-Picher Lead Co.
Emulsion Process Co.
Ferro Enamel Corp.
Fish-Schurman Corp.
The Flintkote Co.
General Paint Corp.
The P. D. George Co.
The B. F. Goodrich Rubber Co.
Goodyear Tire & Rubber Co.
Harpoon Paint Products, Inc.
Headley Emulsified Products Co.
Hill, Hubbell, & Co.
Inertol Co.
Iroquois Gas Corp.
Irvington Varnish & Insulator Co.
The Locomotive Terminal Improvement Co.
McEverlast, Inc.
Andrew McLean Co.
Merchants Basket & Box Co.
Paraffine Companies, Inc.
Pioneer Asphalt Co.
Resistcor Engineering Corp.
H. H. Robertson Co.
Shori Process Corp.
Sherwin-Williams Co.
Jas. B. Sipe & Co.
Southport Paint Co., Inc.
Technical Products, Inc.
The Texas Co.
Thiokol Corp.
Udylite Process Co.
United Gas Impressment Co.
Wailes Dove-Hermiston Corp.

25.3. Suppliers of Labor and of Test Sites

Albuquerque Gas & Electric Co.
Alexandria Water Co.
City of Atlanta, Dept. of Water Works
Atlanta Gas Light Co.
Atlantic City Gas Co.
Atlantic Pipe Line Co.
City of Baltimore, Dept. of Public Works
Boston Consolidated Gas Co.
Brockton Gas Light Co.
Camden Water Dept.
Carolina Power & Light Co.
Cincinnati Gas & Electric Co.
City of Charleston, Water Dept.
The Citadel
City of Cleveland, Dept. of Public Utilities
Colorado Interstate Gas Co.
Community Natural Gas Co.
Dallas Gas Co.
Delaware Power & Light Co.
Des Moines Gas Co.
Duke Power Co.
East Bay Municipal Utility District
East Ohio Gas Co.
Empire Pipe Line Co.
Equitable Gas Co.
Florida Power & Light Co.
Florida Public Utilities Co.
Georgia Railway & Power Co.
Gulf Oil Corp.
Humble Pipe Line Co.
Indiana Pipe Line Co.
City Commission of Jacksonville
Jacksonville Gas Co.
City of Kalamazoo, Dept. of Public Utilities
Kansas City Gas Co.
Los Angeles Gas & Electric Co.
Macon Gas Co.
Memphis Board of Water Commissioners
City of Meridian
City of Middleboro, Mass.
Midwest Refining Co.
City of Milwaukee, Dept. of Public Works
Milwaukee Gas Light Co.
Mississippi Power Co.
Mississippi River Fuel Corp.
City of Mobile, Water Works Dept.
Mountain Fuel Supply Co.
New Orleans Audubon Park Commission
New Orleans Sewerage & Water Board
New Orleans Public Service, Inc.
North Carolina Public Service Co.
Northern States Power Co.
City of Norwood, Mass.
Ohio Fuel Gas Co.
Oklahoma Pipe Line Co.
The Omaha and Council Bluffs Electrolysis Committee
Pacific Gas & Electric Co.
Pensacola-Gulf Power Co.
People's Water & Gas Co.
Philadelphia Electric Co.
City of Phoenix, Water Dept.
Prairie Pipe Line Co.
Public Service Co. of Colorado
Public Service Co. of New Mexico
Pueblo Gas & Fuel Co.
Pure Oil Pipe Line Co.
Raleigh Gas Co.
City of Rochester, Dept. of Public Works
Rochester Gas & Electric Co.
San Antonio Public Service Board
San Diego Consolidated Gas & Electric Co.
San Joaquin Light & Power Corp.
City of Seattle, Dept. of Public Works
Shell Oil Co.
Shell Petroleum Corp.
Shell Pipe Line Corp.
Sinclair Pipe Line Co.
Sinclair-Prairie Pipe Line Co. of Texas
Sohio Pipe Line Co.
Southern California Gas Co.
Southern California Telephone Co.
Southern Cities District Co.
Southern Natural Gas Co.
Southwestern Gas & Electric Co.
City of Springfield, Ohio, Water Dept.
Springfield Railway Co.
Standard Oil Co. of California
Standard Oil Co. of Louisiana, Pipe Line Dept.
Standard Oil Development Co.
Standard Oil Co. of New Jersey
Stanolind Oil & Gas Co.
Sun Oil Line Co.
Susquehanna Pipe Line Co.
Tampa Gas Co.
Tidal Pipe Line Co.
Tidewater Pipe Line Co., Ltd.
Tri City Railway & Light Co.
United Gas Pipe Line Co.
The United Light & Power Service
Union, Light, Heat & Power Co.
Union Light & Railway Co.
Union Oil Co. of California
Vicksburg Gas Co.
Wilmington Gas Co.

26. Appendix 2. Methods Used by the National Bureau of Standards to Clean Soil-Corrosion Specimens

After the soil-corrosion specimens were removed from the trench the loose dirt was scraped off and the specimens were boxed and returned to the National Bureau of Standards. Precautions were taken in packing the specimens to prevent injury during shipment. When the specimens arrived at the laboratory they were identified and stamped with identification symbols and numbers. The specimens were then subjected to chemical and mechanical treatment appropriate to each type of material, to remove the corrosion products with an insignificant loss in weight of uncorroded metal, and to prevent mechanical injury to the specimens.

26.1. Cleaning of Iron and Steel Specimens

If the specimens were sections of pipe, the caps were removed and the inside of the pipes were washed in a cleaning fluid to remove the coating of grease that had been applied prior to burial to prevent internal corrosion. The plate and sheet specimens usually had a bituminous coating applied ½ in. at each end, to protect that portion of metal surface from corrosion, and this coating was removed by means of an appropriate solvent.

Up to 1928, the iron and steel specimens were cleaned by pounding them with a small pointed hammer, then brushing with a stiff wire brush, and treating in a solution of alkaline ammonium citrate heated to about 80°C. In 1928, air-driven hammers were substituted for the hand-pounding operations and were subsequently used on the iron and steel specimens, with the exception of the high-alloy steels. Different shapes and sizes of tools were used in the air hammer to remove the corrosion products and hard flakes of rust that adhered to the specimens. The specimens were then brushed with a motor-driven stiff, circular wire brush and then were placed in an electrically heated, enameled iron tank containing a 10-percent solution of ammonium citrate made alkaline by the addition of ammonium hydroxide. Usually, immersion in the bath at 80°C for 2 to 8 hr was sufficient to clean most specimens. After removal from the bath, the specimens were scrubbed under running water with a stiff wire brush and dried with cotton cloths. Frequently, hard flakes of rust still remained on the specimens. These were pounded again with the air hammer and the process repeated until all the corrosion products were removed.

Tests to show the effect of the various tools and of the citrate treatment on the loss in weight of the pipe were made on new sections of steel and cast-iron pipes. The results obtained, table 109, indicate that the cleaning losses were negligible, even though the air hammer was operated under full pressure on these test specimens. In cleaning specimens after exposure the air hammer was operated under one-third (or less) of full pressure.

The high-alloy-steel materials usually did not require any other treatment than scrubbing with a stiff wire brush under running water.

The iron and steel specimens were removed from the test sites in 1946 and subsequently cleaned by immersion in fused sodium hydride.[17] The sodium hydride process [404, 405] converts the oxide scale to a condition in which it can be rapidly and easily removed from the metal surface which is completely unattacked. The process was developed for cleaning oxide scales from metals and alloys that do not react with fused caustic and whose physical characteristics are not altered at 370°C. The process is applicable to all ferrous materials, and operates as follows:

Table 109. *Effect of mechanical cleaning of the iron and steel specimens*

Specimen	Original weight	Weight after using air hammer and wire brush	Weight after immersion in bath and brushing	Total loss
	g	*g*	*g*	*g*
3-in. wrought iron	1660.450	1660.440	1660.415	0.035
3-in. open-hearth iron	1751.800	1751.785	1751.745	.055
3-in. Bessemer steel	1742.660	1742.650	1742.605	.055
Do	1765.875	1765.870	1765.830	.045
6-in. cast iron	6880.15	6880.09	6879.92	.23
Do	7053.40	7053.31	7053.11	.29
Do	6984.86	6984.70	6984.54	.32

Fused commercial sodium hydroxide maintained at a temperature of 370°C is utilized as the carrier bath. Sodium hydride, the active cleaning agent, is maintained in the bath at a concentration of 1.5 to 2.0 percent by reacting metallic sodium and hydrogen in special generators arranged along the side of the tank and partially immersed in the bath. Sodium hydride emerges from the generator and is distributed throughout the bath by the action of convection currents. The sodium hydride concentration in the bath is controlled by making periodic analyses and adjusting the sodium feed accordingly.

The specimens to be cleaned, after having been heated to 260°C for at least ½ hr to remove all moisture, are placed in racks and immersed in the bath until the reducing action on the corrosion products is completed. Immersion in the bath for 25 min. is usually sufficient to clean the specimens. There is no danger of overtreatment since the reaction ceases when reduction of the corrosion products is complete. After the treating cycle is completed, the specimens are removed from the bath, and allowed to drain for a short period and then quenched in water. During the quenching operation most of the reduced scale is driven off, thus exposing the base metal. A subsequent dip of short duration in an inhibited 5-percent sulfuric acid bath is used to remove any excess caustic adhering to the specimens. Before drying, the specimens were dipped in a 10 percent sodium cyanide bath in order to prevent the formation of rust during shipment to the Bureau. The film of sodium cyanide had no appreciable effect on the weight of the specimens. Weight loss measurements on unburied control specimens which were treated in the same manner as the corroded specimens showed that the amount of uncorroded metal removed by the sodium hydride process was negligible.

Each of the procedures cleaned iron and steel adequately, but the sodium hydride procedure is by far the fastest and easiest to operate.

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[17] The apparatus and facilities of the research laboratories of the Armco Steel Co. and of the United States Steel Co. were made available for cleaning the specimens by the sodium hydride process.

26.2. Cleaning of Copper and Copper-Alloy Specimens

The copper and copper alloys specimens as they came from the field were scrubbed with a wire brush under running water to remove the adhering soil. The specimens were then cleaned in a solution of 5-percent nitric acid and 2½-percent oxalic acid for 5 min or less. After removal from the acid bath, the specimens were scrubbed with a wire brush under running water. If necessary, the treatment was repeated, but one such treatment was usually enough to thoroughly clean all the specimens except those that had been exposed to tidal marsh soil. The specimens of brass, bronze, and copper from tidal marsh soil were covered with a very adherent coating of black graphite-like material, and no suitable chemical solution was found to remove it. These corrosion products were removed by continued hard scrubbing with a wire brush.

The results of nitric and oxalic acids cleaning are shown in table 110. Five- and ten-percent solutions of sulfuric acid were also tried as cleaning solutions for the copper and copper-alloy specimens, but they did not clean as quickly or as well as the solution of nitric and oxalic acids.

