UNDERGROUND CORROSION

Edward Escalante, *editor*

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UNDERGROUND CORROSION

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NOTE

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Foreword

The symposium on Underground Corrosion was presented at Williamsburg, Virginia, 26–27 November 1979. The symposium was sponsored by the American Society for Testing and Materials through its Committee G-1 on Corrosion of Metals. Edward Escalante, National Bureau of Standards, presided as symposium chairman and editor of this publication.

Related ASTM Publications

Corrosion of Reinforcing Steel in Concrete, STP 713 (1980), $22.50, 04-713000-27

Corrosion and Degradation of Implant Materials, STP 684 (1979), $37.75, 04-684000-27

Stress Corrosion Cracking—The Slow Strain-Rate Technique, STP 665 (1979), $39.75, 04-665000-27

Atmospheric Factors Affecting the Corrosion of Engineering Metals, STP 646 (1978), $24.50, 04-646000-27

Dispersive Clays, Related Piping, and Erosion in Geotechnical Projects, STP 623 (1977), $40.75, 04-623000-38

Soil Specimen Preparation for Laboratory Testing, STP 599 (1976), $35.00, 04-599000-38

Corrosion in Natural Environment, STP 558 (1974), $29.75, 04-558000-38

A Note of Appreciation to Reviewers

This publication is made possible by the authors and, also, the unheralded efforts of the reviewers. This body of technical experts whose dedication, sacrifice of time and effort, and collective wisdom in reviewing the papers must be acknowledged. The quality level of ASTM publications is a direct function of their respected opinions. On behalf of ASTM we acknowledge with appreciation their contribution.

ASTM Committee on Publications

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Introduction

Underground corrosion has a greater impact on our lives than many of us realize since it touches practically every aspect of our society. The buildings that we work in, the bridges and overpasses that we cross, the power that comes into our homes are designed and built within the constraints imposed by this form of corrosion. It has been estimated by the National Bureau of Standards/Battelle study that in 1975 the national cost of corrosion of pipelines alone was 158 million dollars, an awesome figure.

Though great strides have been taken in our advance at understanding and combating this problem, much remains to be learned. For example, it is recognized that there are four general types of corrosion in soil. These are (1) corrosion in disturbed soil, (2) corrosion in undisturbed soil, (3) bacterial corrosion, and (4) corrosion by stray currents. (1) Disturbed soil, soil that has been mechanically upheaved, is far more corrosive than its counterpart, undisturbed soil. This difference is attributed to the availability of oxygen in disturbed soil which is necessary for the cathodic reaction. In disturbed soil other factors can have an appreciable effect on the soil corrosivity. These are notably, soil resistivity, soil pH, and soil chemical content. (2) The rate of diffusion of oxygen through undisturbed soil is low and is the rate controlling step for the corrosion process which consequently proceeds at a very reduced rate. In this case it has been observed that soil resistivity, soil pH, and soil chemical content have no affect on the corrosion process which remains low in all cases. It is important to point up that where a metallic structure passes through a disturbed soil/undisturbed soil interface, the structure in the undisturbed soil is anodic to the better aerated portion in the disturbed soil and may undergo some attack. (3) Bacterial corrosion of underground structures has been reported in several studies, and it is recognized that under proper conditions this type of corrosion proceeds at a very high rate, and is unique because it involves living organisms and is totally independent of free oxygen. However, it must have access to sulfates and certain organics for its survival. Much remains to be learned about this form of corrosion. (4) Stray currents can have a devastating effect on buried metals, and, in particular, on long line structures such as pipelines or electric lines. The more commonly encountered situation is that of a cathodically protected system interfering with a nonprotected system near by. The complication is that often times the corrosion effects may develop at some distance from the point of interference. This type of corrosion is independent of all soil parameters.

The purpose of this symposium was to bring together the most recent information on underground corrosion of metals, its evaluation, and the factors that affect it. A discussion of protection techniques and methods of evaluating their effectiveness was also sought. Thus, through the efforts of ASTM Committee G-1 on Corrosion of Metals, and, more specifically, Subcommittee G01.10 on the Corrosion of Metals in Soil, this symposium was developed. The primary interest of ASTM Subcommittee G01.10 has been to develop measurement techniques for identifying soil corrosivity. This effort has been carried out at two fronts. First, it is important to be able to measure the degree of deterioration of a metal in soil. Ideally such a measurement is nondestructive, can be made *in situ,* and is reproducible. For this reason, several polarization techniques are being applied to corrosion in soil and are being evaluated by over ten laboratories in a round robin test. This program is now in progress. The second front involves soil characterization, since corrosion in disturbed soil is the most commonly encountered problem. In this area, two standard test methods now exist in the ASTM Standards. These are: ASTM G 51-77, a standard method for pH of Soil for Use in Corrosion Testing, and ASTM G57-78 a standard method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method. Presently the subcommittee is activity working on methods for characterizing the chemical components of soil that affect corrosivity.

This symposium has resulted in helping to establish new ground work for the direction and scope of the subcommittee. But of greater importance to corrosion engineers and scientists, it has brought together, under one cover, the type of information needed for a better understanding of the processes and measurements involved.

Edward Escalante
National Bureau of Standards, Washington D.C. 20234; symposium chairman and editor.

F. P. Miller,[1] *J. E. Foss,*[1] *and D. C. Wolf*[2]

Soil Surveys: Their Synthesis, Confidence Limits, and Utilization for Corrosion Assessment of Soil

REFERENCE: Miller, F. P., Foss, J. E., and Wolf, D. C., "**Soil Surveys: Their Synthesis, Confidence Limits, and Utilization for Corrosion Assessment of Soil,**" *Underground Corrosion, ASTM STP 741,* Edward Escalante, Ed., American Society for Testing and Materials, 1981, pp. 3–23.

ABSTRACT: Organized efforts in soil classification and mapping in the United States began in 1899 as a cooperative research program of the U.S. Department of Agriculture and the state land-grant universities. Although the original objective of this program was oriented toward the soil as medium for plant growth, much of the data gathered by soil scientists over the last 50 years has been applied to nonagrarian land uses. Modern soil surveys have been prepared for nearly two thirds of the land area of the United States since 1955. This paper will discuss the data acquisition technique used in making soil surveys, the basis for the prediction of soil behavior from this information, the confidence limits of the information, and its application to corrosion engineering.

KEY WORDS: soil surveys, soil classification, confidence limits, prediction of soil behavior, soil corrosivity, underground corrosion

Organized efforts in soil classification and mapping in the United States began in 1899 as a cooperative research effort of the U.S. Department of Agriculture (USDA) and the state land-grant universities. The original objective of this program was to guide people in selecting soils which were responsive to the then-current farm management systems.

The primary purpose of the soil classification program in the United States has been for use in making and interpreting soil surveys. Furthermore, the principal uses of the soil survey in the USDA have been oriented toward interpretations for technical assistance in soil conservation programs, for planning agricultural programs, and as a basis for financial credit [*1*].[3] As the quality and detail of soil surveys improved, and as the agricultural uses of the land intensified and became more complex, it became obvious that the combination of soil properties responsible for a specific soil having a charac-

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[1] Professors of soil science, University of Maryland, College Park, Md. 20742.

[2] Professor of soil science, University of Arkansas, Fayetteville, Ark. 72701.

[3] The italic numbers in brackets refer to the list of references appended to this paper.

teristic crop production and management potential also determined its suitability for a variety of nonagricultural uses.

The early attempts at applying the basic soil classification system to nonagricultural land uses began in the mid and late 1920s. By 1930 the system began to guide highway construction and was later applied in defense planning [*2*]. As nonagricultural land use intensified after World War II, soil survey interpretations accelerated in the areas of community planning, engineering, transportation, and waste disposal technology.

The objective of soil surveys today is to provide information on which to base decisions for land use changes or land management programs.

Soil Surveys: Status and Soil Defined

Soil surveys are one of the most widely available forms of geotechnical surveys. Modern soil surveys have been prepared since 1955 for more than 570 million hectares (1.4 billion acres), or nearly 65 percent of the land area of the United States. In addition, many soil surveys were prepared before 1955. Data from these soil surveys can be obtained in the local office of the Soil Conservation Service.

It is essential that the difference in definition of soil used by pedologists be distinguished from that in common use in engineering and geology. To the engineer, soil refers simply to unconsolidated earthy materials above bedrock. To the geologist, soil is considered to be the upper portion of the regolith altered by weathering. The pedologist defines soil as a three-dimensional natural body at the earth's surface that supports or is capable of supporting the growth of plants, and that part of the earth's crust subject to the influence of the factors of soil formation. To the pedologist, the soil's lower boundary is usually determined by the depth to which biochemical processes have altered the soil's parent material.

In soil surveys, the soil horizons within the upper 1 to 2 m are observed and described. The character of materials below the soil is sometimes described, but only where sufficient observations have been made to provide reliable information.

It has never been appropriate to call soil surveys "agricultural surveys." While the original emphasis was on the soil as a medium for crop production, the morphological, physical, chemical, and mineralogical properties of the soil used as differentiae in soil classification can be used to predict soil behavior for a variety of uses.

Scientific Basis of Soil Surveys

Soil maps, like other types of maps, are miniature and symbolic representations of reality [*3*]. Soil surveyors attempt to delineate or segregate the real landscape into soil units that contain less variable soil conditions than the total population of soils (Fig. 1). What makes soil mapping reasonably accu-

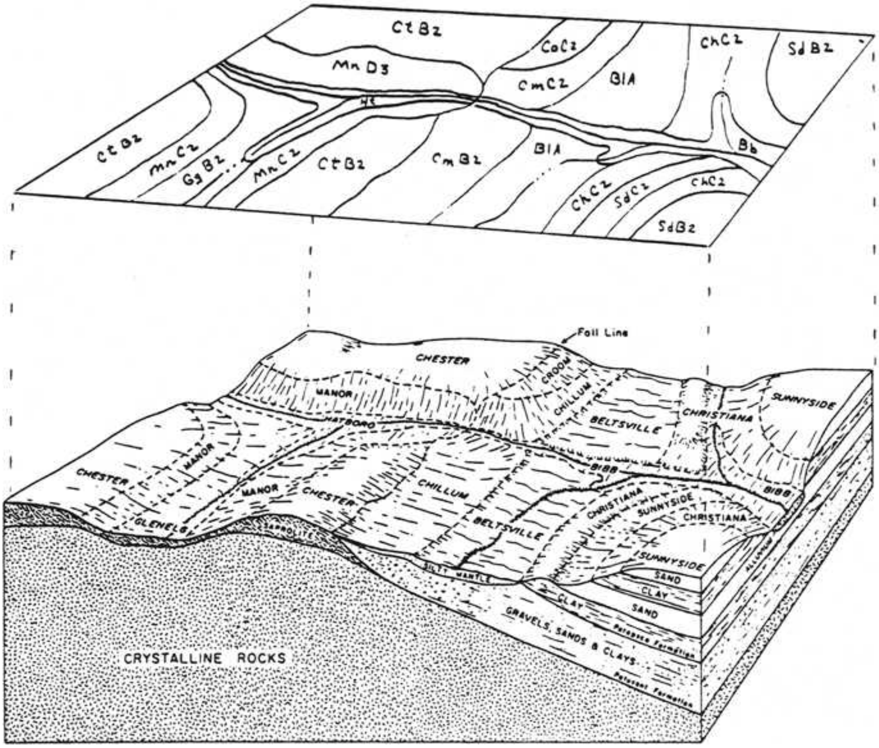

FIG. 1—*Block diagram of contact* (fall line) *between.the Piedmont and Mid-Atlantic Coastal Plain showing relationship of parent materials and topography to soil map units and soil map.*

rate and affordably feasible [*3*] is that soils and their location on the landscape are predictable (to be sure, some more than others) to an experienced soil scientist. This predictable association of the landscape's relation to the soils formed on it is the scientific basis of the soil survey.

The soil survey is basically a data collecting activity. Mapping soils requires data collection by three main approaches:

1. Inferences drawn from landforms and vegetation.
2. On-site borings and excavations.
3. Laboratory characterization.

Soils rarely occur randomly on the landscape. Because of the correlation of soils with landscapes or geomorphic units, soils can be stratified (grouped or classified) and mapped with some degree of predictability and reliability.

Taxonomy[4] is a tool used by the soil scientist to categorize or systematically classify information obtained through observing the landscape, describ-

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[4] Soil taxonomy is that portion of soil classification that deals with relationships among common soil characteristics. Taxonomy is the systematic distinguishing, ordering, and naming of class hierarchies within a subject field. Soil Taxonomy is the title of the most recent publication detailing the principles, definitions, and criteria used in the U.S. to classify soils [*5*].

ing the soil profile and characterizing its properties. Once soils are classified and a map is made of their spatial distribution on the landscape, predictions of soil behavior within delineations on the landscape can be made with some degree of confidence.

The purpose for sampling the soil, therefore, is not to obtain a number of random specimens from which conclusions will be drawn to make a map when subjected to statistical techniques, but to either confirm or reject the soil scientists' hypothesis of what soil is expected on a given landscape unit. Soil mapping, then, is basically the ability of the soil scientist to develop a working model of soil genesis on the landscape and test it by observations.

The soil surveyor observes soil profiles through borings, pits, road cuts, or other types of excavations only at certain points on the landscape. But since soils form a continuum on the landscape, it is necessary to infer through judgement where one soil ends and another begins. Therefore, the delineation of soil map units and the interpretations about their behavior are derived from inferences extrapolated from very small specimens. More than 99.99 percent of the soil delineated by the soil surveyor in making a soil map is not observed below the surface. Since the information on each map unit is obtained through inferences made from one or a few observations extrapolated to the map unit boundaries, the information is not site-specific for each point within the map unit. Yet the association of different kinds of soils with certain landscapes possesses a degree of correlation that is high enough to allow inferences and predictions of soil behavior to be made.

While the soil scientist cannot record what the soil is like at every point on the landscape, nevertheless, those who commission or use soil surveys often want or expect such information [*6*]. It is ironic, however, that these same people do not expect such detail (for example, pot hole locations, bridge widths, etc.) on a Rand McNally road map. Soil survey users often want to be able to infer or predict the nature of the soil at all points on the landscape, even though relatively few observations were made. And although the essential objective of soil surveys is the collection and spatial portrayal of information, the way in which the information is obtained and the way interpretations of soil behavior are inferred are a constant source of misunderstanding by many users. Such misunderstanding is due to the failure of soil survey users to understand the mapping technique used to generate the map. Thus, the user often applies the soil survey beyond its confidence limits.

The basis for the predictive value of soil map units centers on segregating the soil continuum into classes or units with limited ranges in soil properties and soil behavior. The premise used to derive predictability of soil behavior from soil maps, therefore, is that the variance in the map unit is less than the variance of the population of soils in the area as a whole.

Map Unit Imperfections

Taxonomic groups, or classes within the soil taxonomy system (taxa) used to map soils, are conceptual with precisely defined class limits (for example, depth, specific horizonation, chemical properties, particle size, etc.). The taxa are designed to represent actual soil bodies on the landscape. The soil surveyor uses the taxonomic classes as a tool in keying out the soil bodies on the landscape. The soil surveyor then delineates these bodies as map units on the soil survey. Map unit delineations, however, possess attributes beyond those in the taxonomic classes (for example, size and shape of the soil body, slope orientation, and phases of slope, erosion, stoniness, and substrata characteristics). Thus, the taxa and map unit delineations on the soil map, although identified by the same name, are not, in fact, the same. Map unit delineations are seldom, if ever, taxonomically pure.

Despite the fact that soil scientists recognize taxa as being conceptual and actual soil bodies as being real; nevertheless, even the best representations of delineating these soil bodies on a soil map are imperfect. The degree of imperfection varies depending on the scale of the map, the nature and complexity of the soil pattern, and the skill and diligence of the soil surveyor [*4*]. There are several reasons for this imperfection. First, the boundaries between taxa are not always clear or sharp. The predictive value of landscapes is simply not perfect. Taxa cannot be defined precisely enough to relate to all geomorphic histories and landscapes. Second, the soil surveyor must smooth irregular soil boundaries in making a soil map. The map scale (1:15 840 to 1:20 000) often means that the pencil line itself on the map represents several meters in width. Thus, small inclusions of adjoining soil bodies occur within the smoothed boundary as illustrated in Fig. 2. The third problem is identifying the size of the pedon,[5] and the error associated with sampling the population of pedons and measuring their properties [*5*]. The natural scatter or range of values between soil properties varies tremendously.

Variability and Confidence Limits

Soil scientists have been aware of this natural scatter or variability among soil properties since their first attempts to characterize the soil and delineate its spatial distribution. They describe the nature and extent of the dominant soil occurring in delineations along with the component inclusions known to occur within the map unit. The user is thus alerted to these inclusions. These inclusions of nonconforming soils are a natural component of soil maps, resulting from the natural scatter or range of soil properties that fall outside the class limits used to classify and name the map unit. The 1951 Soil Survey Manual [*7*] reminded the soil scientist that ". . . the variation in nature is fixed; failure to recognize it in no way reduces its magnitude . . ."

While the practical objective of soil surveys is to provide information on which to base land use and land management decisions, the scientific objective of the soil surveyor is to segregate the landscape into soil units that contain less variable soil conditions than the total population of soils. The utility

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[5] The smallest soil volume or unit cell that can be called soil; representative of the horizonation and range of properties of the whole soil body. The pedon may vary in size from 1 to 10 m^2. A single soil body is composed of many pedons or polypedons.

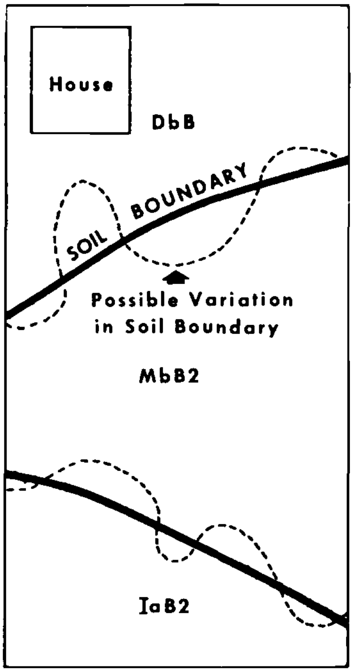

FIG. 2—*Soil map unit boundary in relation to actual soil boundary. Because the soil surveyor must smooth and approximate the real boundary, inclusions of adjacent soils commonly occur within the map unit along the map boundary, reminding us that site-specific planning and design are not the objective of a soil survey.*

of both the taxonomic system used to classify soils and the resulting soil map depends upon the precision of the statements that can be made about the behavior of the delineated units versus the area as a whole [*8*]. However, if the magnitude of the variability or natural scatter of the soil properties within these delineated units is not known, the precision of the statements that can be made about them is compromised.

Figure 3 illustrates the natural topographic variability of the carbonate surface and glacial till surface beneath the present land surface at three locations on a landscape. How can the soil scientist relay the degree and magnitude of this variation to the user? Normally, through the soil surveyors' landscape transects and boring observations, the degree of variation will be observed and described. The user of the resulting soil map will be alerted to the fact that depth to carbonates and depth to the till surface will usually occur within a specified range of depths. Also, the user will be alerted to the fact that shallower or deeper depths may occasionally be encountered. But beyond this subjective assessment of variability based on periodic observations, both the surveyor and map user are unable to know quantitatively the magnitude of this variation and the probability of its occurrence.

Thus, soil scientists are constantly faced with the problem of determining the confidence limits of their data. How many samples are required to obtain

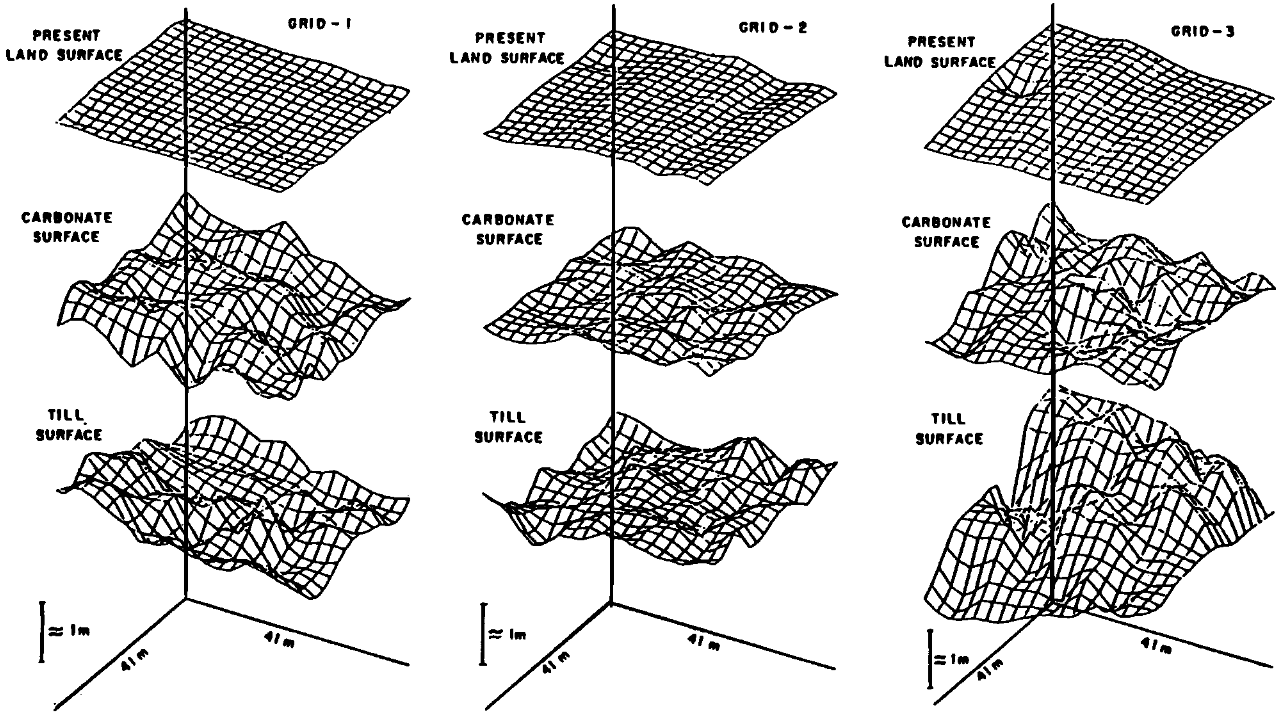

FIG. 3—*A three dimensional computer simulated topographic net of a landscape surface where loess deposits mantle an irregular till surface. This illustration represents an area of about 0.5 ha showing the subsurface configuration of the carbonate leaching limit and the till surface. Note that the vertical exaggeration factor is about ×14.* (*Wilding and Dress* [8]).

a specified confidence interval in estimating the mean of the entire population? And what are the confidence limits of different properties measured from the same number of samples? Can the corrosion engineer interpret soil properties conducive to corrosion (for example, resistivity or conductivity, pH, permeability, ion exchange capacity, etc.) at the same level of confidence that an irrigation engineer or agronomist can interpret a particular suite of properties for their interests?

As an example of how such questions are answered, Wilding and Drees [*8*] determined the coefficient of variability (CV)[6] for selected morphological, physical, and chemical properties within map units using their own research plus data from the literature. Figure 4 shows the variability, as measured by CV, for several soil properties as determined from data analyzed by Wilding and Drees [*8*]. These evaluations of characterization data indicate that soil scientists, as interpreters of the data, cannot speak about exchangeable ions and cation exchange capacity (CEC) as if each had the same confidence limits. The degree of confidence and accuracy of our statements about a soil map unit's CEC is much higher than the accuracy we can express about its exchangeable magnesium. For the latter property, we may need to observe three to four times as many profiles as would be necessary to establish the same degree of confidence or accuracy for the soil's CEC.

Table 1 contains an ordinal ranking of the variability of the soil properties analyzed by Wilding and Drees [*8*] showing the approximate number of pedons necessary to estimate the mean of the population with ±10 percent using a 95 percent confidence interval. These authors point up that, for all of the most variable properties and at least some of the moderately variable ones, less accurate mean estimates will have to be tolerated because the number of observations required to establish the given mean and confidence limits is impractical.

Map Unit Composition

The scale and nature of the map-making process (that is, inferences extrapolated from point observations) result in the process being vulnerable to inclusions of both similar and dissimilar soils. Figure 5 illustrates the concept of the soil surveyors' map unit delineation compared to the actual soil body and its inclusions on the landscape. Despite the amount of inclusions and mismatched boundaries, the information relayed to the user is about as accurate as one can expect from the mapping technique and is adequate for many land use planning decisions. Again, site-specific accuracy is not the objective of the soil survey. The road map compared to the actual road alignment provides a corollary to the soil map example. In both cases the maps portray miniature and symbolic representations of reality and they contain valuable and useful information.

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[6] Coefficient of variability is defined as standard deviation/mean × 100. It is a relative measure of variation expressing the standard deviation as a percentage of the sample mean.

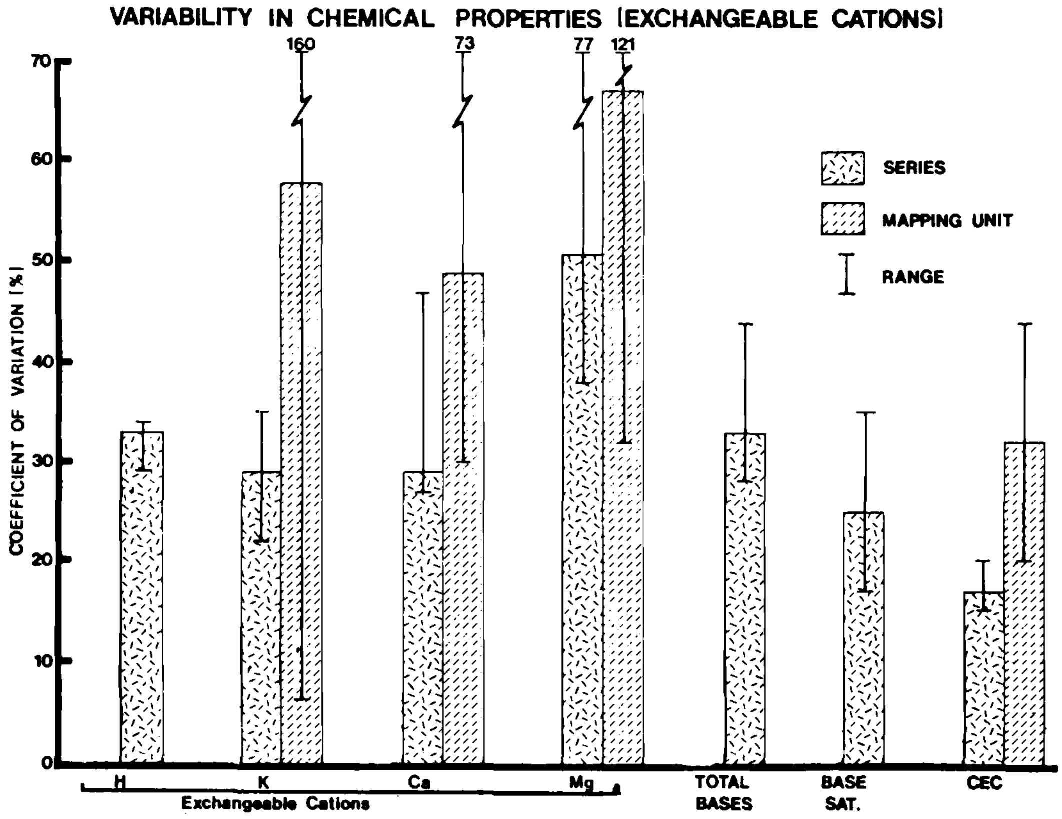


FIG. 4—*Observed variability among selected cation exchange properties as function of landscape units (mapping unit delineations) and respective series concepts. (Wilding and Drees* [8]).

TABLE 1—*Relative ranking of the variability of soil properties and the approximate number of pedons required to estimate the population mean within ±10 percent using a 95 percent confidence interval for the soils studied by Wilding and Drees (1977)* [8].

(*a*) Least variable properties with CVs commonly <15%: <10 pedons
- Soil color (hue and value)
- Soil pH
- Thickness of A horizon
- Total silt content
- Plasticity limit

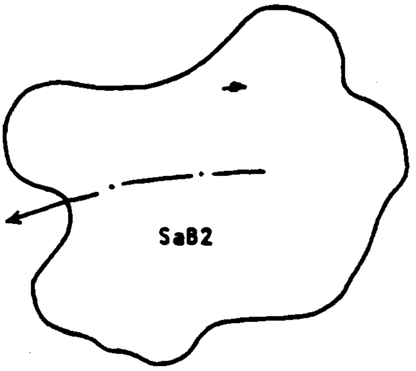
(*b*) Moderately variable properties with CVs between 15 and 35%: 10 to 35 pedons
- Total sand content
- Total clay content
- CEC
- Base saturation
- Soil structure (grade and class)
- Liquid limit
- Depth to minimum pH
- Calcium carbonate equivalent

(*c*) Most variable properties with CVs >35%: >35 pedons
- B2 horizon and solum thickness
- Soil color (chroma)
- Depth to mottling
- Depth of leaching (carbonates)
- Exchangeable H, Ca, Mg, and K
- Fine clay content
- Organic matter content
- Plasticity index

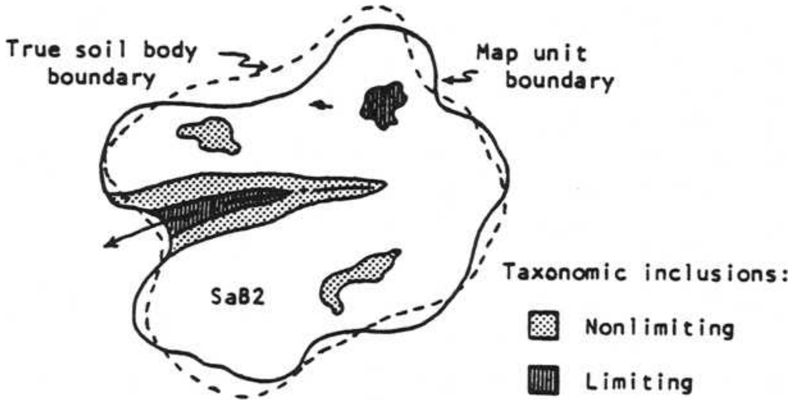
Because soil scientists are aware of inclusions and the limitations of mapping techniques to accommodate all components of map units, studies have been designed to determine quantitatively the composition of map units. These studies have shown that the amounts of inclusions in map units differ enormously among surveys. They also show, however, that many inclusions do not alter the interpretations of the map unit even though taxonomic criteria place those inclusions outside the range of the series or taxon identified in the map unit name.

By using transects, grid sampling procedures, and other techniques, soil scientists are quantifying the composition of map units. The objective of these analyses is to obtain estimates of the composition of soil map units. The soil scientist can then express the composition with a known confidence level, such as; at the 90 percent probability level, Soil A makes up 70 ± 10 percent of the given map unit delineation.

In summarizing such studies to quantify the composition of map unit delineations, Cline [*4*] concluded that delineations were mapped about as well as could have been expected, considering the technique and scale (1:15 840 and 1:20 000) used. Many of the inclusions were not contrasting enough to detract significantly from the interpretive value of the map units. Taxonomically pure map units are attainable using small scale (<1:8000) maps, and in-



Soil Survey Map Unit Delineation



True Soil Body in Relation to Map Unit Delineation

FIG. 5—*Soil survey map unit delineation of soil body as perceived by soil surveyor compared to actual soil body showing taxonomic inclusions. Inclusions may be similar to the taxon for which the map unit is named and, therefore, be nonlimiting for interpretive purposes; or they may be dissimilar enough to restrict the land uses suitable for the dominant taxon.*

tensive boring patterns. Because of the time and cost involved, however, such maps are usually made only for crop research areas and high intensity urban uses.

It is again important to emphasize that taxonomic purity of map units is not a proper measure of the quality or precision of a soil survey. As Cline [*4*], has stated, quality of soil surveys should be measured in terms of the amount and accuracy of the information a soil survey provides as a basis for judgements about soil potential and behavior for land use. The basic test of the delineation name is its value as an index of soil properties and interpretations important to the user, not simply the percentage of inclusions [*4*].

Basis for Predicting Soil Behavior from Soil Maps

Soil maps are used largely as a basis for transmitting soil information specific to geographic areas and predicting the behavior of soils. The confidence of the prediction from the map is a function of how well the variance or scatter of the soil properties have been segregated on the landscape. The utility of the soil survey and the taxonomic system used to generate it are realized through interpretation.

Soil survey interpretation involves the prediction of soil behavior for a variety of soil uses. The method used by soil scientists to derive predictability of soil behavior from soil maps is to correlate observations and sample data with a soil classification of an area. Prediction for any point, therefore, is based on data from the map unit to which the point belongs [*6*]. The basic premise of this technique, as stated by Webster [*6*], is that the variance in the map unit is less than the variance or natural scatter in the population of soils in the area as a whole. Hence, the degree of confidence for predicting the soil behavior of a map unit should be greater than the confidence level for predicting the behavior of the entire population of soils in the area as a whole.

The soil survey, therefore, is designed to provide geographic expression to units or taxa of the natural soil classification system, namely, Soil Taxonomy [*5*]. The properties used to define the taxa are also critical to plant growth, accommodation of wastes, attenuation of waste components, engineering behavior, and many other soil uses. Thus, the soil properties selected as taxonomic differentiae and phase criteria are also the same properties affecting the uses of soils. This relationship provides the key for translating natural soil bodies into groups of soils that behave alike when subjected to specific uses. Interpretation then becomes a matter of rearrangement, subdivision, generalization, simplification, and regrouping of both taxa and map units to provide new classes for the greatest number and most precise interpretations possible [*5*].

Interpreting Soil Surveys for Steel Corrosion

Metallic corrosion in the soil is a physical and biochemical process which results in electron loss from the metallic surface. This process requires soil moisture to form solutions of soluble salts. Any factor that influences the soil solution or the oxidation-reduction reactions in the soil also influences the operation of the resulting corrosion cell. These factors include the amount of soil moisture, the conductivity of the solution, the hydrogen ion activity of this solution (pH), the oxygen concentration (aeration), and the activity of organisms capable of causing oxidation-reduction reactions [*9*].

The estimation of corrosivity for untreated steel pipe in soil is commonly based on:

1. Resistance to flow of electrical current.
2. Total acidity (not pH).

TABLE 2—*Soil corrosivity classes for uncoated steel based on total acidity, resistivity—conductivity of the saturation extract, and drainage-texture-aeration relationships* [9].

				General Relationships	
Soil Corrosivity, class	Total Acidity, meq/100g	Resistivity, Ω cm	Conductivity, mmho/cm	Drainage-Texture Relationship	Water-Air Permeability
Very low	<4	>10 000	<0.1	somewhat excessive—excessively-drained coarse-textured soils	rapid to very rapid
Low	4 to 8	5000 to 10 000	0.1 to 0.2	well-drained with moderately coarse and medium-textured control section; somewhat poorly-drained with coarse-textured control section	moderate to rapid
Moderate	8 to 12	2000 to 5000	0.2 to 0.4	well-drained with moderately fine-textured control section; moderately well-drained with medium-textured control section; somewhat poorly-drained with moderately coarse-textured control section; very poorly-drained with high, nonfluctuating water table	moderately slow to slow
High	12 to 16	1000 to 2000	0.4 to 1.0	well drained and moderately well-drained fine-textured soils; moderately well-drained, moderately fine-textured soils; somewhat poorly-drained; medium and moderately fine-textured control sections; poorly-drained with coarse to moderately fine-textured control sections; very poorly-drained soils; water table fluctuates with ft of surface;	slow and very slow; saturated
Very high	>16	<1000	>1.0	somewhat poorly to very poorly-drained fine-textured soils; mucks, peats with a fluctuating water table	very slow; saturated

TABLE 3—*Electrical resistivity and corrosion potential of soil fines at 4 ft in Bexar County, Texas* [11].

Soil Type	Resistivity, Ω/cm³ Low	High	Mean	Corrosion Potential, class
Austin silty clay	700	1600	1450	very high to moderately high
Bexar stony soils	1800	2700	2200	moderately high
Crawford clay	850	1100	930	high
Houston black clay	300	950	390	very high to high
Tarrant soils, chalk substratum	1800	2700	2500	moderately high

3. Soil drainage.
4. Soil texture.
5. Conductivity of the saturation extract.

Criteria are based on available research data, particularly on data in the National Bureau of Standards Circular 579 [*10*]. The principal source of limits for resistivity and for total acidity is Table 99 in that publication. Despite all the criteria engineers and scientists have used to rank the degree of corrosivity among soils, resistivity is still the most commonly used parameter for assessing soil corrosion potentials.

In the U.S. Cooperative Soil Survey program, soil taxa or map units generally are assigned to one of three classes of corrosivity, low, moderate, or high. Criteria are given for five classes, but the five are used only if knowledge of a specific soil warrants their use for proper interpretation. In the classes commonly used, the very low and very high classes are combined with the low and high classes, respectively [*9*]. Table 2 summarizes these USDA class limits.

Table 3 illustrates an example of the soil corrosivity interpretation for the Bexar County, Texas Soil Survey Report [*11*]. Each mapping unit is rated or grouped into its respective corrosivity class. The corrosivity classes used in the Bexar County Soil Survey are somewhat different than those depicted in Table 2, but the trends and general magnitude of the resistivities are similar. The Ventura Area, California Soil Survey [*12*] also contains resistivity data for each soil series as well as the average sulfate concentration for each series. While no specific corrosion classes are provided, the soil survey interpreter can group each soil taxon into a corrosivity class based on these data and other information (for example, soil reaction) provided.

Resistivity Measurements in Soil Survey

Although there are exceptions [*11*], *in situ* resistivity measurements are not normally made in the preparation of soil surveys. Soil resistivity measurements have been used in research studies to locate saline seeps and to determine potential areas for saline problems [*13,14*]. Soil resistivity measurements have been also used to measure soil moisture [*15*] and for geophysical exploration by soil scientists, geologists, and archeologists.

As soils are mapped in their landscape positions, the delineated soil units will show differences in resistivity. For example, resistivity measurements, using the Wenner Configuration[7] in a soil landscape in southern Maryland showed a range of resistivities from 7660 to 23 650 Ω cm (Fig. 6). The major soil parameters contributing to this variation were texture and moisture content. Other measurements of well-drained soils in Maryland have shown resistivity values of 5000 to 30 000 Ω cm, and thus, are placed in the low corrosivity class of the USDA classification system (Table 2). One type of upland sediment that has shown high corrosivity has been the "cat clays" (soils con-

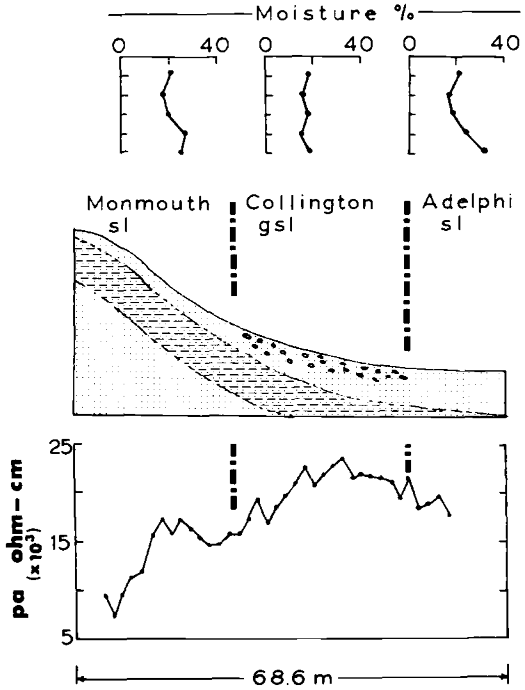


FIG. 6—*Apparent resistivities in three soil mapping units in southern Md. Moisture measurements were made at 25 cm increments to a depth of 125 cm.*

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[7] Resistivity measurements were made at a 15-m (5-ft) spacing with an R-40 Strata Scout Resistivity Meter manufactured by Soiltest, Inc.

taining acid sulfates). Measurements of exposed areas have shown resistivity values of 529 to 576 Ω cm. Thus, this soil would be classified as very high in the USDA corrosivity rating system, and experience shows this high rating is warranted. In addition the "cat clays" have pH values between 1.9 to 3.2 and contain 0.2 to 1.2 percent sulfur, mainly in the form of sulfate.

Despite the common usage of resistivity as a parameter to predict soil corrosion potentials, there are many experiences where resistivity is not a reliable index of potential soil corrosivity [*17*]. Noyce and Ritchie [*18*] maintain that the major contribution of resistivity measurements found in their evaluation of highway metallic culvert corrosion appears to be in identifying potentially corrosive environments where further testing should be conducted.

Microbial Contributions to Corrosion

Because soil reaction (pH) correlates poorly with corrosion potential, pH is not included in the criteria listed in Table 2. Yet, there are some significant exceptions. A pH of 4 or less, almost without exception, indicates a high or very high soil corrosion potential, a condition that is probably induced by relatively high salt concentrations caused by dissolution of mineral ions in the acid environment. The most favorable pH for sulfate-reducing bacteria is 7; progressive departures in either direction indicate less and less favorable pH conditions. In wet or moist soils with anaerobic conditions, especially in clays that contain some organic matter and sulfur, a pH of about 7 is corroborating evidence for a corrosivity rating of high or very high, ratings that such soils also would receive on the basis of drainage and texture criteria [*9*].

Dramatic differences in the soil microbial populations result from different moisture regimes. Similarly, wide ranges in soil moisture can be encountered in a given soil at different levels in the profile. Many soils have upper horizons that remain predominantly aerobic and support a diverse microbial population, but have a lower horizon (for example, a fragipan) which restricts water movement and can result in anaerobic conditions and a restricted microbial population of anaerobes and facultative anaerobes. With a high organic matter level in the soil surface, mineralization of organic sulfur compounds could occur and the sulfate produced could leach into the anaerobic soil horizon where sulfate reduction would be favored and metal corrosion could be accelerated.

Microbial corrosion appears to be most serious in poorly drained soils which have low oxygen levels and redox potentials, high organic matter levels, high clay contents, and neutral pH values [*19,20*]. These conditions are expressed within the soil classification scheme used to make soil surveys and are, therefore, part of the criteria used to predict soil corrosivity in soil surveys.

Other Variables in Soil Corrosion

Penhale [*21*] determined correlation coefficients among various soil properties and corrosion in New Zealand and concluded that corrosion could not be accurately predicted from the chemical and physical soil properties studied (for example, moisture content, bulk density, percent air voids, both *in situ* and laboratory resistivity, and total acidity). The correlation coefficient between soil resistivity and average corrosion for at least 21 sites after 10 years was only −0.615, and was significant at the 1 percent level. The incorporation of the other laboratory data did not improve the prediction. Penhale found that the most highly corrosive soils were those high in soluble salts. Almost equally high in corrosivity were clayey soils with high total acidity that were subject to alternate wetting and drying.

Similarly, Noyce and Ritchie [*18*], using stepwise linear regression analysis on the parameters of chloride, minimum resistivity, pH, moisture content, and sulfate, found that less than 10 percent of metallic highway culvert corrosion variation was explained by the regression equation developed from these five variables in their Michigan study. These researchers reasoned that other variables that do not lend themselves to statistical evaluation are responsible for the metallic culvert deterioration. Therefore, a direct test of break polarization was employed to appraise soil corrosiveness. Corrosion current generated by the moist soil-metal corrosion cell can be determined by measuring changes in the electrical potential between the metal specimen and the soil, while a varying external current is applied both cathodically and anodically. Using this test, Noyce and Ritchie [*20*] obtained a direct relationship between corrosion currents measured on laboratory polarization test specimens and actual field performance of metal culverts exposed to their *in situ* soils. A correlation coefficient of 0.78 was obtained using linear regression analysis to evaluate culvert deterioration and corrosion current. A multiple linear regression analysis using corrosion current and percent soil moisture resulted in these two variables accounting for 83 percent of the variation in culvert corrosion.

Disturbed and Undisturbed Soil Environments

It must be emphasized that the predictions of soil behavior from soil surveys are based on the natural or undisturbed soil profile properties. Excavations, backfilling, and subgrade filling around metallic materials alter the soil environment considerably from its natural state and, therefore compromises at least a portion of the criteria used to predict soil corrosivity. Using soil surveys as a tool for the initial assessment of potential soil corrosivity must be tempered by the need to exercise care in extrapolating the natural condition criteria to the disturbed condition surrounding the metallic installation. Which criteria change? Drainage (soil moisture, permeability) and aeration are typical of soil attributes susceptible to being altered. Installing metallic materials below grade will result in different soil-metal environments than above-grade installations using the same soil. Therefore, the configuration of the installation should be considered with respect to the original or natural landscape configuration when interpreting soil behavior predictions from soil surveys.

Soil Conditions Contributing to the Corrosion Environment

The relative difference between two landscape positions for a given soil or between contrasting soils will induce corrosion more than the conditions encountered at any single soil site [*17*]. Compared to soil resistivity, van Eck [*17*] reported the higher correlation of severe pipeline corrosion with contrasting soil conditions as observed in New York and West Virginia. The probability of corrosion, therefore, is greater for extensive installations that intersect contrasting soil boundaries or soil horizons than for installations that remain in one kind of soil or in one soil horizon. Burying metals in a single soil nullifies the real world condition of long cell corrosion due to contrasting soil conditions in the horizontal plane. Only the vertical contrasts are encountered in such studies, plus whatever other soil properties are conducive to corrosion.

For most engineering uses of soils, the soil can be characterized by an index related to soil behavior for the particular use. This index is usually site-specific, with the surrounding soil condition having little or no impact on the behavior of the soil at the point of interest. The processes responsible for the corrosion reaction, however, involve much of the soil volume beyond the immediate point of reaction. Therefore, a single index or measurement at a specific site to determine a soil's corrosion potential would appear to be difficult to correlate with corrosion.

The value of soil surveys in predicting potential corrosivity, therefore, lies not only in the information contained in the individual map units themselves (from which predictions of corrosivity classes are made), but also, the location of contrasting soils on the landscape which could induce concentration cells along a linear metallic installation. Thus, the engineer can assess potential corrosivity conditions along the installation length without relying solely on site-specific data.

It should be also mentioned that the variation of soil properties with depth and spatial dimensions requires the most detailed soil survey available to make the most meaningful prediction of soil behavior. Too often, agencies in the interest of expediency condense or generalize soil maps into broader taxa or classes to establish zones or major corrosivity groupings. Such generalizations result in critical criteria being combined such that interpretations from the resulting soil class or group become meaningless. While such groupings may correlate well with soil corrosion, it is usually because there are distinct, contrasting conditions. But for many situations, this is not the case. The failure of the Michigan corrosivity zones (based on great soil groups) to distinguish between field corrosion severity classes is a case in point [*18*].

Summary

Corrosion in a particular soil is often attributable to several soil properties which interact to produce the soil's corrosivity aggressiveness. Despite the difficulty in correlating these properties with corrosion, Romanoff [*10*] maintains that it is still possible to quantitatively associate soil characteristics and properties with corrosion of metals. Many of the soil properties responsible for corrosivity are the same criteria or differentiae used in Soil Taxonomy [*5*] to segregate the soil continuum on the landscape into definable soil classes. These soil classes or taxa are the principal components used in making soil maps. Once the landscape is segregated by the soil surveyor into definable map units possessing specified ranges in soil properties, potential soil corrosivity and many other predictions of soil behavior can be expressed geographically.

Much more research and data acquisition are necessary to increase the reliability and confidence limits of soil corrosivity predictions. Soil scientists need to make more measurements of *in situ* resistivity on landscapes and correlate corrosivity and other soil attributes that will enhance the confidence limits of soil survey interpretations.

Despite these data limitations, soil surveys are a valuable tool to the corrosion engineer in assessing the potential corrosivity of a landscape. Like most tools, they are best used with other data and information to derive predictability of soil behavior. To use such surveys properly, however, corrosion engineers must understand the technique used in their synthesis, the composition of the map units, and the confidence limits of their predictions of soil behavior.

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DISCUSSION

R. C. Rabeler[1] (*written discussion*)—How is the corrosion potential for steel and concrete determined in the soil surveys?

F. P. Miller (*author's closure*)—For uncoated steel, the soil corrosivity ranking for each soil series in a survey area is based on the soil's resistivity, total acidity as approximated by extractable acidity, soil drainage, texture or particle size distribution, and conductivity of the soil's saturation extract. These criteria are based largely on data contained in Romanoff's 1957 NBS Circular 579. The resistivity and total acidity limits were determined from table 99 in this NBS publication. The limits for conductivity of the saturation extract were based on data from the Soil Conservation Service's Soil Survey Laboratory in Lincoln, Nebraska. All of these criteria and their class limits are summarized in Table 2 of this paper. There is still a need for research to

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[1] Senior project engineer, Soil Testing Services, Lansing, Mich. 48906.

determine the extent to which these criteria reflect the soil's corrosivity. In my opinion, the strength of the soil survey as a tool in assessing potential corrosivity is the capacity of the document to relay information on moisture characteristics of each soil, textural differences, and contrasting transition zones between soils.

For concrete, the corrosivity ranking for each soil series is related to the amount of sulfates, soil texture, and acidity. The three corrosivity classes range from coarse-to-fine textured soils with pH values above 6.5 or 6.0, respectively, and water-soluble sulfate contents less than 1000 parts per million (low) to coarse to fine textured soils with pH values below 5.5 or 5.0, respectively, and water-soluble sulfate contents greater than 7000 parts per million (high).

K. P. Fischer[1] *and Bente Bue*[2]

Corrosion and Corrosivity of Steel in Norwegian Marine Sediments

REFERENCE: Fischer, K. P. and Bue, Bente, "**Corrosion and Corrosivity of Steel in Norwegian Marine Sediments,**" *Underground Corrosion, ASTM STP 741,* Edward Escalante, Ed., American Society for Testing and Materials, 1981, pp. 24–32.

ABSTRACT: Various guidelines are to be found in the literature for evaluation of soil corrosivity based on parameters like resistivity, pH, water content, redox-potential, content of salt, and bacterial activity. Corrosion studies of steel piles and pipes in Norwegian marine clayey sediments show that these parameters are not always applicable. Studies of piles in undisturbed marine clays below the groundwater table indicate a limited correlation between the resistivity and the corrosion rate. The highest corrosion rates found amount to 30 μm/year indicating that pile corrosion is not a severe problem under the aforementioned conditions. The environmental conditions for pipes are generally much more complex than for piles, as the backfill is disturbed and often includes material other than the original sediment. Studies of pipes in a heterogeneous environment indicate differential aeration to be the most common corrosion cause.

Corrosivity evaluations are also performed with electrochemical probes.

KEY WORDS: steels, corrosions, soils, corrosion tests, environments, underground corrosion

Near the end of the last glaciation melt, water from the Norwegian glaciers transported large amounts of sediments to be deposited in the sea. As the glaciers retreated, the weight of the ice slowly decreased resulting in a gradual upheavel of the land masses. Areas of newly formed marine sediments rose above sea level constituting today the most populated parts of Norway with the highest construction activity. These sediments consist mainly of soft clayey material with quite similar properties throughout the country. The soil resistivity varies from about 1 Ωm at a salt content of 30 g/liter to about 100 Ωm in a clay where subsequent leaching of fresh water removed the salt.

Below the weathered crust one finds a redox-potential of about −200 mV [Standard Hydrogen Electrode (SHE)] almost constant with depth, and a content of organic material generally lower than 0.2 percent. The pH below the weathered crust in the range of 9.0 to 8.5, varies little with depth in con-

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[1] Senior research engineer, The Ship Research Institute of Norway, Sandefjord, Norway.

[2] Research scientist, Norsk Hydro, Sandvika, Norway.

trast to pH-values of 6 and 7 within the weathered crust. The sediments have a maximum cation exchange capacity (CEC) of about 10 to 15 meq/100 g dry soil and consist mainly of the minerals quartz, feldspar, hydrous-mica, chlorite, calcite, and amphibole.

One often finds the aggressive nature of a sediment due to one or more of the following parameters: Resistivity, pH, water content, redox-potential, salt and sulphate content, or bacterial activity; but no well defined relationship exists between these parameters and corrosivity. For several decades researchers considered the soil resistivity as the most important parameter in corrosion evaluation (Steinrath [*1*][3] and Wranglén [*2*]).

Engineers started using steel piles for the foundation of heavy buildings on Norwegian soft clayey sediments four decades ago. These sediments commonly had specific resistances of 1 to 10 Ωm; hence, it was considered an open question as to what degree the piles would suffer from corrosion. To answer this question and to find a method for evaluating corrosivity of the marine sediments, the Norwegian Geotechnical Institute (NGI) started research 25 years ago.

Corrosion—Field Data

Steel Piles

To determine the corrosivity of the marine sediments, NGI decided to extract foundation piles for investigation. One problem in measuring and evaluating corrosion rates was the absence of accurate dimensions of the piles. One had to choose between the nominal dimensions or values measured on a seemingly uncorroded part of the pile. We wanted to calculate average corrosion rates, as reduced pile bearing capacity results from a reduced pile cross section by corrosion. Two or more of the following methods were used: weighing pile sections, ultrasonic thickness measurements, vernier calipers, or a water displacement technique. NGI extracted piles with 10 to 70 years of service. Figure 1 gives the measured corrosion rates as a function of sediment resistivity. These results apply to steel piles exposed to a homogeneous clay sediment below groundwater table. These data do not appear to define an exact relationship between resistivity and corrosion rate, but one can find the expected corrosion rate between the curves for maximum and minimum corrosion. Note that the maximum corrosion curve gives a corrosion rate of only 30 μm/year at a resistivity of 1 Ωm.

Steel Pipes

Pipes are generally exposed to more complex environmental conditions than steel piles. While the natural soil adjacent to driven piles has a minimum of soil disturbance, the backfill around pipes laid in a trench at a depth

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[3] The italic numbers in brackets refer to the list of references appended to this paper.

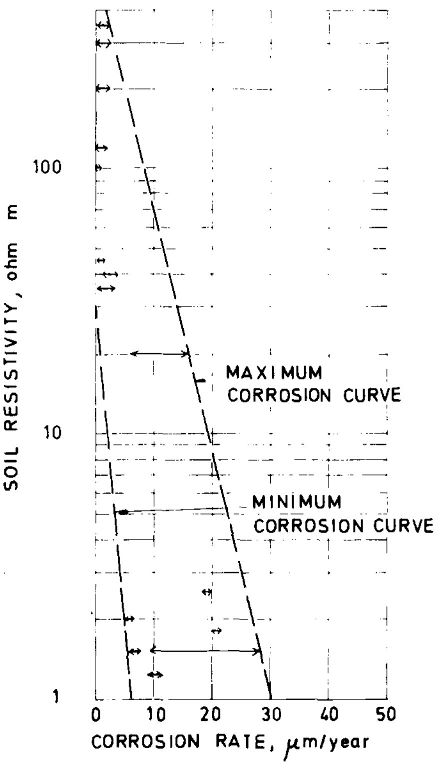

FIG. 1—*Measured steel pile corrosion rates in relation to soil resistivity.*

of about 1.5 to 2.0 m often includes material other than the original sediment. This implies a disturbed and often heterogeneous environment in which corrosion, due to differential aeration, can occur. In the study of pipeline corrosion, one wants to find the pit depth, and consequently for pipes, express the corrosion rate as a pitting rate.

We gained our experience with pipe corrosion in basically two ways. First, through consultation work in connection with pipe failures, and second,

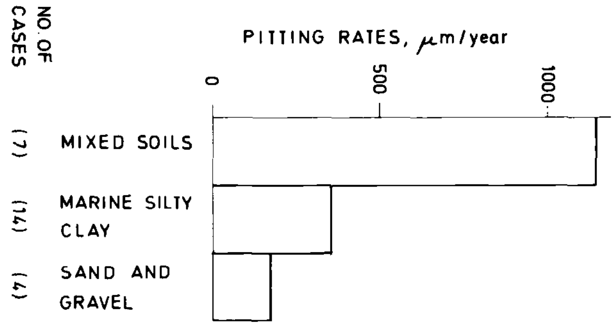

FIG. 2—*Guideline for corrosivity evaluation.*

through a questionnaire sent to all the municipal councils in Norway [*3*]. We often had difficulties in drawing exact conclusions as to the cause of corrosion from our experiences with actual buried pipelines. This was mainly because we could not ascertain the total effect of the ambient environment.

Knowing the number of years of burial, and pit depths, we calculated pitting rates, and found the highest corrosion rates for pipes in mixed soils. This implied that the environment around and along the pipe would show marked heterogenity, increasing the probability of creating differential aeration cells, and resulting in a strongly localized corrosion. The pitting rate in these sediments varied between 90 and 3500 μm/year. The mixed soils where the pore water consisted of undiluted seawater had the highest pitting value.

Pipes in homogeneous clayey marine deposits, the dominant sediment type along the coast line, had pitting rates between 50 and 1000 μm/year, whereas clays with a high resistivity, and where the pipe often lay above the groundwater table, had the lowest corrosion rates. Figure 2 gives the average pitting rate for pipes in various sediment types.

Corrosivity Criteria and Evaluation

Undisturbed Sediments

Earlier researchers thought that foundation piles should have cathodic protection systems to reduce the high corrosion rates expected in the Norwegian marine sediments. However, based on investigation of piles in Swedish soils, Bergfelt [*4*] recommended use of unprotected steel piles in low resistivity clay deposits. In a comprehensive study carried out by the National Bureau of Standards, Romanoff [*5*] stated that corrosion would not significantly affect steel piles in undisturbed soils, whereas piles in disturbed soils would likely suffer severe corrosion. Schwerdtfeger [*6*] reported a maximum corrosion of 17 μm/year for a pile below the groundwater table in a sandy clay deposit with resistivitiy of 4 to 10 Ωm. Support for these results comes from Fitzgerald and Cleas [*7*] who conclude that most corrosion on foundation piles occurs in fill areas, and that very little corrosion occurs in the undisturbed earth below the fill. Our current work in Norwegian marine sediments confirms that undisturbed sediments, in spite of a low resistivity, have surprisingly low corrosivity. The homogeneity of the sediments, which makes differential aeration unimportant, must explain this generally low corrosion rate.

Of criteria commonly used for corrosivity evaluations we have found a limited correlation between the resistivity and the corrosion rate (see Fig. 1) which predicts the corrosion rate between the range of the maximum and minimum curves. We find no correlation between corrosion rate and other criteria like pH and redox-potential for the Norwegian marine sediments.

TABLE 1—*Corrosion causes and parameters to be evaluated.*

Common Causes of Pipe Corrosion in Soils	Corrosion Parameters
Differential aeration	geological and hydrological environment pipe and coating properties
Chemical environment	chemical and mineralogical analysis
Sulphate-reducing bacteria	Eh, pH, sulphides and bacterial growth
Stray current	potential and current measurements

Disturbed Sediments

Corrosion is a much more severe problem in disturbed sediments than in those undisturbed. Pipelines commonly laid in backfilled trenches are therefore often subjected to corrosion. Guidelines for corrosivity evaluations have been established by several authors based on the earlier mentioned parameters: resistivity, pH, water content, redox-potential, salt content, and bacterial activity.

To carry out a corrosivity evaluation, one starts with field measurements. Table 1 gives the most common causes for pipe corrosion in sediments and some of the parameters usually measured. It is important to acertain which of the previously mentioned corrosion causes can be considered possible. After completing such a preliminary investigation or survey, a detailed measurement program can be initiated.

To the authors, differential aeration seems to be the most common cause for corrosion in the disturbed Norwegian marine sediments. Based on our experience with pipelines, we propose to base the corrosivity of disturbed sediments on the three parameters given next. (The scheme is only valid when the main cause for the corrosion is differential aeration).

1. Resistivity measured with a probe.
2. Whether the pipe is above, at, or below the groundwater table.
3. Whether the soil environment is heterogeneous or homogeneous.

A homogeneous environment is defined as one that does not vary along the pipe in grain size distribution or mineralogical composition. Otherwise, the soil is heterogeneous (Table 2). If one suspects causes of corrosion other than differential aeration, one must of course investigate further [*8,9*].

Figure 3 shows an example of a heterogeneous environment, partly marine clay, and partly sand. The resistivity is low, and a high corrosion rate can be expected. Figure 4 shows an example of a homogeneous sand with high resistivity and an expected low corrosion rate. In a homogeneous marine clay, the corrosion rate can be relatively low due to the very low permeability and the difficulties in transportation of species that can be reduced in the cathodic reaction.

TABLE 2—*Average pitting rates for pipes in various sediment types.*

Homogeneous Sediments

Soil Resistivity	Position of Groundwater Table	Pipe Above Groundwater Table	Pipe in Groundwater Table	Pipe Below Groundwater Table
<30	Ωm	aggressive	very aggressive	aggressive
30 to 40	Ωm	nonaggressive	aggressive	slightly aggressive
>40	Ωm	nonaggressive	slightly aggressive	nonaggressive

Heterogeneous Sediments

Soil Resistivity	Position of Groundwater Table	Pipe Above Groundwater Table	Pipe in Groundwater Table	Pipe Below Groundwater Table
<30	Ωm	aggressive	very aggressive	very aggressive
30 to 40	Ωm	aggressive	aggressive	aggressive
>40	Ωm	nonaggressive	slightly aggressive	slightly aggressive

Environmental Conditions	Average Pitting Rate, μm/year
Nonaggressive	<100
Slightly aggressive	100 to 200
Aggressive	200 to 500
Very aggressive	>500

Corrosivity Evaluation

The Galvanic Probe

One can determine corrosivity fast and accurately using an electrochemical probe. Such a probe called the galvanic probe was developed at NGI by Rosenqvist [*10*].

The probe permits a rapid *in situ* determination in saturated sediments of two important factors which control the corrosion rate, the cathodic depolarization and the specific soil resistance. The probe, shown in Fig. 5, consists of a magnesium point electrically insulated from a 0.5-m-long steel tube. The two leads of an electric cable are connected to the magnesium point and to the steel tube, respectively. The corrosivity is related to the measured current flowing between the magnesium point and the steel tube of the probe.

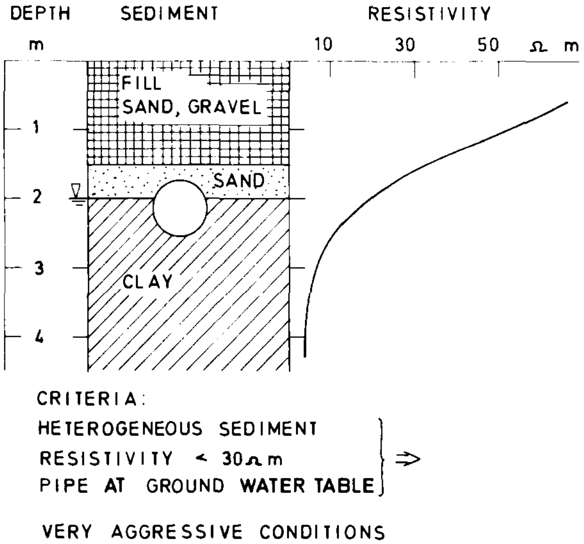

FIG. 3—*Example of a heterogeneous environment.*

Extensive field measurements with this probe showed that measured corrosivity fluctuated greatly with depth. As the extracted piles described earlier never showed localized corrosion, we consider these individual determined corrosivity values invalid. Though consultants still use this probe, we advise them not to rely on individual measurements. We think that the average corrosivity value, from measurements usually taken every 0.5 m for piles deeper

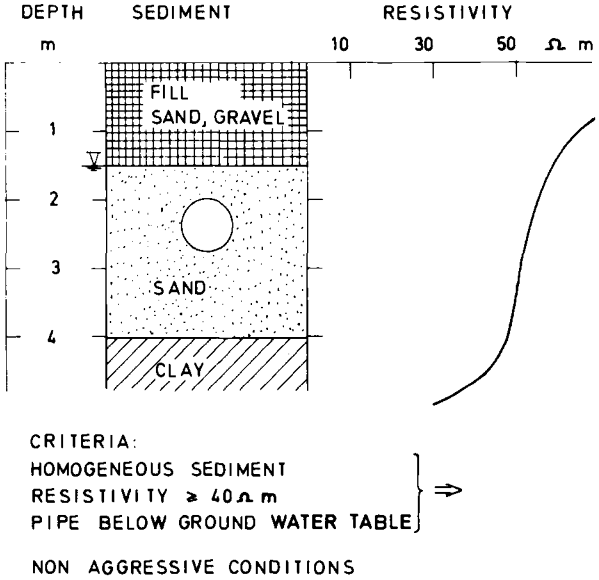

FIG. 4—*Example of a homogeneous environment.*

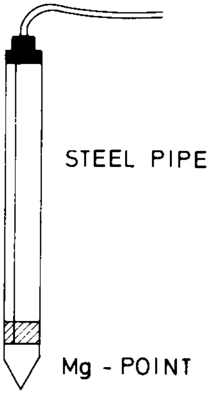

FIG. 5—*The galvanic probe.*

than 10 m, reliably estimates the corrosivity of the sediments. Today the probe is mainly used for the determination of resistivity.

The Amperostatic Polarization Probe

Over the last few years NGI has developed a three-electrode probe consisting of a mild steel working electrode, a platinum counter electrode, and a commercial silver/silver chloride (Ag/AgCl) reference electrode, Fig. 6. One determines polarization curves, in anodic and cathodic directions based on values of current density at a steady state potential, by increasing or decreasing the current in increments, and measuring the potential at the adjusted constant current. Reproducible polarization curves can be obtained after about 24 h. One determines the corrosion rate from either the intercept of the cathodic Tafel slope with the corrosion potential, or from the linear polarization method [*11*]. The corrosion rates determined compared with weight loss of metal plates exposed for one year or more show the intercept method gives corrosion rates 2 to 3 times higher than determined by weight loss studies, while the linear polarization method gives results 3 to 5 times

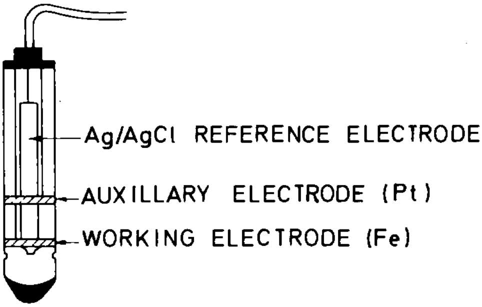

FIG. 6—*The amperostatic polarization probe.*

higher than by weight loss. We think the high corrosion rates represent the initial corrosion rate of the polished steel electrode before corrosion products built up and to some extent limited further corrosion. Based on extensive laboratory tests, we feel the initial corrosion rate by the intercept method divided by a factor of 2.5 gives a good estimate of long term corrosivity.

Conclusion

Corrosion in sediments results from several widely different causes; thus, we would not expect to find the corrosion rate correlatable to the same parameters for all situations. This implies that at the start of a corrosion survey, one should perform a preliminary investigation to establish possible corrosion causes. Studies of piles in undisturbed marine clay below the groundwater table indicate a limited correlation between the soil resistivity and the corrosion rate. Studies of pipes buried in disturbed sediments indicate differential aeration as the most common cause for corrosion at ambient temperatures. Electrochemical probes used for rapid determination of corrosion rates can also give valuable information about the corrosivity of the sediments.

Acknowledgment

The authors wish to thank former colleagues at NGI who did work on corrosion in soils and especially to mention I. T. Rosenqvist, K. Tungesvik, O. I. Sopp, and J. Moum.

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W. P. Iverson[1]

An Overview of the Anaerobic Corrosion of Underground Metallic Structures, Evidence for a New Mechanism

REFERENCE: Iverson, W. P., "**An Overview of the Anaerobic Corrosion of Underground Metallic Structures, Evidence for a New Mechanism,**" *Underground Corrosion, ASTM STP 741,* Edward Escalante, Ed., American Society for Testing and Materials, 1981, pp. 33-52.

ABSTRACT: Anaerobic corrosion of iron occurs throughout the world and, from an economic standpoint, is quite costly. Sulfate-reducing bacteria, primarily of the genus *Desulfovibrio,* are responsible for this type of corrosion. It has been postulated that corrosion by these bacteria is caused by their removal of hydrogen from the surface of iron causing it to go into solution. Evidence is presented which indicates that this mechanism may not be responsible for the main corrosive effect of these organisms. These bacteria appear to cause corrosion by producing extracellularly, under anaerobic conditions, a highly corrosive product in addition to hydrogen sulfide. The factors controlling the fate of iron in anaerobic environments, conducive to the growth of sulfate-reducing bacteria, may depend on whether iron sulfide film formation by hydrogen sulfide occurs first, thereby inhibiting corrosion, or whether the highly corrosive substance comes in contact with the iron before film formation has occurred, thereby accelerating corrosion. The antagonistic actions of these two compounds, hydrogen sulfide and the corrosive product, on corrosion produced by sulfate-reducing bacteria, could explain the conflicting observations on anaerobic corrosion noted by investigators in the field and laboratory.

KEY WORDS: anaerobic corrosion, film formation, microbial corrosion, cathodic depolarization, hydrogen sulfide, overview, corrosion rates, iron phosphide, sulfate reducing bacteria, *Desulfovibrio,* mechanism, vivianite, underground corrosion

The corrosion of iron had been associated with the presence of oxygen for a long time. It was quite startling when the corrosion of pipes was found to occur in soils practically devoid of oxygen. The process was subsequently called anaerobic corrosion. Cast iron pipes under anaerobic conditions were found to undergo a corrosive process called graphitization, so-called because the migration of iron ions from the pipes left a deposit high in carbon which

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[1] Microbiologist, National Bureau of Standards, Washington, D.C. 20234.

became softer as the carbon content became higher [*1*].[2] This property along with its appearance bears a resemblance to black lead or graphite. When the soil is removed from the pipe, the surface of the graphitized pipe is covered with a thick layer of hard, brittle, porous, sulfide-containing black corrosion products in which soil materials are cemented. If these corrosion products are removed, the surface of the metal appears bright and shiny, with no evidence of iron oxide or other compounds. Before removal, the pipe usually looks intact, and in fact the function of the pipe under low pressure remains intact as well, held together by the corrosion products (Fig. 1).

Steel, on the other hand, in anaerobic corrosive environments, shows no evidence of graphitization but only of pitting [*2*]. In the case of isolated pits, the ratio of pit diameter to depth is relatively small, being 2 or 4 to 1. In the case of severe corrosion, many pits form close together and coalesce to form large corroded areas. Because of its appearance, this corrosion is sometimes called slab corrosion or slabbing. The diameter of this corroded area to depth may be as high as 100 to 1.

The pits are generally filled with black corrosion products which usually coat the surrounding areas. Sometimes the corrosion products are covered with a black, hard crust. A black or gray paste-like material, due to iron sul-

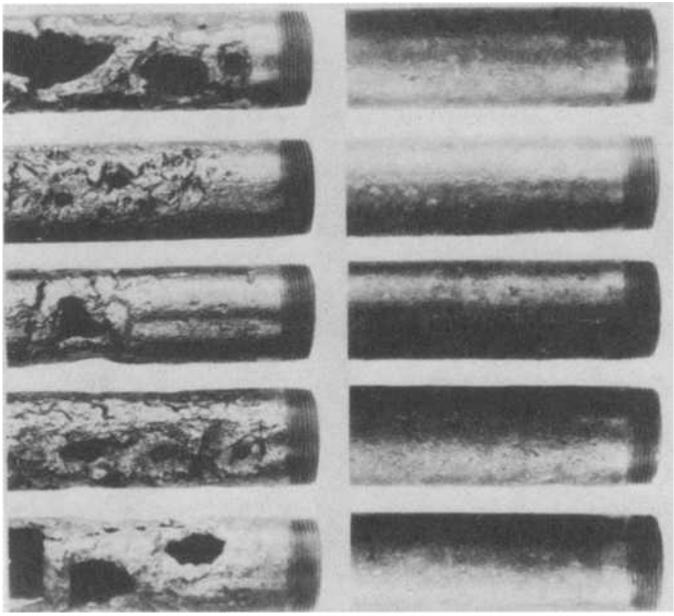

FIG. 1—*Cast iron pipes exposed to five corrosive soils for approximately 11 years, showing graphitization. before* (left row) *and after removal of corrosion products* (right row) [2].

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[2] The italic numbers in brackets refer to the list of references appended to this paper.

fide or iron sulfide mixed with white ferrous hydrate, is usually found beneath the crust. The presence of iron sulfide is detected by adding a little acid to the black corrosion product and noting the odor of hydrogen sulfide. A more sensitive test is the sodium azide test, whereby the presence of iron sulfide is recognized by its ability to catalyze the release of nitrogen, in the form of bubbles, from the azide [*3*].

Anaerobic corrosion has been found to occur throughout the world and is quite costly [*4*]. In England, for example, Booth reported in 1964 that 50 percent or more of buried metal failure was due to this type of corrosion. The rates of anaerobic corrosion reported in the field are quite high, but attempts to reproduce these rates in the laboratory have not been too successful. Table 1, prepared by Costello [*5*], compares some corrosion rates, probably typical examples of anaerobic corrosion. The highest rate of corrosion, reported by Booth [*6*], on cast iron pipes was about 1380 milligrams per square decimeter per day (mdd) (0.64 cm, or 0.25 in. per year).

Sulfate-Reducing Bacteria

Shortly after anaerobic corrosion was discovered, there were many theories to explain this phenomenon. The one theory that has remained, and is

TABLE 1—*Some observed rates of corrosion in the presence of sulphate-reducing bacteria.*

Author	Case of Corrosion	Rate, Given by Author	Rate, mdd
Bunker	steel water main in soil	1 cm in 9 years	235
Doig and Wachter (1951)	steel casing in oil well	3/8 in. in 55 months	443
Copenhagen (1954)	steel sheet piling in harbor	0.6 in. in 12 years	272
Copenhagen (1966)	steel ships' plate by bilge water containing sulphate-reducers	8 mm in 2 years	855
Booth, Cooper and Cooper (1967a)	laboratory culture *Desulfovibrio desulfuricans* strain Hildenborough mild steel	137 mdd	137
	laboratory culture *Desulfovibrio desulfuricans* strain Canvey Island mild steel	206 mdd	206
LaQue, F. L. (1948)	mild steel seawater, absence sulphate-reducing bacteria	0.005 in. per year	25
Booth, Cooper, and Cooper (1967a)	sterile culture medium, mild steel, absence sulphate-reducing bacteria	2.6 mdd	2.6

still referred to in articles on anaerobic corrosion, is the one proposed by von Wolzogen Kühr [*1*]. He proposed in 1934 that anaerobic corrosion was caused by bacteria, namely, a group of bacteria called sulfate-reducing bacteria. These bacteria have the property of utilizing molecular hydrogen for the reduction of sulfur in sulfate to form hydrogen sulfide. From this process they derive most of their energy. They require near neutral conditions to grow and the almost complete absence of molecular oxygen [*7*].

Morphologically, these bacteria (Fig. 2) are tiny comma-shaped organisms, occurring in spiral forms when the cells do not divide. The cells are motile, propelled by a single flagellum at the end of the cell (Fig. 3). I have cultured them on the surface of a special nutrient agar containing ferrous ions [*9*]. Each bacterial cell or clump of cells is capable of giving rise to a visible structure, a colony. These colonies appear as black dots on the surface of agar with ferrous ions (Fig. 4). In the absence of ferrous ions [*9*], the colonies are round and small (1 mm diameter) and quite transparent with a slight yellowish tinge (Fig. 5).

There are two types of sulfate-reducing bacteria, those which form spores, highly environmentally resistant reproductive bodies, and those which do not [*7*]. The organisms which I have been describing are nonspore-forming

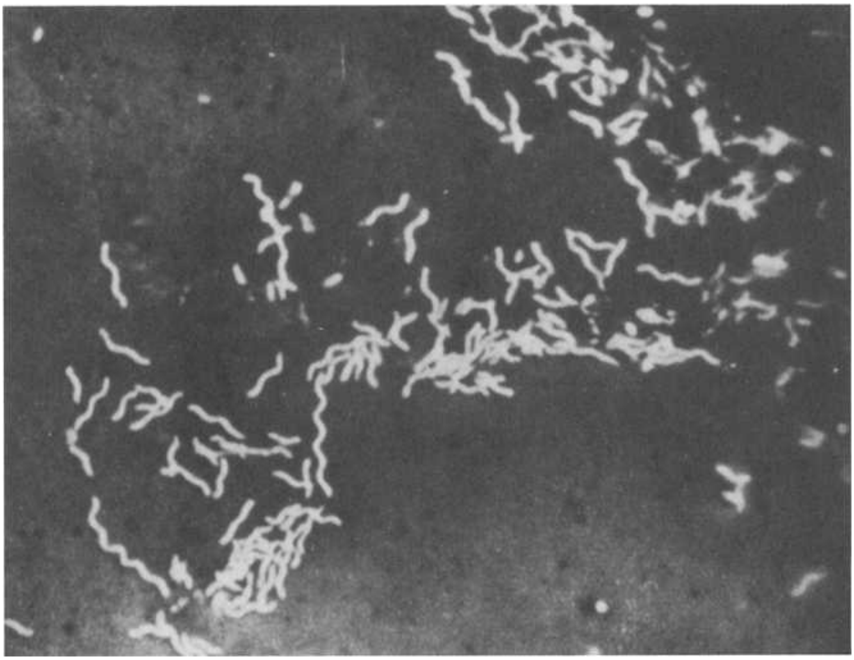

FIG. 2—*Cells of* Desulfovibrio *in chains, forming spirals. Darkfield. Cells are ca. 0.5 μm in diameter* [8].

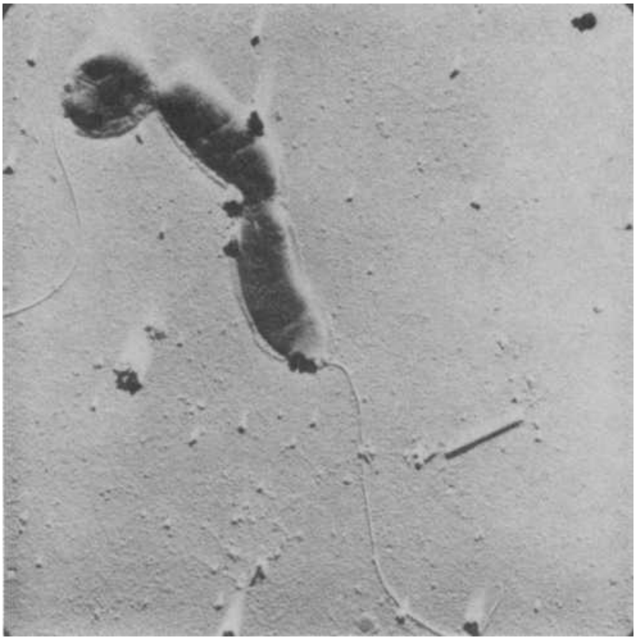

FIG. 3—*Electron micrograph of* Desulfovibrio desulfuricans (*API-midcontinent strain A*). *Cells with a polar flagellum* (*Iverson, 1972, diameter of cells ca. 0.5 μm*).

and are classified in the genus *Desulfovibrio* of which there are now five species or types, the most familiar one being *D. desulfuricans.*

The organisms are universally found in soil and seawater. For growth, they require a hydrogen donor such as molecular hydrogen or lactate, sulfate, a few inorganic salts, and traces of organic materials [9]. This bacterial transformation of sulfate to sulfide using hydrogen, one of the most commonly occurring and extensive microbiological processes on earth, is part of a sulfur cycle in which the sulfide is oxidized again to sulfate (Fig. 6). An excellent example of this transformation can be observed in anaerobic sulfate rich soils. If sulfide-rich soil at a pH near neutrality is exposed to oxygen, the pH soon drops to four or lower.

Theories of Anaerobic Corrosion

The precise mechanism by which iron undergoes anaerobic corrosion as a result of the activities of the sulfate reducing organisms is still unknown. It is true that oxygen concentration cells may be developed on the iron as a result of microbial action. During bacterial growth on an iron surface in the presence of oxygen, the supply of oxygen is diminished under the bacterial mass so that even sulfate reducing bacteria may grow. This differential in oxygen

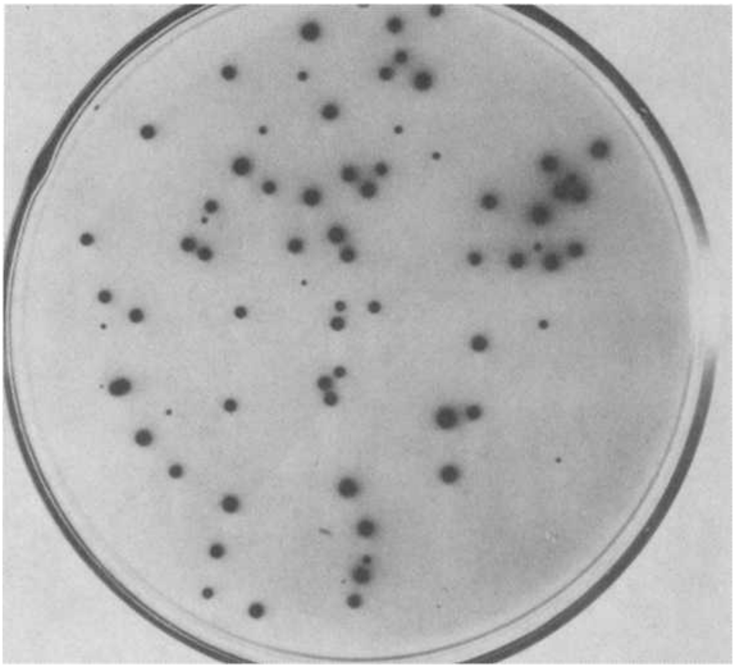

FIG. 4—*Colonies of* D. desulfuricans *(API-midcontinent strain A) on Trypticase Soy agar plus ferrous ions after seven days incubation at room temperature in a hydrogen atmosphere.*

concentration initiates corrosion (Fig. 7). This effect may be localized, as in the formation of tubercles which occur inside water pipes (Fig. 8), or nonlocalized as in the case of so-called "long line effects" in which large areas of a pipeline, passing through the soil, may be exposed to oxygen and other areas with low oxygen concentrations. The hydrogen sulfide, formed by these organisms may be also corrosive, only under conditions where there is intermittent exposure to oxygen, permitting the sulfide to be oxidized to sulfur or sulfuric acid.

In both of these mechanisms, oxygen is essential, however. Any theories to explain anaerobic corrosion must explain the corrosion process in the continued, almost total absence of oxygen.

In 1934, a theory was proposed by von Wolzogen Kühr and van der Vlugt to explain the mechanism of anaerobic corrosion [1]. This is the so-called cathodic depolarization theory (Fig. 9). The essential part of the theory is that sulfate reducing bacteria remove hydrogen from the surface of iron (Step IV) at a cathodic area, thus depolarizing the iron and causing the iron to go into solution in the form of ferrous ions (Step II). The secondary reactions are Steps V and VI in which the Fe^{++} ions react with sulfide ions and OH^- ions, respectively.