Table 110. *Effect of nitric and oxalic acids cleaning solution on copper alloys*

Material	Original weight	Loss in weight after—		
		5 minutes in bath	5 minutes more in bath	5 minutes more in bath
	g	*g*	*g*	*g*
Copper	92.17	0.03	0.00	0.00
Brass	86.34	.02	.02	.00
Bronze	428.04	.02	.02	.01

26.3. Cleaning of Lead and Lead-Coated Specimens

The lead-coated pipes and the lead sheaths removed from the test sites previous to 1937 were scrubbed under water with a fiber brush to remove the soil. They were then placed in a solution of 5-percent nitric and 2½-percent oxalic acids for about 5 min. After removal from the bath, the specimens were scrubbed under running water with fiber brushes and dried. If all the corrosion products were not removed, the treatment was repeated. The losses in weight resulting from this treatment on unburied chemical and antimonial lead are shown in table 111. Where the lead coating had failed on the pipe the rust flakes were chipped off with a pointed knife. Ammonium citrate solution cannot be used to remove this rust as the citrate attacks the lead.

Table 111. *Effect of nitric and oxalic acids on lead specimens*

Material	Original weight	Loss of weight after—		
		5 minutes in bath	5 minutes more in bath	5 minutes more in bath
	g	*g*	*g*	*g*
Chemical lead, A	2131.87	0.18	0.14	0.02
Antimonial lead, H	2075.04	.11	.09	.05

After 1937 the lead specimens were cleaned by placing them in a water bath maintained at 80° to 90°C for several hours. The specimens were then scrubbed under running water with a fiber brush. The corrosion products were removed from the pits with a dull-pointed knife and again scrubbed under running water. Usually two or three such treatments were sufficient to clean the specimens. The latter method was just as effective as the nitric and oxalic acid solution.

26.4. Cleaning of Zinc and Galvanized Specimens

Up to 1939 the approved method for cleaning zinc and galvanized specimens was by immersion in concentrated ammonium hydroxide. Dilute solutions of ammonia attack the corrosion products less and the zinc more than does the concentrated solution. After the treatment in ammonium hydroxide, the specimens were scrubbed with a wire brush; trials had showed that a wire brush does not remove weighable amounts of zinc even though the specimens were scrubbed harder than is necessary to clean them. The results reported in table 112 were obtained by placing specimens of clean zinc in concentrated ammonium hydroxide for 5 min., which is usually sufficient to remove the corrosion products.

Table 112. *Effect of 10-percent-ammonia solution on zinc specimens*

Material	Original weight	Loss in weight after—		
		5 minutes in ammonia	5 minutes more in ammonia	5 minutes more in ammonia
	g	*g*	*g*	*g*
Standard zinc sheet, P	87.92	0.04	0.26	0.01
Zinc sheet, Z_1	90.79	.07	.10	.05
Zinc plate, Z_2	504.19	.06	.07	.03

Beginning in 1939 the following improved procedure was adopted for cleaning the zinc materials. The specimens were immersed in a 10- to 15-percent solution of ammonium chloride maintained at 75° to 85°C for 30 min. After removal from the bath, the specimens were scrubbed under running water with a wire brush. If any corrosion products remained on the specimens, the process was repeated. It was often necessary to loosen the flaky corrosion products by scratching the surface of the zinc with a dull knife. Table 113 shows the losses in weight of unburied zinc specimens cleaned by this method.

Table 113. *Loss in weight of zinc specimens caused by ammonium-chloride bath and scrubbing*

Material	Original weight	Loss in weight after—		
		30 minutes in bath at 75° C	Vigorous scrubbing with wire brush	30 minutes more in bath at 75° C
	g	*g*	*g*	*g*
Rolled zinc, Z	509.76	0.04	0.00	0.04
Die-casting zinc, CZ	504.00	.01	.01	.03

26.5. Cleaning of Nonmetallic-Coated Specimens

The nonmetallic-coated specimens were scrubbed under running water with a fiber brush until all soil particles were removed, and then were dried with cloths. After recording the condition of the coating, one-half of the coating was cut away or scraped from the specimens in order to observe the condition of the bond and of the metal under the coating. The corrosion products were removed from the pits by means of a pointed knife.

27. Appendix 3. Recording of Data and Methods of Calculation and of Reporting the Data

27.1. Recording of Data

The weight of each cleaned specimen was determined and checked, with tolerances ranging from 1 mg (0.000035 oz) for light stainless-steel specimens to 0.1 g for cast-iron specimens weighing in the neighborhood of 6 kg (13.2 lb). These tolerances do not, of course, indicate the precision of the corrosion weight-loss data, as corrosion losses were only small percentages of the total weights and ranged from less than 1 mg to a few hundred grams. However, the factor that controls the reproducibility of the data is the extent to which field conditions can be reproduced, and this factor varies widely. Data on the corrosion of working pipelines indicate that the results of corrosion can not be reproduced within very narrow limits.

After weighing the specimens, the deepest pits were measured and the measurements checked by two different operators, usually within a tolerance of 0.004 in. Pit depth measurements less than 10 mils were not recorded for the first removals made in 1924. For the removals made during 1926 and 1928 pits were not recorded when they were less than 20 mils in depth. For the removals made in 1930 and thereafter, all pits greater than 6 mils in depth were recorded wherever measurements could be obtained. When definite pitting occurred but there were no pits greater than 6 mils, the designation "P" was used. When the metal had been attacked but no definite pitting could be observed the designation "M" was used, and when the specimen was unaffected by corrosion, the designation "U" was used.

After 1930 it was the practice to record the six deepest pits on each pipe specimen and the six deepest pits on each side of sheet and plate specimens.

The depth gage (A of fig. 99) used at the National Bureau of Standards is an ordinary micrometer depth gage that can be read to the nearest 0.001 in. The end of the shaft is pointed so as to reach the deepest part of the pit. The base is cut away near the shaft so that the position of the point can be seen, and the originally flat base is machined to a concave cylindrical surface of ¾-in. radius, the long axis of the base being parallel to the axis of the cylinder. The gage then will not rock when placed on a 1½-in. or larger diameter pipe surface with the long axis of the base parallel to the pipe axis. For making measurements on severely corroded specimens, the length of the base can be increased by use of a bridge. To correct the zero setting for the curvature of the pipe surface the gage is placed on a smooth curved cylinder having the same diameter as the specimen and adjusting the micrometer to read zero. For measuring the pit depths of sheets or plates, the zero reading of the micrometer was adjusted by setting it on a smooth, polished, level surface. Ewing [71] worked out a formula for setting the micrometer on a plane surface and adjusting the gage for the diameter of the pipe to be measured.

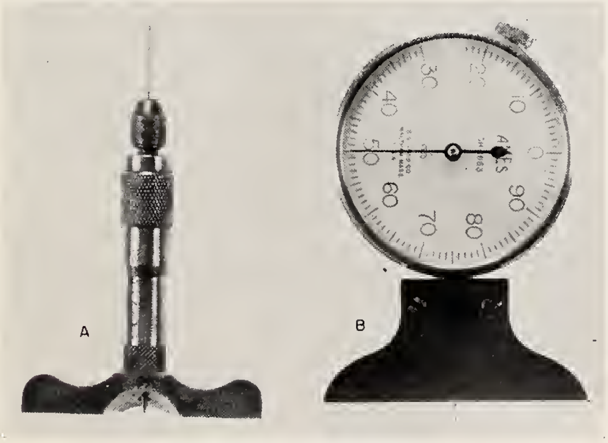

Figure 99. *Pit-depth gages.*

A, Micrometer gage; B, dial gage. Each reads in thousandths of an inch (mils).

After 1941 a more convenient dial type of micrometer, (B of fig. 99) was used for making the pit-depth measurements. The principle of this micrometer is the same as the previously mentioned gage, and the readings are made to the nearest 0.001 in. The base of this gage was machined to a narrow edge, so corrections for the curvature of the pipe were not necessary. A needle extending from the base is moved about in the pit until a maximum reading is obtained on the dial. The zero setting was adjusted on a smooth, polished, level surface. Measurements with the two gages gave results that were in excellent agreement.

After the loss in weight and pit-depth data were obtained, the specimens were photographed. The pipe specimens were photographed by a circuit camera employing panoramic film (6 in. in width) while the pipes were rotating. In this manner photographs of the specimens 6-in. long were obtained in their actual size. For specimens longer than 6-in. the part showing the severest corrosion was photographed. Pictures were made of all specimens on which appreciable pitting could be detected. The specimens were then given a coat of colorless varnish to prevent further rusting, and preserved at the National Bureau of Standards until 1942, when the demand was made for all available scrap metal for the war effort. Specimens removed from burial sites subsequent to 1942 have been discarded 2 years after publication of the report pertaining to the specimens.

27.2. Methods of Calculation and of Reporting the Data

Usually two specimens of each material were removed from each test site. Hence, the data for losses in weight and maximum pit depths, in the tables in this Circular, and in the numerous progress reports to which reference has been made, are the arithmetical averages of two measurements. When only one specimen was available the value given is the actual value for the loss in weight or maximum pit depth of that one specimen.

The data have often been reported as the average total penetration, which is derived from the loss in weight, the area exposed, and the density of the material. To calculate the average total penetration (in mils) the loss in weight (in ounces per square foot) was multiplied by a factor,

$$\frac{750}{\text{density, in lb/ft}^3}.$$

The ratio of the maximum pit depth to the average total penetration is the pitting factor that is to some extent a function of the area of pipe surface considered.

The method for obtaining the maximum pit depths has already been described. The rate of maximum pit depth (in mils per year) is the ratio of the maximum pit depth to the time of burial in years. For the purpose of comparing pit depths on pipes of different sizes (specimens buried prior to 1932), the data were reported as the weighted maximum pit depths for each material. The exposed area of one 6-in. specimen is equivalent to the exposed area of two 3-in. specimens, and likewise the exposed area of one 3-in. specimen is equivalent to the exposed area of two 1½-in. specimens. Therefore, as there are two specimens for every material, the weighted maximum pit depth was obtained as follows: For the 1½-in. specimens the value represents the arithmetical average of the deepest pit on each specimen, a total of two pits for each material; for the 3-in. specimens it represents the arithmetical average of the two deepest pits on each specimen, a total of four pits for each material; for the 6-in. specimens it represents the arithmetical average of the four deepest pits on each specimen, a total of four pits for each of the two cast iron pipe (specimens L and Z) of which only one specimen of each were taken up at each removal, and a total of eight pits for the other 6-in. specimens, of which two specimens were taken up at each removal.

Weighted maximum pit depths were not used for comparing the pipe specimens buried in 1932 and thereafter because these specimens were of the same diameter and length.

28. Appendix 4. Descriptions of Soils at the Test Sites

TABLE 114. *National Bureau of Standards test sites*

Prepared by M. Romanoff. The profiles have been described by S. Ewing, I. A. Denison, G. N. Scott, and by the following soil surveyors from the Bureau of Plant Industry of the United States Department of Agriculture: A. E. Taylor, M. H. Lapham, R. Wildermuth, W. J. Geib, H. H. Bennett, H. G. Lewis, F. A. Hayes, W. T. Carter, R. C. Roberts, Mark M. Baldwin, R. S. Smith.

When the profile at the test site was not described the typical profile of the soil type was taken from soil-survey reports.

Site No.	Soil type	Location	Description of soil profile (Depths are in inches)	Internal drainage	Topography	Depth of specimens
						Inches
1	Allis silt loam	Cleveland, Ohio	0–8 grayish yellow or yellowish gray silt loam mottled with yellow and yellowish brown. 8–23 mottled yellow and gray silty clay loam which contains fragments of shale. 23–30 bluish gray silty clay loam with bands of yellow indicating the bedding planes of the shale. 30–70 silty clay or silty clay loam layer of shale which has a bluish gray color and is streaked along bedding planes with yellow. 70–76 reddish brown shale streaked with gray 76–90 compact bluish gray shale with yellowish brown and reddish brown streaks. 90–100 the streaks become less conspicuous This shale runs high in aluminum sulfate, which, with water, breaks down into aluminum hydroxide and sulfuric acid.	Poor	Undulating to gently rolling.	95
2	Bell clay	Dallas, Tex.	0–10 black to dark brown silty clay. 10–740 black clay. No definitely residual matter was discovered within 40 inches. Small rounded quartzite gravel and lime concentrations disseminated through the subsoil.	do	Level	Below 40
3	Cecil clay loam	Atlanta, Ga.	0–8 grayish brown, rather compact, very fine sandy loam. A few fragments of granite and quartz found on the surface. 8–10 transition layer into 10–32 compact brittle red clay containing very few mica flakes and practically no sand and stones. 32–48 micaceous, more friable, and not as compact as above horizon, red clay loam or clay. 48–52 layer of sandy clay with yellowish mottlings. 52–70 red micaceous clay as in 32–48 70–74 red very fine sandy loam with yellowish mottlings. 74—96 moderately friable, red very fine sandy loam, full of mica crystals, and having a few brownish and yellowish mottlings due to partially decomposed rock. 96–108 very friable fine sandy loam, mottled yellow, red, and brown.	Little excessive	Moderate slope.	30
4	Chester loam	Jenkintown, Pa.	0–10 grayish brown mellow loam gradually getting lighter in color with increasing depth. The top 6 inches of the trench is a mixture of road material and soil. No vegetation. 10–34 mellow, only slightly darker in color and heavier in texture with increasing depth. 34–96 micaceous rather loose friable silt loam containing considerable fine sand. At 36 inches there is a layer of partially decomposed granite. Soil in this site is considerably wetter than the average condition of this soil, as the trench gets all the rain water that falls on the adjacent highway.	Good	Gently rolling	36
5	Dublin clay adobe	Oakland, Calif.	0–10 dark dull gray or drab clay of adobe structure, sticky when wet, contains numerous plant and grass roots and an appreciable amount of fine gritty material and gravel fragments. 10–36 slightly more compact brownish gray or drab friable clay which is sticky when wet. Somewhat mottled with brown and dull slaty gray or black streaks. It contains spherical shotlike iron concretions of black or bluish black color, ranging in size from a pinhead to small buckshot. 36–48 soil grades into a yellowish brown silty clay material. This horizon is mildly calcareous and is the upper limit of lime accumulation. 48–60 yellowish brown compact clay containing many light grayish fragments of lime carbonate nodules localized in thin seams or layers, the material being partially cemented.	Poor	Smooth and level.	30
6	Everett gravelly sandy loam.	Seattle, Wash.	0–8 brown to light brown sandy loam darkened by presence of organic matter. 8–24 light brown sandy loam. Both this and the above horizon contain little gravel, and considerable coarse sand. Both horizons are loose and friable and contain numerous grass roots. 24–30 grayish brown gravelly sandy loam. Slightly compact. Below 30 inches hard cemented gravel and sand, with very little lime of a grayish brown color.	Excessive	Moderately rolling.	36

TABLE 114. *National Bureau of Standards test sites*—Continued

Site No.	Soil type	Location	Description of soil profile (Depths are in inches)	Internal drainage	Topography	Depth of specimens
						Inches
7	Maddox silt loam	Cincinnati, Ohio	0–5 brownish yellow friable silty clay loam 5–15 brownish yellow smooth, plastic, heavy, moderately tight clay mottled light gray. The mottles are of moderate extent and development and occur in small irregular veins. The soil material fractures into irregularly shaped lumps, ranging in size from ½ to 1½ inches in diameter. 15–22 brownish yellow or yellow sticky, plastic, slowly pervious, moderately compact heavier clay containing a moderate amount of light gray mottles. It has a fragmental structure forming hard, irregular aggregates from ½ to 1½ inches in diameter. 22–30 varicolored bluish gray and olive-green tight, smooth, plastic, very heavy clay or silty clay having occasional staining of rust-yellow. This layer has been developed from the weathering of underlying shale rock materials.	Fair	Smooth ridge top.	22
8	Fargo clay loam	Fargo, N. Dak.	0–24 black noncalcareous clay loam. Rather friable. Breaks with concoidal fracture into pea-size pieces. 24–42 calcareous transition layer with tongues of both horizons extending into the layer. 42–88 grayish brown heavy clay loam. Light gray when dry—highly calcareous. Below 88 parent material of old lake laid deposits. Grayish brown color containing rusty brown streaks and mottlings. Few hard concretions that are largely lime.	Poor	Level	66
9	Genesee silt loam	Sidney, Ohio	0–10 brownish gray silt loam, slightly streaked with reddish brown. 10–16 gray loam streaked reddish brown and mottled yellowish brown and brownish yellow. 16–22 transition to fine sandy loam mottled reddish brown. At 22 bed of gray gravel	do		22
10	Gloucester sandy loam	Middleboro, Mass.	Surface—light brown sandy loam Subsoil—light grayish brown fine sandy loam containing some gravel.	Fair		36
11	Hagerstown loam	Loch Raven, Md.	0–12 dark brown or brown friable loam 12–33 reddish brown or red clay loam. Moderately compact. Contains fragments of stone, chert. 33+moderately friable rusty brown heavy silt loam with a reddish cast. This extends to the underlying rock, which is rather clear, crystalline, and hard (not limestone). In one place in the trench the rock is at a depth of about 4 feet.	Good	Slight slope	36
12	Hanford fine sandy loam	Los Angeles, Calif.	The entire profile is a grayish brown friable, loose, micaceous fine sandy loam containing thin layers of material as heavy as loam and as tight as sand. Noncalcareous at surface, and only faintly calcareous at 6 feet. This soil differs from soil 13 in that it does not contain soluble carbonates in appreciable amount.	do	Practically level.	24
13a	Hanford very fine sandy loam.	Bakersfield, Calif.	0–56 light grayish brown smooth, friable, micaceous very fine sandy loam. 56–62 light grayish brown very fine sand 62–66 same as 0–56 68–72 same as 56–62. The soil is high in alkali in the carbonate form, and formerly called black alkali.	Fair	Almost level	30
13b	do	do	0–6 grayish brown very slightly compacted loam 6–84 light grayish brown friable loose micaceous very fine sandy loam. Numerous roots in first 3 feet. Few light colored specks at 3 feet. A special set of specimens are buried at the site. The profile is similar to site 13a, but differs by being low in alkali content.	Good	Very gently undulating.	
14	Hempstead silt loam	St. Paul, Minn.	0–15 dark brown (almost black) silt loam 15–24 transition layer consisting of tongues and streaks of the two adjoining horizons extending into each other. 24–42 brown silt loam with yellowish cast, slightly compact. 42+ grayish brown sand containing some gravel Entire profile is noncalcareous	Fair	do	44
15	Houston black clay	San Antonio, Tex.	0–36 black clay with no appreciable change. Highly calcareous. Small fragments of lime are found throughout the section.	Poor		36

TABLE 114. *National Bureau of Standards test sites*—Continued

Site No.	Soil type	Location	Description of soil profile (Depths are in inches)	Internal drainage	Topography	Depth of specimens
						Inches
16	Kalmia fine sandy loam	Mobile, Ala.	0–8 grayish brown fine sandy loam, which appears to have been disturbed. 8–42 yellowish brown very fine sandy loam. Texture gradually gets finer and compactness increases with depth. Some reddish mottlings and a few iron concentrations about ¼ inch in diameter, which are most numerous at about 3 feet and disappear at 6 feet. 42–48 brownish yellow or yellow silt loam mottled with red. 48–96 mottled red, gray, and yellow material containing thin layers of clay and fine sand but with the average texture of silt loam. Below 72 inches the color is light yellowish brown with light gray mottlings.	Fair	Gentle slope	30
17	Keyport loam	Alexandria, Va.	0–6 grayish brown loam or silt loam without structure. Moderately loose and friable. 6–14 transition layer, slightly compact clay loam 14–48 light yellowish brown rather compact clay loam with concoidal fracture exposing shiny surfaces. Slightly mottled with gray. Texture gets a little lighter with increasing depth. 48–74 brown fine sandy loam with slight reddish cast. 74–76 light gray clayey sand. 76–96 brown sand almost saturated with water. 96+gravel. Entire profile is noncalcareous	do	do	36
18	Knox silt loam	Omaha, Neb.	0–8 dark brown silt loam full of brickbats, plaster, rotten wood, etc. The surface soil partly removed and mixed with foreign matter. 8–72 light brown very uniform smooth friable silt loam that gets a little lighter in color with depth. Moderately moist. Contains a few brown spots due to rotten roots at 8 to 24 inches. Very faintly calcareous at 48 inches and below.	Good	Practically level.	48
19	Lindley silt loam	Des Moines, Iowa	0–4 dark brown silt loam, friable and full of organic matter. 4–18 slightly compact heavy silt loam, yellowish brown. 18–34 transition layer into 24–50 rather compact more yellowish brown clay containing a few dark-colored specks. 50–76 grayish brown clay loam with bright yellow mottlings and a few white specks. Less compact than above. 76–84 gritty material of variable texture and color, containing light colored cherty material. 84 large boulder or gravel	Good	Moderate slope.	36
20	Mahoning silt loam	Cleveland, Ohio	0–4 brownish gray heavy silt loam or light silty clay loam. 4–8 pinkish red clay, mottled brownish yellow, yellow, yellowish brown, and gray. 8–24 mottled drabbish gray-yellow, brownish yellow, and yellowish brown clay. 24–46 drabbish gray clay, mottled with brownish yellow, and pinkish red. 46–50+ mottled gray, brownish yellow, and yellowish brown, calcareous clay.	Poor	Gently undulating.	48
21	Marshall silt loam	Kansas City, Mo.	0–28 brown or chocolate brown friable, uniform silt loam 28–36 transition layer 36–84 light brown silt loam very uniform and smooth. Noncalcareous to 6 feet. 84+light brown noncalcareous clay slightly mottled with grayish brown.	Good	Moderately rolling.	60
22	Memphis silt loam	Memphis, Tenn.	0–4 light brown silt loam containing thin discontinuous layers of darker color probably due to the turning under of organic matter when the soil was cultivated. 4–96 light brown slightly compact silt loam with some grayish mottlings but no hard lime concretions. Very uniform in color and texture.	do	Very gently undulating.	33
23	Merced silt loam	Buttonwillow, Calif.	0–14 dark brown (almost black) silt loam. ¼-inch crust, 3-inch mulch, which is underlaid by slightly compact very lightly moist material with no definite structure. 14–72 light gray loam, moderately compact and moist with somewhat lighter texture and a more open structure below 48 inches, where thin layers of sandy loam occur. Friable and loose. Thin layers of grayish brown sand occur at 60 inches. Location has all indications of a soil high in alkali. Highly calcareous up to surface.	Fair	Level	30
24	Merrimac gravelly sandy loam.	Norwood, Mass.	0–4 brown loam containing considerable sand and coarse sand. 4–33+grayish coarse sand or fine gravel.	Good		33