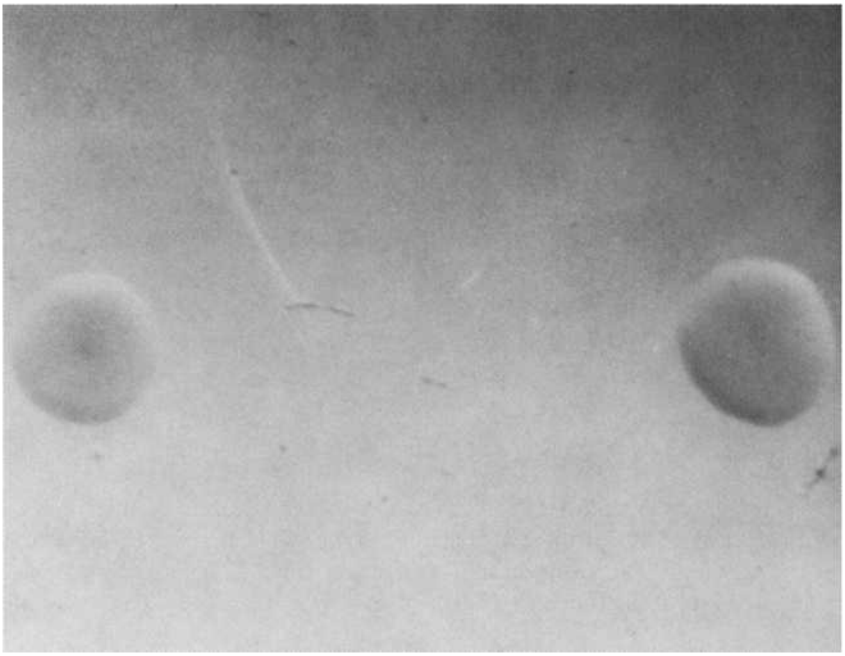

FIG. 5—*Colonies of* D. desulfuricans *(API-midcontinent strain A) on Trypticase Soy broth plus agar after seven day incubation at room temperature in a hydrogen atmosphere. Diameter of colonies ca. 1.0 mm.*

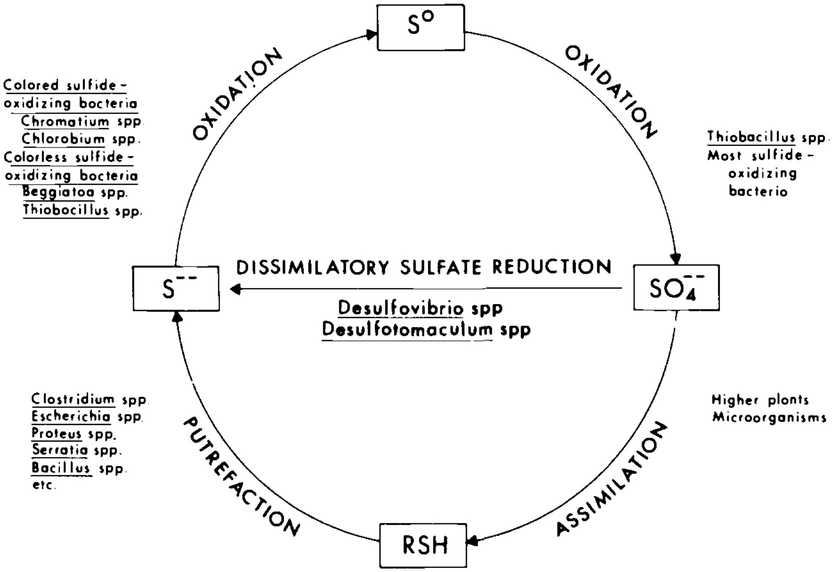

FIG. 6—*The sulfur cycle indicating sulfur transformations by various groups of bacteria.*

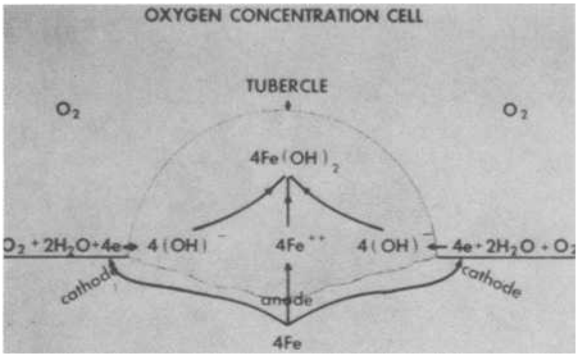

FIG. 7—*Oxygen concentration cell formed underneath tubercles.*

Experimental Observations

In the remainder of this paper some of the observations which were noted during a study of this proposed mechanism [*10*] will be discussed. To set up a model, based on the cathodic depolarization theory, I inserted two electrodes (1010 mild steel) in a Petri dish cover (Figs. 10 and 11). The electrodes

FIG. 8—*Tuberculation formed on the inside of a steel waterpipe.*

CATHODIC DEPOLARIZATION THEORY
of Von Wolzogen Kühr and Van Der Vlugt

I $8H_2O \longrightarrow 8OH^- + 8H^+$

II $4Fe \longrightarrow 4Fe^{++} + 8e$ (anode)

III $8H^+ + 8e \longrightarrow 8H$ (cathode)

IV $SO_4^{--} + 8H \xrightarrow{\text{(bacteria)}} S^{--} + 4H_2O$ (cathodic depolarization)

V $Fe^{++} + S^{--} \longrightarrow FeS$ (anode)

VI $3Fe^{++} + 6(OH)^- \longrightarrow 3Fe(OH)_2$ (anode)

$$4Fe + SO_4^{--} + 4H_2O \longrightarrow FeS + 3Fe(OH)_2 + 2(OH)^-$$

FIG. 9—*Equation I—the ionization of water, Equation II—the ionization of iron (corrosion), Equation III—the formation of hydrogen, Equation IV—the removal of hydrogen (electrons) by the bacteria causing iron to corrode (Equation II), Equation V and VI—secondary reactions.*

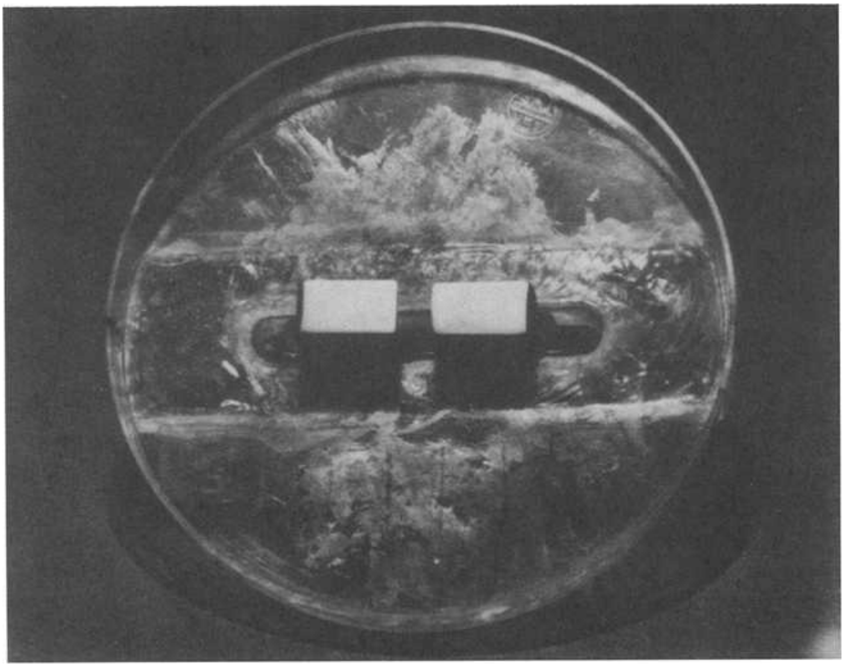

FIG. 10—*Underside of Petri dish cover with two mild steel electrodes each area approximately 1 cm^2.*

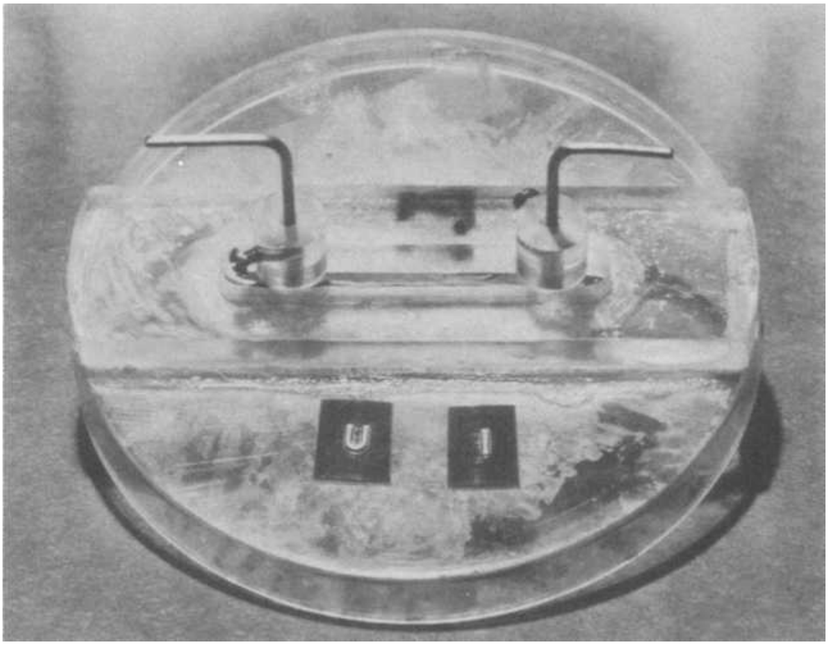

FIG. 11—*Topside of Petri dish cover with electrode supports.*

were encased in resin, (not indicated in Fig. 10) and the surfaces polished and degreased. On a portion of the surface of agar in the bottom half of the Petri dish containing benzyl viologen, a redox-dye, and an organic buffer, (Tris pH 7.0), was placed a mass of *Desulfovibrio* cells (API strain). The cover containing the electrodes was placed over the bottom portion of the Petri dish so that one of the electrodes rested on the bacterial cells, the other electrode, of course, resting on the agar surface with no bacterial cells. The dish was placed in a jar, the electrodes connected to a microammeter, and the air replaced with a nitrogen or argon atmosphere. After about 17 h, the dish was removed from the jar and the electrodes were removed from the surface of the agar. Under the electrode in contact with the bacterial cells (Fig. 12*a*), was an area of reduced benzyl viologen (BV) as indicated by the violet color. To demonstrate the presence and location of ferrous ions, the agar surface was flooded with ferricyanide which reacts with ferrous ions to form ferrous ferricyanide, blue-green in color. The results indicated that the ferrous ions went into solution at the electrode not in contact with the bacterial cells, (Fig. 12*b*).

Figure 13 is a diagram of the experiment, showing ionization of iron at the anode and the reduction of BV at the cathode. This result is in accordance with part of the classical depolarization theory, namely, that bacteria can

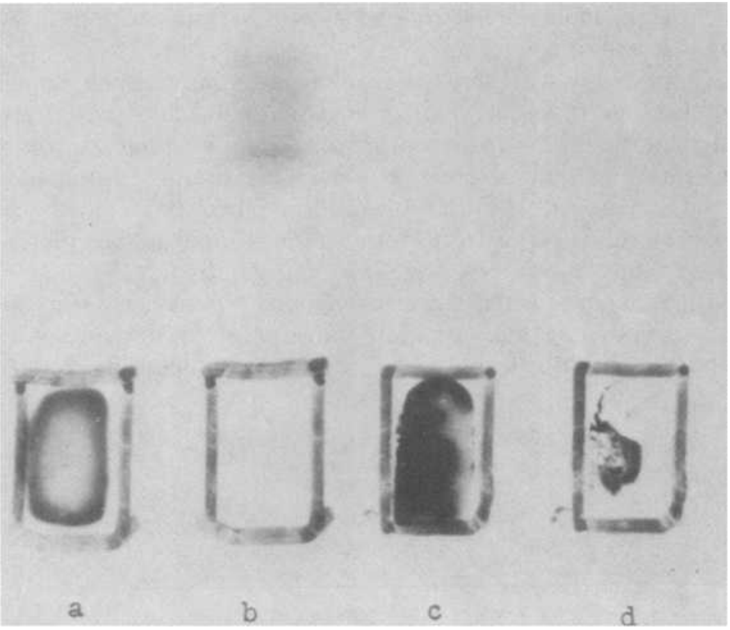

FIG. 12—*Areas in agar under electrodes, indicating location of iron and reduced benzyl viologen (BV).* (a) *Yeast extract (YE) agar plus BV, immediately after removal of electrodes. Dark area of reduced BV (violet) under cathode due to reduction of BV by* Desulfovibrio *cells,* (b) *Same petri plate, 15 min after addition of aqueous potassium ferricyanide (10 percent weight per volume) indicating concentration of Fe^{2+} ions at the anode (no cells). The reduced area of BV under the cathodic becomes oxidized (colorless).* (c) *YE agar minus BV, immediately after removal of steel electrodes indicating dark area under the electrode.* (d) *Same plate, 15 min after addition of aqueous potassium ferricyanide, showing concentration of FE^{2+} ions. Similar observations to* c *and* d *were also noted when SO_4^{2+} ions were added to the YE agar, replacing BV as electron acceptor.*

remove hydrogen or electrons from the surface of the iron, thereby ionizing the iron. The corrosion current density was about 1μA/cm^2 (2.5 mdd). In this experiment, however, BV was substituted for sulfate, to avoid the complicating effects of hydrogen sulfide (H_2S), were it to be produced.

If, however, sulfate was substituted for BV, no cathodic depolarization current could be detected [*11*]. Furthermore, ferrous ions were found to

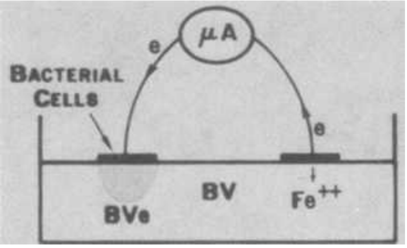

FIG. 13—*Measurement of "Cathodic Depolarization Current."*

occur in the agar, under the electrode which was in contact with the bacterial cells (Fig. 12*c* and *d*).

It thus appeared that cathodic and anodic reactions were taking place at the same electrode. The same results were also obtained if yeast extract was substituted for the Tris buffer to provide conditions favorable for growth, as the organisms were found to grow very well in a medium with sulfate, yeast extract and a hydrogen (H_2) atmosphere. If, in place of agar, the steel coupons were placed in yeast extract broth with or without sulfate, blackening of the yeast extract broth took place in a matter of hours (Fig. 14).

One's first thought was that the black material probably was iron sulfide. However, since the medium was near neutral in pH this could not be the case, as hydrogen sulfide would then form a film on the surface of the iron

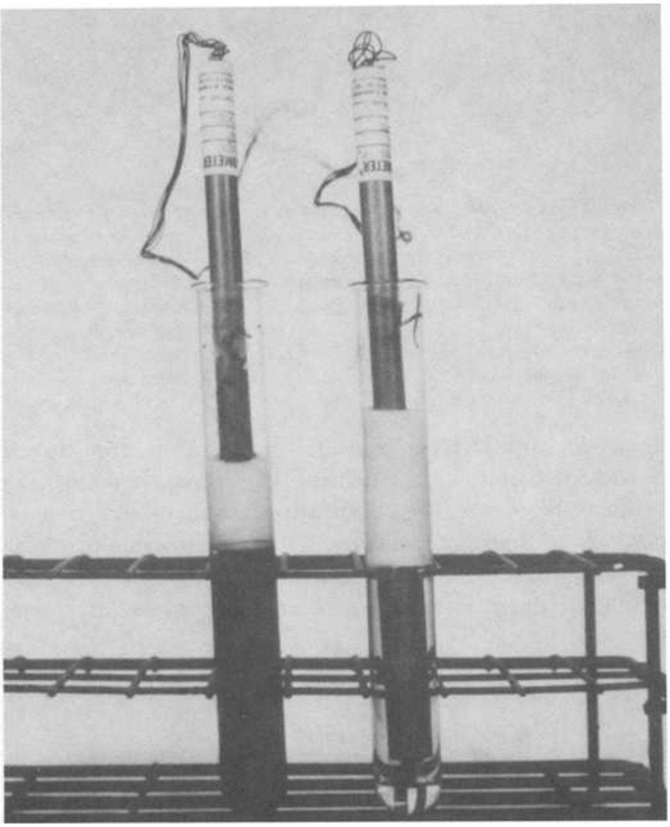

FIG. 14—*Electrical resistance corrosion probes in tubes of yeast extract broth (pH 7) sealed with a mixture of paraffin and petrolatum. Tube at right is uninoculated and mild steel band is seen at bottom of tube. Tube at left was inoculated with* Desulfovibrio *cells and blackening occurred within 8 h after inoculation.*

without darkening the medium. This black material was collected and subjected to X-ray analysis. The first results indicated that it was amorphous. The material was then heated in a vacuum oven at 1232°C and allowed to cool to ambient temperature. When the material was again analyzed, the X-ray diffraction pattern of the material indicated it was iron phosphide (Fe_2P).

Further evidence of phosphorus [*12*] in the reaction was indicated when coupons of 1010 steel were kept in yeast extract broth inoculated with *Desulfovibrio* for about a month. When the coupons were removed from the blackened medium, crystals were found on the surface of the coupons in places where the black film had disappeared, suggesting its conversion to the crystalline form (Figs. 15 and 16). No pits were found under the crystals.

X-ray analysis of the crystals showed them to be vivianite [$Fe_3(PO_4)_2 \cdot 8H_2O$]. In this connection it is of interest to mention the findings in England, where Roman nails were unearthed from an anaerobic bog and found to have had a layer of vivianite over the entire surface [*13*].

The next series of experiments to be described were carried out with a marine strain of *Desulfovibrio* in a seawater medium fortified with some organic materials. (Trypticase and Phytone, Baltimore Biological Laboratories). The

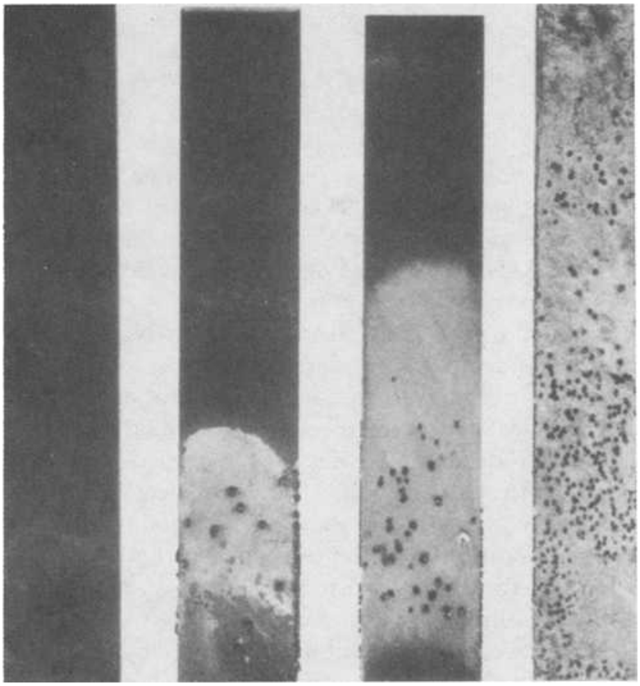

FIG. 15—*Crystals of vivianite on steel coupons upon removal from separate tubes of inoculated yeast extract broth after 1 month incubation at room temperature. Disappearance of black film appears to be related to crystal formation.*

FIG. 16—*Enlarged view of vivianite crystals* (×*10*).

observations and conclusions, I believe, can be related to anaerobic corrosion in the soil. As electrochemical techniques had been worked out to measure instantaneous corrosion rates at the National Bureau of Standards [*14*] and elsewhere [*15*], it was most desirable to quantitate these observations using this marine strain.

Corrosion cells were set up in beakers. Immediately after sterilization of the medium, sterile electrodes were inserted into the hot medium and the surface of the medium covered with vaspar (a mixture of petrolatum and vaseline). The electrical leads from the specimen (1010 mild steel), the platinum gauze auxillary electrode, and the potassium chloride (KCl) bridge from the Luggin capillary to the calomel half-cell were connected (Figs. 17 and 18). Polarization measurements, using the so-called polarization "break method" [*14*] as well as the polarization resistance method [*15*], were initiated on the iron electrode for several days to provide background corrosion rates. Redox-potential measurements were made with the platinum electrode. If there was no evidence of contamination, as indicated by cloudiness, gas formation or both, *Desulfovibrio* cells were then introduced into the medium and the polarization studies continued [*16*]. The results from a typical corrosion cell are shown in Table 2. After a slight initial increase in the corrosion rate, the rate decreased to quite low values for some time. This was evidently

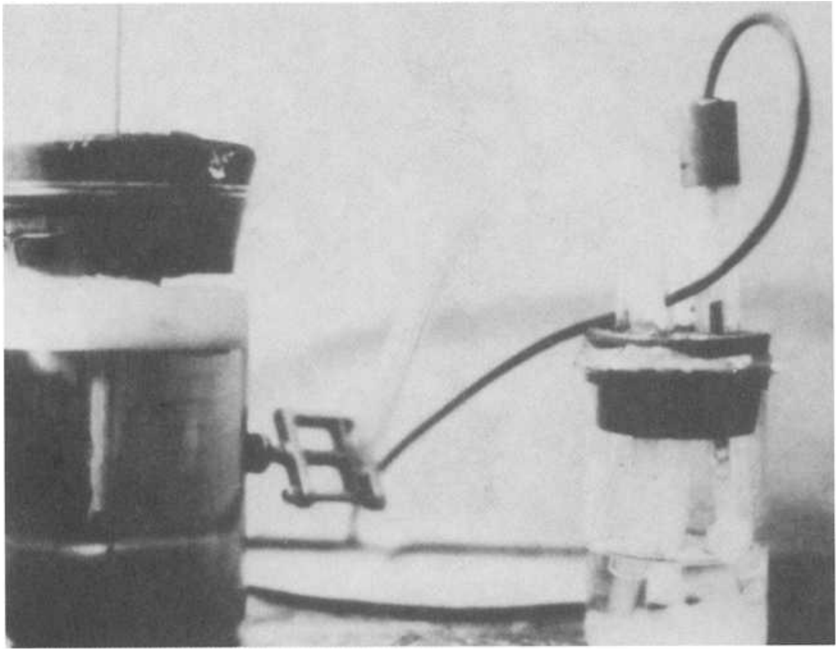

FIG. 17—*Electrochemical cell* (right) *and calomel half-cell* (left).

due to the formation of a film of iron sulfide. Occasionally, the film would rupture and the corrosion rate would increase dramatically.

Since it had been reported that the corrosion rates in anaerobic soils, containing high concentration of iron, were significantly greater than in soils with less iron [*17*], ferrous iron in the form of ferrous ammonium sulfate (0.25 percent) was initially added to the medium. The results (Table 3) indicated that the corrosion rate began to substantially increase after inoculation, and then later decrease.

It was suspected that the ferrous ions were inhibiting film formation and that some additional corrosive product was formed. If this were a reasonable hypothesis, then the total removal of the free sulfide ions should greatly enhance corrosion. The bacteria were allowed to grow for about nine days in a separate vessel under a H_2 atmosphere. They were then removed from the medium by filtration through an asbestos filter (Seitz filter) and ferrous ions added to the filtrate until all of the free sulfide ions were removed with a slight excess of ferrous ions. Again the solution was Seitz-filtered. This filtrate, free of both bacterial cells and sulfide ions, was added to the corrosion cells, and the sterile electrode positioned in the medium. The results (Table 4) [*14*] indicated a dramatic increase in the corrosion rate after about 3 1/3 days. Simultaneously, the open circuit potential became less negative and the

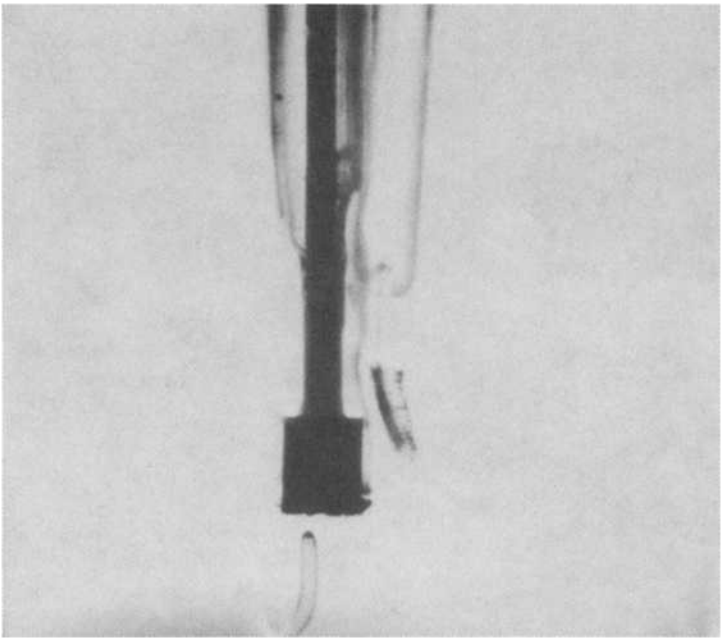

FIG. 18—*Enlarged view of electrochemical cells showing platinum gage electrode, mild steel electrode and Luggin capillary tube.*

TABLE 2—*Corrosion of mild steel in (TPSW) culture-cell 1.*

Open Circuit Corrosion				
Time, days	Potential Steel, V	Redox Potential, V	Current Density, $\mu A/cm^2$	Rate, mdd
1	−0.717	+0.270	0.70	1.75
4	−0.711	+0.250	0.48	1.20
7	−0.699	+0.261	0.42	1.05
1[a]	−0.695	+0.271	2.30	5.86
7	−0.564	−0.199	0.28	0.70
14	−0.550	−0.200	0.13	0.32
21	−0.491	−0.194	0.04	0.10
51	−0.604	−0.180	3.20	8.00

[a] Days after inoculation.

TABLE 3—*Corrosion of mild steel in (TPSW) culture with added* Fe^{++} *ions.*

Open Circuit Corrosion				
Time, days	Potential Steel, V	Redox Potential, V	Current Density, μA/cm²	Rate, mdd
2	−0.699	−0.101	0.92	2.30
6	−0.699	−0.189	1.06	2.65
12	−0.692	−0.082	1.08	2.70
1[a]	−0.685	−0.155	2.20	5.50
7	−0.683	−0.191	3.52	8.81
28	−0.678	−0.238	12.42	31.06
49	−0.688	−0.227	10.30	26.15
101	−0.610	−0.201	4.16	10.40

[a] Days after inoculation.

redox potential more negative. The medium also became black. Coinciding with the change in the electrochemical values, this blackening appeared to be the same phenomenon earlier observed in the yeast extract cultures containing steel coupons and inoculated with the American Petroleum Institute's strain of *Desulfovibrio*. The corrosion rate continued to increase until a peak rate of about 1000 mdd at 13 days was reached, and then decreased rapidly thereafter. This high rate is about 40 times the corrosion rate of mild steel in seawater. Figure 19 shows the surface of the coupon after removal. Repeating the experiment, this time, using iron nails in the cell-free, sulfide-free filtrate, the average corrosion rate was still found to be quite high over a period of 20 days (Table 5) [*4*]. It appears, judging from these observations, that the sulfate reducing bacteria produce, in addition to hydrogen sulfide a highly corrosive material possibly a compound containing sulfur and phosphorus

TABLE 4—*Effect of TPSW culture filtrate* $+Fe^{++}$ *ions on the corrosion of mild steel.*

Open Circuit Corrosion				
Time, days	Potential Steel, V	Redox Potential, V	Current Density, μA/cm²	Rate, mdd
1	−0.796	−0.162	2.3	5.7
3	−0.762	−0.295	2.0	5.0
3.3	−0.662	−0.335	20.8	52.0
4	−0.595	−0.318	115.5	288.7
6	−0.578	−0.319	172.8	432.0
9	−0.565	−0.303	198.4	496.0
13	−0.548	−0.278	460.8	1152.0
15	−0.542	−0.223	69.4	173.5

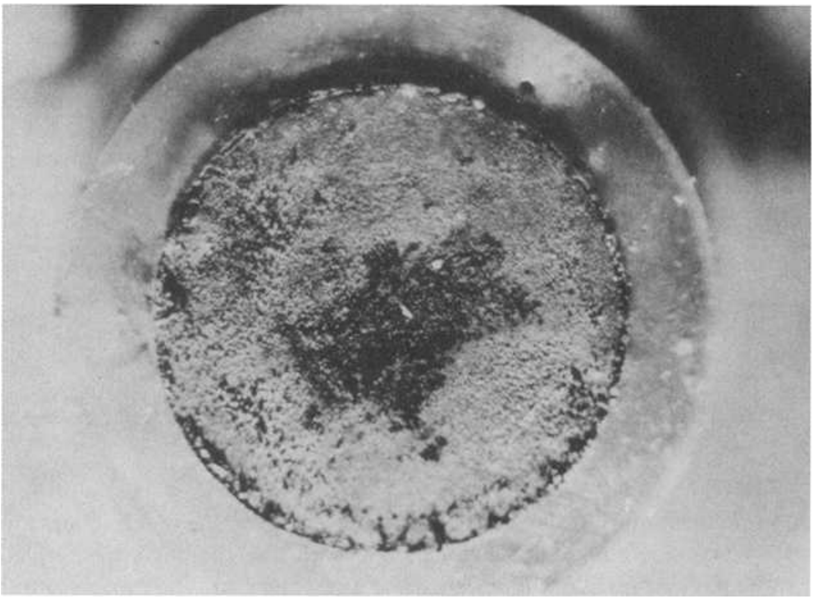

FIG. 19—*View of corroded mild steel surface after exposure to cell-free filtrate for 16 days.*

which causes the iron to literally dissolve under anaerobic conditions at a neutral pH.

The outcome of this corrosion process seems to depend on whether the hydrogen sulfide reaches the iron surface first, forms a film and protects it, or whether the highly corrosive substance comes in contact first, with resultant corrosion. These results may indicate why workers in the field and laboratory have made conflicting observations, some reporting high corrosion losses and others very low corrosion rates for iron and steel in anaerobic corrosive environments.

TABLE 5—*Effect of TPSW culture filtrate* $+Fe^{++}$ *ions on the corrosion of mild steel 20 days.*

No. Nails	Weight Loss, mg			Original Weight Loss, percent			Corrosion Rate, mdd		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
5	9.7	15.1	19.6	1.20	1.92	2.50	22.2	33.3	39.7
Control (uninoculated TPSW medium)									
5	0.4	0.6	0.7	0.05	0.07	0.09	0.92	1.29	1.62

The results of these experiments with two strains of sulfate reducing bacteria appear, therefore, to indicate the mechanism proposed by von Wolzogen Kühr and van der Vlugt for the anaerobic corrosion by bacteria cannot account for the extensive anaerobic corrosion noted in the field and also, the corrosion is caused by a highly corrosive metabolic product produced by sulfate reducing bacteria. Based on chemical analysis of the corrosion products, it is postulated that the product is a compound of sulfur and phosphorus.

Protective Measures

After describing the corrosion process, a few statements are appropriate concerning protection of iron and steel structures in the corrosive anaerobic environments.

A number of possibilities for protection of steel exist depending primarily on economic factors:

1. Selecting noncorrosive environments.
2. Modification of corrosive environment (aeration of soils and drainage, surrounding the structures with gravel).
3. Use of protective coatings.
4. Cathodic protection (0.950 V versus standard. Cu/$CuSO_4$ cell, has been suggested).
5. Combination of cathodic protection and coating system (usually, the most satisfactory protection system).

Summary

Anaerobic corrosion is caused by sulfate-reducing bacteria.

Sulfate reducing bacteria do not cause corrosion by the mechanism postulated in the cathodic depolarization theory in which bacterial cells remove hydrogen from the surface of iron reducing sulfate to hydrogen sulfide in the process.

Sulfate reducing bacteria cause corrosion under anaerobic conditions by producing, extracellularly, a highly corrosive product.

Phosphorus appears to be involved in the corrosion process.

Hydrogen sulfide, also produced by sulfate reducing organisms, inhibits corrosion by forming a sulfide film on the iron.

The factors controlling the fate of iron in anaerobic environments conducive to the growth of sulfate-reducing bacteria, may depend on whether film formation occurs first, thereby inhibiting corrosion, or whether the highly corrosive substance comes in contact with the iron before film formation has occurred, thereby accelerating corrosion. If film formation has occurred first, subsequent breakdown of film formation, providing access to the highly corrosive substance could also result in an increase in corrosion. The opposing action of these two materials produced by *Desulfovibrio* on iron, namely, hydrogen sulfide and the corrosive substance, could explain the conflicting observations of anaerobic corrosion noted by investigators in the field and laboratory.

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Bernard Husock[1]

A Statistical Probability Method for Soil Resistivity Determination

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REFERENCE: Husock, Bernard, "**A Statistical Probability Method for Soil Resistivity Determination,**" *Underground Corrosion, ASTM STP 741,* Edward Escalante, Ed., American Society for Testing and Materials, 1981, pp. 53–60.

ABSTRACT: This paper presents a new method of interpreting soil resistivity measurements by a statistical technique. The method may prove to be very useful where large variations in soil resistivity, in a given area, are found.

Actual field measurements are used to demonstrate the usefulness of this technique.

KEYWORDS: underground corrosion, soil resistivity, measurements, field measurements

All calculations, related to the design of grounding systems and for the determination of step and touch potentials, require information about the soil resistivity at the site [*1*].[2] Despite the obvious need for accurate soil resistivity information to achieve correct and useful results, procedures for determining the resistivity values to be used in the formulas have been given little attention. This paper indicates an approach which will enable the designer to use soil resistivity information in a more exact way than has been the case to date.

Description of the Problem

In most of the formulas given in the Institute of Electrical and Electronic Engineers Guide for Safety in A-C Substation Grounding (No. 80), ρ is defined merely as the resistivity in ohm-metres and in at least two formulas, [*2,3*] is defined as the "average ground resistivity" in ohm-metres. In completely homogeneous or relatively uniform soils, the soil resistivity value to be used is readily determined from a limited number of measurements using the Wenner Four Pin Method. But where substantial variations in resistivity are encountered, both horizontally and in depth, there is little guidance presently available on how to cope with these variations. On smaller sized ground electrodes used in past years, the effect of these variations may not

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[1] Vice-president and chief engineer, Harco Corp., Medina, Ohio 44256.

[2] The italic numbers in brackets refer to the list of references appended to this paper.

have been of great significance, but, as the size of these electrodes has grown, the effects of soil resistivity variations have played a greater role than is often appreciated.

Laurent [*4*] comments on this problem with respect to the "heterogeneous nature of the ground" as applied to his fundamental equations by stating that "the apparent accuracy of the equations we are going to give should not, therefore, give rise to any illusions. . . Strict accuracy must not be expected in the final mathematical result."

Guide 80 recognizes the need for on-site electrical measurements [*5*] recommending the Wenner Four Electrode Method [*6*], and states that "these should preferably be made at a number of places within the site and with different probe spacings, to get an indication of any important variations of resistivity with location or depth." There is no guidance given with respect to the number of readings required except the statement that "the number of such readings taken will normally be greater where these variations are large." Although layer and stratification methods have been suggested [*7,8*], there have been no suggestions that we could find for coping with large horizontal variations in resistivity. Because grounding grids lie in horizontal planes, most often at depths of less than 6 m (10 ft) (even through vertically driven ground rods to greater depths may be also used), the resistivity variations in the horizontal plane will have a significant influence on the performance of the grounding network.

This paper presents a statistical probability method for use in assessing the soil resistivity variations at a given site and suggests procedures for determining values of resistivity to use in the grounding equation.

Probability Method

To demonstrate that substantial variations in resistivity indeed exist within limited areas, Table 1 lists a set of four electrode soil resistivity measurements taken in 1975 at the site of a power generating plant now under construction.

The readings at Location 5 obviously do not fit and will not be considered. This Location 5 was a fill area and dumping ground for what is obviously low resistivity material. Even when the readings at Location 5 are discarded, there remain very large variations in resistivity. Although the variations with depth (or probe spacing) are sizable, the variations from location to location are considerable. Thus, among the measurements taken at 1.5 m (5 ft) probe spacing, we find more than a tenfold difference between the readings at Locations 11 and 12, a distance of less than 60 m (200 ft), and more than a thirtyfold difference between the readings at Locations 13 and 14, a distance of approximately 106 m (350 ft). Although the variations seen at this site are more extreme than might normally be encountered, they are not entirely unusual. Such variations in soil resistivity within relatively short distances are

TABLE 1—*Soil resistivity data, Ωm.*[a]

Location No.	5	10	20	30	40	50
1	153	165	176	207	217	249
2	192	211	306	420	544	689
3	1 720	1 053	843	976	919	1 050
4	278	148	134	149	153	182
5	16	10	10	8	6	5
6	6 990	3 640	2 830	2 060	2 300	2 390
7	1 245	479	310	419	575	843
8	4 790	6 130	8 040	7 470	5 750	5 070
9	316	249	333	414	483	555
10	2 970	2 870	2 340	1 780	1 920	2 110
11	6 510	5 940	8 040	6 890	4 440	3 450
12	527	402	460	534	659	718
13	431	498	613	494	459	460
14	14 440	12 800	14 560	12 640	10 720	8 235
15	2 110	610	421	460	429	402
16	6 800	7 280	6 890	8 040	7 500	6 320
17	3 640	3 260	2 720	2 590	2 150	1 820
18	575	498	536	747	919	1 053
19	1 053	900	1 230	1 320	1 530	1 920
20	7 950	11 000	9 960	9 190	8 430	7 090
21	2 490	3 830	4 210	2 990	2 830	3 640
22	13 400	10 530	45 960	15 500	22 200	12 450
23	29 700	15 300	16 000	11 500	9 200	84 300
24	584	613	689	860	1 070	1 250
25	12 450	10 340	9 200	6 320	4 980	2 590
26	21 000	13 600	12 260	12 000	13 000	11 500
27	17 250	14 200	8 800	8 620	9 200	8 710
28	4 200	5 940	6 900	9 200	9 960	11 500

[a] Probe spacing/depth in feet; 1 ft = 0.3048 m.

often observed in rocky and mountainous regions. Personal observations in Western Pennsylvania, New York State, West Virginia, and Kentucky have noted even larger variations in resistivity than those illustrated here. Although the values at this particular site are of very high resistivity, similar large variations have been observed in areas where the resistivity values are lower.

When resistivity values with these variations are encountered even where the variations are less extreme, there arise questions.

1. What value or values of resistivity should be used in the design calculations?
2. How many measurements are required to determine the correct values?

A paper by Scott published in 1958 entitled "The Distribution of Soil Conductivities and Some Consequences" [9] noted that the logarithms of the soil resistivity values at a particular site follow a normal distribution function almost irrespective of the magnitude of the variations. Thus, if the readings in Table 1 are arranged in ascending order and assigned probability values in accordance with the method suggested by Gumbel [*10*] as shown in Table 2, and the values in Table 2 are then plotted on logarithmic-. . . probability graph paper as shown in Fig. 1, the resultant plot approaches a straight line indicative of normal distribution. Once this relationship has been established, the complete set of readings can be now designated by the notation

$$N(\bar{x}, s)$$

where

$\bar{x}$ = mean value and
s = standard deviation.

It can be seen that the standard deviation is a measure of the variation in the soil resistivity; the lower the value of s, the more uniform the soil resistivity. This designation makes it possible to identify and compare the soil resis-

TABLE 2—*Ordered soil resistivities and estimated probabilities.*[a]

Location No.	Resistivity, Ωm	Probability, percent
1	153	3.6
2	192	7.1
4	278	10.7
9	316	14.3
13	431	17.9
12	527	21.4
18	575	25.0
24	584	28.6
19	1 053	32.1
7	1 245	35.7
3	1 720	39.3
15	2 110	42.9
21	2 490	46.5
10	2 970	50.0
17	3 640	53.6
28	4 200	57.1
8	4 790	60.7
11	6 510	64.3
16	6 800	67.9
6	6 990	71.4
20	7 950	75.0
25	12 450	78.6
22	13 400	82.1
14	14 330	85.7
27	17 250	89.3
26	21 000	92.9
23	29 700	96.4

[a] Measurements at 5 ft; 1 ft = 0.3048 m.

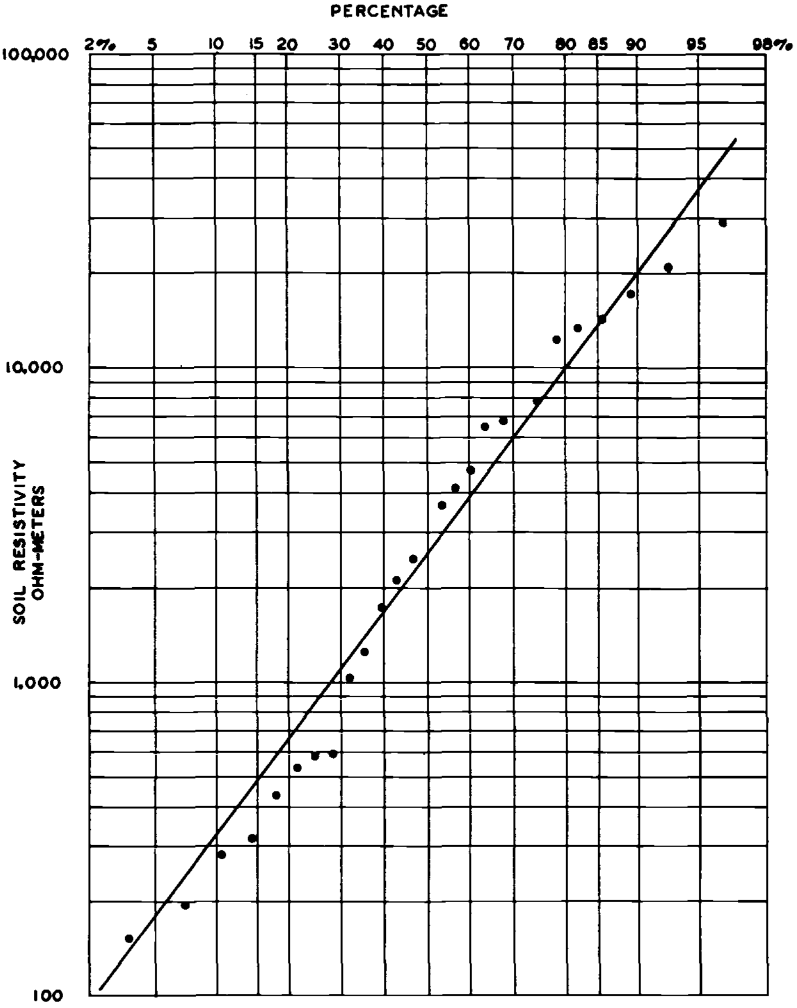

FIG. 1—*Soil resistivity versus probability.*

tivity characteristics at the same site at different times such as before and after excavating and grading. Thus, the values listed in Table 2 and plotted in Fig. 1 can be designated as

$$N(\bar{x}, s) = N(7.80, 1.54)$$

At this same site, a soil resistivity survey had been previously performed in 1969, and the set of four-probe measurements taken with 1.5 m, (5 ft) spacing are listed in Table 3. The two sets of readings were not taken at the same locations, and a point to point and location to location comparison was not

TABLE 3—*Soil resistivity readings, 1969.*[a]

Location No.	Resistivity, Ωm
1	1 720
2	335
3	1 243
4	5 449
5	1 912
6	2 294
7	9 460
8	10 516
9	10 516
10	12 428
11	3 250
12	16 252
13	8 317
14	8 317
15	688
16	382
17	746
18	201

[a] Probe spacing at 5 ft; 1 ft = 0.3048 m.

possible. These readings show that

$$N(\bar{x}, s) = N(7.87, 1.40)$$

It is apparent that despite the work that was done at this site and the elapsed time between the two sets of readings, the overall soil resistivity characteristic has remained essentially unchanged. When we consider that there are variations in resistivity of almost two orders of magnitude, these two probability graphs are very close to one another.