TABLE 114. *National Bureau of Standards test sites*—Continued

Site No.	Soil type	Location	Description of soil profile (Depths are in inches)	Internal drainage	Topography	Depth of specimens
						Inches
25	Miami clay loam	Milwaukee, Wis.	0–6 grayish brown silt loam 6–30 yellowish brown, stiff, heavy clay loam to clay, containing a small amount of gritty material. 30–48 slightly calcareous browinsh yellow heavy clay loam, somewhat lighter than the above and also contains some gritty material.	Fair		36
26	Miami silt loam (mottled phase).	Springfield, Ohio	0–2 grayish brown silt loam 2–7 brownish gray to yellowish-gray silt loam 7–10 gray silt loam mottled faintly with yellow 10–16 mottled yellow and gray silt loam. 16–24 brown clay loam to clay mottled brownish yellow and yellowish brown. 24–36 reddish brown stiff clay 36–48 yellowish brown gravelly friable clay, somewhat calcareous in the lower part of the layer.	Good		36–48
27	Miller clay	Bunkie, La.	Dull red heavy calcareous clay extending down below the depth at which the specimens are buried. Soil map shows Miller clay at this location and a sample of the soil was identified as typical Miller clay.	Very poor	Level	30
28	Montezuma clay adobe.	San Diego, Calif.	0–8 filled material—brickbats, gravel, etc. 8–46 gray or light grayish-brown adobe containing some gritty material and gravel in the first foot. Noncalcareous. 46–50 light gray sandy clay, somewhat sticky. 50–60 grayish brown or yellowish brown gravelly sand. 60+ gravel.	Poor	Level to gently rolling.	40
29	Muck	New Orleans, La.	Surface—to varying depths consists of dark colored material of variable texture, most of which is fill. Subsoil—black, semifluid mass of well-decomposed mulch which rests upon an almost solid mat of old cypress stumps and roots that are in an excellent state of preservation. Substratum—stiff, putty-like gray clay. The land was originally a cypress swamp.	Very poor		24
30	Muscatine silt loam	Davenport, Iowa	0–6 dark brown silt loam (grayish brown when dry). 6–7 gray or grayish brown silt loam with yellow mottlings that are evenly distributed and containing a few brown specks. Noncalcareous throughout.	Poor	Level	36
31	Norfolk fine sand	Jacksonville, Fla.	0–4 grayish brown fine sand containing organic matter. 4–15 gradual transition into very slightly compact, very pale yellow sand. Deepest in color and more compact at 15 inches. 15+compactness gradually decreases and the color gets a little lighter. Slight yellow mottlings at 60 inches. The same sand probably extends to 20 or 30 feet. This soil was called Norfolk sand in previous corrosion reports.	Good	Almost level	24
32	Ontario loam	Rochester, N. Y.	0–8 brown to grayish brown (when dry) mellow and friable, fine sandy loam to fine sand. 8–18 slightly more compact, though crumbly loam to fine sandy loam, light brown to yellowish brown in color. 18–33 grayish brown to brownish gray compact loam in place, though friable when bored out. 33+partially weathered till material. Parent material from which the soil is derived is largely limestone, with some sandstone, shale, and igneous rocks. Gravel and small stones are abundant in lower portions. The soil is calcareous at from 15 to 24 inches.	Good	Gently sloping to undulating.	48
33	Peat	Milwaukee, Wis.	A black well-decomposed peat 30 to 36 inches deep, where it rests on a drab or bluish plastic clay loam. The lower part of the section was saturated with water. The peat merges into clyde loam, the line of separation being rather indefinite. A sample of this soil lost 42 percent on ignition.	Very poor		24
34	Penn silt loam	Norristown, Pa.	0–8 brown or dark brown silt loam 8–24 reddish brown silt loam containing considerable sand. 24–38 slightly lighter in color than above layer 38–56 Indian red or reddish-brown silt loam 56+ shale	Fair	Gentle slope	36
35	Ramona loam	Los Angeles, Calif.	0–22 light brown moderately compact loam with slight reddish tint and a slight admixture of organic matter to 2 inches of surface. Very dry. 22–54 slightly moist, hard, gritty, compact, brittle, reddish brown clay loam containing numerous white specks. 54–72 light reddish brown or light-brown gritty silt loam. White specks present but not as compact as horizon above. Entire profile is noncalcareous.	Good	Moderately rolling.	36

TABLE 114. *National Bureau of Standards test sites*—Continued

Site No.	Soil type	Location	Description of soil profile (Depths are in inches)	Internal drainage	Topography	Depth of specimens
						Inches
36	Ruston sandy loam	Meridian, Miss.	0–8 light brown, loose, friable sandy loam 8–30 brownish red or rusty brown heavy fine sandy loam. Rather compact and hard. 30–60 reddish brown, rather compact, heavy fine sandy loam. 60–96 mottled red and yellow compact heavy fine sandy loam. No gravel or stones present in the profile.	Good	Gently rolling.	36
37	St. John's fine sand	Jacksonville, Fla.	0–2 dark gray or grayish brown fine sand. The organic matter imparts the dark color. 2–10 the material merges into a rather compact yellowish layer having a distinct lower boundary. The organic matter decreases with depth and the yellow color becomes brighter. The yellow sand contains a few very hard round black iron concretions about ¼ inch in diameter that are surrounded by reddish brown sand. 10–28 light gray slightly compact fine sand which becomes lighter with increasing depth and is almost white at 28 inches. 28–36 dark brown hard compact iron cemented hardpan with the characteristic coffee ground color. 36–60 pale yellow fine sand saturated with water	Poor	Practically level.	30
38	Sassafras gravelly sandy loam.	Camden, N. J.	0–8 grayish brown gravelly sandy loam which gradually changes into a light yellowish brown or yellowish gray. 8–28 light gray or yellowish brown gravelly sandy loam which is darker than the horizon below. 28–96 light gray gravelly sandy loam with faint yellow cast. Entire profile is loose and open and is noncalcareous. The amount of gravel is rather small for a gravelly type soil. The size of the gravel varies up to 8 inches in diameter and is all smooth and waterworn.	Good	Moderate uniform slope.	30
39	Sassafras silt loam	Wilmington, Del.	This soil has been so disturbed that an accurate description of the profile is impossible. 0–12 grayish brown moderately friable silt loam 12–30+ slightly yellowish-brown silt loam which extends below the specimens. The trench bottom shows considerable gravel and a little gravel exists throughout the profile.	Fair	Practically level.	30
40	Sharkey clay	New Orleans, La.	0–8 dark brown or brown clay loam containing organic matter and full of grass roots. Rather compact. 8–30 stiff, plastic gray clay mottled with rusty colored material. No definite hard iron concretions. 30–60 gray silt loam mottled with rusty brown. The rusty colored spots get lighter in color with depth and practically disappeared at 60 inches.	Poor	Gently undulating to level.	30
41	Summit silt loam	Kansas City, Mo.	0–22 very uniform and smooth brown silt loam. 22–36 light brown smooth silt loam. 36–108 light brown uniform silt loam faintly mottled with grayish brown. Noncalcareous to 9 feet at which depth the soil is underlain by shale.	Fair	Gentle slope	36
42	Susquehanna clay	Meridian, Miss.	Top soil corroded away 0–6 rather compact but friable light reddish brown clay. 6–45 mottled red, yellow, and gray very hard compact clay that has a cubical structure. 45–56 mottled red, yellow and gray heavy silt loam. 56–84 same as 6–45	Fair	Steep slope	30
43	Tidal marsh	Elizabeth, N. J.	Entire soil profile, and especially the surface foot, contains a large percentage of undecayed organic matter and has a black color when wet. Upon drying the color changes to grayish brown. The soil contains hydrogen sulfide and a considerable amount of soluble salts, but no lime. The surface portion of the soil lost 20.7 percent on ignition.	Very poor	Level	36
44	Wabash silt loam	Omaha, Neb.	Except for the addition of grass roots to the top 8 to 12 inches, the entire profile consists of a uniform dark brown silt loam (black when wet) or silty clay loam, to a depth of at least 8 feet. Noncalcareous throughout.	Good	Practically level.	30
45	Unidentified alkali soil	Casper, Wyo.	0–6 light gray to light grayish brown sand to heavy silt loam. Little organic matter. 6–20 brown to grayish brown heavy compact, gritty clay. Plastic and waxy when wet, but becomes hard and tough when dry. 20–30 abrupt change to a light gray sandy clay. More friable than upper horizon due to higher sand content. 30–48 sand content decreases, color slightly darker and texture more compact than above horizon. Type is highly alkaline, and white streaks and splotches of concentrated salts occur abundantly throughout the profile except in the surface soil.	Poor	Level	30

TABLE 114. *National Bureau of Standards test sites*—Continued

Site No.	Soil type	Location	Description of soil profile (Depths are in inches)	Internal drainage	Topography	Depth[3] of specimens
						Inches
46	Unidentified sandy loam	Denver, Colo.	0–12 brown or light brown sandy loam 12–14 layer of brickbats and debris 14–20 light brown sandy loam. All the above material is loose and friable. 20–22 hard compact layer of cinders. All the above material is full and the next horizon is probably the original surface of the profile. 22–36 hard, compact brown sandy loam 36–120 light brown sandy loam which gets a little lighter in color and is calcareous below 60 inches, where it is slightly cemented.	Good	Very gentle, uniform slope.	50
47	Unidentified silt loam	Salt Lake City, Utah	0–12 grayish brown or brown silt loam containing considerable organic matter. Highly calcareous at all depths. 12–72 light gray moderately compact clay containing occasional mottlings of brownish yellow and reddish brown. A few lime concretions and occasional water-worn pebbles that are partly coated with lime are present.	Poor	Moderate slope.	36
51	Acadia clay	Spindletop, Tex.	The area is a transition from Acadia clay to prairie of Lake Charles clay. The test site is in the two soil types. The 20 feet of south end of trench is Lake Charles clay. Acadia clay, prairie phase. 0–12 very dark gray (almost black) heavy acid clay spotted with yellowish brown. 12–30 dense gummy dark-acid clay with yellowish brown and rust brown spots and splotches. 30–60+ gray dense clay with yellow and yellowish brown spots. Large amount of fine soft crystals of gypsum, neutral in reaction. Lake Charles clay 0–24 black heavy clay. 24–40+ yellow heavy clay with some gray mottling and fine crystals of gypsum.	Very poor	Level.	30
52	Lake Charles clay loam (mound phase).	League City, Tex.	0–12 dark gray silt loam. White incrustation of soluble salts on the surface. 12–20 gray silty clay loam mottled with yellowish brown, containing some black concretions. 20–30+ gray and yellow dense gummy mottled clay containing a few calcium carbonate concretions. Parent material of calcareous clay lies several feet beneath the surface.	do	do	30
53	Cecil clay loam	Atlanta, Ga.	Same as site 3.			
54	Fairmount silt loam	Cincinnati, Obio	0–5 gray or light yellowish gray gritty, friable, silt loam stained or specked with light gray and rust brown. Moderate quantity of small calcareous shale chips present. 5–12 light gray or light brownish gray gritty, slightly compact friable silt loam containing a large amount of small chips of calcareous shale and limestone. 12–24 gray calcareous thin beds of shale partly weathered to clay stained light gray. 24–34 dark gray bedded calcareous shale containing small irregular pockets of gray, plastic, heavy clay or partly weathered shale.	Poor	Steep slope	30
55	Hagerstown loam	Loch Raven, Md.	Same as site 11.			
56	Lake Charles clay	El Vista, Tex.	0–12 black, noncalcareous, very heavy clay 12–32 dark bluish, gray. noncalcareous, waxy clay 32–48+ light gray waxy, noncalcareous, clay with some yellow spots.	Very poor	do	30
57	Merced clay adobe	Tranquillity, Calif.	Same as site 117.	Poor		
58	Muck	New Orleans, La.	Description not available Soil very similar to site 29	do		
59	Carlisle muck	Kalamazoo, Mich.	0–13 black or very dark gray granular, smooth, loamy, thoroughly decomposed organic material. Moderately acid. 13–30 dark gray fibrous, stringy, moderately compact plant remains partially decomposed and containing brown raw felty peat. Slightly acid. 30+ partly decomposed remains of swamp-loving plants displayed.	Very poor	do	20