Determining Resistivity Values

The establishing of the log-normal relationship for values of soil resistivity makes it possible to predict with a determinable degree of confidence the probability of encountering soil of a particular value (or less) at any given site. For example in the graph plotted in Fig. 1, it can be seen that the probability of encountering soils whose resistivity is 1000 Ω m or less is 28 percent, and that the probability of encountering soils of 100 Ω m or less is only 2.2 percent.

These probabilities can be calculated from the relationship

$$p = f\left(\frac{\ln z - \bar{x}}{s}\right)$$

where z is the soil resistivity of interest.

The percent probability is then calculated using the normal probability integral or taken from the tables for that integral [*11*].

Although in many calculations it may be sufficient to use the mean value of the resistivities measured, the procedure indicated makes it possible to use a given value of resistivity with a calculable probability of encountering that value or one which is lower. To determine the boundaries for a given number of readings at a specific confidence level, the following equation can be used

$$f\left(k - a\sqrt{\frac{2+k^2}{2n}}\right) \leq p \leq f\left(k + a\sqrt{\frac{2+k^2}{2n}}\right)$$

where

a = coefficient for a specific confidence level,
= 1.65 at 90 percent,
= 1.96 at 95 percent,
n = number of readings, and
$k = \dfrac{\ln z - \bar{x}}{s}$

In the example just given, there were 27 readings used to determine that there was a 28 percent probability of encountering soils at this site whose resistivity is 1000 Ωm or less. Using the equation for determining the boundaries at a 90 percent confidence level we find

$$f\left(k - 1.65\sqrt{\frac{2+k^2}{2\times 27}}\right) \leq p \leq f\left(k + 1.65\sqrt{\frac{2+k^2}{2\times 27}}\right)$$

$$k = \frac{\ln(1000) - 7.80}{1.54}$$

$$= -0.58$$

$$f(-0.58 - 0.34) \leq p \leq f(-0.58 + 0.34)$$

$$f(-0.92) \leq p \leq f(-0.24)$$

$$18.1 \text{ percent} \leq p \leq 40.5 \text{ percent}$$

Thus, with readings at 27 locations, the probability of encountering soil resistivities of 1000 Ωm is 28 percent, and there is a 90 percent confidence that the probability falls within the 18.1 and 40.5 percent boundary.

Conclusions

The procedure demonstrated in this paper has shown:

1. Soil resistivity measurements follow a log-normal relationship.
2. Using this relationship, it is possible to delineate the soil characteristics at a particular site by the designation $N(\bar{x}, s)$.
3. It is possible to determine by graph or by calculation the probability of encountering soil resistivity of any given value or less.
4. An equation for determining the boundaries of that probability at a given level of confidence for the number of readings taken at a site.

References

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DISCUSSION

J. B. Lankes[1] (*written discussion*)—The paper presents data taken at the 15 m (50 ft) level as part of the input of the probability equation. Does not this distance approach "remote earth" and as such is relatively meaningless as significant data? I understood the answer to perhaps be true in case of pipelines at one or two metre depths, but could be significant in cases of well casings or deep well anodes.

B. Husock (*author's closure*)—In most instances, resistivity measurements are rarely taken to depths of 15 m (50 ft). It is presented here to illustrate that the log-normal relationship exists even at those depths.

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[1] Corrosion control engineer, consultant, Richmond, Va. 23220.

Victor Chaker[1]

Simplified Method for the Electrical Soil Resistivity Measurement

REFERENCE: Chaker, Victor, "**Simplified Methods for the Electrical Soil Resistivity Measurement,**" *Underground Corrosion, ASTM STP 741,* Edward Escalante, Ed., American Society for Testing and Materials, 1981, pp. 61–91.

ABSTRACT: The "Wenner Four Electrode" method; and the "Barnes Layer" method of computation, for the electrical soil resistivity, are both time consuming but very useful and reliable. Pre-measured cables can simplify and reduce the field time by at least 75 percent. A computerized program for calculation and graphical representation could achieve the same savings, when compared with manual production.

KEY WORDS: average resistivity, true resistivity, current electrodes, potential electrodes, soil corrosivity, boring logs, underground corrosion

Resistivity is a fundamental property of a material which characterizes that material almost as completely as does its density. Field resistivity measurements of such materials as clays, sands, gravels, various types of sedimentary and igneous rocks, etc. afford an opportunity for distinguishing one type from another without making a physical excavation.

Electrical Soil Resistivity Theories

The resistivity of any material is defined as the resistance in ohms, between opposite faces of a unit cube of that material. If R is the resistance of a block of conductive material having length (L), in a cross-sectional area (A), then the resistivity (ρ), is expressed by the formula

$$\rho = \frac{R\ A}{L}$$

Thus, resistivity, being a fundamental property of the material, is independent of the volume; whereas, resistance depends upon the shape and the size of the specimen. The conductance of a material is defined as the reciprocal of its resistance.

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[1] Corrosion control/electrical grounding consulting engineer, Gilbert/Commonwealth, Reading, Pa. 19603.

The units of resistivity are ohms multiplied by length. Ohm-cm is most commonly used. The units of conductance are Mhos.

In order to explain the resistivity method in its simplest case, consider a very large solid with uniform resistivity (ρ). Four electrodes are inserted into this material at positions *A, B, C,* and *D* as shown in Fig. 1*b*. An electric current (*I*), is impressed between the outer two positions *A* and *B,* into the material. When current is introduced into a material which has resistance, a potential gradient (*V*), is developed between any two points in the material, such as *C* and *D*. By Ohm's law $R = V/I$. In effect, then, the resistivity method is a field application of it.

The current flowing into the earth spreads out vertically and horizontally. Hemispherical equipotential surfaces develop if the material has uniform resistivity. The volume of material through which the current passes is proportional to the distance between the four electrodes. This implies that the depth of the material included in the measurement is proportional to the distance between electrodes. Thus, it is possible to measure the resistance for a volume of earth proportional to the known distance between the electrodes.

Figure 2, shows a vertical cross section of the earth through the line of the electrodes and presents a few electrical field lines or paths of current flow. Figure 3, shows the same phenomenon as viewed looking down onto the surface of the earth. The patterns shown in Figs. 2 and 3 result only if the material has an ideally uniform resistivity. Any deviation from uniformity will cause changes in the pattern of current flow.

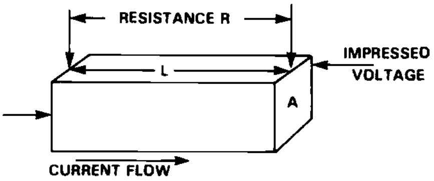

FIG. 1*a*—*Relationship between resistivity and resistance.*

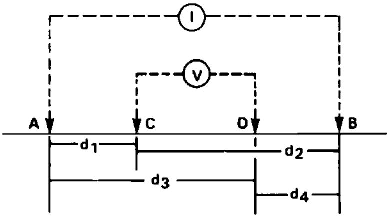

FIG. 1*b*—*Uniform resistivity material.*

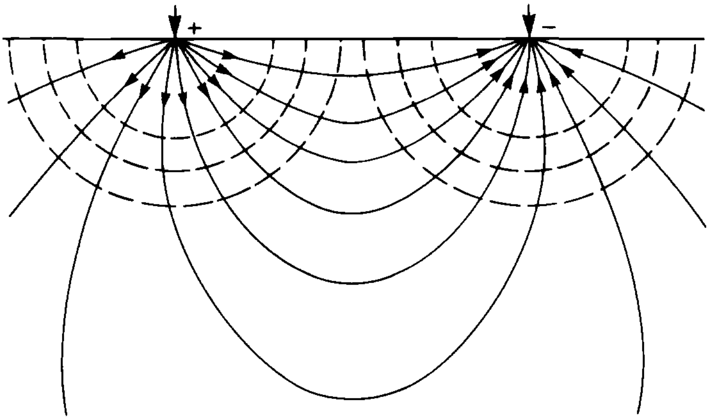

FIG. 2—*Earth vertical cross-section showing paths of current flow.*

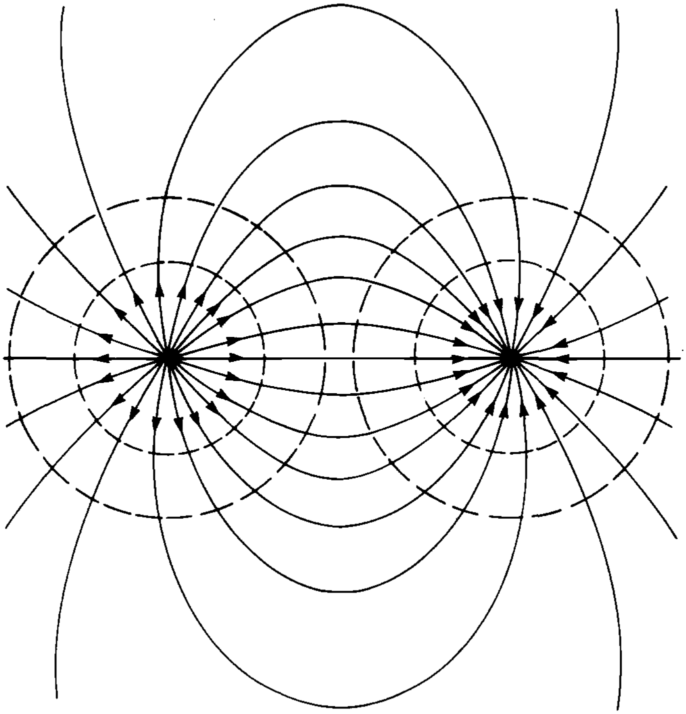

FIG. 3—*View of current flow as looking down onto the surface of the earth.*

Referring to Figs. 1 and 2, the potential at electrode C resulting from the current flow is [*1*].[2]

$$V_c = \frac{I\rho}{2\pi}\left(\frac{1}{d_1} - \frac{1}{d_2}\right)$$

Similarly, the potential at electrode D is

$$V_d = \frac{I\rho}{2\pi}\left(\frac{1}{d_3} - \frac{1}{d_4}\right)$$

The potential difference (V), measured between electrodes C and D is simply

$$V_c - V_d \text{ and } \rho = \frac{2\pi V}{I}\,\frac{1}{\left(\frac{1}{d_1} - \frac{1}{d_2}\right) - \left(\frac{1}{d_3} - \frac{1}{d_4}\right)}$$

This is the fundamental equation of the resistivity method. It gives the resistivity in terms of quantities which can be measured, V, I, and the electrode separation distances.

In this equation, the material is considered to have a uniform resistivity. When the resistivity is not constant throughout the material, the effective resistivity will vary with the position of the electrodes. In the case of a nonuniform material, the value given by the last equation is called the apparent resistivity.

Such an ideally uniform subsurface is rare; therefore, most of the work with resistivity is based upon apparent resistivity instead of true resistivity. The variations in the apparent resistivity readings are a method to distinguish one type of subsurface material from another.

Wenner Four Electrodes Theory

The Wenner method [*2*] is the most widely used in earth resistivity studies. It is an approved method by all of the involved technical associations, such as the National Association of Corrosion Engineers, the Institute of Electrical and Electronic Engineers, and the National Bureau of Standards [*3*].

In this method, an electrical current is induced through two outer electrodes, and the potential difference is measured across two inner electrodes, as shown in Fig. 4.

This constitutes a four-terminal conductor the resistance of which depends upon the distance between the electrodes and the resistivity, mainly, in a region whose linear dimensions are of the same order as the distance between the outside electrodes, but does not depend appreciably upon the size of the electrodes nor the kind of electrical connection they make with the earth. If

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[2] The italic numbers in brackets refer to the list of references appended to this paper.

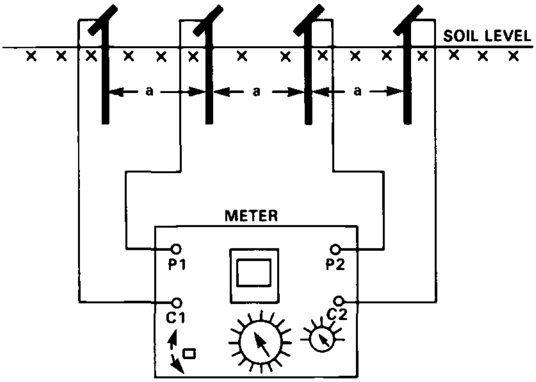


FIG. 4—*Four electrode method for the electrical soil resistivity measurement.*

the depth of the electrodes in earth is *b*, the distance between them is *a* and the resistance is *R*, then the value of average apparent resistivity is given by

$$\rho = \frac{4\pi a R}{1 + \dfrac{2a}{\sqrt{a^2 + 4b^2}} - \dfrac{2a}{\sqrt{4a^2 + 4b^2}}} = \frac{4\pi a R}{n} \qquad (1)$$

Where n has a value between 1 and 2 depending upon the ratio of b to a. In case b is large in comparison with a

$$\rho = 4\,\pi\, a\, R \qquad (2)$$

and when b is small in comparison with a

$$\rho = 2\,\pi\, a\, R \qquad (3)$$

where a is in centimetres, R in ohms, and ρ in ohm-centimetres.

Since the electrodes are small, the resistance between the current electrodes and earth, or between any of the electrodes and earth, is large in comparison with the resistance (R) of the terminal conductor, and usually not very constant. Also, since earth acts as an electrolyte, there is, in general, an electromotive force in any circuit containing two of the electrodes and polarization at any electrode through which electrical current passes, even though the current may be alternating. Usually, there is no need to measure the resistance to a high accuracy.

Barnes Layer Method of Computation of Electrical Soil Resistivity

The Barnes layer method [*4*] was developed to make use of the average resistivities of subsurface data. This method endeavors to distinguish the resistivity of layers of the earth. The thickness of the layer is assumed to be equal to the increment in the electrode spacing. The layers of soil are assumed to be analogous to resistors in a parallel circuit.

$$\frac{1}{R_n} = \frac{1}{R'_n} - \frac{1}{R'_{n-1}} \tag{4}$$

Where

$1/R_n$ = layer conductance of a given increment, in mhos,

$1/R'_n$ = total conductance between the ground surface and the bottom of the given increment, in mhos, and

$1/R'_{n-1}$ = total conductance between the ground surface and the bottom of the increment directly above the given increment, in mhos.

The layer resistivity value for any given increment can be computed by the formula

$$\rho_L = \frac{2\,\pi\,\alpha_L}{1/R_n} \tag{5}$$

where a_L is the layer spacing in centimetres.

Interpretation of the Electrical Soil Resistivity Data

The basic two principles used in the interpretation of the electrical soil resistivity [5] are:

1. The lines of current flow will be deflected toward a good conductor.

2. The difference in potential between the potential electrodes is produced by the current flow along the lines joining them.

The voltage drop (V) will be proportional to the true resistivity and to the current density in the small near surface volume between the potential electrodes.

$$V \propto \rho_0 i$$

where

ρ_0 = true resistivity, and

i = current density (the current passing through a unit cross sectional area).

The apparent resistivity (ρ) is proportional to the true resistivity multiplied by the ratio of the current density to the current

$$\rho \propto \frac{i}{I}\rho_0$$

The current density changes in direct proportion to the changes in the total current, thus the measured apparent resistivity is independent of changes in the total current into the ground. Different surface conditions will produce different apparent resistivity readings. If a small volume element is imagined as extending along the earth surface between the two potential electrodes, it will have a certain current density and a certain true resistivity. The measured apparent resistivity will be directly proportional to these two quantities.

Two basic principles are used for interpretation of the layer soil resistivity.

Low Resistivity Layer Over High Resistivity Layer (Fig. 5).

A completely uniform subsurface whose resistivity equals that of the top layer would have lines of current flow as shown by the dotted lines.

As the electrode spacing increases, the presence of the rock stratum starts to alter either the current density or the true resistivity measured by the instrument along the surface line between the two central potential electrodes.

The true resistivity of the surface material is not changed by the presence of rock, since the rock does not extend to the surface. Thus, the true resistivity will be completely unaffected by the rock substratum and cannot contribute to the change in the apparent resistivity readings.

The bedrock effect upon the current density at the surface will depend upon the electrode spacing, more precisely, upon the ratio of the electrode spacing to the depth of the bedrock.

High Resistivity Layer Over Low Resistivity Layer (Fig. 6).

In this case, the lines of current flow are deflected downward to the low resistivity substratum. This results in reduced current density along the surface between the potential electrodes. Hence, the apparent resistivity readings are reduced.

The general acceptable relationship [*6*] between the electrical soil resistivity and the soil corrosivity is given in Table 1.

Table 2 lists some typical electrical soil resistivities [*5*]. Figure 7 shows these characteristics in a graphical presentation.

Correlation of Resistivity Data to Materials

It should be emphasized that a resistivity unit is not a measure of the true resistivity of any particular volume of earth unless the material is homogeneous. Instead, it indicates a weighted average of all of the different resis-

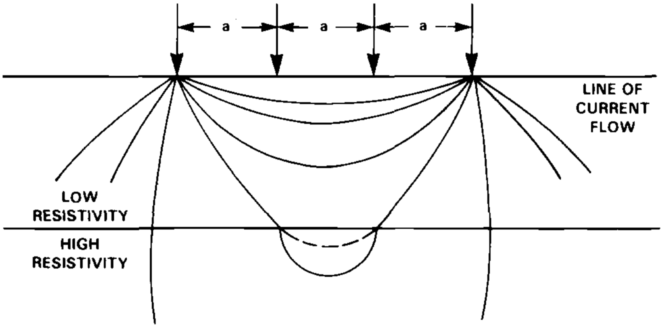


FIG. 5—*Low resistivity layer over high resistivity layer.*

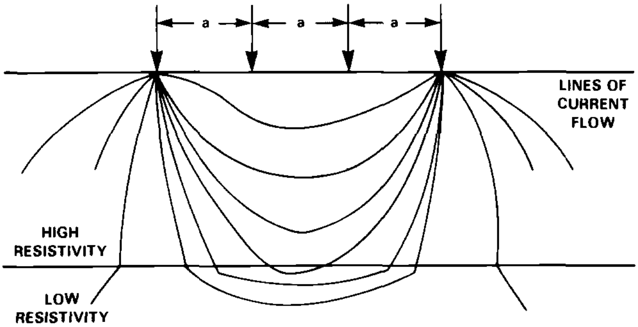


FIG. 6—*High resistivity layer over low resistivity layer.*

tivities present in the volume. The resistivity of the surface material has greater influence on the readings than do deeper laying materials [7].

For nearly all earth materials, an essential theoretical fact to keep in mind is that resistivity decreases with increasing water content and with increasing water salinity.

This principle leads to the conclusion that nonporous materials will exhibit relatively high resistivity values since the water content will be small. This category includes nearly all of the igneous and metamorphic rocks such as granite and salt, plus many sedimentary rocks such as dense limestone or sandstone.

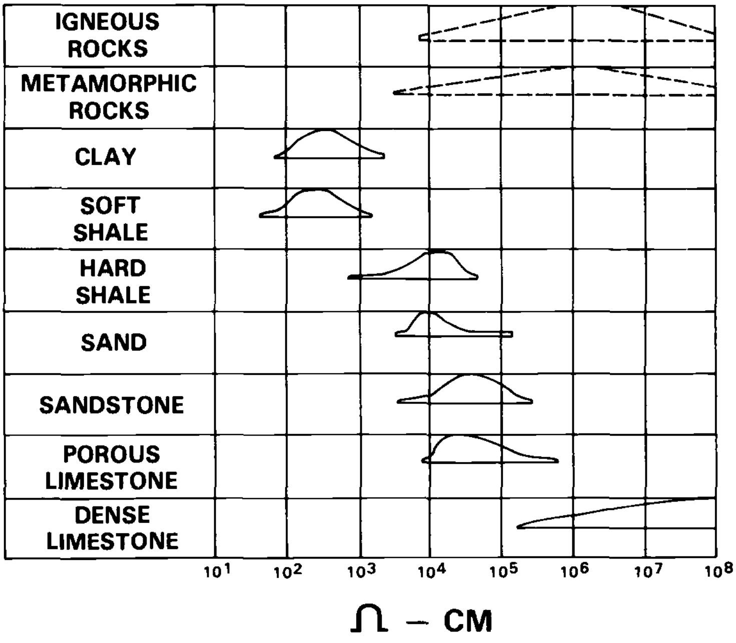


FIG. 7—*Graph of typical electrical soil resistivities.*

TABLE 1—*Soil corrosivity versus resistivity.*

Soil Corrosivity	Soil Resistivity, Ωcm
Very corrosive	0 to 2 000
Corrosive	2 000 to 5 000
Moderately corrosive	5 000 to 10 000
Mildly corrosive	10 000 to 25 000
Relatively less corrosive	25 000 to 50 000
Progressively noncorrosive	50 000 to 100 000

TABLE 2—*Resistivities of various minerals and soils.*

Minerals and Soils	Resistivity, Ωcm
Minerals	
Galena	0.5 to 5.0
Pyrite	0.1
Magnetite	0.6 to 1.0
Graphite	0.03
Rock salt (impure)	3×10^3 to 5×10^5
Serpentine	2×10^4
Siderite	7×10^3
Igneous rocks	
Granite	10^8
Granite	5×10^5
Diorite	10^6
Gabbro	10^7 to 1.4×10^9
Diabase	3.1×10^5
Metamorphic rocks	
Garnet gneiss	2×10^7
Mica schist	1.3×10^5
Biolite gneiss	10^8 to 6×10^8
Slate	6.4×10^4 to 6.5×10^6
Sedementary rocks	
Chattanooga shale	2×10^3 to 1.3×10^5
Michigan shale	2×10^5
Calument and hecla conglomerates	2×10^5 to 1.3×10^6
Muschelkalk sandstone	7×10^3
Ferruginous sandstone	7×10^5
Muschelkalk limestone	1.8×10^4
Marl	7×10^3
Glacial till	5×10^4
Oil sand	4×10^2 to 2.2×10^4

Other high resistivity materials will include those which are porous but contain little or no water, such as dry sand, or those which are both porous and water saturated but containing very little soluble salt. Clean gravels and sand fall in the latter category.

While surface topography can complicate the job of interpreting subterranean conditions, it remains true that the resistivity of materials tend to keep their same ranking, moist or dry. Thus, as an example, clay will be lower in resistivity than silt, silt lower than sand, and sand lower than sand and gravel, for a given topography.

The resistivity of bedrock can vary considerably depending upon the type of bedrock and the extent of weathering and fracturing. Massive bedded limestone, sandstone, and igneous bedrock will have higher resistivities than thinly bedded formations which can contain low resistivity moisture and soil deposits. Shale layers in sedimentary bedrock will also decrease the resistivity of the rock. A shale bedrock formation will generally have lower resistivity values than any other sedimentary bedrock. Bedrock, as it ages, has a tendency for its surface to crack and break up. These voids become filled with lower resistivity materials, and trap the water which cannot seep into the lower, solid portion of the rock. Thus, the weathered top of the bedrock layer may have resistivity values lower than those for the solid rock.

The resistivity readings for sand and gravel deposits will generally be high and uniform, while the readings for many bedrock formations will be high and erratic.

Field Equipment Used for the Measurements

Premeasured Cables

Four premeasured cables, in sets of two, are used in a typical survey. The first set is designed to measure the electrical soil resistivity to 8 m (25 ft) in 0.8 m (2.5 ft) increments and to 15.9 m (50 ft) in 1.5 m (5 ft) increments in one setting (Table 3). This is accomplished by the use of a selector switch and 26 stainless steel soil pins (Figs. 8 and 9). The second set is designed to measure the soil resistivity to 31.7 m (100 ft) in 3.2 m (10 ft) increments and to 95.2 m (300 ft) in 15.9 m (50 ft) increments (Table 4), in the same manner (Fig. 10).

Cable Design

The preceding cables are constructed from 12-conductor No. 16, Awg in a plastic sheath. Each take-off in the cable is accomplished by the use of a lead terminal, shown in Fig. 11. A test lead with clips on both sides is used to connect between each take-off and a spring type stainless steel soil pin as shown in Fig. 12. One end of each cable is terminated with one half of a connector plug (Figs. 13 and 14). The other ends are terminated in a cable holding reel as shown in Fig. 15. Two selector switches are used with these cables

TABLE 3—*Cable design for measuring electrical soil resistivity, 0.8-m (2.5-ft) and 1.5-m (5-ft) increments.*

Spacing, ft	Pin Numbers	Factor	Actual Spacing, m
2.5	12, 13, 14, 15	500	0.8
5	11, 13, 15, 16	1 000	1.6
7.5	10, 12, 15, 17	1 500	2.4
10	9, 11, 15, 18	2 000	3.2
12.5	9, 12, 16, 20	2 500	4.0
15	8, 11, 16, 21	3 000	4.8
17.5	7, 11, 17, 22	3 500	5.6
20	6, 10, 16, 22	4 000	6.3
22.5	5, 10, 17, 23	4 500	7.1
25	4, 9, 16, 23	5 000	7.9
30	4, 10, 19, 24	6 000	9.5
35	3, 8, 18, 24	7 000	11.1
40	2, 8, 19, 24	8 000	12.7
45	1, 6, 18, 25	9 000	14.3
50	1, 6, 19, 26	10 000	15.9

(Figs. 16 and 17) that contain the other half of connector plugs and a spacing selector switch as shown in Figs. 18–21.

Meter

A Nilson, Model 400 soil resistance meter is used to measure the resistance (Fig. 21). The meter is a four terminal, null balancing ohmmeter. It measures resistance from 0.01 Ω to 1.1 MΩ. The unit generates a low voltage 97 Hz square wave current between the two current electrodes. The detector, whose input is connected between the two potential electrodes, is only sensitive to 97 Hz and so is not affected by stray a-c or d-c currents. The detector senses

TABLE 4—*Cable design for measuring electrical soil resistivity, 3.2-m (10-ft) and 15.9-m (50-ft) increments.*

Spacing, ft	Pin Numbers	Factor	Actual Spacing, m
10	10, 11, 12, 13	2 000	3.2
20	9, 10, 12, 14	4 000	6.3
30	9, 11, 14, 15	6 000	9.5
40	8, 10, 14, 16	8 000	12.7
50	7, 9, 13, 16	10 000	15.9
60	6, 9, 14, 17	12 000	19.0
70	7, 10, 15, 19	14 000	22.2
80	6, 10, 16, 20	16 000	25.4
90	5, 9, 15, 20	18 000	27.0
100	4, 9, 16, 21	20 000	31.7
150	3, 7, 16, 22	30 000	47.6
200	2, 7, 18, 23	40 000	63.5
250	2, 9, 22, 24	50 000	79.4
300	1, 4, 21, 24	60 000	95.2

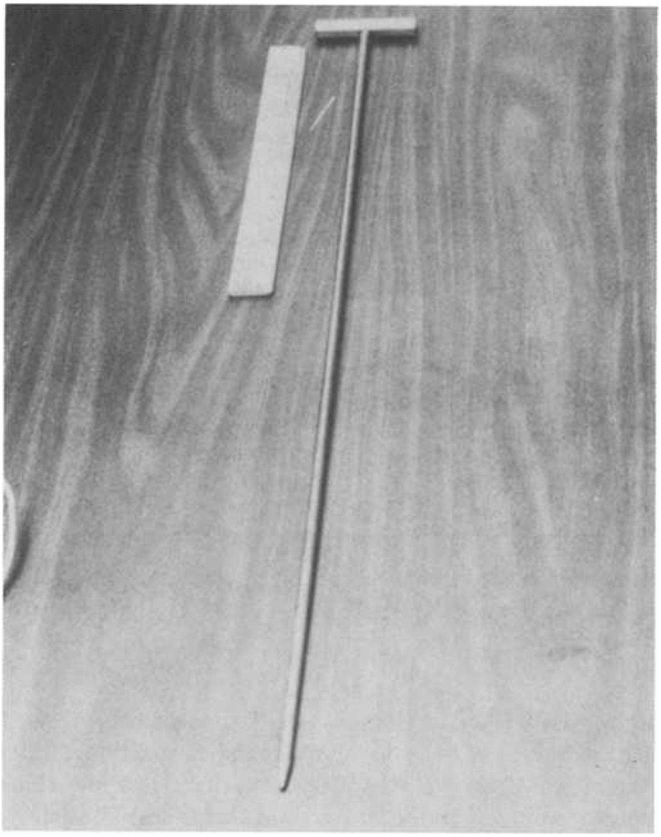


FIG. 8—*Stainless steel soil pin.*

the voltage drop between the two potential electrodes, compares it to internal standard resistors, and indicates a difference on the null detector. When the null detector is balanced, using the range switch and the dial, the resistance in ohms between the inner electrodes is the dial reading multiplied by the range switch position.

Computer Program

A computer program was used to calculate the average soil resistivity at each test location and at each increment depth. The same program includes the computation of the Barnes layer soil resistivity for each step.

Another computer program was used to plot the data in four different ways.

1. Average soil resistivity for individual locations.
2. Layer soil resistivity for individual locations.

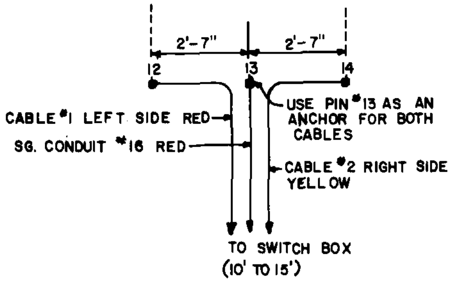


FIG. 9*a*—*Field equipment setup.*

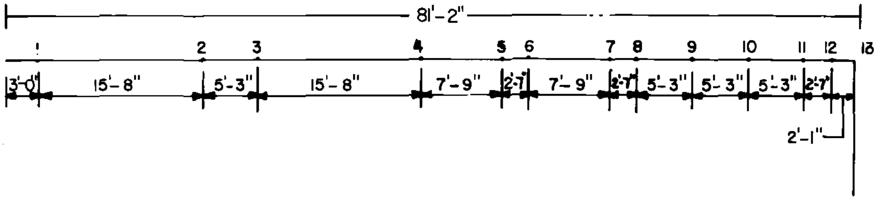


FIG. 9*b*—*Cable No. 1 left side red.*

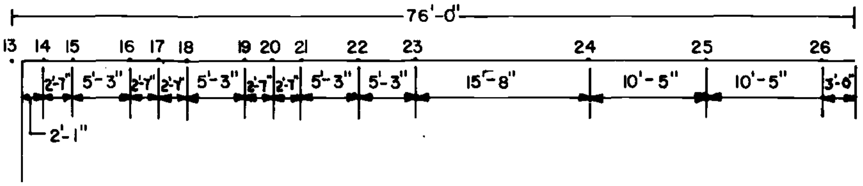


FIG. 9*c*—*Cable No. 2 right side yellow.*

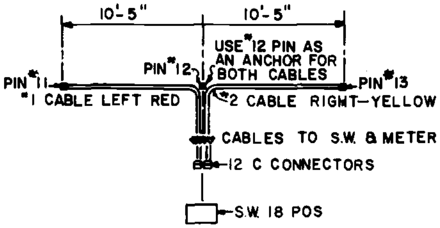


FIG. 10*a*—*Field equipment setup.*

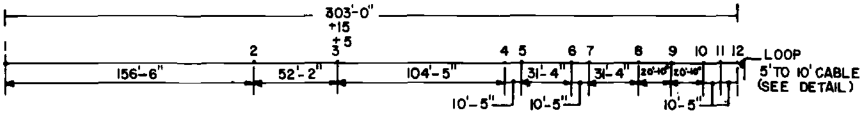


FIG. 10*b*—*Cable No. 1 left side red.*

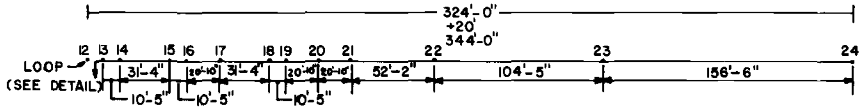


FIG. 10*c*—*Cable No. 2 right side yellow.*

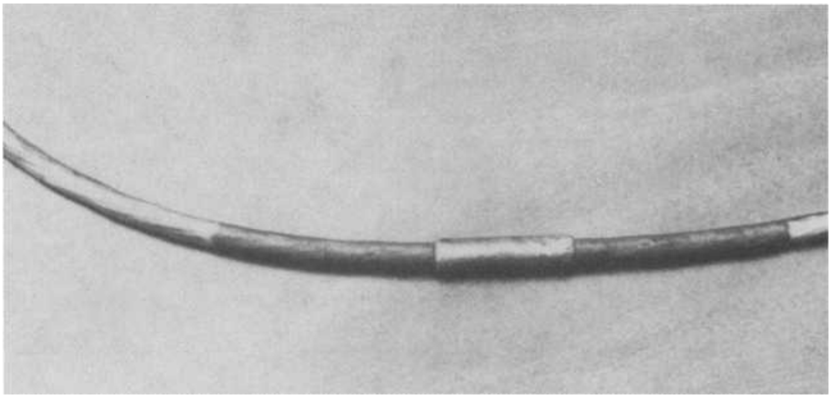


FIG. 11—*Lead terminal.*

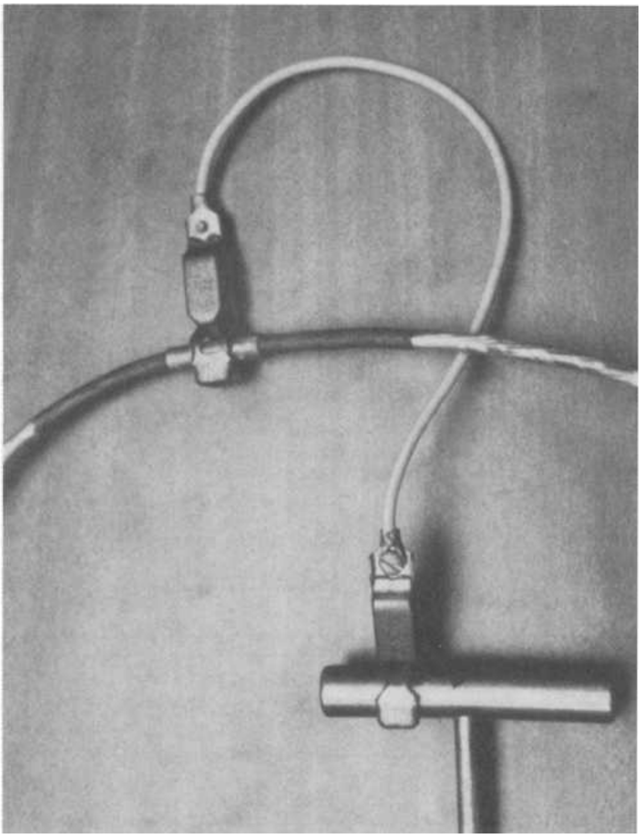


FIG. 12—*Test lead.*

3. Average soil resistivity at each individual depth, for all of the surveyed locations.

4. Layer soil resistivity at each individual layer, for all of the surveyed locations.

Examples are seen in Figs. 23–38.

Conclusion

It is clear that these methods correlate very well with the actual boring logs, as shown on the computer sheets.

It has been proven repeatedly that the field work using these cables saves at least 75 percent of the field time to achieve the same results without their use. The computer program achieves similar savings in office time when compared with the production of the same work manually.

In closing, the complete package of the field equipment and the computer program produces a very important, accurate, and reliable information that is necessary to complete any soil studies.

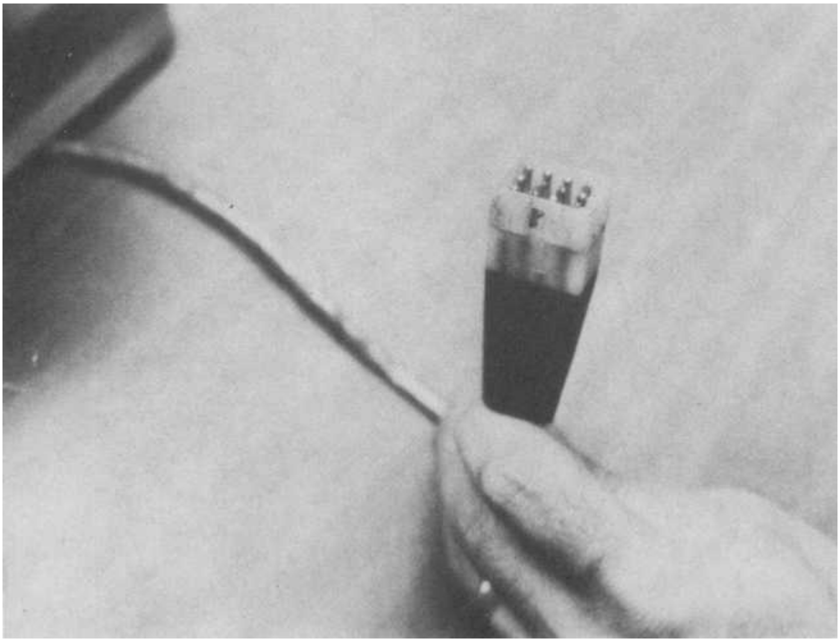


FIG. 13—*One half of a connector plug.*

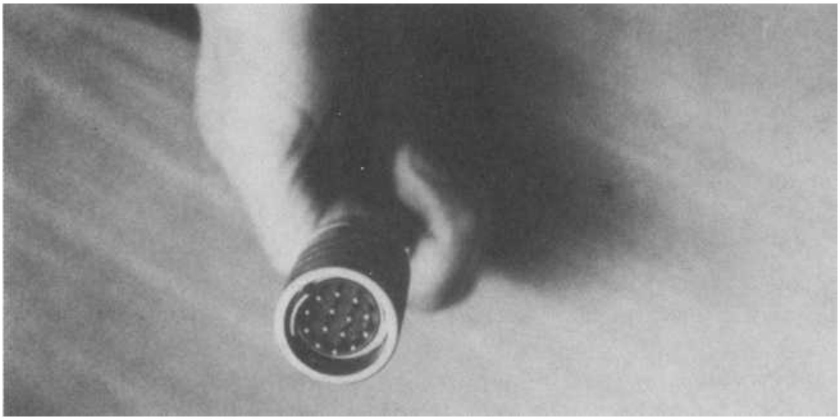


FIG. 14—*One half of a connector plug.*

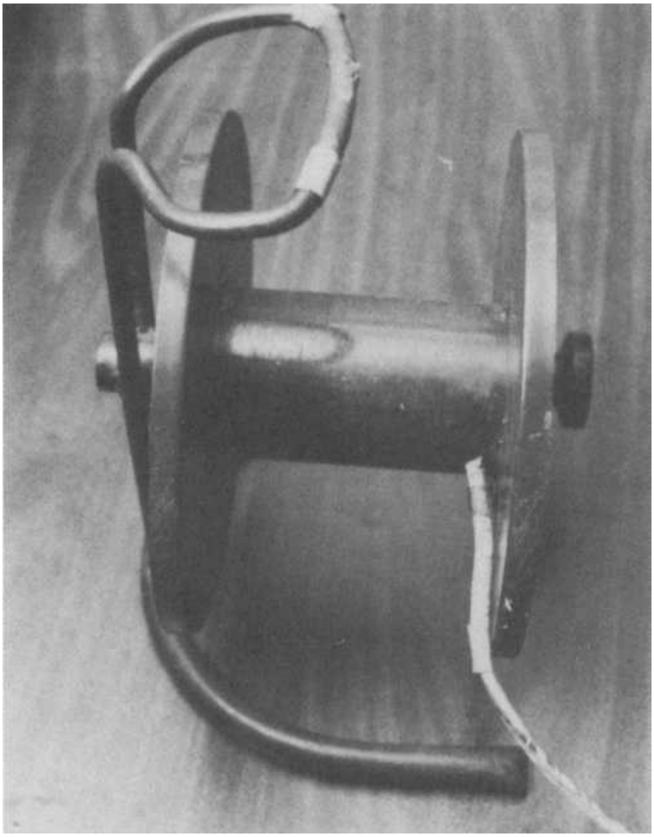


FIG. 15—*Cable holding reel.*

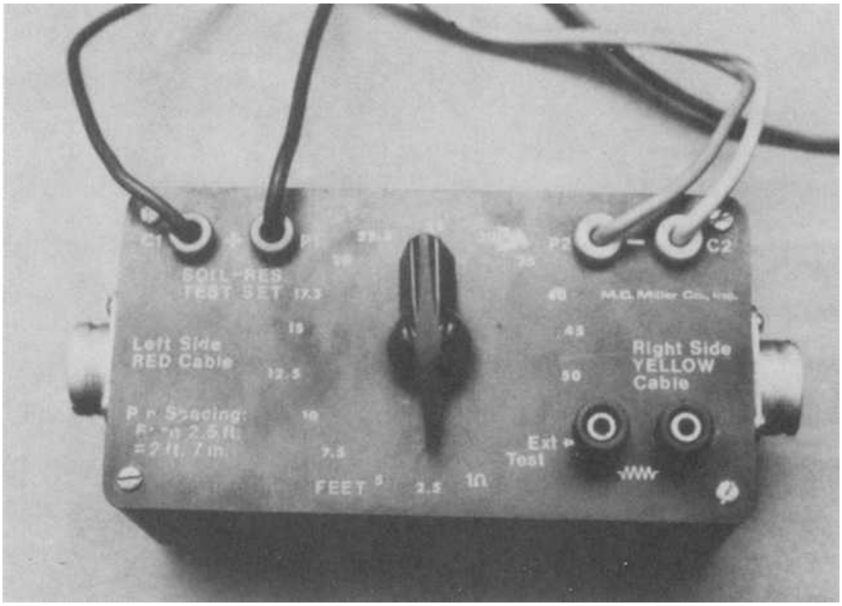


FIG. 16—*Selector switch.*

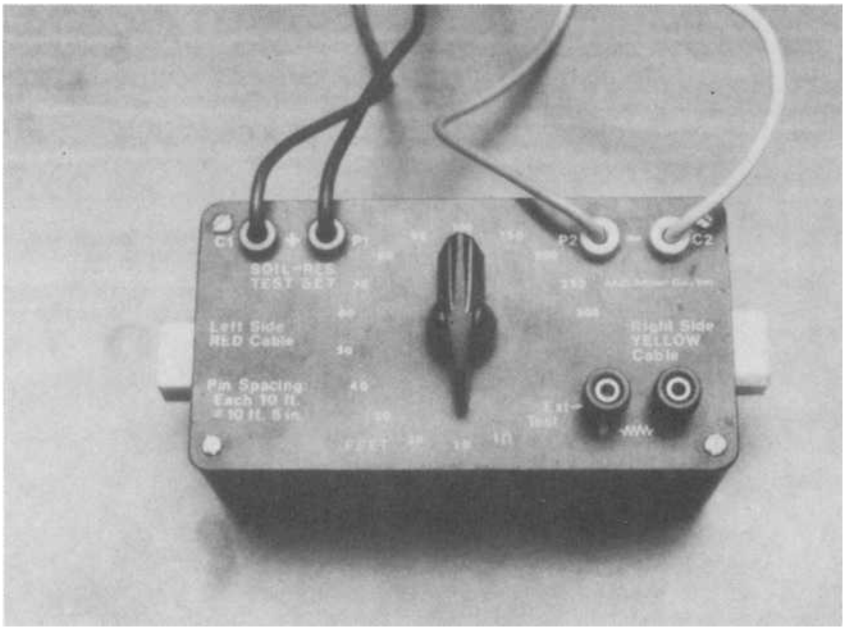


FIG. 17—*Selector switch.*

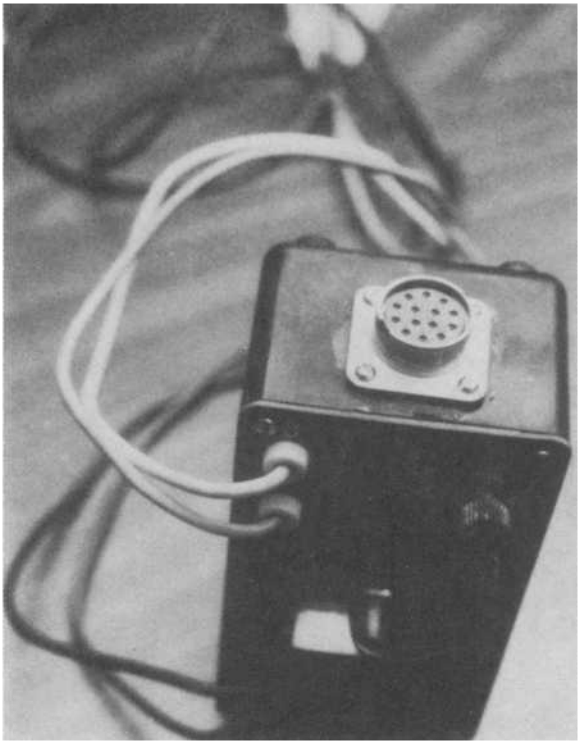
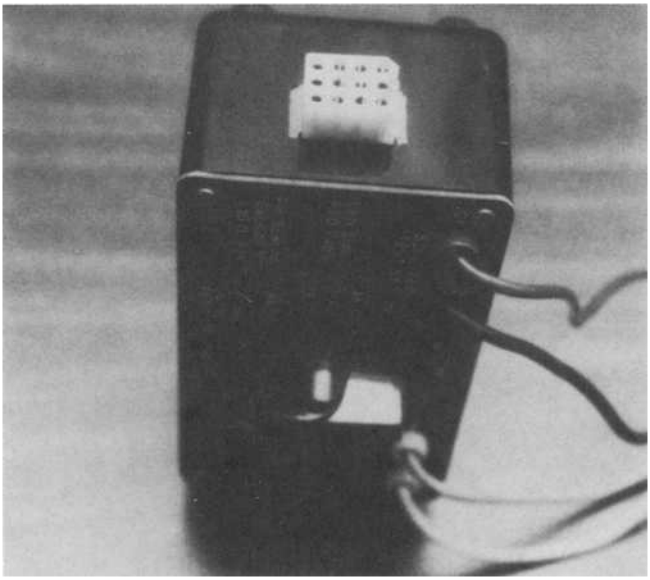


FIG. 18—*Other half of connector plug.*



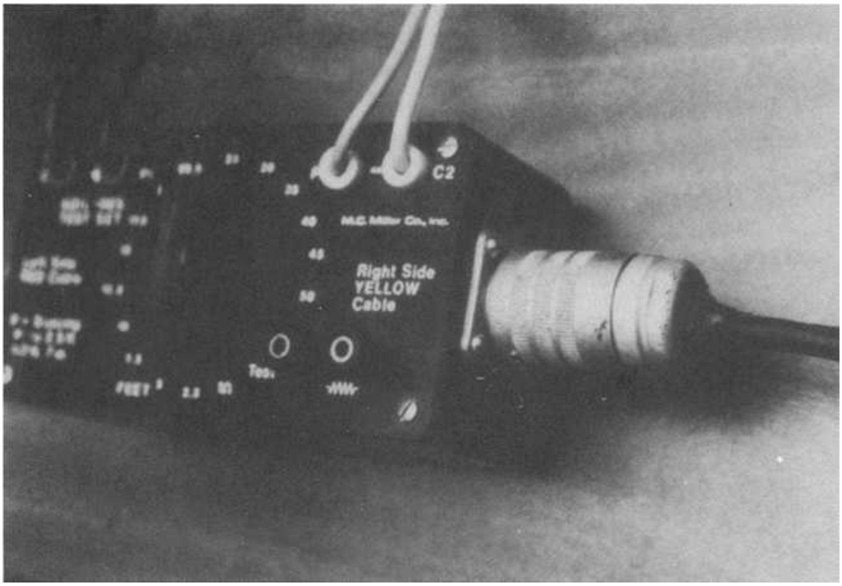


FIG. 20—*Connector plugs and spacing selector switch.*

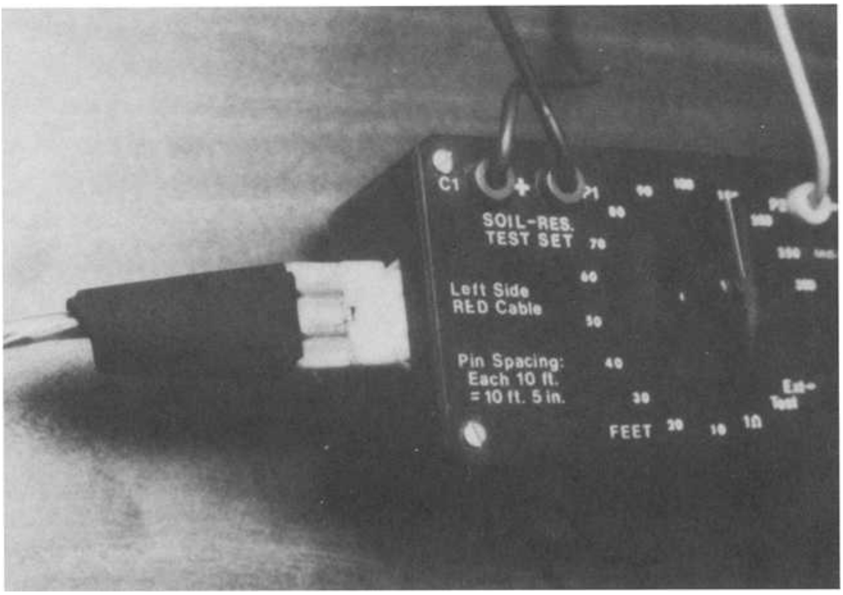


FIG. 21—*Connector plugs and spacing selector switch.*

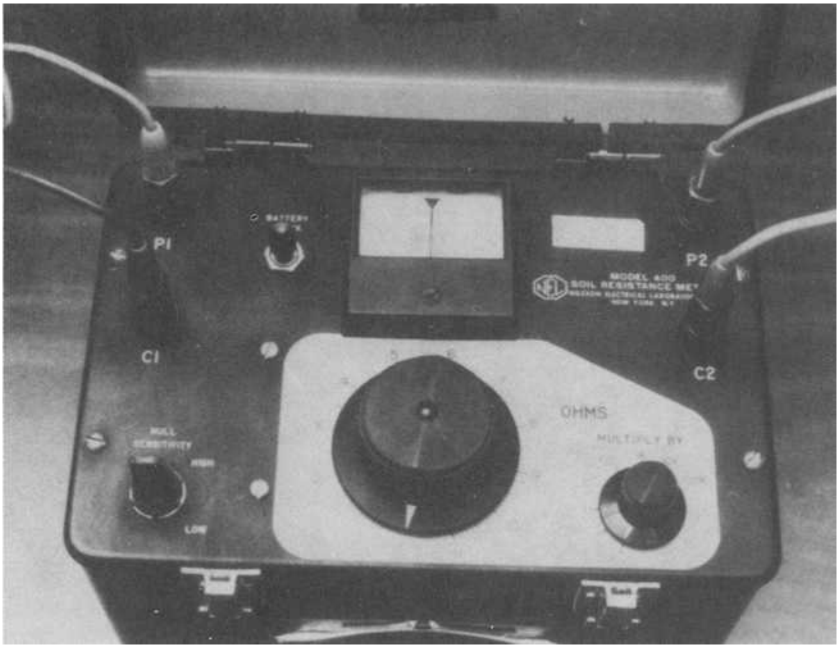
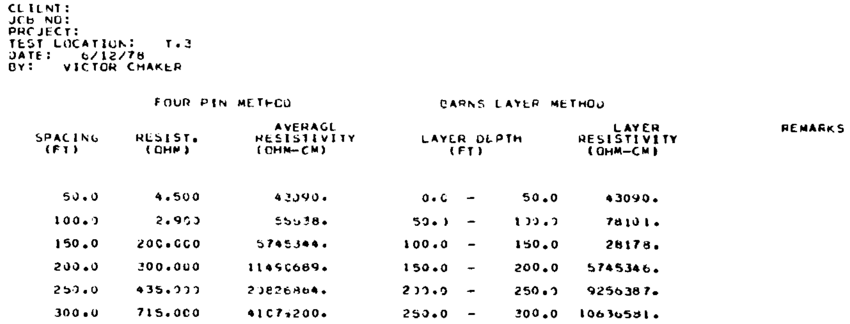


FIG. 22—*Nilson Model 400 soil resistance meter.*



```
CLIENT:
JOB NO:
PROJECT:
TEST LOCATION:   T.3
DATE:    6/12/78
BY:    VICTOR CHAKER

              FOUR PIN METHOD                    BARNES LAYER METHOD

                             AVERAGE                                       LAYER                    REMARKS
 SPACING       RESIST.      RESISTIVITY        LAYER DEPTH              RESISTIVITY
  (FT)          (OHM)       (OHM-CM)              (FT)                   (OHM-CM)


   50.0         4.500          43090.         0.0   -     50.0            43090.
  100.0         2.900          55538.        50.0   -    100.0            78101.
  150.0       200.000        5745344.       100.0   -    150.0            28178.
  200.0       300.000       11490689.       150.0   -    200.0          5745346.
  250.0       435.000       20826864.       200.0   -    250.0          9256387.
  300.0       715.000       41077200.       250.0   -    300.0         10636581.
```

FIG. 23—*Computer output for the top 95.2 m (300 ft).*

```
CLIENT:
JOB NO:
PROJECT:
TEST LOCATION:    T.3
DATE:    6/12/78
BY:    VICTOR CHAKER

           FOUR PIN METHOD                     BARNS LAYER METHOD

                             AVERAGE                                   LAYER
SPACING    RESIST.        RESISTIVITY        LAYER DEPTH           RESISTIVITY
 (FT)       (OHM)          (OHM-CM)             (FT)                (OHM-CM)

   2.5     150.000          71817.          0.0  -       2.5        71817.
   5.0     120.000         114907.          2.5  -       5.0       287267.
   7.5     100.000         143634.          5.0  -       7.5       287267.
  10.0      72.500         138846.          7.5  -      10.0       126223.
  12.5      49.500         113498.         10.0  -      12.5        74705.
  15.0      35.500         101980.         12.5  -      15.0        60095.
  17.5      25.000          83786.         15.0  -      17.5        40468.
  20.0      17.500          67029.         17.5  -      20.0        27929.
  22.5      12.500          53863.         20.0  -      22.5        20947.
  25.0      10.000          47878.         22.5  -      25.0        23939.

POINT NUMBER:    03
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Compared to Boring Log E_{70}

REMARKS

SOIL MATERIAL	RESISTIVITY OHM-CM
Very Loose Black Silty Sand- Trace Of Organic Roots	10,000 - 100,000
Very Loose to Loose Dark Brown Medium Sand- Trace of Gravel and Silt	10,000 - 100,000
Medium Dense to Very Dense Brown Sand	3,000 - 300,000
Medium Hard Tan to Light Brown Very Broken to Slightly Broken Line Sand Stone. Poorly Cemented, Stained with Iron Oxide	3,000 - 300,000

FIG. 24—*Computer output for the top 8.2 m (25 ft), and corrolation with the boring results.*

```
CLIENT:
JOB NO:
PROJECT:
TEST LOCATION:    T.3
DATE:    6/12/78
BY:    VICTOR CHAKER

              FOUR PIN METHOD                      BARNS LAYER METHOD

                                AVERAGE                                      LAYER                REMARKS
  SPACING     RESIST.         RESISTIVITY          LAYER DEPTH            RESISTIVITY
   (FT)        (OHM)           (OHM-CM)               (FT)                 (OHM-CM)              SOIL MATERIAL      RESISTIVITY OHM-CM

      5.0     120.000          114907.          0.0   -     5.0            114907.               Sand, Stone         3,000 - 300, 000
     10.0      72.500          138846.          5.0   -    10.0            175384.
     15.0      35.500          101980.         10.0   -    15.0             66608.
     20.0      17.500           67029.         15.0   -    20.0             33049.
     25.0      10.000           47878.         20.0   -    25.0             22343.
     30.0       9.700           55730.         25.0   -    30.0            309612.
     35.0       7.500           50272.         30.0   -    35.0             31665.
     40.0       5.000           38302.         35.0   -    40.0             14363.
     45.0       4.500           38781.         40.0   -    45.0             43090.
     50.0       5.300           50751.         45.0   -    50.0             28547.