TABLE 114. *National Bureau of Standards test sites*—Continued

Site No.	Soil type	Location	Description of soil profile (Depths are in inches)	Internal drainage	Topography	Depth of specimens
						Inches
60	Rifle peat	Plymouth, Ohio	0–4 dark brown or brown loamy, smooth well-decomposed organic matter intermixed with finely fibrous, partly decayed vegetable matter that includes some woody material in different stages of decomposition. A small quantity of gray quartz grains is present throughout the layer. Strongly acid. 4–11 dark grayish brown, smooth loamy well-decomposed organic matter containing a large quantity of only partly decayed peaty material which includes fragments of partly rotted woody matter. Very strongly acid. 11–19 dark gray or brownish gray, loamy, smooth, well-decomposed, and finely divided partly decayed vegetation that includes some woody material in different degrees of decay. Very strongly acid. 19–26 very dark gray smooth, loamy decomposed vegetable matter interstratified with mottled layers of finely fibrous peaty material and thin seams of dark gray silt loam and clay mineral material. Very strongly acid. 26–34 bluish or bluish gray smooth, nongritty, tight, slowly pervious clay which displays mottles of light gray and stains of rust yellow with increasing depth. Medium acid. Specimens were buried in both the clay and peat layers.	Poor	Steep slope	22
61	Sharkey clay	New Orleans, La.	Same as site 40.			
62	Susquehanna clay	Meridian, Miss.	Same as site 42.			
63	Tidal marsh	Charleston, S. C.	This soil is typical of the tidal marshes found along the seacoast. The soil materials from tidal marshes vary from dark, oozy sediments interspersed with coarse marsh-grass roots to a yellowish or dark colored clay. The subsoil and the free water in the soil are usually charged with hydrogen sulfide. A similar soil is site 43	Very poor	do	
64	Docas clay	Cholame, Calif.	0–12 very dark grayish brown clay that is plastic when wet and has fairly large cracks when dry. Soil blocky and moderately compact when dry. Many salt crystals. 12–24 grayish brown clay that is plastic when wet and has friable consistence when moist. It has less visible lime than the surface soil but is highly calcareous. 24–30 similar to layer above, except that it contains many lime splotches. 30–42 light grayish brown clay mottled with gray	Fair	Level	24–30
65	Chino silt loam	Wilmington, Calif.	This soil is a poorly drained phase of Chino silt loam. 0–13 dark-brown friable, micaceous, highly calcareous silt loam mottled with rust brown and gray silt loam or clay loam. 13–23 brownish gray highly mottled with rust specks, firm clay loam that is highly calcareous. 23–30 highly calcareous olive gray and grayish brown mottled, very fine sandy loam, not so much iron mottling as layer above. 30–48 highly calcareous gray silty clay loam, very plastic when wet and becomes light gray when dry.	Good	Almost level	36
66	Mohave fine gravelly loam. (Tucson fine gravelly loam.)	Phoenix, Ariz.	This area is mapped as Mohave fine gravelly loam (highly calcareous phase), but it would now be classified as Tucson fine gravelly loam. Within the length of the trench is a thin stringer of Pinal fine gravelly loam. These two soils grade into each other and are therefore not typical of either. Descriptions of the two soil profiles follow. Mohave fine gravelly loam (Tucson fine gravelly loam). 0–1 fluffy white and pink alkali crust fine sandy loam, highly calcareous. 1–14 overwash material, reddish brown, highly calcareous, friable fine gravelly loam. 14–36 reddish brown, friable, highly calcareous gravelly loam with much gravel, lime coated. 36–48 soft caliche layer, reddish brown, much gravel. Pinal fine gravelly loam. 0–12 reddish brown, friable, highly calcareous fine gravelly loam with much loose gravel. More or less overwash material. 12–23 reddish brown loose, friable, highly calcareous gravelly loam. 23–36 hard caliche of lime carbonate, gravel and reddish brown fine sand loam.	Fair	do	34–48

TABLE 114. *National Bureau of Standards test sites*—Continued

Site No.	Soil type	Location	Description of soil profile (Depths are in inches)	Internal drainage	Topography	Depth of specimens
						Inches
67	Cinders	Milwaukee, Wis.	Test site is adjacent to a canal and the trench is always more or less wet. The trench was evacuated to a depth of 5 feet and filled with fresh cinders, in which the specimens were buried to 3 feet. An analysis of the cinders showed it to contain 26 percent of carbon. Following is the description of the profile before backfilling with the cinders: 0–8 sandy clay with surface of a mixture of cinders, canal dust, and oxide. 8–17 layer of spent oxide purifying material containing iron borings and shavings with about 50-percent sulfur content and some cyanide compounds. 17–60 mixture of sandy clay and loam with appreciable quantities of marl and traces of cinders and ashes. 60+ stiff clay	Very poor	Level	48
68	Gila clay	Phoenix, Ariz.	0–12 uniform chocolate brown granular, highly calcareous clay that is friable when moist. This layer is quite plastic when moist but not so much as the layers below. 12–24 uniform brown massive, firm, highly calcareous clay which gradually grades into. 24–36 more friable red tinted brown, highly calcareous clay that also grades into. 36–48 slightly mottled reddish brown, brown, and rusty brown, highly calcareous clay that is very plastic when wet. 48–60+ very little change in texture or lime content. Mottlings are more intense with depth.	Imperfect	Level	40
70	Merced silt loam	Buttonwillow, Calif.	Same as soil 23.			
71	Mahoning silt loam	West Austintown, Ohio.	Description of profile not available. Soil type is subject to change upon better identification.	Fair		36
72	Papakating silty clay loam.	Deerfield, Ohio	This soil is a dark bluish black when wet and has a pH of 7.2. When air-dried it is a light gray with a brownish cast and has a pH of 4.1. Active anaerobic sulfate-reducing bacteria have been identified here. Typical profile from soil survey report of Portage County. Surface—varies from a clay loam to a silty clay loam, generally of a somewhat bluish cast in very wet places. The drier portions have a brownish cast. The soil, while heavy, carries sufficient sand to be noticeable. Subsoil—consists of a clay loam to silty clay loam, light gray or gray mottled with some drab and brown. Clay content increases with depth and mottling usually becomes more pronounced. The gray generally changes to a bluish drab or even a steel-blue, soft, plastic clay. Presence of iron stains and concretions throughout the soil mass is characteristic.	Very poor	Gradual slope.	36
73	Wabash silty clay loam	E. St. Louis, Mo.	Description of profile not available.	do		36
74	Otero clay loam	Rocky Ford, Colo.	do	Fair		36
75	Unidentified silt loam	Albuquerque, N.M.	do	do		36
76	Chino silt loam	Los Angeles, Calif.	do	Good		36
77	Susquehanna clay	Louisville, Miss.	do	Fair		36
78	Caddo fine sandy loam	Latex, Tex.	do	Poor		36
101	Billings silt loam (low alkali).	Grand Junction, Colo.	0–6 gray silt loam containing a few cinders and showing evidence of being disturbed. Rather compact and dry. 6–45 grayish brown slightly compact silt loam full of white streaks and spots. 45–108 grayish brown sandy loam, loose and rather wet at 108 inches.	Fair	Very gentle uniform slope.	34
102	Billings silt loam (moderate alkali).	Grand Junction, Colo.	0–6 grayish brown silt loam, lighter than lower soil probably because it is dryer. 6–108 grayish brown silt loam mottled with white streaks and specks and containing a few thin layers of fine sandy loam below 36 inches.	Fair	Very gentle slope.	36
103	Billings silt loam (high alkali).	do	0–2 surface crust underlain by mulch, grayish brown silt loam. 2–74 grayish brown heavy silt loam. White streaks and specks appear below 14 inches and become most numerous at about 6 feet. 74–108 light grayish brown micaceous fine sandy loam.	do		36
104	Cecil Clay	Charlotte, N. C.	0–72 bright red clay, smooth and brittle with no noticeable change, except slight addition of organic matter in first few inches.	Good	Gentle slope	40

TABLE 114. *National Bureau of Standards test sites*—Continued

Site No.	Soil type	Location	Description of soil profile (Depths are in inches)	Internal drainage	Topography	Depth of specimens
						Inches
105	Cecil clay loam	Macon, Ga.	0–8 grayish brown sandy clay loam, pine needles and trash above 1 inch. 8–28 red brittle clay, compact and hard. 28–72 micaceous light red silt loam. 72–100 mottled red and yellow micaceous silt loam. No visible granite, but soil section has a few veins of quartz that have structure-like petrified wood.	Good	Gentle slope	26
106	do	Salisbury, N. C.	0–4 grayish brown clay loam 4–72 red clay which gets a little more crumbly and slick with increasing depth.	do	do	36
107	Cecil fine sandy loam	Raleigh, N. C.	0–8 grayish brown fine sandy loam with a little gravel mixed with it, rather compact. 8–18 yellowish brown clay loam, more friable 18–34 red clay 34+ mottled, gritty red and yellow partially decomposed granite with some hard fragments of parent rock.	do	do	
108	Cecil gravelly loam	Atlanta, Ga.	0–2 grayish brown sand loam 2–42 typical red clay 42–72 red clay with mica crystals	Excellent	Gentle slope	36
109	Fresno fine sandy loam (low alkali).	Fresno, Calif.	0–2 loose grayish brown fine sandy loam 2–18 very hard, compact grayish brown, micaceous fine sandy loam containing a few light colored specks. Breaks with concoidal fracture. 18–84 grayish brown compact shale-like micaceous very fine sandy loam containing rusty mottling in places. Light gray streaks between plates.	Poor	Level	36
110	Fresno fine sandy loam (moderate alkali).	do	0–6 gray moderately compact fine sandy loam 6–18 compact light brown fine sandy loam 18–24 very hard, compact, tough layer, breaks with concoidal fracture. 24–56 moderately compact light brown silt loam 56–68 light brown moderately compact fine sand 68–72 same as above with rusty mottling	do	do	
111	Fresno fine sandy loam (high alkali).	Kernell, Calif.	Description of profile not available. (See site numbers 109 and 110.)	do		
112	Imperial clay (moderate alkali).	Niland, Calif.	0–50 brown shale-like compact clay with thin layers of a coarser material and gravel scattered through the profile. Practically no gravel on surface. 50–56 layer containing considerable gravel 56–72 brown clay	do	Gentle uniform slope.	36
113	Imperial clay (high alkali).	do	0–1 light brown crust 1–4 light brown mulch 4–96 brown clay with a slightly reddish or purplish cast, hard and compact with platy structure. If the entire profile had the same moisture content, it would probably have the same color. Texture is heavy throughout and practically no gravel or coarse material.	Fair	do	36
114	Lake Charles clay	El Vista, Tex.	Same as soil 56.			
115	Memphis silt loam	Vicksburg, Miss.	0–12 grayish brown silt loam 12–72 light brown silt loam with slightly reddish cast. No lime or mottling.	Good	Gentle slope.	
116	Merced clay	Los Banos, Calif.	Description of profile not available. Profile most similar to site 117.	Fair		
117	Merced clay loam adobe.	Tranquillity, Calif.	0–3 loose grayish brown mulch 3–18 dry, grayish brown clay, showing characteristic adobe cracks. The lumps are very hard, and the cracks are lined with light colored salts. Profile appears as though there was a heavy concentration of alkali at about 18 inches. 18+ moist clay with no well-defined structure	Poor	Level	24
118	Niland gravelly sand (low alkali).	Niland, Calif.	0–26 stratified light gray or grayish brown gravelly sandy loam. 26–32 brown compact clay 32–54 light gray gravelly sandy loam—same as surface clay. 54–72 light grayish brown sandy clay	Fair	Moderate slope.	36
119	Norfolk sandy loam	Macon, Ga.	0–4 grayish brown sandy loam 4–50 yellowish brown or dirty yellow fine sandy loam. These two layers are rather compact. 50–84 pale red or reddish yellow open, loose clay loam. 84+ gravel layer of variable thickness	Good		
120	Norfolk sand	Pensacola, Fla.	0–2 yellowish gray sandy loam 2–72 pale yellow fine sand with some clay mixed with it.	do	Level	

TABLE 114. *National Bureau of Standards test sites*—Continued

Site No.	Soil type	Location	Description of soil profile (Depths are in inches)	Internal drainage	Topography	Depth of specimens
						Inches
121	Norfolk sand	Tampa, Fla.	0–4 gray or grayish brown 4–12 gradually changes into pale yellow sand. Color typical of Norfolk at 12 inches. 12–66 yellow color increases in brightness and depth until it is a light brown with brownish yellow mottlings. Few iron concretions at 34 inches. Deeper subsoil has a little clay mixed with it.	Good	Level	36
122	Panoche clay loam	Mendota, Calif.	Typical profile from reconnaissance soil survey of the lower San Joaquin Valley, Calif. Panoche clay loam is a gray or brownish gray clay loam, rather low in organic matter content, and relatively high lime content. Subsoil occurs at a depth of 18–30 inches and resembles the surface in essential features. Calcareous, effervescing freely with sand, and the lime in many places is concentrated in seams, veins, and nodules. The deeper subsoil and substratum sometimes includes strata of small gravel, sand, and finer sediments.	Fair		
123	Susquehanna clay	Shreveport, La.	0–2 reddish brown fine loose sandy loam 2–14 red compact clay 14–42 compact mottled red to yellow clay 42–52 yellowish gray mottled with light gray clay 52–72 bluish gray compact clay	Poor	Steep slopes.	
124	Susquehanna silt loam	Troup, Tex.	Typical profile from soil survey of Rapids Parish, La. 0–4 brownish to grayish silt loam 4–12 pale yellow or mottled yellowish and grayish silt loam. 12+ yellow clay, which becomes mottled first with gray and in the lower part with red and drab. Lower subsoil is very plastic and adhesive when wet.	do		
125	Susquehanna fine sandy loam.	Shreveport, La.	0–10 light-brown slightly compact fine sandy loam. 10–30 yellowish-brown rather compact clay loam containing some sand, slightly mottled in lower part. 30–48 mottled red, yellow, and gray silt loam 48–72 mottled red, yellow, and drab clay. Compact and hard.	Poor	Moderate slope.	40
AMERICAN PETROLEUM INSTITUTE SITES						
201	Bell clay	Temple, Tex.	Typical profile from soil survey report of Bell County, Tex. 0–12 black clay 12–30 gray, heavy plastic clay 30+ gray clay	Poor	Gentle slope.	
202	Oswego silt loam	Arkansas City, Kans.	Soil described as black, tough, heavy clay. Location of the site on the soil map accompanying the soil survey of Cowley County, Kans. shows the soil to be Oswego silt loam. The typical profile consists of a black silt loam, underlain at a depth of 6 to 10 inches by a clay hardpan consisting of black tough, heavy clay. The material shows little change within the 3-foot section, except that in the lower part it is frequently lighter colored being very dark drab to very dark brown or nearly black with some yellowish brown and dark colored concretionary material. This type is the black equivalent of Gerald silt loam. It is locally known as "hardpan" land.	Good	Level	
203	Lake Charles clay	Beaumont, Tex.	Same as National Bureau of Standards site 56.			
204	Lake Charles clay loam	League City, Tex.	This test site is in the same area as site 52 of the National Bureau of Standards sites. The National Bureau of Standards specimens were buried in the mound phase, which is different from the surrounding soil in which these specimens were buried. Typical profile from soil-survey report of Galveston County, Tex. 0–12 dark gray, very fine sandy clay loam 12+ gray clay	Very poor	do	
205	Miami silt loam	Preble, Ind.	Typical profile from soil-survey report of Blackford County, Ind. 0–2 dark gray loose silt loam mixed with well-decomposed organic matter. 2–6 pale yellowish, gray friable silt loam that is soft and crumbly. The lower half contains very little organic matter. 6–12 heavier silt loam, which is rather firm but porous and has little or no definite structural arrangement. 12–24 moderately hard silty clay loam which breaks into aggregates from ⅛ inch to ¼ inch in diameter. The granules separate easily when moist. Rust brown colorations in the lower part. 24+ dense and lighter-colored massive till, yellow stains occur along the fissures.	Poor	do	

TABLE 114. *National Bureau of Standards test sites*—Continued

Site No.	Soil type	Location	Description of soil profile (Depths are in inches)	Internal drainage	Topography	Depth of specimens *Inches*
206	Unidentified	Council Hill, Okla.	Surface—dark brown friable clay loam Subsoil—yellowish brown clay	Poor	Level	
207	Oswego silt loam	Caney, Kans.	Soil type named from location on soil survey map of Montgomery County, Kans. Typical profile follows: 0–8 dark gray to black silt loam underlain abruptly. 8–36 black or very dark brown heavy clay. Texture of the subsoil does not change with depth, but the color usually becomes slightly mottled with yellowish brown. 36+ yellowish brown color The soil at this test site has been identified as follows: Surface—black silt loam. Subsoil—heavy yellowish clay loam.	do	do	
208	Acadia clay	Spindletop Gully, Tex.	Same as prairie phase at National Bureau of Standards site 51.			
209	Hanford fine sandy loam.	Long Beach, Calif.	Soil type named from location on soil-survey map of the Anaheim Area, Calif. See National Bureau of Standards site 12 for typical profile.	Good	do	
210	Muscatine silt loam	Mt. Auburn, Ill.	Typical profile from soil-survey report of Poweshiek County, Iowa. 0–2 very dark grayish brown or heavy black silt loam. 2–18 very dark grayish brown silt loam that is very sticky when wet but friable when dry. In places the soil is heavy in texture, approaching a silty clay loam. 18–25 very dark brown silty clay loam 25–28 yellowish brown silty clay loam 28–42 yellowish brown silty clay loam mottled with gray. Conspicuous orange brown and rust brown iron stains and concretions. 42+ yellowish brown silty clay loam highly mottled with gray, with nodules, stains, or splotches of rust brown or black.	Poor	do	
211	Unidentified	Skiatook, Okla.	Upper soil—striated brown sandy clay Subsoil—black clay Most of the line is in a salt wash.	do	do	
212	Merced clay loam	Mendota (Tranquillity), Calif.	Same as National Bureau of Standards site 117.			
213	Miller clay	Bunkie, La.	Same as National Bureau of Standards site 27.			
214	Hagerstown loam	Chambersburg, Pa.	0–6 loose, mellow dark brown silt loam 6–12 loose, yellowish brown silt loam 12–24 reddish yellow compact silty clay loam, becoming heavier with depth. Limestone was encountered at various depths from 24 inches to 36 inches.	Good	Gentle slope	
215	Docas clay	Cholame, Calif.	Same as National Bureau of Standards site 64.			
			AMERICAN GAS ASSOCIATION SITES			
301	Cinders	Pittsburgh, Pa.	The soil is all fill (at least 10 years old) to a depth considerably below the bottom of the trench. It consists mostly of cinders from the gas plant, but also present was some boiler-flue dust, tar from retorts, clay, concrete, a little gravel, and other material. The dark colored and cleaner cinders were placed next to the specimens.	Good	Level	36
302	do	Milwaukee, Wis.	Same as National Bureau of Standards site 67.			
303	Tidal marsh	Brockton, Mass.	This site is covered with about 6 inches of water at high tide. The soil consists of 12 inches of a thick mat of grass roots, which is underlain by gravel and sand mixed with organic matter. The lower part of the first foot is darker than the surface 6 inches, and it has a distinct odor of hydrogen sulfide.	Very poor	Level	12
304	do	Atlantic City, N.J.	0–24 heavy mat of grass roots 24+ loose, semifluid mass	do	Very gentle uniform slope.	18–24
305	Muck	West Palm Beach, Fla.	Muck is above sand, being about 3 feet deep at one end of the trench and a few inches deep at the other end. The sand was thrown out of the trench and muck placed next to the specimens to a depth of at least 1 foot all along the trench. Most of the muck is black, but it contains a few lenses of brown fibrous peat.	do	Depression	24

Table 114. *National Bureau of Standards test sites*—Continued

Site No.	Soil type	Location	Description of soil profile (Depths are in inches)	Internal drainage	Topography	Depth of specimens
						Inches
306	Muck	Miami, Fla.	0–8 black well-decomposed muck 8–16 transition layer 16–56 brown fibrous peat 56–72 black semifluid sand, which is white sand containing organic matter.	Very poor	Level	24
307	Cecil clay loam	Atlanta, Ga.	Same as National Bureau of Standards test site 3.			
308	----do	Raleigh, N. C.	0–4 grayish brown sandy loam 4–8 yellowish brown sandy loam of heavier texture than above horizon, which changes to red clay loam. 8–36+ red clay loam or clay merges into rotten rock characteristic of cecil soils.	Fair	Rolling	20
309	Susquehanna clay	Shreveport, La.	Same as Natiional Bureau of Standards site 123.			
310	Miller clay	Shreveport, La.	0–72 dull red or reddish-brown clay containing occasional thin lenses of lighter textured material of the same color.	----do	Practically level.	24
311	----do	Bryan, Tex.	0–10 dark brown (almost black) heavy clay 10–72 mottled mixture of dull red and dark brown clay.	Poor	----do	24
312	White alkali soil	Los Angeles, Calif.	This soil is a Hanford fine sandy loam containing a large amount of sulfate. Otherwise the profile is similar to the National Bureau of Standards site 12.	Good	----do	24
313	Black alkali soil	Los Angeles, Calif.	This soil is a Hanford fine sandy loam unusually high in carbonates. Otherwise the profile is similar to the National Bureau of Standards site 12.	----do	----do	24
314	Marshall silt loam	Kansas City, Mo.	0–20 dark brown smooth silt loam 20–24 transition layer 24+ light brown silt loam	Excellent	Almost level	30

29. Appendix 5. Modified Denison Corrosion Cell

The dimensions and construction of Schwerdtfeger's [143] modification of the Denison corrosion cell are shown in figure 100. The cell consists essentially of a weighed anode, A, and a weighed cathode, B, made of the same material, both provided with electrical connections and separated by soil of a definite moisture content. The soil is contained in two Lucite cylinders, C. Other parts of the cell that serve to hold the soil in place and thus insure good contact with the electrodes are two stainless-steel screens, D and E, the rubber stopper, H, and the rubber band, G. The components are joined with asphalt, F, which also serves as a sealer. Aeration of the cathode is accomplished by adjusting the moisture content of the soil, and access of air to the anode is restricted by mechanically working the layer of soil in contact with it, which results in a difference of potential between the electrodes. Details concerning the preparation of the cell follow:

The apparatus for moistening and adjusting the water contents of the soil samples is shown diagrammatically in figure 101. Because four cells are desirable for testing a soil, the apparatus provides for simultaneously moistening the soil contained in 8 Lucite cylinders. Distilled water absorbed from the water dispenser, 12, resting on the upper surface of the soil, 9, is distributed uniformly throughout the soil by a pressure difference of 30 cm of mercury. Suction is applied to 500-ml suction flasks, 3, through fritted-disk Buechner funnels, 1, (150 ml, fine) to the soil contained in the Lucite cylinders, 7. Paraffin, 8, serves to confine the suction to the soil. The battery of eight suction flasks are connected to the suction apparatus with rubber tubing and glass fittings. The vacuum in the line is controlled by valve, 5, and to each flask by valve, 4.