PCINT NUMBER:    03
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FIG. 25—*Computer output for the top 15.9 m (50 ft), and corrolation with the boring results.*

```
CLIENT:
JOB NO:
PROJECT:
TEST LOCATION:    T.3
DATE:    6/12/78
BY:    VICTOR CHAKER

               FOUR PIN METHOD                  BARNS LAYER METHOD
                             AVERAGE                               LAYER            REMARKS
  SPACING     RESIST.     RESISTIVITY       LAYER DEPTH         RESISTIVITY
   (FT)        (OHM)       (OHM-CM)            (FT)              (OHM-CM)
                                                                                  SOIL MATERIAL          RESISTIVITY OHM-CM
   10.0       72.500       138846.        0.0  -    10.0        138846.
   20.0       17.500        67029.       10.0  -    20.0         44178.
   30.0        9.700        55730.       20.0  -    30.0         41678.
   40.0        5.000        38302.       30.0  -    40.0         19762.
   50.0        4.500        43090.       40.0  -    50.0         86180.     Fine Sand Stone with     3,000 - 300,000
   60.0        4.350        45984.       50.0  -    60.0        249924.     Thin Layers of Shale
   70.0        3.200        42899.       60.0  -    70.0         23181.
   80.0        2.750        42133.       70.0  -    80.0         37451.     End of Boring 65.2'
   90.0        2.700        46537.       80.0  -    90.0        284392.
  100.0        2.900        55538.       90.0  -   100.0         74977.

PCINT NUMBER:    03
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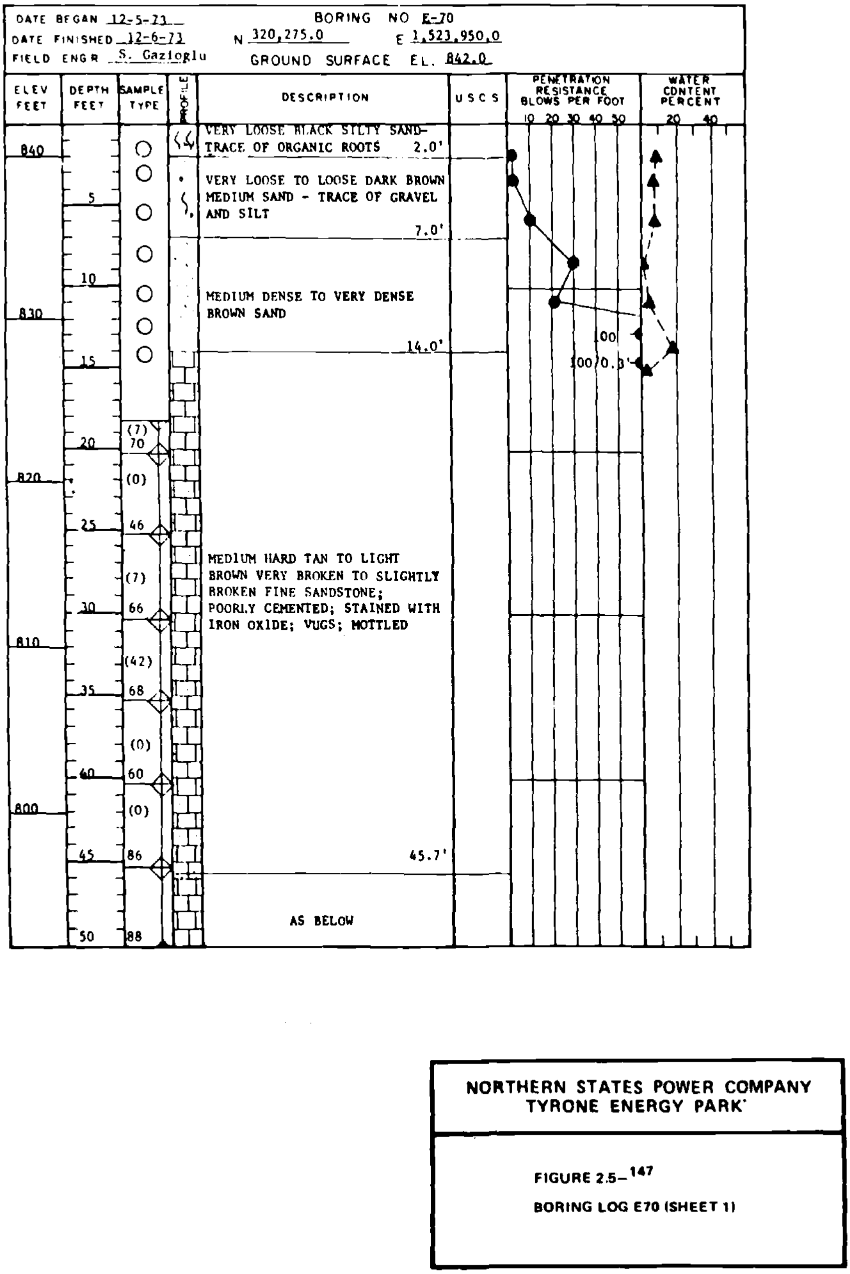
FIG. 26—*Computer output for the top 31.7 m (100 ft), and corrolation with the boring results.*



DATE BEGAN 12-5-71

DATE FINISHED 12-6-71

FIELD ENGR S. Gazioglu

BORING NO E-70

N 320,275.0

E 1,523,950.0

GROUND SURFACE EL. 842.0

VERY LOOSE BLACK SILTY SAND-TRACE OF ORGANIC ROOTS 2.0'

VERY LOOSE TO LOOSE DARK BROWN MEDIUM SAND - TRACE OF GRAVEL AND SILT 7.0'

MEDIUM DENSE TO VERY DENSE BROWN SAND 14.0'

MEDIUM HARD TAN TO LIGHT BROWN VERY BROKEN TO SLIGHTLY BROKEN FINE SANDSTONE; POORLY CEMENTED; STAINED WITH IRON OXIDE; VUGS; MOTTLED 45.7'

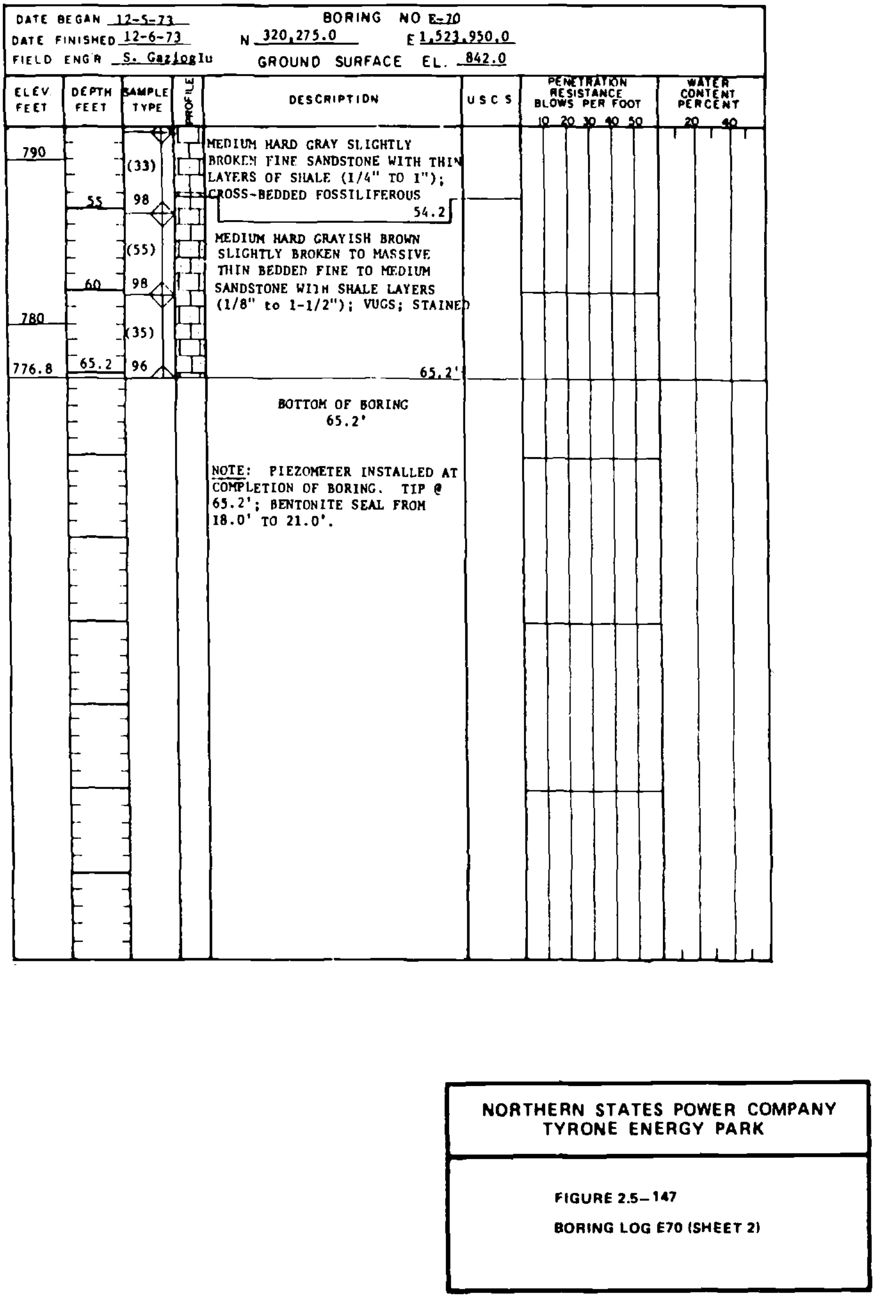
AS BELOW

NORTHERN STATES POWER COMPANY
TYRONE ENERGY PARK'

FIGURE 2.5-147

BORING LOG E70 (SHEET 1)

FIG. 27—*Boring logs.*



DATE BEGAN 12-5-73
DATE FINISHED 12-6-73
FIELD ENG'R S. Gazioglu

BORING NO E-70
N 320,275.0 E 1,523,950.0
GROUND SURFACE EL. 842.0

ELEV. FEET	DEPTH FEET	SAMPLE TYPE	PROFILE	DESCRIPTION	USCS	PENETRATION RESISTANCE BLOWS PER FOOT 10 20 30 40 50	WATER CONTENT PERCENT 20 40
790		(33)		MEDIUM HARD GRAY SLIGHTLY BROKEN FINE SANDSTONE WITH THIN LAYERS OF SHALE (1/4" TO 1"); CROSS-BEDDED FOSSILIFEROUS			
	55	98		54.2			
		(55)		MEDIUM HARD GRAYISH BROWN SLIGHTLY BROKEN TO MASSIVE THIN BEDDED FINE TO MEDIUM SANDSTONE WITH SHALE LAYERS (1/8" to 1-1/2"); VUGS; STAINED			
	60	98					
780		(35)					
776.8	65.2	96		65.2'			
				BOTTOM OF BORING 65.2'			
				NOTE: PIEZOMETER INSTALLED AT COMPLETION OF BORING. TIP @ 65.2'; BENTONITE SEAL FROM 18.0' TO 21.0'.			

NORTHERN STATES POWER COMPANY
TYRONE ENERGY PARK

FIGURE 2.5-147
BORING LOG E70 (SHEET 2)

FIG. 28—*Boring logs.*

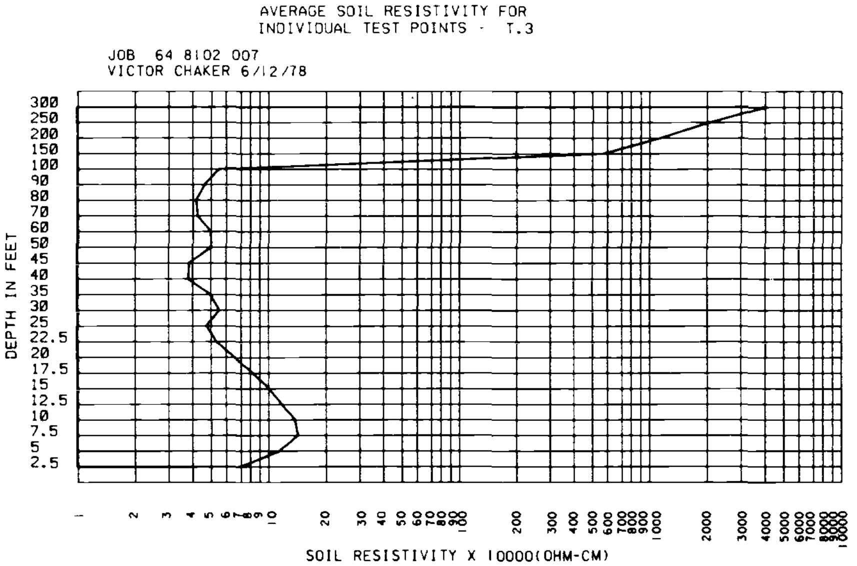


FIG. 29—*Plot of the average soil resistivity for individual test point.*

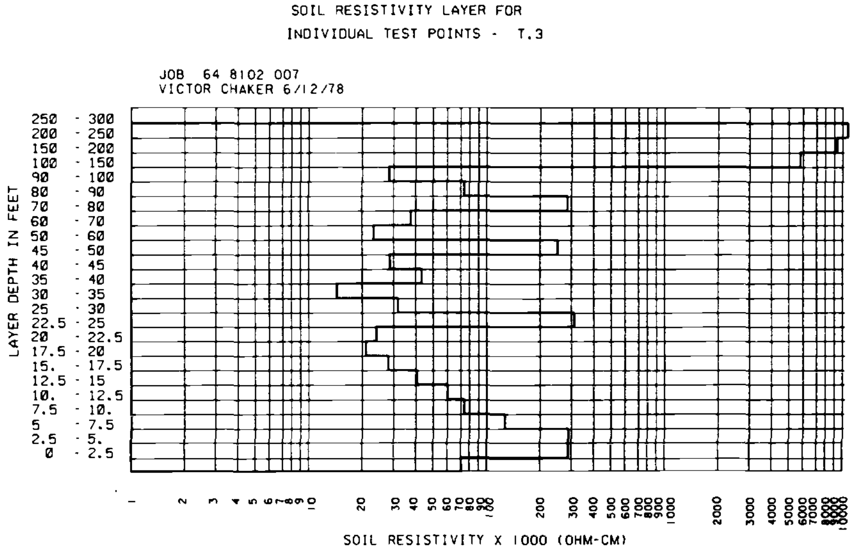


FIG. 30—*Plot of the layer soil resistivity for individual test point.*

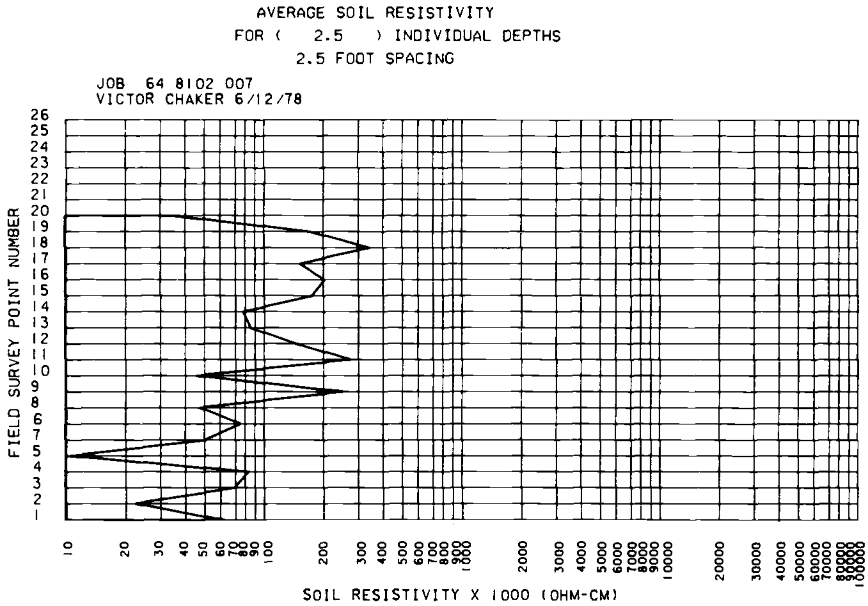


FIG. 31—*Plot of the average soil resistivity at 0.8 m (2.5 ft) depth for all of the surveyed locations.*

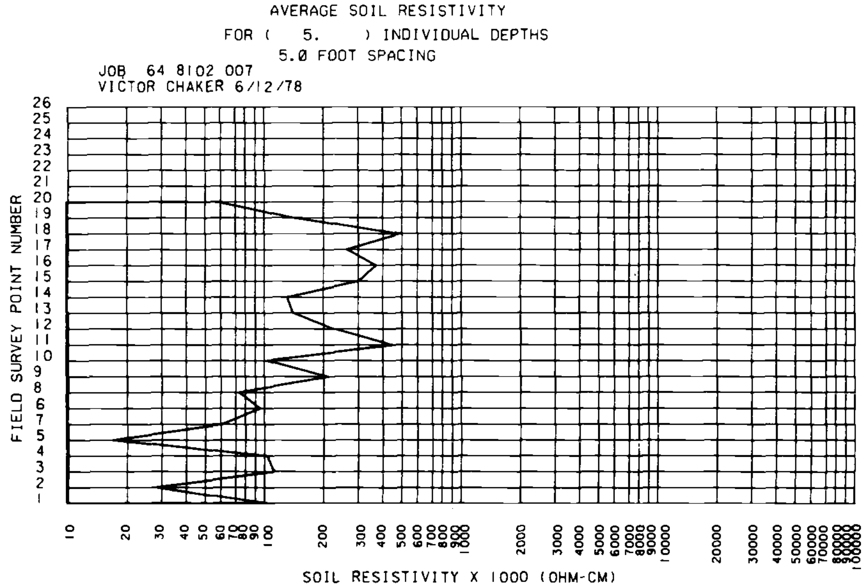


FIG. 32—*Plot of the average soil resistivity at 1.6 m (5 ft) depth for all of the surveyed locations.*

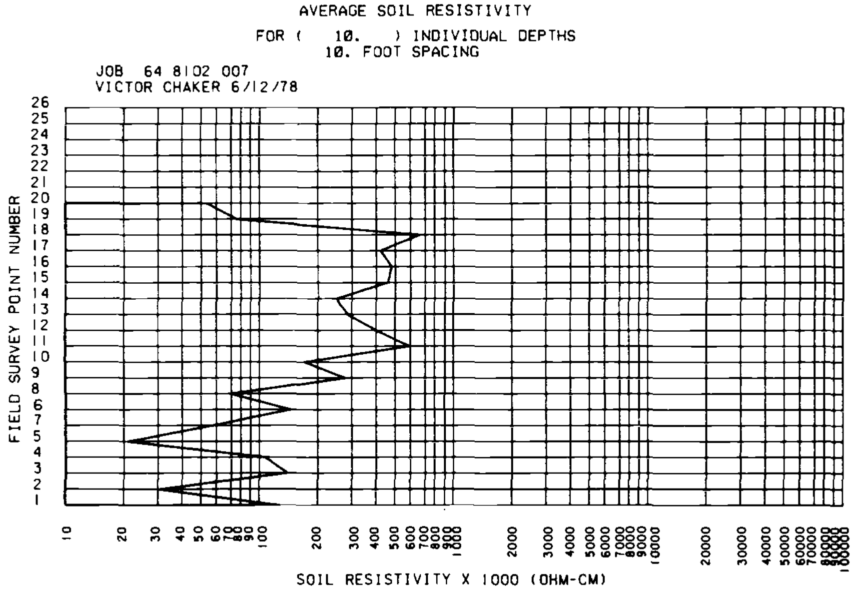


FIG. 33—*Plot of the average soil resistivity at 3.2 m (10 ft) depth for all of the surveyed locations.*

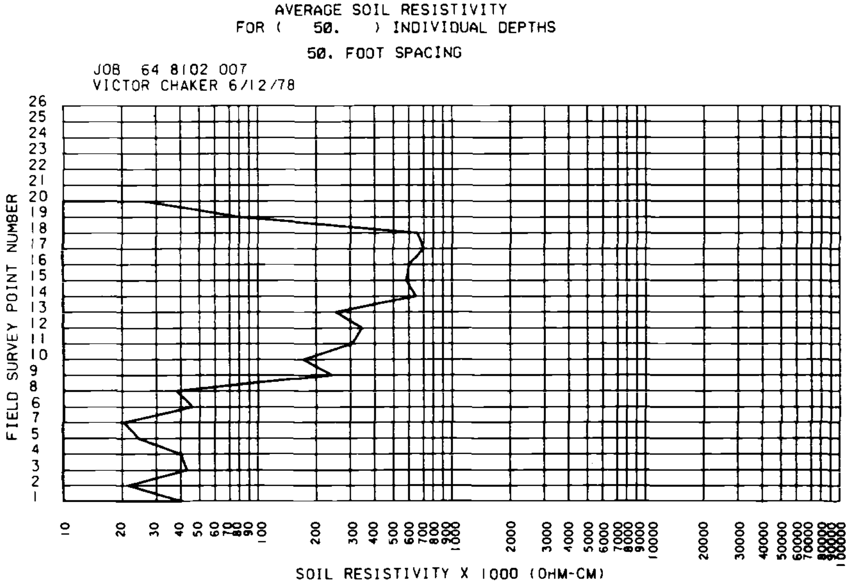


FIG. 34—*Plot of the average soil resistivity at 15.9 m (50 ft) depth for all of the surveyed locations.*

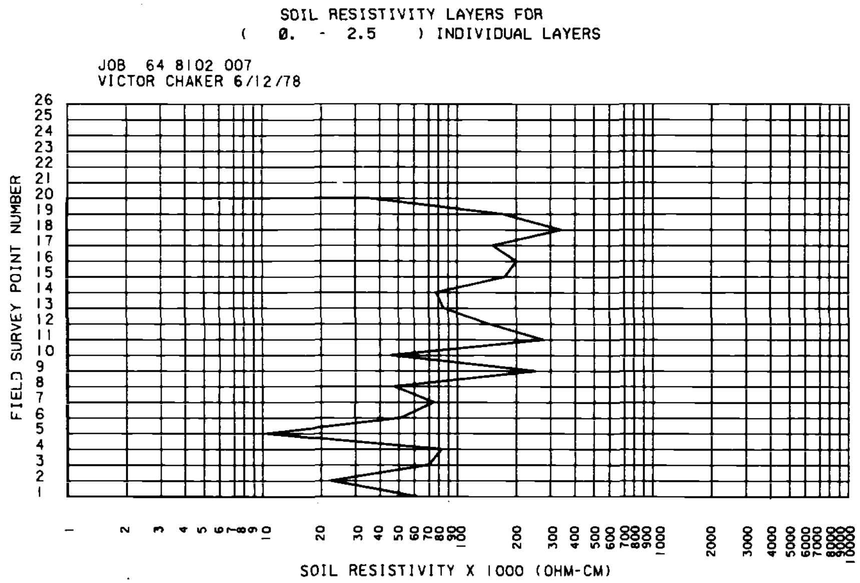


FIG. 35—*Plot of the 0 to 0.8 m (0 to 2.5 ft) layer soil resistivity for all of the surveyed locations.*

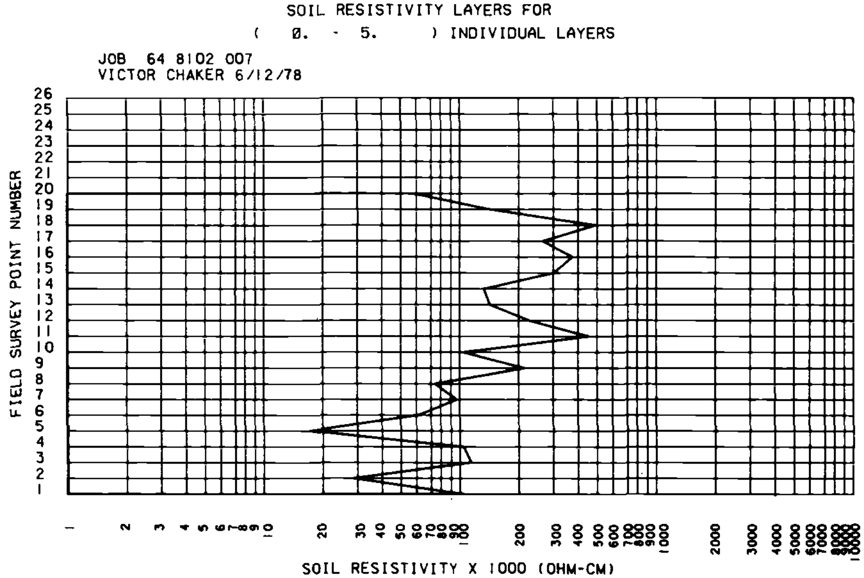


FIG. 36—*Plot of the 0 to 1.6 m (0 to 5 ft) layer soil resistivity for all of the surveyed locations.*

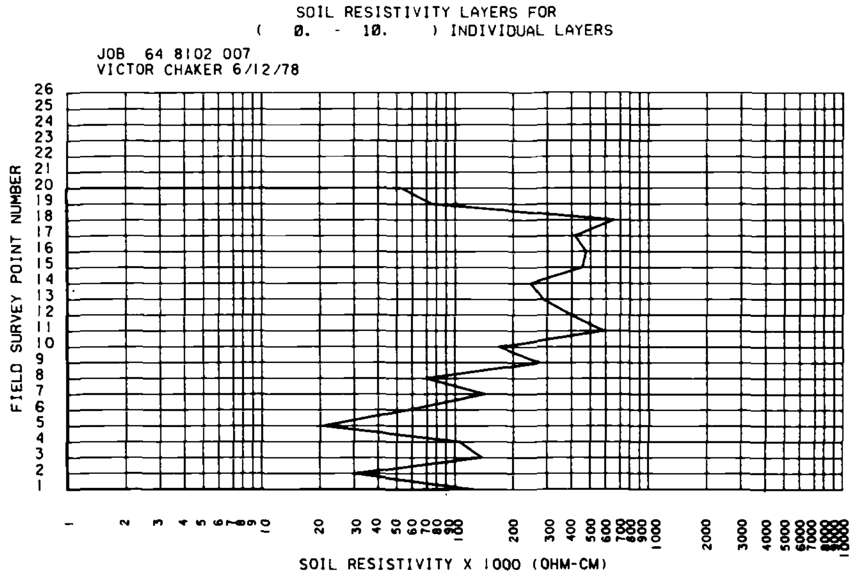


FIG. 37—*Plot of the 0 to 3.2 m (0 to 10 ft) layer soil resistivity for all of the surveyed locations.*

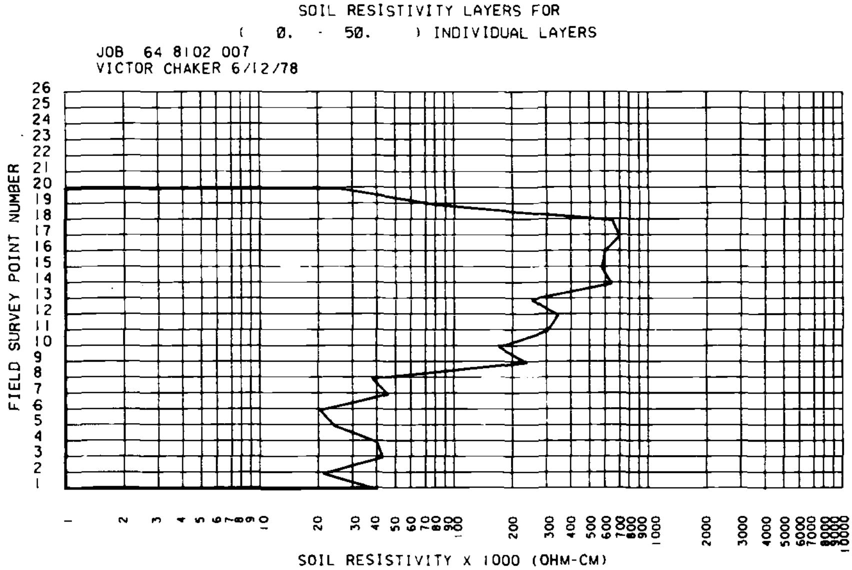


FIG. 38—*Plot of the 0 to 15.9 m (0 to 50 ft) layer soil resistivity for all of the surveyed locations.*

References

[*1*] Uhlig, H. H., *Corrosion and Corrosion Control,* Wiley, New York, 1953.

[*2*] Wenner, Frank, "A Method of Measuring Earth Resistivity," NBS Bulletin No. 12 (469), National Bureau of Standards.

[*3*] "Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method," ANSI/ ASTM G 57-78, American Society for Testing and Materials, 1978.

[*4*] Barnes, H. E., *Electrical Survey Detects Underground Rock,* Pipeline Industry, April, 1959.

[*5*] *The Application of Geophysics to Highway Engineering,* Michigan State Highway Department, 1964.

[*6*] Peabody, A. W., *Control of Pipeline Corrosion,* National Association of Corrosion Engineers, 1967.

[*7*] *Earth Resistivity Manual,* Soiltest, Inc., Evanston, Ill., 1968.

S. A. Arcone[1]

Some Field Studies of the Correlation Between Electromagnetic and Direct Current Measurements of Ground Resistivity

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REFERENCE: Arcone, S. A., "**Some Field Studies of the Correlation Between Electromagnetic and Direct Current Measurements of Ground Resistivity,**" *Underground Corrosion, ASTM STP 741,* Edward Escalante, Ed., American Society for Testing and Materials, 1981, pp. 92–110.

ABSTRACT: Electromagnetic (em) and direct-current (d-c) methods of measuring ground resistivity have been compared at permafrost and nonpermafrost sites. The em methods utilized the principles of magnetic induction and plane wave surface impedance. Layered ground models were derived from the d-c sounding data, and the theoretical values of the em methods for these models were compared with the em field results. Both em methods correlated well with the d-c data in the two cases of simple, multilayered ground of large extent. In several cases of resistive inhomogeneities, the magnetic induction data correlated well with the d-c data. In one case of a resistive inhomogeneity, the surface impedance responded well only qualitatively and may have given some false indications of resistive substructure. It appears that in all cases where the volume of exploration was comparable, there was reasonable correlation. It is estimated that the standard data analysis procedure which assumes layering of infinite extent will apply well for the surface impedance method when disturbances in the local layering are greater than a skin depth away from the point of measurement; and for the magnetic induction method when disturbances in the layering are at a distance from the interloop axis that is greater than the interloop separation.

KEY WORDS: resistivity surveying, electromagnetic resistivity surveying, plane wave exploration methods, magnetic induction, surface impedance, underground corrosion

This paper presents a general discussion with specific field examples of the use of the electromagnetic (em) methods of magnetic induction and plane wave surface impedance for measuring direct-current (d-c) ground conductivity and resolving its variations. These principles have been recently utilized by commercial manufacturers for developing noncontact methods for rapid resistivity surveying. Present instruments operate at frequencies between 1 and 400 kHz. Hoekstra et al [*1*],[2] Arcone et al [*2,3*], Hoekstra [*4*], and Rennie

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[1] Research geophysicist, United States Army Cold Regions Research and Engineering Laboratory, Hanover, N.H. 03755.

[2] The italic numbers in brackets refer to the list of references appended to this paper.

et al [5] have discussed their use for permafrost, but their use in temperate zones has been rarely discussed in the literature. Although these instruments were developed primarily for geophysical exploration, they are equally as useful to the engineering community for resolving variations in d-c conductivity under many circumstances. This paper will discuss some of these circumstances and present some field studies in which d-c and em results are compared.

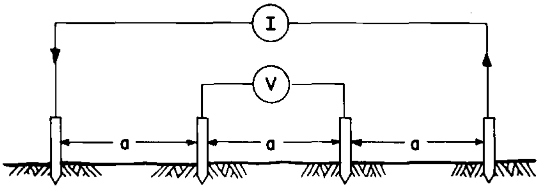
General discussions of ground resistivity are available in numerous texts and articles and will not be discussed here. Therefore, the report will begin with a discussion of d-c and em methods and some limitations of the latter.

Field Techiques for Measuring Ground Resistivity

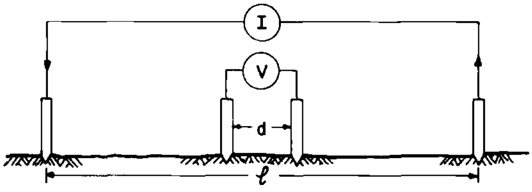
Direct-Current (d-c) Methods

All d-c methods utilize earth contact electrodes which deliver a current into the ground. Separate electrodes are then used to measure a resulting potential gradient. The comparison of voltage to current is utilized in determining a ground conductivity in mhos/m (Siemens/m), or its inverse, ground resistivity in ohm-metre (Ωm). Various electrode configurations are designed for obtaining geometric information about horizontal and vertical resistivity structure.

Most commonly in geophysical exploration, the four electrode, linear Schlumberger and Wenner arrays are used (Fig. 1). In these arrays, current *I* is delivered and received between the outer electrodes and the voltage differ-



a. Wenner



b. Schlumberger

FIG. 1—*Common direct current, multi-electrode arrays used in resistivity surveying. In the Schlumberger array* d *is usually held constant while* l *is increased.*

ence, V, is determined between the inner electrodes. For the Wenner array, which was utilized for the studies of this report, an apparent resistivity ρ_a is computed from the formula

$$\rho_a = 2\pi a \frac{V}{I} \tag{1}$$

where a is the interelectrode spacing. The quantity a is varied to make a sounding, and the data are then compared with theoretical models to derive resistivity information with depth. Sometimes the array is moved as a unit to profile the horizontal resistivity changes.

Modern equipment is designed to overcome two major obstacles in making a measurement. The first is excessive resistance caused by poor contact between electrode and ground and almost always occurs with hard rock or permafrost. In these cases either holes must be drilled for the electrodes and filled with a salt solution of the electrode metal (for example, copper sulfate for copper electrodes), or porous pot electrodes can be used. The second obstacle is natural earth currents. These are eliminated by using an extremely low frequency instead of d-c (for example, 10 Hz or less) and averaging the readings over many cycles. This also eliminates any electrode buildup caused by ion migration in the ground. For these studies a Huntec[3] Lopo Mark 3 transmitter and Mark 3 receiver was used.

Electromagnetic (em) Methods

Magnetic Induction

This method is widely used in geophysical exploration in a variety of patented systems. A primary magnetic field is established within the ground with a transmitting loop or long wire antenna. This field induces earth currents which produce a secondary magnetic field that is then detected with a receiver loop. Over strongly conducting bodies such as ore deposits, this secondary field will be relatively strong.

In certain situations, the ratio of secondary (B_s) to primary (B_p) field strength can be related to ground resistivity. Figure 2 depicts the portable instrument (Geonics Ltd. EM-31[4]) used in these studies. The particular model used operated at 40 kHz using loop antennas to transmit and receive. The ratio B_s/B_p depends on ground conductivity but also interloop separation and orientation, loop height above ground, and transmitter frequency.

The quantity measured is the mutual impedance, Z, which may be normalized by the mutual impedance Z_o between loops in free space. The quantity Z is defined as V/I where V is the voltage induced in the receiver loop and I is the current in the transmitter loop. At very low frequencies the normalized

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[3] Huntec Limited, Toronto, Ontario.

[4] Geonics Ltd., Mississauga, Ontario.

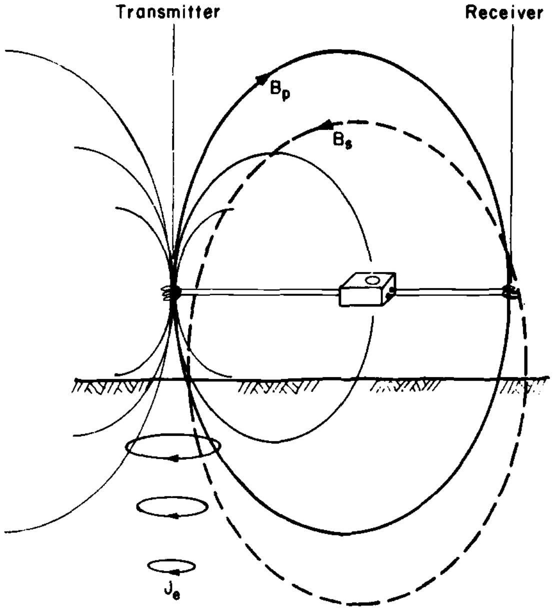

FIG. 2—*Portable magnetic induction unit and associated fields and currents during operation. The primary field* B_p *induces eddy curents* Je *in the ground. These in turn produce a secondary magnetic field* B_s. *The ratio* B_s/B_p *is indirectly measured by the receiver and is related to the ground conductivity.*

quadrature phase mutual impedance Z_q/Z_o for two horizontal coplanar loop antennas upon a homogeneous model earth is linearly proportional to conductivity and can be expressed by the formula

$$\frac{Z_q}{Z_o} = i\,\frac{\pi f \mu_o r^2 \sigma}{2} \tag{2}$$

where

r = interloop separation,
f = operating frequency in Hz,
μ_o = free space permeability ($4\pi \times 10^{-7}$) Henry/m,
σ = conductivity, and
$i = \sqrt{-1}$.

This equation is an approximation of an equation developed in Keller and Frischknecht [*6*] and is valid for when $r/\delta < 1$, where δ is known as the skin depth and is expressed as

$$\delta = \sqrt{\rho/\pi f \mu_o} \tag{3}$$

where ρ is resistivity in Ωm, and equals $1/\sigma$. The quantity δ is the depth at which any of the electromagnetic field components will have exponentially attenuated to e^{-1} of their value at the surface.

When the earth is layered, an apparent resistivity must then be defined which corresponds to the equivalent resistivity that would produce the same modulus of mutual impedance above a homogeneous earth. Interpolation curves or computational integrations of integral equations (see for example, Sinha [*7*]) must be then used to resolve the different layer resistivities and thicknesses.

In practice, the transmitter and receiver loop antennas may be oriented horizontally (HCP) or vertically (VCP) coplanar, or even coaxially (CA) in some instruments. For these studies the Geonics EM-31 ($r = 3.66$ m; HCP, VCP) and the Geonics EM-34 ($r = 15$, 30 m; HCP, VCP) were used. The EM-31 operated at 40 kHz and the EM-34 at 1 kHz.

Plane Wave Surface Impedance

This method derives ground resistivity values from comparisons between the electromagnetic field components of propagating ground or sky waves. In the VLF band (3 to 30 kHz) powerful transmitters operated by military organizations allow radiation to be monitored over a range of several thousand kilometers. At this distance, radio waves propagate in the sky wave mode via one or more skips off the ionosphere. Within the LF-MF band (200 to 415 kHz), transmitters are available locally that radiate between 25 and 2000 W. At these low power levels, the radio waves used for surveying are usually in the ground wave mode. The reader is referred to the texts by Wait [*8*] or Budden [*9*] for general discussions of sky and ground wave modes.

The electromagnetic field components of a ground or sky wave radiated by a vertically polarized antenna are illustrated in Fig. 3. The electric field components E_x and E_z and the magnetic field component H_y are referenced to local x, y, z coordinates. The quantity of interest is the surface impedance Z_s defined as

$$Z_s = E_x/H_y|_{z=0} \tag{4}$$

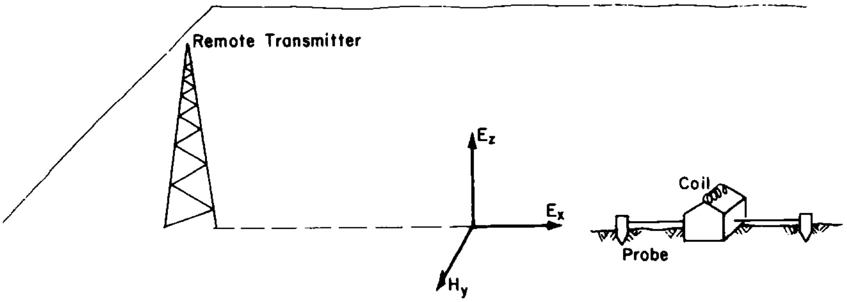

FIG. 3—*Electromagnetic field vectors of a radio ground wave propagated from a distant, vertically polarized transmitter.* H_y *is in the negative* y *direction. The instrument depicted is properly oriented for comparing* E_x *and* H_y.

Over a homogeneous model earth, ground resistivity is derived from Z_s through the relationship

$$\rho = \frac{|Z_s|^2}{2\pi f \mu_o} \tag{5}$$

In fact, Z_s is a complex quantity having phase as well as amplitude. Phase values near 45 deg usually indicate homogeneity with depth. Phase values less than 45 deg usually indicate that resistivity is increasing with depth, while values greater than 45 deg usually indicate that resistivity is decreasing with depth. Phase is always between 0 and 90 deg for a vertically stratified earth.

Simultaneous measurements at several frequencies, usually one each between 15 and 25 kHz, 200 and 415 kHz, and 550 and 1600 kHz can help resolve resistivity layering. This is because earth penetration increases with decreasing frequency and increasing resistivity. A measure of this penetration within any one material is given by the skin depth of Eq. 3.

The unit shown in Fig. 3 represents units commercially available from Geonics Ltd. for operation within both VLF and LF bands. E_x is determined from the voltage measured between two probes inserted in the ground, and H_y is determined from the current induced in a ferrite loaded coil. The input impedance of the E_x voltmeter is extremely high so that contact resistance between probes and ground does not affect the readings. For these studies the Geonics EM-16R (VLF) unit was used.

Limitations of the Techniques

In the magnetic induction method, as resistivity increases the accuracy of a measurement decreases. This results from the weak secondary magnetic fields that are generated in resistive ground. In contrast, the surface impedance method is less accurate at low resistivities because of the weaker electric fields induced in the ground by the advancing wave. At high resistivities, although the measurement may be accurate, it may be also influenced by the dielectric properties of the ground. For a homogeneous ground model of resistivity, ρ, and relative dielectric permittivity, κ, the surface impedance Z_s may be found from the formula

$$Z_s = 1 \Bigg/ \sqrt{\frac{\kappa \epsilon_o}{\mu_o} - i \frac{1}{\omega \mu_o \rho}} \tag{6}$$

Figure 4 shows the change in apparent resistivity ρ_a and phase, ϕ, as a function of κ at two frequencies above a homogeneous earth of 10 000 Ωm resistivity. As κ increases, both ρ_a and ϕ decrease, but most dramatically at 300 kHz for κ-values greater than 10. In layering situations, ρ_a and ϕ may increase or decrease as κ increases for any one layer. Since most earth materials

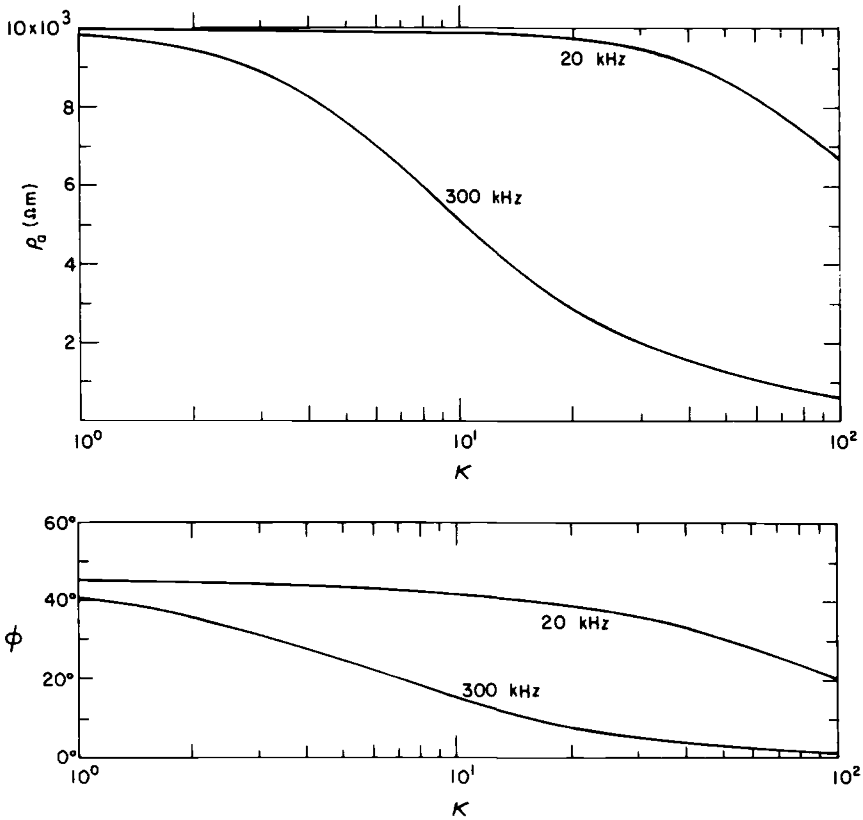

FIG. 4—*The effect of increasing dielectric constant* κ *upon apparent resistivity* ρ_a *and phase* ϕ *at 300 kHz and 20 kHz for homogeneous earth model of 10 000 Ωm resistivity.*

are generally less than 10 000 Ωm, measurements in the VLF range are marginally affected by dielectric properties.

The data supplied by both methods can be directly related to ground resistivity and geometry when the ground is composed of vertically stratified, homogeneous layers. Lateral variations in resistivity are most usually resolved by qualitative comparisons to theoretical responses over model inhomogeneities. However, because all subsurface situations are ultimately resolvable into adjacent, "local" layering situations, an important question is then how local must the layering be below a given instrument so that its resistivity structure may be still resolved by the standard data analysis procedures which assume the layering to extend infinitely.

In the magnetic induction device, Eq 2 showed that the secondary coupling was affected by loop separation *r*. As *r* is increased, induced currents from deeper in the ground and from greater lateral distances contribute relatively more to the coupling. No simple formula exists which defines the ground volume of greatest influence upon the coupling. However, some generalizations based on theoretical and field research (Arcone et al [3]) can be made concerning the r-values of 3.66 and 15 m which are used in this report. At $r = 3.66$ m, the technique is most sensitive to about 7 m depth in the HCP mode and to about 3 to 4 m in the VCP mode. At $r = 15$ m, this depth is about 18 m in the HCP mode and about 13 m in the VCP mode. The greatest horizontal sensitivity is in the region between the two loops with this volume being more constricted towards the interloop axis in the VCP mode. This is because the magnetic field energy in this mode is more constricted towards the vertical plane containing the interloop axis. The estimated lateral sensitivity is about $r/2$ from either side of the interloop axis for the VCP mode and about r for the HCP mode.

In the surface impedance method, the skin depth defined by Eq 3 is a helpful parameter for estimating the local significance of a single measurement. In the case of vertically stratified layers, uniform reflections occur at each interface, ultimately contributing to a uniform reflected wave at the surface. E_x and H_y of Eq 4 are the vector sums of both incident and reflected waves. When a disturbance in a layered resistivity structure occurs, energy is nonuniformly scattered in all directions. This scattered energy can be shown mathematically to be a superposition of an infinite number of spherical waves of varying amplitude and phase. Therefore, the influence of the scattered energy within the uniform region is limited by the skin depth effect within this region (for example, at 20 kHz, $\delta = 36$ m in 100 Ωm material). Consequently, a disturbance in the layering should be at least a skin depth (of the most resistive layer) away from the point of measurement in order to use the infinitely extended layers analysis over the section that is uniformly layered.

Field Studies

Three field studies are presented. The first is a smoothly layered case where em and d-c methods correlate well. The second is an isolated resistivity anomaly for which several different em and d-c profiles are compared. The third study contained several resistive inhomogeneities. The first two studies were done in New Hampshire and the third near Fairbanks, Alaska. The site locations are shown in Fig. 5.

Smoothly Layered Ground, Lebanon, New Hampshire

This site is in the Connecticut Valley just south of the Hanover and Lebanon townships border. The ground surface is a level hay field of about 100 acres below which are stratified sand and silt deposits with bedrock at an unknown depth. A deep d-c resistivity sounding in the Wenner configuration is shown in Fig. 6. The smooth curve generated from the layered model fits the data points excellently, and verifies the stratified nature of the subsurface. The data at the larger electrode spacings suggest that the lowest layer probably extends to at least 50 or 60 m.

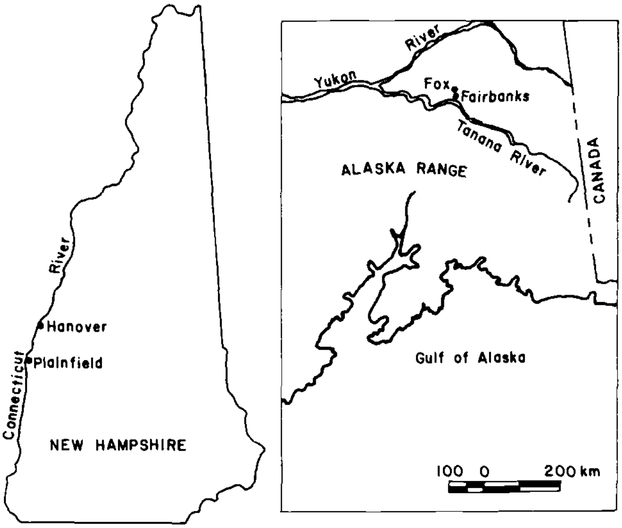

FIG. 5—*Location map for the field studies.*

Fourteen measurements were made at 17.8 kHz with the surface impedance method and at $r = 3.66$ m in both the HCP and VCP modes with the magnetic induction method. The measurements were made along the line of the d-c sounding. At 17.8 kHz the average reading along the d-c line was 76 Ωm at a phase angle of 36.8 deg. The standard deviation was less than 6 percent for both averages. This compares favorably with a theoretical value of 104 Ωm at 38 deg for the model in Fig. 6. In the HCP mode the average reading was 88.8 Ωm with a standard deviation of 1 percent while at VCP the av-

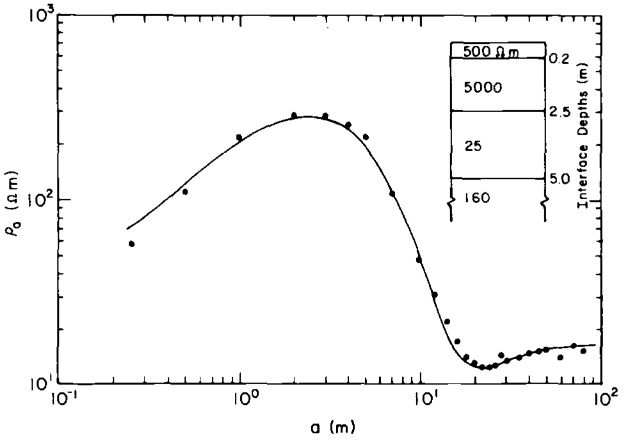

FIG. 6—*D-c resistivity sounding using the Wenner array over stratified sand, silt and gravel near Hanover, New Hampshire. The smooth curve is generated by the layered model.*

erage was 131 Ωm at 3.7 percent. Again this agrees excellently with the theoretical values of 82.5 Ωm (HCP) and 135 Ωm (VCP) for the model in Fig. 6.

This excellent agreement of em and d-c data resulted because the design of each instrument is based on the theory for smoothly layered ground which was encountered. The resistivity values were not so high as to introduce errors due to dielectric properties nor so low as to cause nonlinear responses. The surface material was fine-grained and consistent enough to avoid any contact resistance problems with the d-c technique. If any disturbance to the homogeneity of the layering existed off the traverse, it should have been at least 20 m away, which is approximately the skin depth at 17.8 kHz in 25-Ωm material.

The disadvantages of the em techniques are readily apparent, however, when we note that the em instrumentation was unable to indicate the presence of the resistive surface layer which extended to about 2.5 m depth. To resolve this near surface structure would require a much closer loop spacing for the magnetic induction method or else a very much higher frequency in the surface impedance method. However, at higher frequencies (above 0.2 MHz), dielectric properties would become important and thus complicate the interpretation.

Isolated Resistive Anomaly, Plainfield, New Hampshire

This site is situated in a small valley containing stratified sand, gravel, and clay deposited by glacial outwash and streams. The ground surface is a level hay field extending over about 15 acres. On one side of the field adjacent to a stream is a gravel deposit covered by a thin layer of soil. The water table is generally at a depth of about 1.5 m in the early spring and that portion of the gravel above the water table is very resistive. The depth to bedrock is unknown but may be as great as 65 m as evidenced from a deep d-c sounding taken along the profile line shown in Fig. 7. Five other shallower soundings in the field verified the consistency of this layer structure under the entire field. The site was first investigated by Delaney et al [*10*].

A model which fits the deep sounding data is shown in Fig. 7 and generally verifies the preceding description. The top 0.5 m is a conductive soil at about 150 Ωm. Below this is a gravel deposit at about 700 Ωm. The water table is at about 2 m depth, and at 9 m depth some unknown change in material type begins. This model will be termed the background model in contrast to a later anomaly model.

Seven em and d-c profiles were taken along the deep sounding line and are shown in Fig. 8. The two d-c profiles are at $a = 3$ and 6 m interelectrode spacings, and reveal a rather shallow, high resistivity anomaly at about 110 m. In the vicinity of each peak along the 6 m spacing profile, large voltage differentials between the center electrodes were observed and indicated severe resistive lateral inhomogeneity beneath the center of the array. The volt-

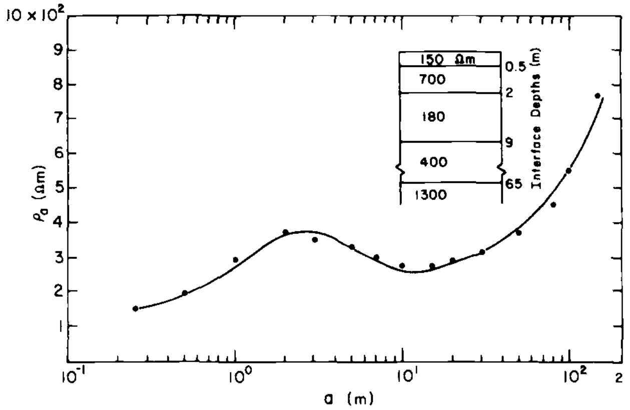

FIG. 7—*D-c resistivity sounding using the Wenner array over stratified sand, silt and gravel near Plainfield, New Hampshire. The smooth curve is generated by the layered model.*

age measured near each peak was not the same for both current reversals and may have indicated that the voltage electrodes were very near a material resistive contact. The mean levels on either side of the anomaly are both similar at about 300 to 400 Ωm.

The magnetic induction profiles are at interloop spacings of $r = 3.66$ m in the VCP and HCP modes, and $r = 15$ m in the VCP mode. A clear anomaly is evident only in the VCP mode at $r = 3.66$ m, the shallowest penetrating combination of mode and r-value of the three. At $r = 3.66$ m in the HCP mode there is also an anomaly but of less amplitude. At $r = 15$ m there is only a slight increase to the north of the anomaly at about 60 m. The general levels between 0 and 200 m and 500 and 700 m all average between 200 and 300 Ωm, which agree well with theoretical values for the background model of 267 Ωm (3.66 m, HCP), 254 Ωm (3.66 m, VCP), and 268 Ωm (15 m, VCP).

A layer model of the anomalous region, which provides theoretical magnetic induction data similar to that observed over the anomaly, has from top to bottom, layer resistivities and interface depths of 300 Ωm to 0.1 m, 50 000 Ωm to 3.5 m, and 150 Ωm to 10 m. The lowest layers are the same as those of the background model. This gives theoretical values of 701 Ωm (3.66 m, VCP), 433 Ωm (3.66, HCP), and 358 Ωm (15 m, VCP). The first two values are very close to the data, and the third is reasonably close. The d-c values for this model are about 9000 Ωm at $a = 3$ m and 13 000 Ωm at $a = 6$ m. The first number agrees well with the data, but the second number is too high, probably because the width of the inhomogeneity (perpendicular to the profile) was more comparable with the length of the electrode array.

The surface impedance profiles are of ρ_a and ϕ at 21.4 kHz. The transmitter is located to the south in Annapolis, Maryland. The ρ_a profile reaches a peak of 800 Ωm at about 120 m, but then peculiarly extends to the north for about another 40 m. There are no anomalies in the ϕ profile but only a grad-

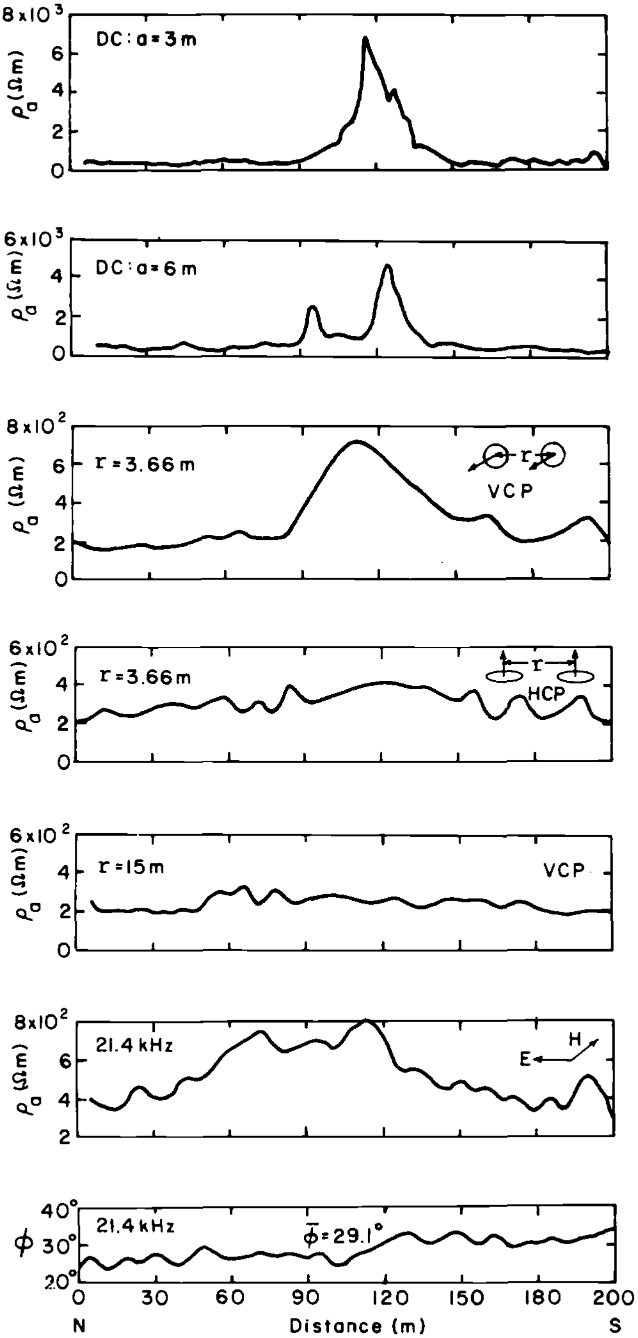

FIG. 8—*Magnetic induction and surface impedance profiles over a resistive gravel bed at Plainfield, New Hampshire.*

ual increase from north to south. The theoretical value corresponding to the background model is 295 Ωm at 36.2 deg, which is reasonably close to the data on either side of the anomaly, but the values for the anomalous model are 305 Ωm at 37.9 deg; a minimal change in phase as observed, but a minimal change in resistivity as not observed. Theoretically for this shallow anomaly, the change at 21.4 kHz should be marginal, but an amplitude response is observed.

Two separate effects are probably occurring here to produce this surface impedance behavior. The first effect is known as current streaming and may have occurred around the small, near-surface anomaly. In the near field (that is, within an *in situ* wavelength[5]) of an anomaly, ground currents become unevenly distributed in amplitude and direction as they flow around or over the zone of high or low resistivity. The distortion and intensifying of the current field can then cause an amplitude change but leave phase unaffected because both real and imaginary parts of E_x will undergo the same changes while H_y will remain unaffected.

The second effect is just simply a greater (than the other systems) VLF sensitivity to a change in resistivity at depth, which is most likely the cause of the northern extension of this anomaly. If in the background model of Fig. 7 the 400 Ωm layer is increased to 1300 Ωm, then the surface impedance changes from 295 Ωm at 36.2 deg to 658 Ωm at 32 deg, which is very similar to the observed data. The response of the other systems would be marginal except for the VCP configuration at $r = 15$ m which would increase from 268 to 325 Ωm, a change which is also similar to the data. Therefore, it is most likely that a second resistive disturbance existed in this area but at a depth to which mainly the VLF system was responsive.

Multiple Resistivity Anomalies, Fairbanks, Alaska

This site was situated between Fairbanks and Fox, Alaska. At the time of the survey it was proposed for a new highway route. Figure 9 shows that the material types are a silt (undifferentiated Quaternary silt units are labeled Qsu) of about a 6 to 7 m thickness overlying a bedrock of schist (precambrian Birch Creek schist units are labeled $p \in bc$ units). Permafrost extends into the bedrock. The silt contains many large ice masses which occur frequently in this region. The ice content of this silt is probably well in excess of saturation as usually occurs when large ice masses are present. The masses depicted are interpretations of well logs provided by the Alaska Highway Department. The data were taken in early April 1977, and first discussed by Delaney, Arcone, and Sellmann [*11*].

The data shown in Fig. 9 are d-c profiles at a spacings of 3 and 6 m, and a magnetic induction HCP profile at $r = 3.66$ m. Therefore, these data mainly represent variations occurring within the silt mantle. The profile at $a = 3$ m

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[5] At VLF, an *in situ* wavelength is $2\pi\delta$.

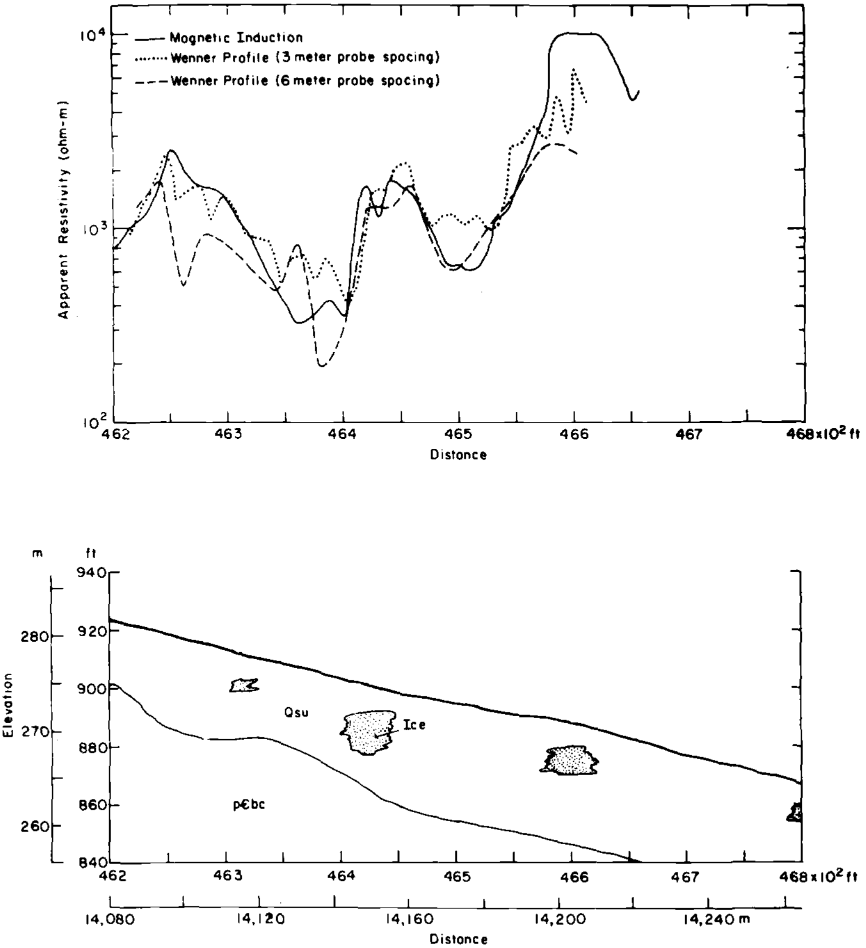

FIG. 9—*Magnetic induction and d-c resistivity profiles over resistive ice masses between Fairbanks and Fox, Alaska.*

shows the most variation with peak values above the ice masses greater than those of the $a = 6$ m profile. The mean value of the 3 m profile is 1686 Ωm as compared with 1225 Ωm for the 6 m profile. Both means exceed the value 800 Ωm measured by Hoekstra et al [*1*] on a saturated Fairbanks silt at a temperature of about −4°C (the minimum temperature found at this site to about 4 m depth in early April). Since massive ice is generally greater than 10 000 Ωm, we may conclude that the 3 m profile is responding mainly to ice content which is therefore greatest above 3 m depth.

The magnetic induction profile behaves similarly to both d-c profiles but has a greater mean value at 2390 Ωm. Although the effective penetration depth is more comparable to that of the 6 m *a* spacing, the values determined were more comparable to those of the 3 m *a* spacing. This is because the 3 m separation between the two inner electrodes, where voltage gradients are measured, is more comparable to the interloop spacing (3.66 m) of the induction unit and hence the ground volume of sensitivity is more similar. Therefore, it is probable that in cases where a great deal of inhomogeneity exists, the best correlations are between comparable *a* spacings and interloop spacings.

Summary and Conclusions

Both low frequency em methods of magnetic induction, and plane wave surface impedance may be used to determine the d-c resistivity structure of the ground when it is smoothly layered and resistivity is between about 10 and 10 000 Ωm. The main difference in performance for these situations was mainly in depth of sensitivity, as seen in Study 2. There, the use of a magnetic induction system in the HCP configuration with an intercoil spacing of about 30 m would probably have given results comparable to those of the VLF system.

When lateral changes in material type are severe, then layering theory may be only applied when the lateral dimension of sensitivity of an instrument is less than the lateral extent of the layering. Such dimensions are usually about equal to the intercoil or interelectrode spacings of the induction and d-c systems, respectively, and the skin depth of the medium under surveillance for the surface impedance method.

Meaningful correlations between any one d-c profile of a certain electrode spacing and any one magnetic induction profile of a certain interloop spacing must be found by experiment and cannot be predetermined. Generally, good correlations will result when the anomalies encountered extend to a depth comparable to, and to a width greater than, the largest value of *a* or *r*. Study 3 gave good correlations between peak anomaly values, because the ice masses may have extended to 15 m in width and 6 m in depth, well within the depth of sensitivity of the d-c and induction profiles used. In Study 2 the correlations were poorer. The gravel deposit was probably lens-shaped and of about 50 m width but only extended to about 3 m depth so that the $r = 3.66$ m instrument was integrating over a greater depth than that of the d-c instrument. Closer loop spacings would have given better correlations. Therefore, several interloop spacings and orientations should always be used.