Details of a water dispenser, 12, are shown under detail C, figure 101. The reservoir, A, is cut from Lucite tubing of 1.75-in. outside diameter and 0.125-in. wall thickness. The bottom edge, B, is tapered or rounded so that it will fit readily into the cylinder containing the soil. The dispenser is assembled as follows: With the reservoir placed on a flat surface in the position shown, asbestos paper, C, 0.125 in. thick cut into the form of a disk slightly larger than the inside diameter of the tubing, is pressed from the top to the bottom and sealed with molten beeswax, D. A saucer shaped stainless steel screen (16 mesh), E, held in place by friction and beeswax, serves to keep the weight of the glass beads, F, off of the asbestos. The beads (6-mm solid glass) added to within ½ in. from the top of the dispenser furnish weight to insure good contact for absorption of water by the soil. A second screen, G, identical with screen, E, is pressed over the glass beads to prevent their loss.

The cell electrodes (fig. 100) are prepared for the corrosion tests in the following manner: The electrodes are degreased and all burrs removed with 1G French emery cloth. After being weighed, the electrodes are fitted with 0.5 in.×2–56 steel fillister head machine screws and stranded copper wire (RC No. 18) leads, approximately 8 in. long, are soldered under the heads. The edges and unfinished surfaces of the anodes are given a heavy coat of bituminous paint. The edges and unfinished sides of the cathodes, excluding the cylindrical surface of the holes, are similarly treated. The machine screws and soldered connections are also coated to prevent corrosion and to facilitate removal of the screws at the conclusion of the test.

In setting up the corrosion cells eight Buechner funnels, 1, are fitted with rubber stoppers, 2, and positioned as shown in

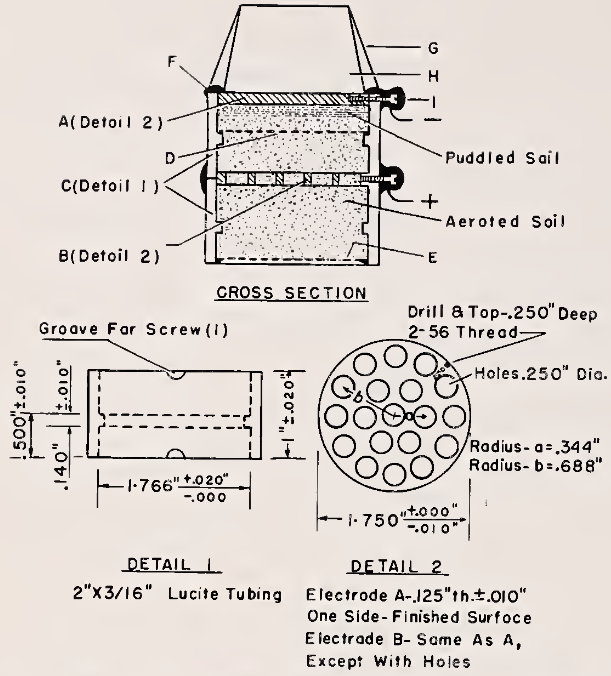

FIGURE 100. *Modified Denison soil-corrosion cell [143].*

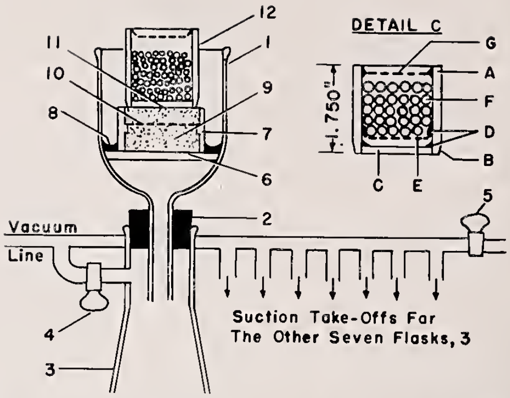

FIGURE 101. *Cross-sectional view of the soil-moistening apparatus [143].*

figure 101. Two sheets of filter paper (No. 42, 5.5-cm diam), 6, are placed in each funnel to prevent direct contact between the soil and the fritted glass. The screw holes in the Lucite cylinders, 7, are filled with saturated soil and a cylinder is centered in each funnel. Paraffin is heated just to the melting point and a sufficient amount applied with a dropper to the space around each of the cylinders to adhere to both the funnel and the cylinder. Dry soil, previously passed through a No. 20 standard sieve, is poured into each cylinder approximately to the upper edge of the ridge and compacted by placing a cylindrically shaped brass weight 1.75 in. in diameter and 2.25 in. long on the surface of the soil. Disks of stainless-steel wire mesh, 10, are then placed on the ridges of 4 of the 8 cylinders, and the process of filling the cylinders and compacting the soil is resumed until all of the cylinders are filled. As excessive swelling usually accompanies the moistening of heavy clay soils, allowance for this may be made by filling the cylinders just short of capacity.

After the asbestos of the water dispensers is saturated with distilled water, 15 ml of water are poured into each of the reservoirs and the dispensers then positioned on the surfaces of the soil samples but separated therefrom by a sheet of filter paper, 11, cut to conform to the inside diameter of the cylinder. Vacuum equivalent to 30 cm of mercury is then applied for periods ranging from 1 to 8 hr, depending on the soil texture. Sufficient moistening of the soil is indicated by water dripping from the funnels, sweating underneath the fritted glass, or by the appearance of the soil. The valve, 4, to the particular cell is then closed and the water dispensers removed. Usually, all sections are sufficiently wet within 20 percent of the average wetting time peculiar to the soil. If it is necessary to delay assembly of the cell, evaporation of water can be prevented by placing a pad of cheesecloth saturated with water in the funnel and covering the funnel with an inverted crystallizing dish.

The cell components are assembled in the following manner: The adhesion between the paraffin around the Lucite cylinders and the funnels is broken with a spatula, and the four funnels containing the cylinders fitted with the screen disks D, are removed. The four funnels are inverted, and the cell sections are dropped into the palm of the hand. The four cylinders, paper-capped ends down, are placed on a flat surface, and the soil on the upper surface of the cylinders is slicked over with a spatula occasionally dipped into distilled water until all evidence of porosity has disappeared. The unpainted surface of four anodes (A, fig. 100) are lightly scratched with 1G French emery cloth and cleaned with distilled water. The anode is again moistened with distilled water, the screw alined with the notch in the Lucite cylinder, and with an oscillatory motion combined with some pressure, the anode is placed in good contact with the soil. Excess soil is then removed, the components wiped dry, and the junction of the anode and the cylinder sealed with molten asphalt. The paraffin seal around the Lucite is loosened with a spatula, and the cylinders are turned over so as to rest on the anodes, after which the filter paper and adhering paraffin are lifted off in preparation for the positioning of the cathodes.

The cathodes (B, fig. 100) are prepared in the manner described for the anodes and positioned over the soil in the ends of these four inverted cylinders, previously described, with the uncoated surfaces facing the anodes. The cathode perforations are then filled with dry soil. The four remaining soil cylinders are removed from the funnels and positioned over the cathodes so that the edges from which the paraffin was removed are adjacent to the cathodes. The screen disk, E, is positioned, and the components are joined with molten asphalt, as shown in figure 100. The rubber stopper, H, is then placed in position and held firmly against the anode by a No. 32 rubber band, G, wrapped once around the stopper and the cell. Each cell is placed on nonconducting supports in a 1-qt friction-top can containing about 25 ml of water to maintain a saturated atmosphere. The water level is maintained throughout the period of the test. Leads from the cell are passed through holes in the side of the can and the electrodes short-circuited by a Fahnestock clip soldered to one of the wires.

30. Appendix 6. Pattern and Conductance Tests for Pipe Coatings

The pattern and conductance tests for measurement of continuity of pipeline coatings are made by first cleaning the soil particles from the section of coated pipe to be tested and then painting it with a slurry of kaolin, or iron-free clay, to fill the holes, cracks and depressions. The clay surface is wrapped with a wet sheet of thick paper, which will absorb a considerable quantity of water. The paper is cut in lengths equal to the circumference of the pipe and 1 ft wide. Its position on the pipe is marked, so that if desired, it can be replaced in its original position. Over the paper is wrapped several layers of wet cotton flannel or outing cloth, which is held in place by means of a saddle made of several strips of sheet copper held together at the ends by cross strips, as shown in figure 102. A 22-v battery and a voltmeter are connected between the saddle and the pipe, the pipe being made the anode. The circuit is closed until the product of the applied voltage and the time in minutes is approximately 100. The paper is then removed from the pipe and washed in a 1-percent solution of potassium ferricyanide (7 g of potassium ferricyanide per liter of water which is also approximately equivalent to 2 tbsp/gal of water). Current flowing from the pipe through holes or other discontinuities in the coating will cause ferrous hydroxide to be deposited in the paper which will show up as blue spots corresponding to the holes in the coating when the paper is developed by immersion in the potassium ferricyanide solution. The number and size of the spots are indications of the condition of the coating and the pattern serves as a record of the test and assists in the location of small pinholes and cracks. Patterns from different coatings, however, are not comparable unless the resistivities of the waters used and the voltage-time products are the same for each coating.