Table 1 presents a comparison of the three techniques. Included in this table is the surface impedance method between 200 and 415 kHz (LF to MF in the Table), which is the band where numerous airplane navigational aid transmitters operate. The Geonics Company of Ontario also produces an instrument for operating in this band called the EM-32. This device was available but not used for these studies due to an inadequacy of signal strength at the particular sites. Most LF transmitters radiate at 50 W or less.

TABLE 1—*Comparison of three methods for measuring ground resistivity.*

Method	Instrument Name or Configuration	Depth of Sensitivity	Vertical[a] Resolution	Horizontal Resolution	Speed of Measurement	Limitations[b]
dc	Wenner array	~a	decreases with increasing a	most sensitive to regions within the inner, voltage electrodes	depends on a ~1 min for $a \leq 10$ m 1 to 3 man operation	contact resistance in highly resistive materials profiling is time consuming large a required for deep probing
Magnetic Induction r = 3.66 m	loop-loop or double dipole EM-31	~7 m HCP ~3 m VCP	decreases with increasing r	most sensitive to regions between the transmit and receive coil lateral sensitivity	instrument response time, 0(s) 1 man operation	nonlinear below 10 Ωm sensitivity decreases with increasing resistivity due to decreasing Z_q
r = 15 m	EM-34	~18 m HCP ~13 m VCP		~r/2 off interloop axis for VCP and ~r	instrument requires balancing for a null, 0(30 s)	
r = 30 m	EM-34	~25 m HCP ~19 m VCP		for HCP	2 man operation	

TABLE 1—*Continued.*

Surface Impedance						
VLF 3 to 30 kHz	EM-16R	~δ	decreases with increasing δ	most sensitive to regions within δ of point of measurement	instrument requires balancing for a null, 0(30 s)	surface inhomogeneities may cause distortion requiring many readings for quality subsurface data
					1 man operation	sensitivity decreases with decreasing resistivity due to decreasing amplitude of E_x dielectric influence above 10 000 Ωm
LF-MF 200 to 415 kHz 550 to 1600 kHz	EM-32 not available					surface inhomogeneities may cause distortion requiring many readings for quality subsurface data
						sensitivity decreases with decreasing resistivity due to decreasing amplitude of E_x
						poor coverage of existing transmitters
						dielectric influence above 1000 Ωm.

NOTE—a = interelectrode spacing; r = interloop spacing; δ = skin depth; O = order of; HCP = horizontal coplanar loops; VCP = vertical coplanar loops.

[a] Shallow conductors can mask deep resistors in all cases. All techniques more sensitive to conductive rather than resistive layers.

[b] Standard data interpretation for all methods based on vertically layered models.

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DISCUSSION

J. B. Lankes[1] (*written discussion*)—The red, red soil of Virginia is not due to the blood of brave soldiers, as is popularly supposed, but is due to iron ore. What has been your experience with electromagnetic measurements in iron or other metalliferous ore areas? I understand the answer to be that no data are at hand, but in the author's opinion it was probable that the results would be nonlinear and hence of doubtful value.

S. A. Arcone (*author's closure*)—The electromagnetic methods I have discussed have certain restrictions for interpreting data. Both the surface impedance and magnetic induction methods require a model of smoothly layered ground to interpret readings, circumstances which do not often occur in metalliferous ore areas. For the magnetic induction instrument, resistivity should be greater than about 10 Ωm or else the instrument response becomes nonlinear, as over highly conducting ore bodies. For the surface impedance instrument, extremely conductive bodies may make the horizontal electric

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[1] Corrosion control engineer, Consultant, Richmond, Va., 23220.

field so small as to give readings of 0 Ωm, and disturb the horizontal magnetic field so strongly as to violate the plane wave assumption and give unreal values to the phase angles. For mineral prospecting, the Geonics EM16-R is readily converted to the (original) EM16 which was designed to detect disturbances in the plane wave magnetic field radiated from distant transmitters.

E. T. Serra[1] *and W. A. Mannheimer*[1]

On the Estimation of the Corrosion Rates of Metals in Soils by Electrochemical Measurements

REFERENCE: Serra, E. T. and Mannheimer, W. A., "**On the Estimation of the Corrosion Rates of Metals in Soils by Electrochemical Measurements,**" *Underground Corrosion, ASTM STP 741,* Edward Escalante, Ed., American Society for Testing and Materials, 1981, pp. 111-122.

ABSTRACT: Studies are described to characterize soil aggressivity along electrical transmission lines and substation sites.

Electrochemical methods of corrosion rate measurement were used in laboratory tests. Metallic specimens were exposed to actual soil specimens. Results are used together with soil properties data to furnish indication on corrosion behavior to be expected for the metals, and design possible protection methods. The ultimate goal of this program is to define *in situ* procedures to rapidly estimate corrosion rates and soil aggressivity.

An attempt has been also made to study the influence of counter electrode position on electrochemical measurements.

KEY WORDS: corrosion, underground corrosion, electrochemical measurements, soil aggressiveness

Weight loss measurement constitutes the classical method to evaluate the corrosion behavior of metals in contact with specific aggressive media.

Whenever these measurements are made in actual service conditions of the metal, they allow a precise knowledge of its performance. However, the weight loss method usually requires long periods of exposure to the environment of interest.

In order to overcome such long exposure times, electrochemical methods were developed to determine instantaneous corrosion rates. These methods, besides furnishing information on the behavior of the metal throughout its exposure period, allow an estimate of its performance, based on tests of short duration.

Recently, four electrochemical methods to determine corrosion rates in soils were critically compared[2] and, among those considered applicable to

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[1] Research engineer and head, Materials Department, respectively, Electrical Energy Research Centre - the Centro de Pesquisas de Energia Eletrica (CEPEL), Rio de Janeiro, RJ, Brazil.

[2] Serra, E. T., Mannheimer, W. A., and Araujo, M. M., *Proceedings,* 7th International Congress on Metallic Corrosion, Vol. 2, 1979, pp. 1290-1294.

corrosion rate measurements, we selected the so called polarization resistance method as best suited to the problem in hand of measuring metal performance in soils. This technique has been used by the Centro de Pesquisas de Energia Eletrica (CEPEL) to provide electric utilities with information regarding aggressivity of soils, and required protective systems. Such information is normally used in the design stage of substations and transmission lines.

The present work presents some achieved results, and discusses further tests presently being carried out on the influence of counter-electrode positioning in field tests.

Polarization Resistance Method

When a metal is exposed to a given environment, it acquires a certain potential, known as corrosion potential (E_{corr}), at which anodic current density, due to metal dissolution, is numerically equal to cathodic current density, due to reduction of the oxidation agent, and corresponds to the corrosion current density (i_{corr}).

If a potential (E), differing from E_{corr}, is applied to such an electrode, a net current flow (i) will be observed, since anodic and cathodic currents are no longer equal. The resulting relation between current i and E, known as the polarization curve, is of the form

$$i = i_{corr}\left\{ \exp\left[\frac{2.3\,(E - E_{corr})}{\beta a}\right] - \exp\left[-\frac{2.3\,(E - E_{corr})}{\beta c}\right]\right\} \tag{1}$$

Where βa and βc are taken as constants for a given system.

Following from Eq 1, the slope of the polarization curve at E_{corr} is given by

$$\left(\frac{di}{dE}\right) E_{corr} = 2.3\, i_{corr}\left(\frac{1}{\beta a} + \frac{1}{\beta c}\right) \tag{2}$$

The reciprocal of the polarization curve slope at the corrosion potential is called polarization resistance (Rp).

From a theoretical consideration of Eqs 1 and 2, Mansfeld[3] has proposed that the determination of βa, βc, and Rp, and consequently of corrosion current density, should be made from the fitting of experimental data to theoretical curves. Such fitting is done by the least square method.[3,4]

The weight loss and the corrosion rate at the end of the exposure time can be calculated using Faraday's law

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$$W = k \int i_{corr} dt$$

where

W = weight loss, and
k = electrochemical equivalent.

Materials and Methods

Specimens of steel, aluminum, and copper were obtained, respectively, from cold drawn AISI 1020 steel, commercially pure aluminum (AA 1100), and electrolytic copper. Galvanized steel specimens were taken from galvanized cold rolled structural angles (approximately 700 g zinc/m^2).

The specimens (galvanized steel excepted) were mechanically polished to 600 paper. Before testing, all specimens were chemically cleaned with ultrasound and degreased in acetone. The polarization cell used in the tests, shown in Fig. 1, provided for a specimen exposure of 6 cm^2. Soil samples obtained from sites of interest were used as electrolytes in a moisture saturated state. Table 1 gives the main characteristics for the used soils. Polarization resistance tests were run in the range ±30 mV overvoltage, using the potentiodynamic technique with 0.1 mV/s scanning speed.

Experimental Results

Figures 2 and 3 provide a comparison between results obtained electrochemically in the laboratory on steel specimens, and those obtained in the field through periodic weight loss measurements. It is intended that this comparison should provide an estimation, both qualitative and quantitative, of the behavior of a metal under field and laboratory conditions.

Figure 4 shows the change in corrosion current density, along the exposure interval, of galvanized steel specimens in four different soil specimens. Such experiments are designed to provide a comparison of the aggressivity of different soils with respect to a particular metal.

Figure 5 shows the change in corrosion current density, along the exposure interval, of four different metals in the same soil. In this case, from the estimation of the behavior of various metals in a given soil, the aim is to provide materials alternatives in the design of transmission tower grounding.

In order to extend the measurement of instantaneous corrosion rates to field tests, a preliminary study was begun on the influence of counter-electrode positioning on results. Figure 6 shows the dimensions and positioning of such electrodes.

Polarization resistance tests in this case, were run potentiostatically in the range ±30 mV overvoltage varying 3 mV each 5 min. Ohmic resistance due to the environment, was automatically corrected by feed-back to the potentiostat.

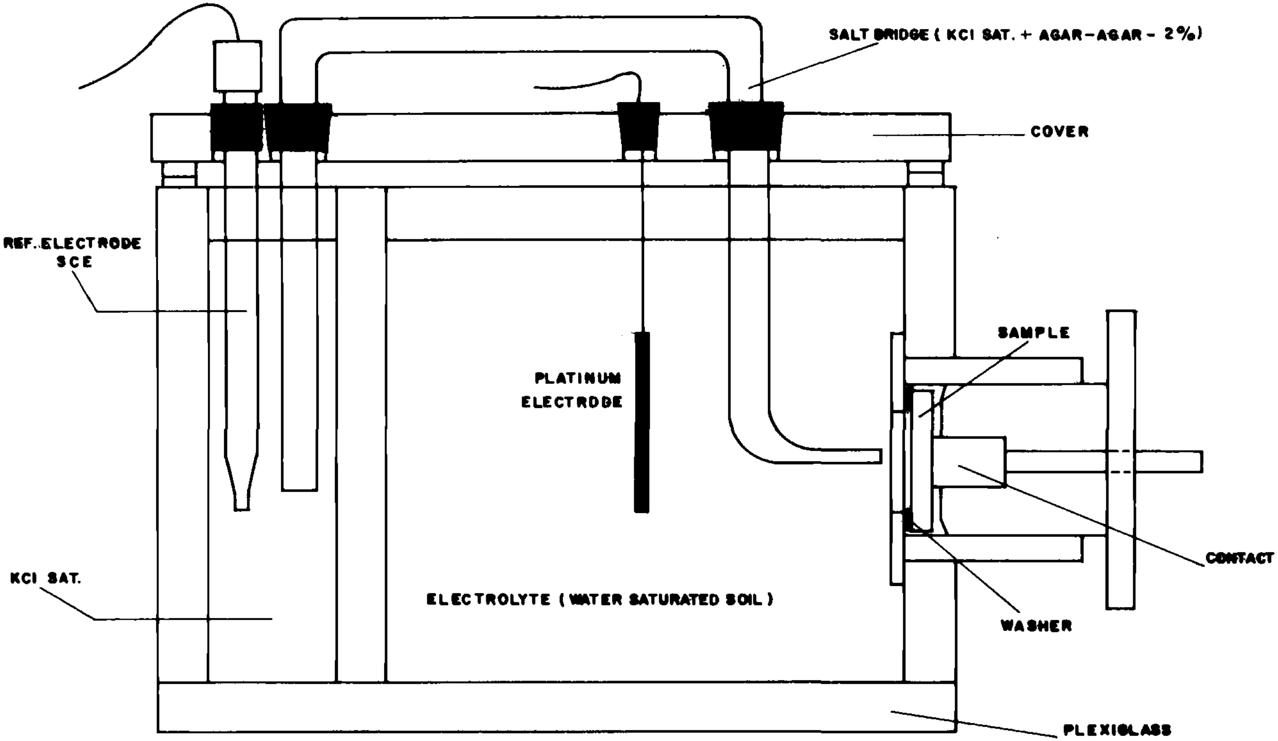

FIG. 1—*Corrosion cell.*

TABLE 1—*Characteristics of soil used in tests.*

Soil	ρ_1,[a] Ωcm	ρ_2,[b] Ωcm	pH	Cl^-, ppm	SO_4^{2-}, ppm	S^{2-}, ppm
1	2.6 × 10^3	0.8 × 10^3	6.9	254	150	absent
2	5.0 × 10^3	2.5 × 10^3	7.7	absent	136	absent
3	45.0 × 10^3	14.0 × 10^3	4.2	absent	58	absent
4	11.0 × 10^3	10.0 × 10^3	4.4	absent	180	absent
5	230 × 10^3	8.0 × 10^3	4.6	100	not determined	absent

[a] Field measurements.

[b] Laboratory measurements (soil box) water saturated.

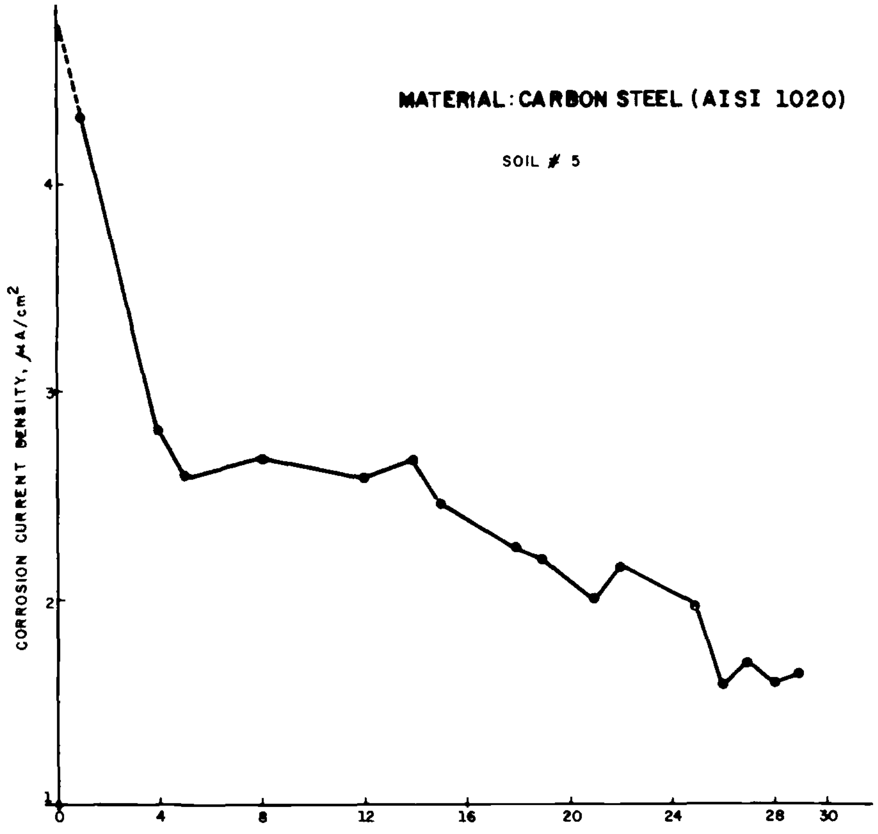

FIG. 2—*Change in corrosion current density, along time, for a steel specimen, tested in the laboratory.*

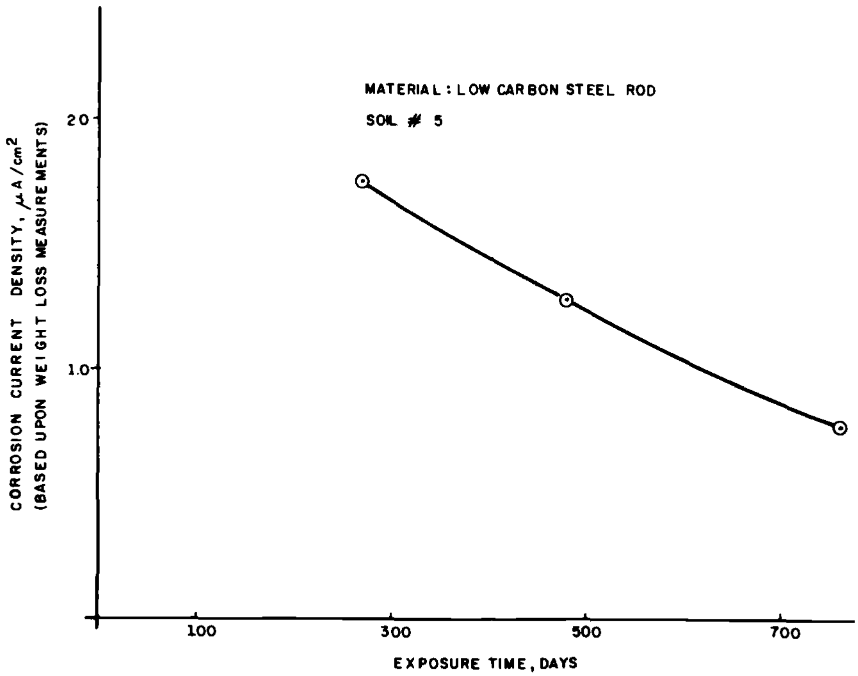

FIG. 3—*Change in corrosion current density, along time, based upon weight loss measurements, for a steel specimen tested in the field.*

Figure 7 shows corrosion current density change during a period of 84 days of exposure.

Discussion

Consideration of results shown in Figs. 2 and 3 indicate a qualitative agreement between tests run in the field, and those performed in the laboratory on soil specimens. In both cases, a tendency to corrosion rate stabilization is observed. Quantitative differences were attributed to varying moisture, packing, and oxygen content, which are necessarily different in the two tests situations. Our observations indicate, for steel in laboratory conditions using water saturated soil, a corrosion rate (obtained from the mean current density) two to four times larger than in the long exposure field measurements (actual weight loss divided by time). As previously reported[2] the difference between the measured weight loss and that calculated by polarization resistance method is around 20 percent, when tests are made in identical conditions.

Figure 4 indicates that the use of electrochemical tests to evaluate the corrosion behavior of a particular metal in several soils, can be a powerful tool, considering the difficulty of performing the same comparison based on the properties of soils, as shown in Table 1. From such studies, different protec-

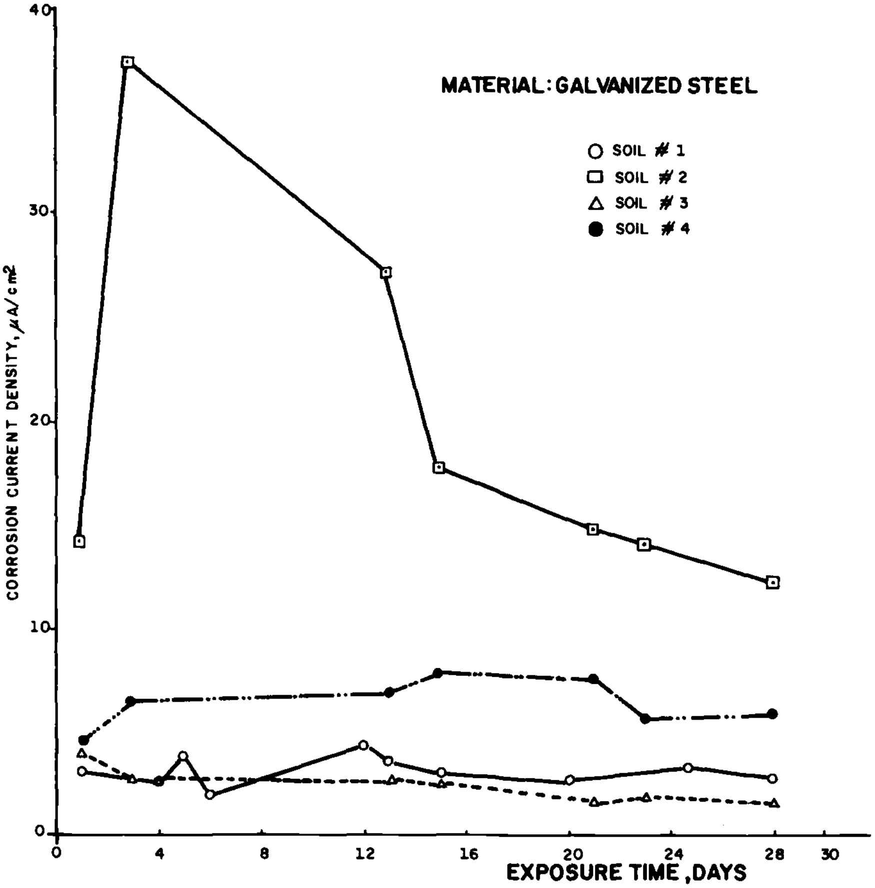

FIG. 4—*Change in corrosion current density, along time, for galvanized steel specimens in four different soil specimens.*

tion systems for galvanized transmission tower foundations in contact with soil, can be proposed.

Figure 5 presents the corrosion behavior of different metals, measured with the polarization resistance technique, in contact with the same soil. This type of test has been shown to be very useful during the design of transmission towers, providing for the adequate selection, both technically and economically, of grounding systems.

Results presented in Fig. 7 show that the positioning of the counter-electrode introduces differences in values obtained for corrosion current density. Two points seem worthy of consideration in discussing these results.

1. The smallest corrosion current density variations were obtained using a counter-electrode parallel to the working electrode, and having half of its length. The largest variation corresponded to a counter-electrode similarly positioned, but of equal length to the working electrode.

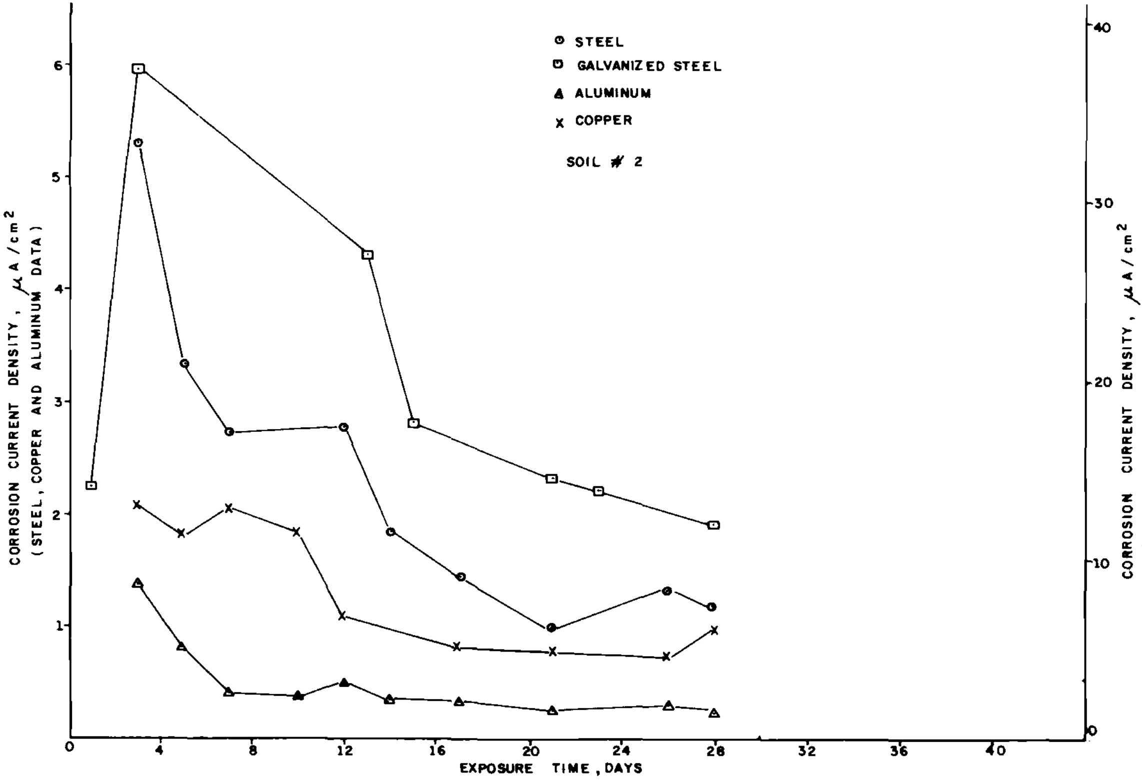

FIG. 5—*Change in corrosion current density, along time, for different metals in the same soil specimen.*

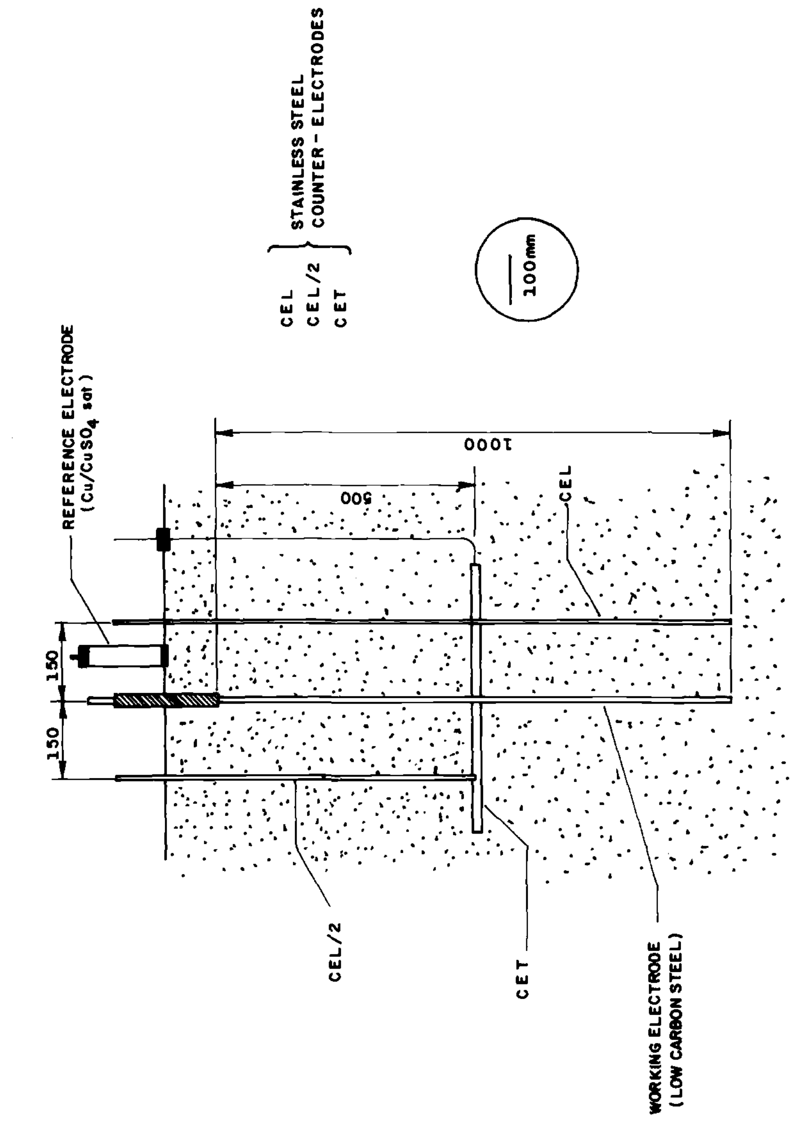

FIG. 6—*Dimensions and positioning of counter-electrodes in field tests.*

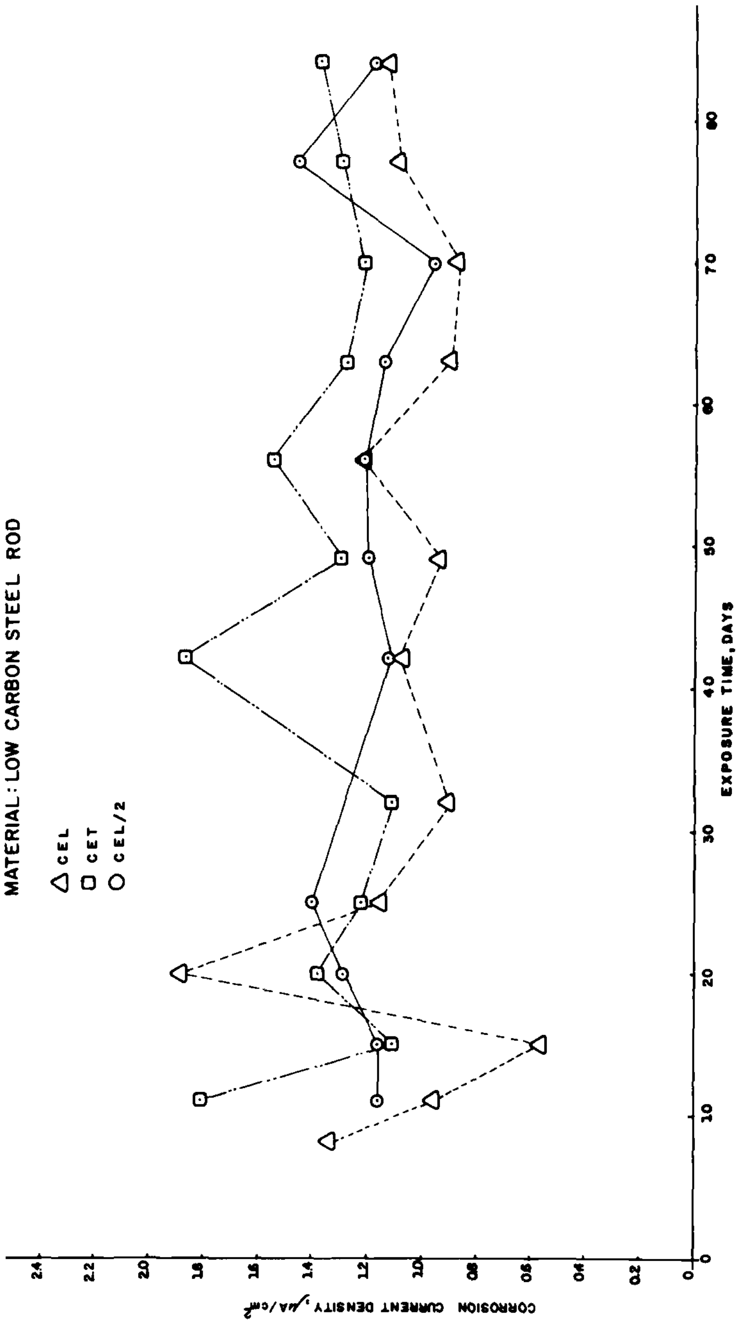

FIG. 7—*Change in corrosion current density, along time, for a steel rod, from tests with counter-electrodes as in Fig. 6.*

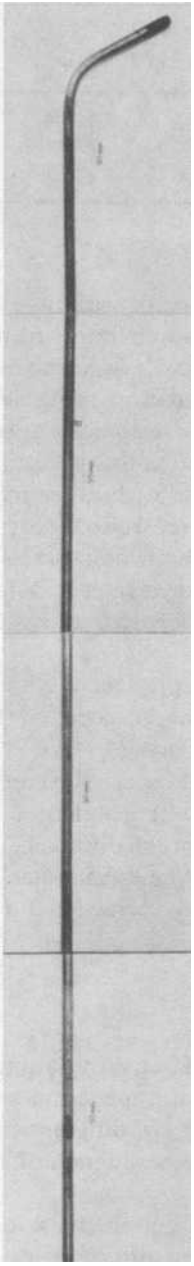

FIG. 8—*Steel rod used as working electrode after exposure.*

TABLE 2—*Results from tests with counter-electrodes positioned as in Fig. 6.*

Stainless Steel Counter-Electrodes	i^{a}_{corr}, $\mu A/cm^2$	Δp, g	Corrosion Rate, mdd
CEL	1.06	0.6	2.6
CEL/2	1.17	0.7	2.9
CET	1.31	0.8	3.3

[a] Average.

2. Notwithstanding the observed variations for the three counter-electrode positions, calculation of weight loss from current integration, and use of Faraday's law resulted in closely agreeing results, as shown in Table 2.

Figure 8 shows the steel bar used as working electrode, after the exposure covered in this report. General corrosion can be seen over the top region of the electrode which can be attributed to soil conditions at the test site, consisting of several layers of landfill, with different degrees of packing. Such lack of soil uniformity, allowing a localized corrosion process over certain areas of the specimen, suggests the use of working electrodes with several insulated sections to measure corrosion rates at different depths. Such work is being carried out and will be reported elsewhere when results become available.

After removal of the corrosion products, following the American Society for Testing and Materials Recent Practice for Preparing, Cleaning, and Evaluating Corrosion of Test Specimens (G1-72-79), the weight loss of the specimen was determined. This weight loss (1.0 g) compares well with calculated values in Table 2, and shows the applicability of the polarization resistance method to field tests. We attribute the difference between calculated values and real weight loss to the lack of uniform attack along the extension of the bar and the lack of precision in correction for ohmic drop due to soil resistivity.

Conclusions

1. Electrochemical tests carried out in the laboratory are shown to be useful in estimating corrosion rates of a metal in a certain soil.
2. Estimation of the aggressivity of different soil types towards a certain metal can be made through the determination of corrosion current densities along time, in laboratory tests.
3. Counter electrode positioning in field test, even though it affects periodic corrosion current density measurements, does not modify the estimation of total metal weight loss.

D. A. Jones[1]

Principles of Measurement and Prevention of Buried Metal Corrosion by Electrochemical Polarization

REFERENCE: Jones, D. A., "**Principles of Measurement and Prevention of Buried Metal Corrosion by Electrochemical Polarization,**" *Underground Corrosion, ASTM STP 741*, Edward Escalante, Ed., American Society for Testing and Materials, 1981, pp. 123–132.

ABSTRACT: Mixed potential theory has been briefly reviewed to show the basis for the measurement of corrosion rate by polarization resistance and the suppression of corrosion by cathodic protection. Polarization data on buried steel and aluminum are presented to show the applicability of the theory. Limitations on the applicability of the theory to large buried surfaces, bare and coated, are discussed. It is concluded that further experimental work is needed to determine potential distribution on large surfaces and the effects of polarization on the size, distribution, and current density of anodic and cathodic surface areas.

KEY WORDS: underground corrosion, soils, buried metals, polarization, cathodic protection, linear polarization, polarization resistance

It has long been known that corrosion of metals in aqueous solutions proceeds by an electrochemical mechanism. Corrosion of buried metals is no exception since the necessary electrolyte is provided by water trapped in the interstitial pores of soil. Furthermore, cathodic protection of buried metal structures is one of the oldest known electrochemical methods for corrosion mitigation.

Unfortunately, the quantitative application of modern electrochemical principles to corrosion of buried metals has not kept pace with progress in other areas of corrosion technology. The purpose of the present paper is to review those areas of electrochemical theory which apply to the measurement and prevention of corrosion in buried metal systems. Further attention is then given to an experimental approach to electrochemical measurements on buried metals and to the physical difficulties which impede such measurements. Areas of research are discussed which would further the useful application of electrochemical principles to the corrosion of buried metals.

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[1] Associate professor, University of Nevada, Reno, Nev. 89557.

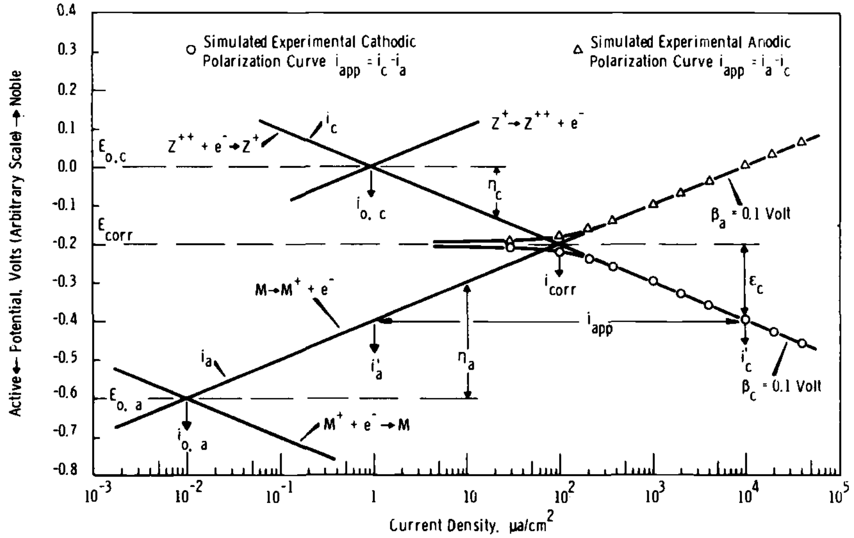

FIG. 1—*Graphical representation of anodic and cathodic partial processes under activation control during corrosion* [4].

Electrochemical Theory

The mixed potential theory of corrosion as it applies to the present discussion has been reviewed previously [*1*—*5*].[2] Therefore, only the essentials are treated here. Corrosion occurs by an anodic oxidation and a cathodic reduction process, respectively

$$M \rightarrow M^+ + e^- \tag{1}$$

$$Z^{++} + e^- \rightarrow Z^+ \tag{2}$$

where the reaction in Eq 1 represents anodic dissolution of metal atoms, and the reaction in Eq 2 represents cathodic reduction of some dissolved species Z^{++}. The exchange of the electron, e^-, classifies the reaction as an electrochemical one, and as such becomes dependent on surface potential, which is a measure of electron activity. The rates of these reactions, Eqs 1 and 2, represented by current densities i_a and i_c, are plotted as a function of potential in Fig. 1. The linear relationships on a semilog plot reflects the commonly observed exponential relation between change in potential or polarization and the current density, i, required to cause the change [*1*]. That is

$$\eta = \pm\beta \log\frac{i}{i_o} \tag{3}$$

where β is the slope on the semilog plot and i_o is the exchange current density at the equilibrium potential E_o for the reaction. The linear relationship of

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[2] The italic numbers in brackets refer to the list of references appended to this paper.

Fig. 1 is termed Tafel behavior, and the slope β the Tafel slope, after the German investigator who first observed it.

An externally applied cathodic polarizing current i_{app} has the effect of increasing the rate of the reduction reaction of Eq 1 and suppressing the rate of the anodic dissolution reaction of Eq 2, such that charge is conserved, and

$$i_{\text{app}} = i_c - i_a \tag{4}$$

When $i_a \ll i_c$ then $i_{\text{app}} = i_c$, and the experimental curve assumes the linear, Tafel, behavior on the semilog plot. The curves in Fig. 1 are calculated from the difference between the theoretical curves, i_a and i_c according to Eq 4, at each potential. The anodic polarization curve in Fig. 1 was obtained by the same procedure except that $i_{\text{app}} = i_a - i_c$ in this case. The curves in Fig. 1 are of the same general shape and appearance as those observed in actual practice when distortions due to ohmic resistance and concentration polarization are absent [*1-5*].

Predictions from Theory

Polarization Resistance Measurement of Corrosion Rate

The theoretical foundation for the polarization resistance method was described by Stern and Geary [*1*], and given experimental verification by a number of investigators [*6-11*]. A comprehensive review of the subject has appeared recently [*12*].

The difference between two exponential functions, as in Eq 4, approaches a linear function of the overvoltage ϵ, as ϵ approaches zero. At sufficiently low ϵ the deviation from linearity is not easily discernable, and the slope R_p of this "linear polarization" curve is related to corrosion rate, i_{corr}, as follows [*1*]

$$R_p = \frac{\Delta\epsilon}{\Delta i_{\text{app}}} = \frac{\beta_a\beta_c}{2.3 i_{\text{corr}}\,(\beta_a + \beta_c)} \tag{5}$$

The deviation from linearity, or the error in assuming linearity to determine $\Delta\epsilon/\Delta i_{\text{app}}$ in Eq 5, has been calculated analytically by Oldham and Mansfeld [*13*] and graphically by Bandy [*14*].

Cathodic Protection

The degree of cathodic polarization required to obtain any desired level of cathodic protection can be derived from Fig. 1. For example, the applied current designated i_{app} in Fig. 1 reduces the corrosion rate from i_{corr} at 100 μa/cm^2 to i_a' or 1 μa/cm^2. The new corrosion rate is 2 orders of magnitude or 99 percent less than the original. Inspection of Fig. 1 shows that the anodic Tafel slope β_a governs the amount of cathodic protection which can be expected from a given level of cathodic polarization [*4,5,15*]. This is further

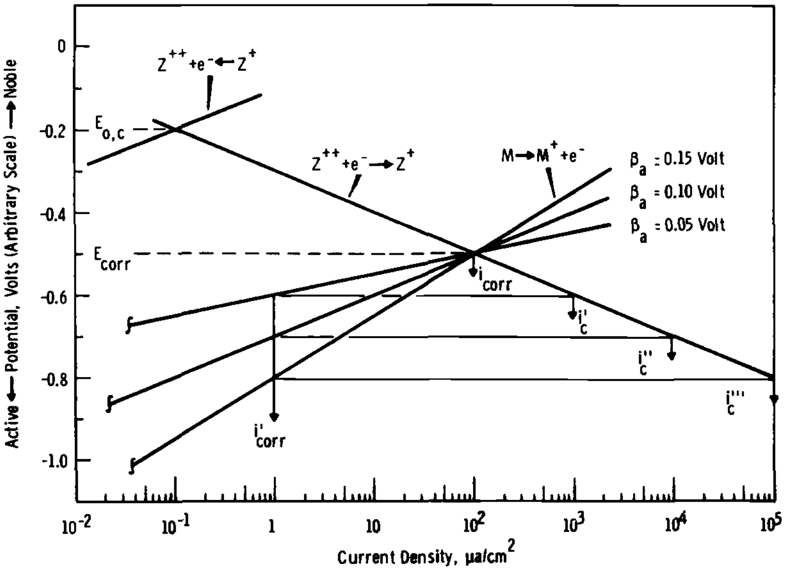

FIG. 2—*Effect of anodic Tafel slope on polarization and current necessary for cathodic protection* [4].

illustrated in Fig. 2, which shows that the lower is β_a the greater the reduction of corrosion which can be expected from a given level of cathodic polarization.

Thus, one only needs an experimental determination of β_a to calculate the polarization (potential change) necessary to reduce corrosion to any desired level. The most desirable level of corrosion is dictated by the economics of rectifier design and the personal judgment of the designing corrosion engineer. It is not necessarily true that the corrosion rate should be reduced to zero at a potential of $E_{o,a}$ (Fig. 1). A considerable economic penalty may result from the considerably greater current that is required. For example, to reduce the corrosion rate from i'_a to zero in Fig. 1, the applied cathodic current density would have to become 10^6 μa/cm², a hundredfold increase.

Polarization Measurements on Buried Metals

Polarization studies were conducted by the author [*16*] on buried specimens of aluminum and steel. Polarization apparatus utilizing a modified wheatstone bridge circuit [*17*] was employed, as shown in Fig. 3. The entire apparatus with the exception of the null detector was housed in a portable box which could be carried into the field. The null detector may be a battery operated electrometer of high internal resistance. Thus, the entire apparatus is suitable for field investigation.

A cathodic linear polarization curve is shown in Fig. 4 for buried aluminum. The curve has the expected linearity and the corrosion rate can be eas-

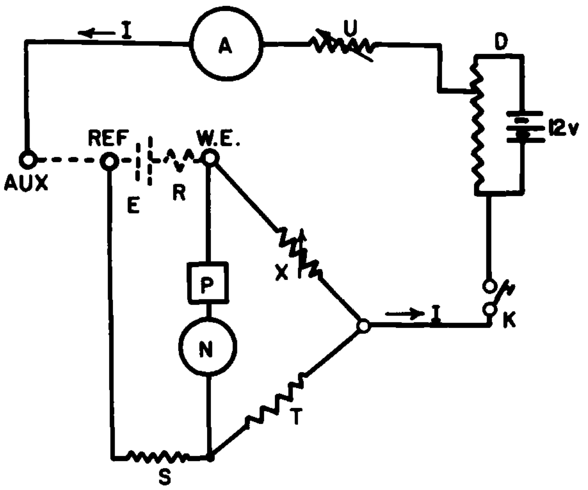

FIG. 3—*Wheatstone bridge circuit to compensate for ohmic IR errors in polarization measurements on buried metals* [16].

ily calculated from the slope R_p using Eq 5, providing the constants β_a and β_c are known. These constants may be evaluated directly from the full anodic and cathodic polarization curves as shown in Fig. 4. At times, an accurate value of β_a cannot be derived from the anodic polarization curve because of anodic film formation. Instead, the anodic curve can be derived from the applied cathodic curve, i_{app}, and the extrapolation of the linear Tafel cathodic curve which gives i_c [*18*]. Substitution of these values of i_{app} and i_c into

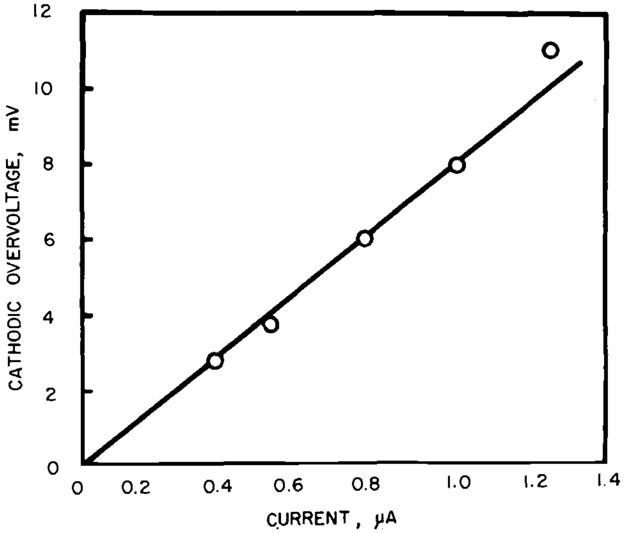

FIG. 4—Polarization resistance (linear polarization) curve for buried aluminum [15].

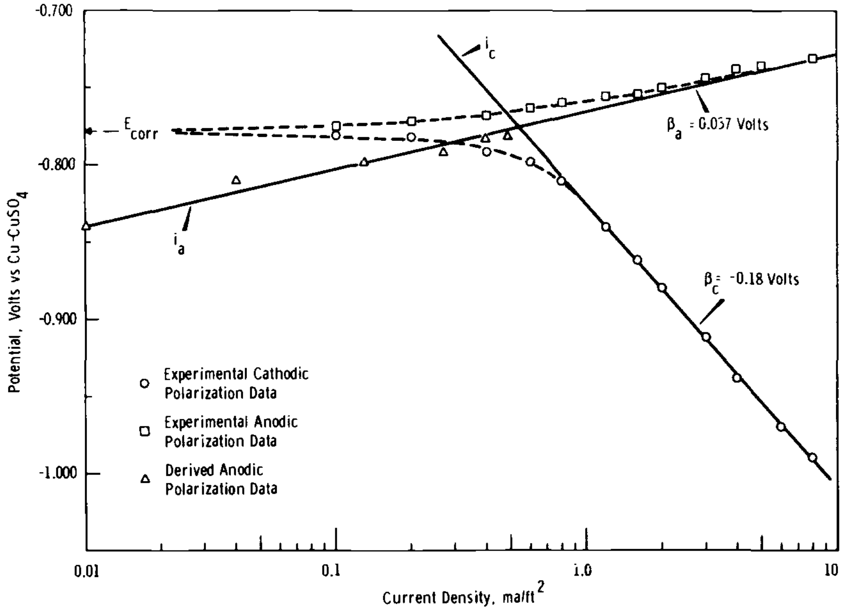

FIG. 5—*Polarization data for buried steel* [16].

Eq 4 at several potentials gives the anodic polarization curve at potentials active to the corrosion potential, E_{corr}. In Fig. 5, the data from both direct polarization and calculated values from cathodic data lie on the same line. However, the value of the method is illustrated in Fig. 6 where the direct anodic polarization curve for aluminum does not give a sensible value for β_a.

As discussed previously, the value of β_a gives a parameter for the design of cathodic protection systems. The data of Figs. 5 and 6 show that β_a can be readily obtained for buried metals. However, more work is needed to evaluate the changes of β_a for seasonal differences in soil conditions. Also β_a may change with time under continuous cathodic polarization due to precipitation of insoluble compounds in the alkaline environment which accumulates around a cathodic surface under limited mass transport.

Discussion

The data of Figs. 5 and 6 show that the anodic Tafel constants can be readily determined for metals buried in soil. However, to the author's knowledge this parameter has never been used in the design of a cathodic protection system. Some possible reasons for this lack of progress are discussed in the remainder of this paper.

The measurement of potential on a buried structure is relatively easy, but the interpretation of the potential so measured is rather difficult. It is usually recommended that the reference electrode, generally copper-saturated copper sulfate ($CuSO_4$), be placed directly over the buried structure. The exact relationship between the potential measured relative to a reference electrode placed over the structure, (for example, pipeline) and the actual potential of the surface at various positions on the structure is unknown as far as the present author can determine. It is difficult to determine the amount of the ohmic potential gradient through the soil which is included in potential measurements of buried structures. Furthermore, the variation of potential around the surface of a structure of even relatively simple shape, such as a pipeline, is unknown and has never been measured experimentally. Effect of seasonal variation on moisture content and soil resistivity can be evaluated only very qualitatively. Soil texture and compaction around a buried structure has an undefined effect on the corrosion rate and electrochemical behavior of a buried structure.

These same factors have hampered the application of polarization resistance to measuring corrosion rate on real buried structures. Polarization of a large structure with a relatively small auxiliary anode would have an effect on nearby corroding areas which would be difficult to evaluate. The quality of coatings, the "throwing" power of the applied current, the distribution of current to hidden surface areas all have, at present, unknown effects on any measured potential at the ground surface. Clearly, experimental work is needed to answer some of these questions.

Early applications of electrochemical theory to corrosion [*19*] assumed that the anodic and cathodic partial process of Eqs 1 and 2 occur on discrete, separate areas on the corroding surface. The more modern mixed potential theory [*1*] makes no restriction on size or distribution of areas assigned to anode and cathode reactions. In fact, the anodic, Eq 1, and cathodic, Eq 2, reactions may occur at the same point on the surface in consecutive time intervals. Conversely, the anode and cathode areas could be fixed or varying as potential changes. The only requirement that must be met is that the overall rate of anode and cathode reactions each bears an exponential relationship with potential as in Eq 3.

The modern "mixed potential" theory [*1*] has been very useful in laboratory studies on small specimens in acid solutions with well defined conditions of mass transport. However, translation of this theory to larger surface areas in neutral solutions has been more difficult. Cleary [*20*] made microelectrode pH and oxygen measurements on 1-in.^{2} iron surfaces in 3 1/2 percent sodium chloride (NaCl) and found that even on such a small total area there were definite areas of anodic and cathodic activity developed. Cathodic areas were relatively bright, developed a pH of 9.0 to 9.5, and showed higher oxygen gradients. The neighboring anodic areas showed a pH of 6.0 to 6.5, lower oxygen gradients and definite anodic etching of the surface. It was suggested that oxygen is also consumed near the anodic areas by formation of hydrated iron hydroxide

$$2Fe^{+2} + 1/2\ O_2 + 3H_2O \rightarrow 2\gamma\text{-}FeOOH + 4H^+ \qquad (6)$$

From Cleary's data it would appear that the cathodic reduction of dissolved oxygen,

$$O_2 + 2H_2O + 4\bar{e} \rightarrow 4OH^- \qquad (7)$$

at any given position on the surface generates hydroxyl ions which inhibit the anodic reaction

$$Fe \rightarrow Fe^{+2} + 2e \qquad (8)$$

at that position. The formation of the hydrated iron oxide (γ-FeOOH) by the reaction in Eq 6 generates acid, H^+, which lowers the pH in the anode area. Although there may be some reduction of H^+ in the anodic area, it seems clear that a steady state is set up in the absence of any solution agitation between adjoining areas of cathodic reduction of dissolved oxygen and anodic dissolution of the iron surface.

La Que and May [*21*] showed distinct areas of anodic attack adjoining separate cathodically protected areas on relatively large specimens (1 in. by 3 in.). Application of cathodic protection caused shrinkage of the anodic areas. These investigators reported that the anodic areas were rust covered. Thus, there is evidence that reaction products, OH^-, H^+, and FeOOH, as generated by reactions (Eqs 6 to 8), are retained at the surface and cause local discontinuities of pH and oxygen (O_2) transport. Turbulent flow does not guarantee efficient mass transport away from a large surface, because of the diffusion boundary layer [*22*]. However, further experimental work is needed to confirm any such suggestions.

It should be clear from the foregoing discussion that corrosion on buried surfaces probably proceeds by the action of separate and distinct anodic and cathodic areas. The presence of such areas does not necessarily invalidate the analysis of cathodic protection presented previously. The mixed potential theory in no way specifies the distribution or location of sites for the partial electrochemical reactions, Eqs 1 and 2. The regular shape of the curves in Figs. 5 and 6 for buried specimens of relatively large surface area suggest that the theory is indeed valid. However, experimental work is needed to study the variation with potential of area and current density on anodic and cathodic surfaces. Further, such work is necessary to convince any potential user that the theory can be usefully applied in the design of cathodic protection systems.

Finally, the effect of coatings must be considered when applying electrochemical theory to cathodic protection of buried structures. Holidays in coatings are inevitable, but how do the frequency and distribution of holidays affect the design of a cathodic protection system? There is no clear answer to this question. Engineers generally allow for a lower rate of attenuation of cathodic protection in the presence of good quality coatings [*23*], but a quantitative evaluation of the effects of coating quality has not been forthcoming.

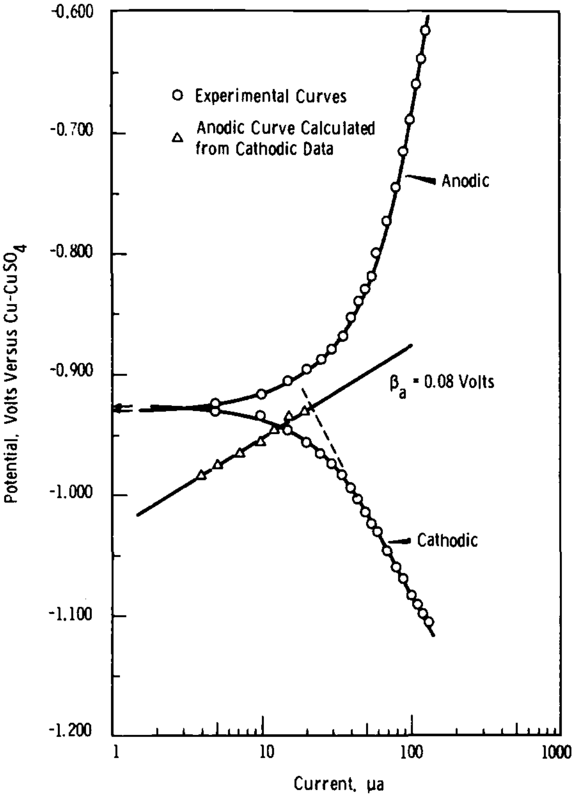

FIG. 6—*Polarization data for buried aluminum* [16].

Summary and Conclusions

1. Modern mixed potential theory provides the basis for quantitative corrosion rate measurement and application of cathodic protection to buried structures.

2. The predictions of mixed potential theory have been verified by electrochemical polarization measurements on buried aluminum and steel.

3. The interpretation of buried structure potentials are difficult with remote reference electrodes. This hampers the quantitative application of mixed potential theory to large buried structures.

4. Evidence indicates that separate, distinct anodic and cathodic surface areas are established on steel corroding in neutral electrolytes, including soil. While the application of mixed potential theory is not precluded by the presence of such areas, experimental work is needed to quantitatively determine the effect of polarizing current on the size, distribution, and current density in these anodic and cathodic surface areas.

5. A careful study of effects of coating quality on cathodic polarization and cathodic protection of buried structures is necessary.

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J. B. Lankes[1]

Practical Aspects of Underground Corrosion Control

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ABSTRACT: This paper presents a description of the underground jungle of structures and materials in their various environments. Methods to combat corrosion problems are given. Some of the pitfalls are discussed. A suggestion is made for American Society for Testing and Materials (ASTM) Standards that would be helpful to the corrosion control engineer.