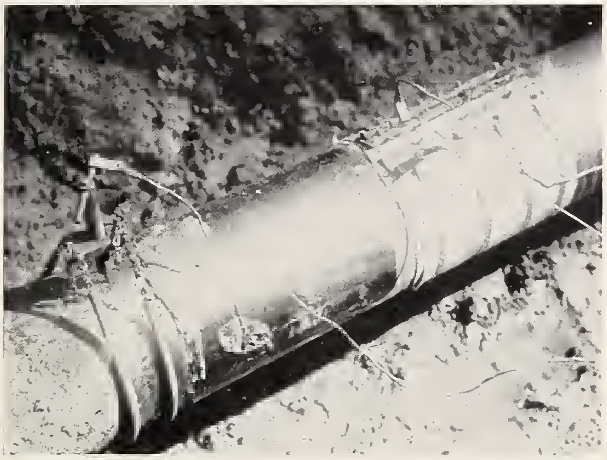

Figure 102. *Setup for making pattern and conductance tests of pipe coatings.*

By this method, the current and voltage supplied by the battery are observed, the resistance or conductance of the coating can be calculated, provided care is taken to avoid leakage by keeping the coating dry on either side of the pad. The conductance is usually expressed as micromhos per square foot. The conductance measured in this way involves the conductances of the pad, paper, and test solution which are negligible if the coating is good; there is nothing to be gained by testing a coating with an obvious hole. As the range of conductance values of coatings is very large, a special instrument, such as that designed by Shepard [210] for measuring them, is desirable. After these tests are completed, the coating is removed and the condition of the pipe is determined.

31. Appendix 7. Determination of the Total Acidity of Soils

The determination of total acidity of soils is somewhat difficult because of the slight solubility of soil acids. The details of the procedure followed in determining acidity by the "difference" method as described by Denison [406] are as follows; the capacity of the soil to absorb exchangeable bases was first determined. A 25-g sample of soil was placed in a 250-ml Erlenmeyer flask together with about 1 g of calcium carbonate and 150 to 200 ml of 1-normal sodium chloride solution that had been heated to 80° to 90°C. The mixture was maintained at this temperature for 1 hr, with occasional shaking. The mixture was then poured into a 400-ml bottle and shaken overnight in an end-over-end shaker and also for 2-hr periods on 2 succeeding days. After standing another night the extract was decanted and filtered into a 1-liter beaker. Then 200 ml of 1-normal sodium chloride solution was added to the soil at room temperature. The mixture was shaken 1 hr, allowed to settle, and the extract then decanted through the filter as before. This process was repeated until 1 liter of extract was obtained. For the final filtration, the entire quantity of soil was poured on the filter and washed. The 1-liter extract was then mixed thoroughly, and the calcium in a 400-ml portion was determined gravimetrically. From the value thus obtained was subtracted the quantity of calcium equivalent to the solubility of calcium carbonate in 1 liter of 1-normal sodium chloride.

The quantity of replaceable calcium in the soil was determined in a manner similar to the determination of the exchangeable base capacity, except that no calcium carbonate was added and the shaking was limited to 18 hr. For those soils in which calcium carbonate occurred naturally, a correction was made for the calcium that had been dissolved as carbonate by the salt solution. This quantity was calculated from the amount of bicarbonate in solution, which was estimated by titrating an aliquot portion of the extract with standard acid to the color change of methyl orange. The total acidity of the soil was obtained by subtracting from the exchange capacity of the soil the absorbed calcium found to be present.

Ewing [71] devised a shorter method that duplicated the results of Denison's method within about 15 mg equivalents per 100 g of soil. Ewing's method is as follows: Two 5-g portions of the air-dried soil, previously pulverized and passed through a 20-mesh sieve, are placed in two 25- by 200-mm test tubes, and then 25 ml of normal sodium chloride solution is added to each tube at room temperature. One milliliter of 0.2-normal sodium carbonate solution is pipeted into one tube and 2 ml into the other. (One milliliter is equivalent to 4 meq of acid per 100 g of soil for the 5-g sample.) The *p*H of the more alkaline solution is then determined. If the *p*H is found to be below 8, 2 ml more of the carbonate solution are added to each tube and the process repeated until the *p*H of the more alkaline solution is above 8. The tubes are allowed to stand, with occasional shaking, until the solutions are in equilibrium with the soil and show no further changes of *p*H with time. The solutions usually reach equilibrium after a period of 24 hr. The *p*H of the solution in each tube is then determined. Usually the resulting *p*H values are so near to *p*H 8 that by interpolation or extrapolation the amount of alkali required to bring the soil to *p*H 8 can be determined. For example, if 12 meq (3 ml) of the carbonate solution give a *p*H of 7.7 when in equilibrium with the soil and 16 meq (4 ml) give a *p*H of 8.1, the acidity of the soil will be 15 meq/100 g. The titration curve is assumed to be a straight line through the range of interpolation and extrapolation.

32. Appendix 8. Darnielle's Modification of the Hickling Apparatus for Measuring Potentials

The Hickling method for measuring the potential of polarized electrodes utilizes an electronic interrupter and an electronic potentiometer, by means of which potentials can be measured very shortly after the current has been interrupted.

Figure 103 shows the essential parts of the interrupter and measuring circuit. Capacitor C_1, is charged through resistor R_1 until the plate of the thyratron V_1 is at a certain potential, depending on the grid voltage. The tube then becomes conducting and capacitor C_1 discharges through the tube and resistor R_2 until the capacitor voltage drops to about 15v, when the tube becomes nonconducting, and the process is repeated at a rate depending on the values of R_1 and C_1.

The cell is in the plate circuit of the pentode V_2. This current may be controlled by potentiometer P_1 and the IR drop across R_2. Each voltage pulse across R_2 imparts a large negative potential to the grid of the pentode tube, thereby interrupting the current in the cell.

The measuring circuit is an oscillating type similar to the interrupter circuit but will not oscillate when the grid of the thyratron V_3 is below a certain critical potential.

In measuring electrode potentials, the electrodes are connected to the grid circuit of the thyratron, V_3, the grid having been adjusted by means of the potentiometer, P_2. The cell is so connected that the grid of V_3 is most negative between interruptions of the current because of the IR drop in the cell. When the plate current in V_2 is interrupted, the grid potential of V_3 will be above or below the critical potential by a value equal to the potential difference of the electrodes in the plate circuit of the V_2. Adjustment of the potentiometer, P_3, also in the grid circuit of V_3, so that the frequency of oscillation previously set by P_2 is restored, permits measurement of the electrode potential difference as indicated by the voltmeter, V.

In operation, the switch, S_2 (key type) is pressed down so that contact is made in the normally-open (N.O.) position and the potentiometer P_2 adjusted so as to result in a slow ticking sound from the loudspeaker, the volume of which can be controlled by rheostat R_3. By letting switch S_2 snap back to the normally-closed (N.C.) position, the cell and the voltmeter-potentiometer, P_3, are introduced into the V_3 grid circuit. If, by so doing, the grid becomes more negative than the critical grid setting, no sound will come from the loudspeaker. On the other hand, if the grid is made more positive, very rapid ticking will be heard. Potentiometer P_3 is then adjusted until the ticking frequency is identical with that heard when S_2 was closed in the normally-open position, and the potential difference between the electrodes is read on the voltmeter. Because switch S_2 is quick-operating, potential changes as small as 3 mv will produce detectable changes in the ticking frequency, thus permitting fairly good synchronization.

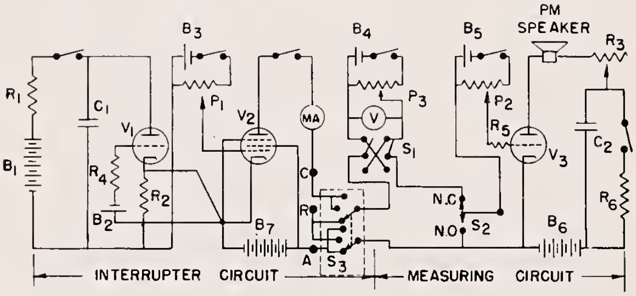

FIGURE 103. *Modified Hickling potentiometer-voltmeter circuit for soil potential measurements.*

V_1, V_3 = Thyratron 884.
V_2 = vacuum tube 6AC7.
B_1, B_7 = 90-v battery.
B_6 = 45-v battery.
B_3, B_5 = 6-v battery.
B_4 = 1.5-v battery.
B_2 = 4.5-v battery.
C_1, C_2 = 0.5-mfd, 600-v condenser.
R_1, R_6 = 100,000-ohm, 1-w resistor.
R_2 = 100-ohm, 1-w resistor.
R_3 = 1,000-ohm rheostat.
R_4, R_5 = 5,000-ohm, 1-w resistor.
P_1, P_2, P_3 = 2,500-ohm potentiometer.
V = 0–1–2 voltmeter.
MA = 0–0.1–1.0–10 milliammeter.
C = cell cathode connection.
A = cell anode connection.
R = reference electrode.
S_1 = DPDT switch.
S_2 = make-break key-type switch.
S_3 = rotary switch.

It is important to note that the connection of measuring circuit to the cell are determined by the directions of IR drop and not by the polarity of the electrodes. Switches S_1 (D.P.D.T. type) and S_3 (rotary type) provide for this. Hence, in measuring the voltage between the anode, A, and the cathode, C, the cathode of the cell is connected to the grid of V_3. When the potential difference between the anode of the cell and the reference electrode, R, is measured, the reference electrode is connected to the grid, and for measuring the potential difference between the cathode and the reference electrode, the cathode is connected to the grid.

When the cell current is interrupted, it drops quickly to a very low value and immediately begins to increase as C_1 discharges. The time required for the current to decrease to a minimum and then increase until the IR drop is more than 0.01 v, the approximate limit of accuracy of the measurement, may be designated as the "effective" period of interruption. This interval corresponds to the maximum time during which the electrode depolarizes before its potential is measured.

Hickling's measurements were made with high current densities in cells of very low resistance, a triode being used as the vacuum tube. In order to make the effective period of interruption independent of the polarizing current, the latter was controlled by adjusting the filament current. For measuring potentials in soil cells in which the resistance is high and the current low, the use of a sharp cutoff pentode permitted control of the plate current in the usual way, that is, by regulation of the grid voltage. By eliminating lag in the adjustment of the current in this manner, potential measurements could be made immediately after the current was changed, which is usually desirable in measurements with soil cells. With variation of current and resistance over the extreme range used in corrosion studies, the effective time of interruption was found to be reasonably constant. However, the chief advantage of the pentode over the triode was the greatly improved accuracy of measurement obtained with the former tube. Pentodes of the types 6J7 and 1852 have a very sharp cutoff and provide sufficient plate current for potential measurements in the soil cells. Calculation of the effective period of interruption indicated that this time was about 8×10^{-5} sec when R_2 was 75 ohms.

Data show that within the range of current commonly applied to soil-corrosion cells and within the normal range of resistance of these cells, the combined effect of current and resistance on the accuracy of potential measurements is not over 0.01 v. Measurements accurate to 0.01v were made with a current of 4 ma and a cell resistance of 6,000 ohms.

As the period of interruption of the current is related to the resistance R_2 in the interrupter circuit, varying this resistance provides a convenient means for varying the period of interruption, and hence for studying the rate of depolarization of the soil cells. This was found to be subject to wide variation. In a few soils the change in voltage resulting from a change in R_2 from 100 to 20,000 ohms was little more than 0.01 v. In other soils this difference was 0.1 v or more. Rapid depolarization may occur at the anode as well as at the cathode. This period of interruption of the current should be kept as short as possible by keeping R_2 at the lowest practicable value. Measurements of cell potentials by means of the apparatus described have been found to be in good agreement with those by other less generally applicable methods.

The Soil Bureau of the New Zealand Department of Scientific and Industrial Research [407] in their studies with soil corrosion cells modified the aural method described above for measuring potentials by using a visual method with an oscilloscope as the null indicator.

WASHINGTON, March 19, 1955.

33. Index

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