KEY WORDS: aluminum, carbon, cast iron pipe, concentric neutral, copper, corrosion control, electrical grounding, galvanized pipe, graphitization, lead cables, magnesium anodes, polarization, reinforced concrete, strand shielding, underground corrosion

The papers presented at this symposium make my story a little bit ordinary. However, they are generally limited to very specific areas of interest within the field of underground corrosion control. I propose to touch upon the area where the engineer works, and where he must try to apply the lessons learned at symposia like these to the solution of his client's problem.

I will risk being repetitious in saying that corrosion is nature's way of returning metallic substances, worked by man, to their native state, such as auto fenders to iron oxide, galvanized coatings to zinc carbonate, or, somewhat far-fetched, aluminum to sapphires. Corrosion is an electrochemical process, requiring an anode and a cathode electrically connected in an electrolyte. Corrosion is a self-poisoning process, and in order for it to continue over a length of time, a mechanical or chemical means of depolarization or depassivation must exist. Interference with any one of these requirements will reduce the corrosion rate. Coatings, for instance, will separate anode from cathode or isolate the electrolyte from the metal, provided that it is a perfect coating.

When I got deep into this business, about 1955, estimates of the annual cost of corrosion was about six billion dollars in the United States. Within a

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[1] Corrosion control consultant, Richmond, Va. 23220.

year or two, eight billion was suggested, soon to be raised to eleven billion. Now the widely quoted figure is eighty billion. The Russian expert, Tomashov, painted a gloomy picture in 1965. His estimate was that one third of the total output of refined metal was eliminated from technical consumption because of corrosion. Two thirds of this was presumed recoverable as scrap, leaving 10 percent completely lost. He said this meant, in 1965 20 million tons of iron and steel were lost worldwide. He pointed up that cost of coatings and cost of overbuilding to compensate for cross-section losses were among the many facets in loss to the economy due to corrosion. These figures apply to all corrosion, not just the underground corrosion which is the theme for this conference.

In this paper, I want to describe the complexities of underground corrosion with particular reference to the urban areas; to suggest what can be done to simplify the complexities; and to hint at a few things where ASTM can contribute to the cause of underground corrosion control, in test methods or in material specification.

The greatest mass of material in underground structures is probably utilities; gas, water, electric, telephone, and sewer. Cast iron is used in gas, water, and sewer. It may or may not be electrically continuous, depending on the type of joint connection. Technically, cast iron pipe is uncoated, but anyone who has tried to make a low voltage electrical connection knows that the oxide film has considerable electrical resistance. An interesting line of research would be to determine whether or not this coating is sufficiently effective to make cathodic protection of cast iron pipe a practical thing. Every time I have tried to make a long-term test on this possibility, a bulldozer has invaded my test site before meaningful results can be obtained. It is my feeling that under the influence of cathodic protection, the oxide coating will be eventually reduced back to iron. It seems to me that an investigation of this could be of substantial value, if one could wait ten years for results.

Cast iron does not visibly corrode. The corrosion action results in "graphitization," whereby the pipe is changed electrochemically to the equivalent of a carbon or graphite pipe. This has considerable bursting strength, Bureau of Standards tests having shown that graphitized pipe will resist internal pressures of up to 3450 kPa (500 psi). The problem with cast iron in this condition is that it is extremely brittle, so it might break completely under temperature stresses or traffic impact.

Cast iron cannot conveniently be made into pipes of less than 76 mm (3 in.) in diameter, so much wrought iron was used in the smaller sizes, before the advent of coated steel pipe. Uncoated steel pipe has been widely used, in large and small sizes. As with other piping systems, steel pipe is not necessarily electrically continuous when mechanical couplings are used.

In water and gas service, much galvanized steel pipe has been installed. This may be correctly termed a coated pipe since a "chemical conversion" coating is formed in service. The zinc-iron alloy surface reacts with the electrolyte to create a tightly adhering zinc hydroxide, zinc carbonate, or other chemical, depending on the environment. Iron seems to be a catalyst in this chemical change, and we have found out that if zinc anodes are to be effective, their iron content must be not more than 0.0014 percent. The zinc alloy in a galvanized coating runs up to 30 percent iron.

Copper is still being used for water service and up to lately has been used for gas. A complication in the corrosion control engineer's life can be the brass fittings in a ferrous pipe. Lead has not been used for water lines for some time, but plenty of it can still be found in service.

The electric and communications utilities add their materials to the underground world. In urban areas much lead sheathed cable, electric and phone, still exists. A required part of these systems is a grounding scheme, far too much of which is copper-clad ground rods. The informed tendency today is to use the galvanized rod, which I believe to be fully adequate. European practice has been to ground with black iron rods, and this scheme has been used for plant grounding in a major American steel company. A proof of the adequacy of the galvanized ground is the galvanized anchor and anchor rod. Since these are installed to hold a strain, a slack wire (or worse) would immediately indicate failure of the rod or anchor.

For the suburban developments, a very popular form of electrical distribution is the Underground Residential Distribution system (URD). The cable used is a concentric neutral construction, with the hot wire at the center coaxially, and the neutral spiraled over the outer surface as a shield or sheath. For a 1/0 conductor, the neutral would be sixteen No. 14 bare tinned copper wires or, in some experimental work, ten No. 10 aluminum wires, EC grade. The neutral is left uncovered for safety reasons. The surface on which the neutral is wound is a semiconducting layer, so-called because the plastic material is heavily impregnated with lamp black which provides some conductance. The effect is to evenly distribute electrical stresses over the cable insulation. The "semi-con" is more properly called strand shielding or insulation shielding. Carbon is highly electro-positive and concern has been felt that this will lead to a strong galvanic cell between the "semi-con" layer and the tinned copper (or aluminum) neutral. Some investigators, including myself, are of the opinion that carbon polarizes quickly and that the galvanic cell after carbon polarization is negligible.

I would like, for a moment, to invade the academic domain. "Polarization" is a word which needs a better definition and is a physical effect which needs a better exposition of the basic theory. To my mind, polarization is the accumulation and retention of electrons in the cathode; that is, in the electropositive material of a galvanic cell. However, the accumulation of hydrogen on a cathodic surface is also called polarization. The ASTM Definitions Committee might be able to help us here.

Direct buried transformers add another dimension to the underground mix, especially if the case is stainless steel or other exotic metal. Galvanized transformer tanks are a real possibility in future underground electrical distribution.

Pipe enters into electrical distribution in the form of conduits and "pipe-type" cable. Pipe-type cable is used for bulk power transmission in urban areas, and the three or four conductors are carried inside a pipe. Circulating oil is used for cooling. One leak could lead to complete failure of this expensive system, so very complete corrosion control measures are required and installed. Design must be such that thousands of amperes of a-c fault current can flow to ground without interfering with or deranging the cathodic protection system.

The local electric substation in the built-up areas plays a part in the corrosion picture. The large copper grounding grid creates a large cathodic area. I have a notion that this polarizes in time so that it is not as effective a cathode as might seem in theory.

Perhaps the same polarization effect applies to the considerable area of reinforcing in concrete structures and foundations. This responds very readily to protective current and builds up considerable polarization in time.

It was mentioned that much cast iron was used in sewer service. The trend now is to go to large concrete cylinder pipe. This pipe is built up on a reinforced steel foundation, but since it is seldom electrically continuous, the external surface does not normally enter into the corrosion picture. However, in big electrical power stations where this pipe is used for cooling water circulation, provisions can be made to link the metals parts across each joint. If this is not done, and hundreds of amperes are applied for cathodic protection of the entire station, stray currents jumping from section to section could destroy the pipe in a relatively short time.

In the underground world, we find many buried tanks, such as residential heating oil and service station gasoline tanks. The sti-P_3 system is useful here for the protection of newly installed tanks, and the principle is fine for existing tanks. However, in applying protection to existing facilities, the engineer does not have the advantage of design information. He will be lucky if he can be sure of the size of the tank. Some might worry about static electricity causing a spark across insulating devices used to isolate the tank from the electrical neutral. I am of the opinion that existing codes specifically permit such insulations.

The bottoms of multi-million gallon petroleum product surface tanks could be construed as being a part of the underground complex. Major problems here occur in voids under the bottoms, and of course cathodic protection does not work through an air-filled void.

A little realized problem is corrosion of hydraulic elevators and hydraulic lifts. John Fitzgerald, in his lecture on Miscellaneous Structures at the Appalachian Underground Short Course, reports that three of twelve automotive hoists failed within two years after installation. It is not likely that failures will be catastrophic, but it is certain that replacements will be expensive and time consuming. Cathodic protection of these would seem to be a good investment.

And, finally, the bothersome gnat in the corrosion control engineers work is the metal fence post. This has been known to touch a gas line and short out the cathodic protection through the metal fence or metal clothes line, to the aluminum siding of the house, to the grounded electrical meter socket.

The electrical power stations, sewage disposal plants, open water drilling platforms, well casings, marine sheet piling, drinking water treatment facilities, and steel mine shafts are other universes which we will not attempt to explore.

As a general rule, all of these various metallic structures are electrically connected together. This presents a problem when one entity proposes to protect their part of the complex. Of course, it might be said that everything underground ought to be protected. No doubt this could be done if a sufficiency of rectifiers and ground beds could be installed. But there are complications. Lead and aluminum are directly subject to damage from overprotection. The ferrous metals, and perhaps others, can suffer from hydrogen or caustic embrittlement under the right conditions. Reinforced concrete is said to soften when subjected to high current densities. And there almost certainly will be stray current damage from current pickup near the ground beds with discharge at convenient points some distance away, also damage at insulating joints of concrete cylinder pipe and on Dresser-coupled steel pipe.

A bone of contention will be who pays for the cost of protection. The gas company can say that their need is much less than the others, and the electric people will say they need no protection at all. Protection of all underground structures as a group will not be an easy thing to administer.

So up to now each owner of underground structures has done what he thinks necessary to protect his property from corrosion. Materials selection has played its part with lead pipe, copper pipe, plastics, exotic metals, etc. Such selection is not always economically practical, and sometimes not in the best interest of the public.

Early attempts at protection in gas distribution was the application of the coal-tar product from the manufacture of "city gas." At the work site, one man would pour this goo onto the pipe while another would "granny-rag" it; that is, he would pass a cloth under the pipe and apply the tar to the bottom of the pipe by pulling alternately on the ends of the "rag." Since it costs little, no one thought about economic evaluation. Now we find that coating a structure can actually hasten failure. It is popularly said that corrosion will concentrate at the coating defects or "holidays." There are two primary reasons for this. First, the cathode, wherever it may be, is vastly larger than the anode at the holiday in the pipe coating, and second, the electrical resistance to remote earth of the exposed area is not a direct proportion of its ratio to the entire pipe surface.

It is instructive to make a practical demonstration of this ratio. I have two small coupons, one bare and the other coated, and I show that so much current flows when the bare coupon is coupled electrolytically to a cathode. Then I substitute the coated electrode and hope that no current flows. If it does not, I make a pin hole in the coating, and it is then seen that the resulting current is 50 percent or more of the current from the entire bare coupon. As a poor substitute for this experiment, I have prepared a mathematical analysis of the comparison of the resistance to remote earth of a square centimetre of a 100-m of 2-in. bare pipe against a square centimetre of a holiday in a coated pipe. It may be seen that, theoretically, the corrosion rate at the holiday is 100 times that of an equivalent surface on a bare pipe (see appendix). Actually, practical considerations such as formation of corrosion product change this picture dramatically.

I have, in a somewhat roundabout way, indicated that the cathodic protection of the entire underground complex is impractical, that coating alone cannot be depended on, and that corrosion resistant materials such as copper or lead might not be economically feasible, or might not be acceptable to environmental activists.

I must correct myself in suggesting that copper might be an absolute answer to corrosion problems. It has been my experience that copper, isolated from the rest of the underground system, is highly susceptible to differential concentration corrosion. In the past, I have been a bit dubious about this, having seen a number of instances where copper corrosion was due to a-c corrosion. Since then, I have found unmistakeable evidence that a 6 m (20 ft) length of copper water pipe has corroded through in less than six months. This was during construction, and the piping was definitely not connected to other structures, nor was it in a stray current area, nor was it used as a ground in welding operations. Four and a half metres (15 ft) of the copper was in sand, and 2 m (6 ft) was in clay. An example of a differential concentration cell, without doubt.

So, as far as I am concerned, there is but one answer to the problem of protection of the jungle that makes up the world of underground structures. That is the isolation of the property of one owner from the property of others, and cathodic protection to the extent needed. Each owner has his peculiar problems, and it is the duty of each to solve these problems as best he can.

We should be aware that a very particular public problem could arise. In fact, with the use of plastic for water and gas services, it could be with us now. Safety grounding of electrical systems concerns us all. Where will we be if the water system, gas system, electrical distribution grounding system, and the reinforced concrete systems are insulated from each other? It is doubtful if we can depend on the safety provided by a 2 m (6 ft) ground rod, which could have a resistance of hundreds of ohms.

Now let me turn to a few suggestions where the good offices of ASTM could be helpful to the corrosion control engineer.

I have mentioned that it might be possible to protect cast iron pipe on the basis that the oxide coating is a dielectric. The problem of protection of cast iron is one that is sure to arise in the next ten years, and ten years is barely enough time to make a proper investigation. The start of a study is urgently needed unless some theoretician can state and prove positively whether or not cathodic protection of cast iron is feasible.

The detection of graphitization is a real puzzle for the man in the field. The scientist has magnetic and electronic devices in his laboratory to examine a specimen, but the street foreman has no such advantage. An old-timer once told me to use the Clang and Clunk Test. That is, the pipe is struck with a hammer. If the resulting sound is "clang," the pipe is good. If the sound is "clunk" or the pipe breaks, graphitization is possible. Some say test with a knife-point which will penetrate into the graphite. Pipeline Safety Regulations concerning gas pipe require that piping exposed in digging operations must be examined for evidence of corrosion. Cast iron pipe is not made an exception. What method, then, must management tell the street foreman to use to find if graphitization exists? Is it possible that the device used to check paint thickness could be adapted for this service?

I have pointed up that if zinc anodes are to be effective, they must conform to the limits of ASTM Standard for Cast and Wrought Galvanic Zinc Anodes for use in Saline Electrolytes B 418. We do not have such a specification for magnesium anodes, although there are four industry accepted alloys and quite a number of standard shapes. It is not a question of engineering expertise; it seems to be a matter for diplomatic negotiations between two organizations with conflicting and strongly held opinions.

There is, at least in my mind, a question of whether or not the potentials for protection of aluminum and copper could have lesser values. The National Association of Corrosion Engineers (NACE) has published recommended values, but I believe these to be extremely conservative. Some investigations and a few published papers might be helpful. The protective level for iron has been questioned, but since it is relatively easy to protect coated pipe, there is doubt that time spent on this could be rewarding.

Also worthy of investigation would be protection of reinforcing in concrete. J. M. Pearson pointed up that concrete would soften at the reinforcing under high current densities, but my impression is that these densities would not be found in a normal installation. An ASTM standard of maximum allowable current density to be impressed on reinforcing could dispel some anxiety.

A standard for evaluating polarization of reinforcing is also needed. Under low current densities, full polarization might not be reached for three months or more.

I hope that ASTM would be willing to define and identify polarization as it applies to cathodic protection. The Institute of Electrical and Electronic Engineers (IEEE) Standard Dictionary has a paragraph on "electrolytic polarization," but this applies only during current flow. There is a change of potential that persists to some degree, and for some short or extended time after current is turned off. I am a little of the opinion that there is much information on this subject in the American Institute of Electrical Engineers (AIEE) Transactions of around 1900, when batteries were given a great deal of basic study. These old references are not too easily available to the field engineer.

I realize that some of these notions for action might not fit in with ASTM aims and objectives. Perhaps there are areas where other organizations should act. I feel, though, that a genuine interest in an investigation is authority enough to proceed. A little competition will help to dispel the fog of complacency.

APPENDIX

Mathematical Analysis of Comparison of Rate of Corrosion of One Square Centimetre at a Holiday in Coated Pipe Versus One Square Centimetre at the Surface of a Bare Pipe

Resistance of circular plate to remote earth

$$R = \rho/8a + \rho/d\, 8\, \pi \qquad \text{Sunde 3.22}$$

Resistance to remote earth of horizontal pipe

$$R = \rho/L\pi\ (2.3 \log 2L/2ad^{1/2} - 1) \qquad \text{Sunde 3.36}$$

ρ = resistivity: assume 1000 Ω cm

a = radius: assume 1 cm for holiday and 2.54 cm for pipe

d = depth: assume 1 m or 100 cm

L = length: assume 100 m or 10 000 cm

Area of 1 cm radius = $\pi \times 1 \times 1 = 3.14$ cm^2

Resistance of above = $1000/8 + 1000/800\ \pi = 125$ Ω total or roughly 400 Ω/cm^2.

Surface area of 100 m of 2 in. outside diameter bare pipe =

$$2.54 \times 2.54 \times \pi \times 10\,000 = 200\,000 \text{ cm}^2 \text{ roughly.}$$

Resistance to remote earth of above =

$$1000/10\,000\ \pi\ [2.3 \log 20\,000/(2 \times 2.54 \times 100)^{1/2} - 1] = 0.184\ \Omega$$

or roughly 36 800 Ω/cm^2.

Therefore, the metal at the holiday will corrode 36 800/400 or roughly 100 times faster than the square centimetre on the surface of the bare pipe.

K. G. Compton[1]

Corrosion of Buried Pipes and Cables, Techniques of Study, Survey, and Mitigation

REFERENCE: Compton, K. G., "**Corrosion of Buried Pipes and Cables, Techniques of Study, Survey, and Mitigation,**" *Underground Corrosion, ASTM STP 741,* Edward Escalante, Ed., American Society for Testing and Materials, 1981, pp. 141–155.

ABSTRACT: Some of the techniques for studying the corrosion behavior of buried structures in the laboratory and in the field are described with illustrations, and methods of mitigation are described and discussed. The author draws upon experience with underground corrosion of steel, lead, and copper, and discriminates between profitable and unprofitable procedures.

KEY WORDS: underground corrosion, pipelines, buried cables, polarization, cathodic protection, steel soil corrosion, copper soil corrosion, lead soil corrosion, protective coatings

Due to increased interest in the corrosion and leaking of buried metal gas pipes, and the corrosion of the concentric neutrals of underground electric distribution cables, a considerable effort is being made in research and mitigative measures. In the background is the desire to promote safety in accordance with government agencies and utility companies. This paper addresses the problems and methods employed in research, surveys, and control of corrosion.

Research

In developing a research program, one must be mindful of the numerous variables encountered in any study of underground corrosion. The actual influence of many of the variables is not known with any degree of precision, in spite of the many years that underground corrosion has been studied. In many situations, several of the variables are operating simultaneously.

The use of salt solutions to simulate a soil will give unrealistic results. The vast ion mobility differences between a soil and a solution, the concentrations developed at the soil-structure interface, and the trace species present,

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[1] Professor of Mechanical and Ocean Engineering, University of Miami, Miami, Fla. 33149.

all influence the electrochemical reactions in the corrosion cell. In the laboratory, one must duplicate the "buried" conditions as nearly as possible. The pH at the structure-soil interface is significantly different from that in the body of the soil. The observations made in the laboratory on a small scale should be verified by larger scale observations outdoors.

Soils

The actual effects of the various ions in a soil are not clearly established due to the synergistic effects of the specific ions, the resistivity of the soil, its oxygen content, acidity, electric currents, and other variables. Only one generality appears to be consistent, soils of low resistivity containing significant concentrations of chloride and sulfate ions are usually the most corrosive. Sulfides and nitrates sometimes distort this picture.

Soils are usually described by their relative percentage of sand, silt, clay, and gravel, and not by the ionic content. However, a student of corrosion in soils needs a knowledge of the relative concentration of the principal ions. This need not be highly precise and is usually given in milli-equivalents of the ion per unit of weight of the dry soil. This is not completely satisfactory, because the fineness of the particles of the soil plays a role in the effective concentration of the ions. A satisfactory analytical technique for most purposes is to make a water extract of a given weight of dry screened soil and use one of the simple water analysis kits to determine the concentration of the ions in the extract, then convert back to milli-equivalents of ion per 100 g of dry soil.

The ions that need determination are usually chlorine, sulphate (SO_4), nitrate (NO_3), phosphate (PO_4), calcium, and sodium. In some cases, the presence of sulfides such as hydrogen sulfide (H_2S) should be determined. The acidity as measured by pH and the resistivity at one or more degrees of water saturation should be determined. Again, highly precise measurements of these properties are not necessary. In some cases a determination of the total acidity is desirable. The aeration of the soil is important but very difficult to quantify; hence, we speak of a sandy, gravelly soil as highly aerated, and compact clays as poorly aerated, with the water content and the porosity being controlling variables. A good discussion of soils is given by Romanoff [*1*].[2]

Materials

The materials of interest in underground corrosion addressed in this paper belong in the three broad classes of steel, lead, and copper. In practice, steel is sometimes modified by a zinc coating, and copper by a tin or a lead-tin alloy coating. In the case of the buried power cables, there is an additional

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[2] The italic numbers in brackets refer to the list of references appended to this paper.

variable in the form of a highly carbon filled polyethylene shield over the insulation and under the neutral wires to eliminate concentrations of high electric stress. The materials aspect of the problem is much simpler than others, but any research program on power cables needs to be aware of the behavior of metal surfaces in contact with or coupled to carbon. In the field measurements described later, the investigator may not know what the specific material is to which he is making his measurements in studying corrosion of power cables.

Steel and lead do not impose the complications presented by the power cables. The coatings on the copper neutral wires are very thin and may disappear during the experiment due to corrosion. They are several hundred millivolts negative to copper in a soil, and tin forms an inter-metallic compound with copper that is more positive, or "noble" to copper. The difference in potential between oxidized steel and lead, and bare steel or lead appears to be considerably greater than the potential differences between oxidized copper and bare copper (assuming cuprous oxide). An example of the difference between oxidized lead and bright lead is shown in Fig. 1.

External Factors

The principal external factor in underground corrosion is stray current, either dc or ac. The stray dc produces effects on the corrosion rate that are largely governed by Faraday's law. On the other hand, ac is a different story and is not fully understood. Compton [*2*] demonstrated that at significant current densities ac accelerated the corrosion in most soils. This was related to a depolarization effect.

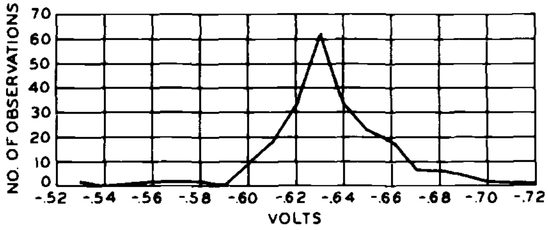
Laboratory Techniques

Potential Measurements

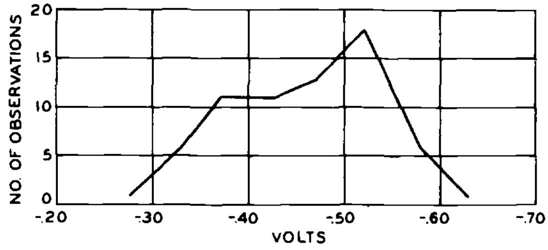
In the laboratory, a selected natural soil or mixture of sand, natural soil, or chemicals is used in place of aqueous solutions. The metal specimens are inserted into the soil, and the salt bridge of the reference electrode is placed in contact with the soil, usually near the surface. A suitable high impedance voltage measuring device will measure the open circuit or corrosion potential (E_k) of the metal specimen with respect to the reference electrode. In the absence of an impressed current on the metal, a capillary tip (or Luggin Probe) is unnecessary, but, if a significant current is passed through the soil, it may be necessary to bring the end of the salt bridge very close to the surface of the metal being measured.

The potential will be found to shift with time from the initial measurement. Typically, a freshly abraded specimen of copper will have a potential of nearly −0.200 V to the saturated copper sulfate electrode. This will, at first, shift rapidly in the positive direction, then slowly settle down to about

THE POTENTIAL OF BRIGHT (FRESHLY SCRAPED) LEAD
AND OF BURIED (OLD) LEAD PLATES IN CONTACT WITH SOIL
OF pH 5 TO 6.5 VS COPPER-COPPER SULPHATE
REFERENCE ELECTRODE (HALF-CELL)



POTENTIAL OF BRIGHT LEAD VS $Cu/CuSO_4$ HALF-CELL
231 OBSERVATIONS



POTENTIAL OF "OLD LEAD" VS $Cu/CuSO_4$ HALF-CELL
73 OBSERVATIONS

CABLE SHEATH TO COPPER-COPPER SULPHATE
ELECTRODE VOLTAGE DISTRIBUTION CURVE

FIG. 1—*Potential of freshly abraded lead cable sheath compared to the potential of sheath that has been in service for several years and is oxidized and passive.*

—0.060 V after several hours, depending on the soil. A new specimen will have a different initial potential of say —0.180 V, and shift to —0.070 V. If the specimen is not freshly abraded, it will have an initial potential nearer the value of —0.060 V. If it is removed from the soil and then replaced, a different initial potential will be observed. This behavior results from the film on the metal and the particular ion environment it encounters in the soil. The author has found that averages of ten or more readings in the same time frame are required to get consistent results, starting with freshly abraded specimens.

Polarization Measurements

Either galvanostatic or potentiostatic methods may be used, but the relatively steady state builds up slowly so that rapid scans may be misleading. Figure 2 shows the slow buildup of potential during a galvanostatic study.

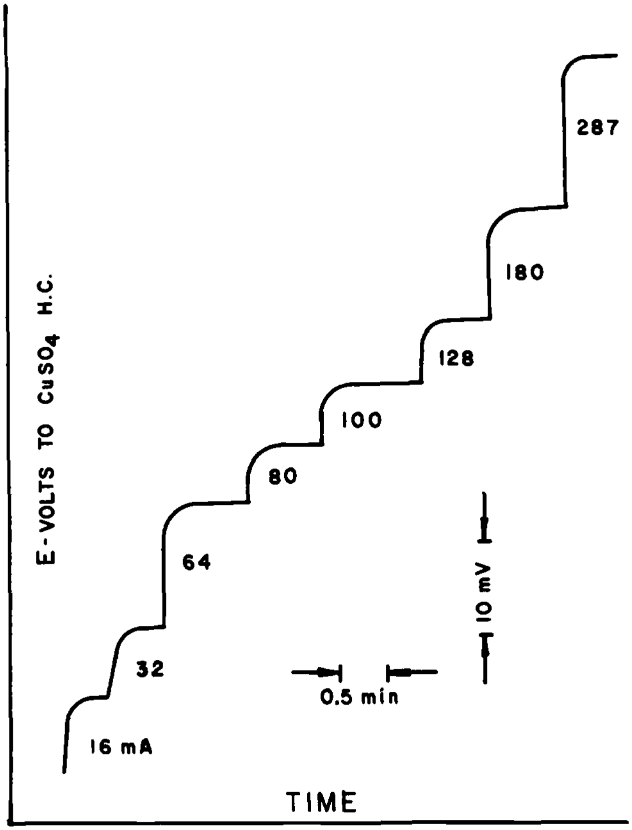


FIG. 2—*Potentials as a function of time as polarizing currents are increased in steps showing the slowness with which the final steady potential is reached.*

The current is built up in increments and held constant until the potential reaches a relatively steady value. If the dwell time is extended, usually, the potential continues to shift by a small amount. No rules have been established for the degree of stability required at the time of recording the potential as a function of current or vice versa. A typical plot of the log of the current density is shown in Fig. 3 for lead-tin alloy coated copper. The open circuit or corrosion potential (E_k) of these wires was −0.380 V. The polarization curves in soils are not reversible as a result of alteration in the surface of the specimens by the polarizing current and by changes in the soil composition adjacent to it. This requires repetition of the same experiment with freshly prepared surfaces.

In attempting to use the "linear polarization resistance" method of determining corrosion rates one finds "resistance" of the anode differs from that of the cathode due to concentration effects, and the oxidation or reduction reactions at each electrode. Many polarization curves on all three metals in-

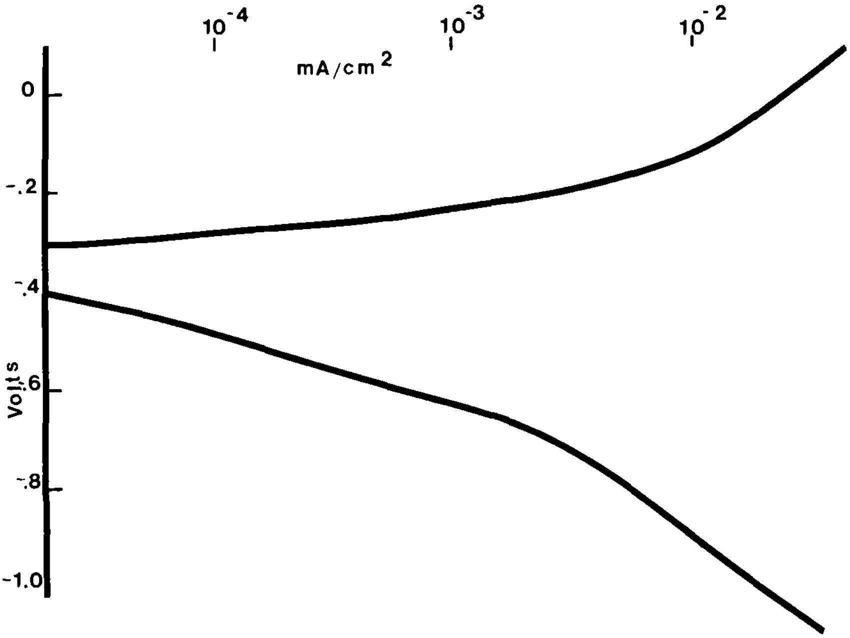


FIG. 3—*Polarization curves for lead-tin coated copper concentric neutral wires. Potential to the copper sulfate electrode.*

dicate that corrosion is controlled by a combination of anodic and cathodic polarization skewed heavily in the direction of cathodic control. This suggests that one can not use a polarization resistance taken entirely on the cathodic side. The writer has used the corrosion rates calculated by using the polarization resistance for both the anodic and the cathodic sides of the inflection point as a range.

Laboratory Techniques

One cannot use specimens that have been exposed for long periods of time for the polarization resistance method of Stern [*9,10*] because of the influence of the thick protective corrosion film. This makes the area in question subject to error because much of the film is insulating and the cathodic current is used, in part, to reduce the corrosion film. This method of corrosion rate estimation reaches its highest precision in a situation where the corrosion product is completely soluble in the corroding fluid, and where the cathodic reaction is the reduction of hydrogen ions or water.

The most satisfactory measure of corrosion rate is weight loss per unit of area combined with pitting depth. In instances of highly localized corrosion or pitting, a decrease in tensile strength could be a more realistic criterion. In any weight loss studies as well as the Stern-Geary technique, the pH and the aeration must be controlled.

If the laboratory work involves impressed alternating current, the experimenter must be certain that his measuring instruments are capable of discrimination between ac and dc. Similarly, he must keep dc out of the ac section of his circuit and ac out of the dc section by means of condensers and chokes. In most cases, the potentials and currents change with time or "drift" so that an arbitrary degree of stability has to be accepted. Exceptionally long stabilization periods may permit reactions at the surface that give misleading data, and the converse may not permit the reaction to reach a reasonable degree of completion.

The writer has determined many time-corrosion potential curves on steel, lead, and copper in a variety of soils and has observed large variations in their behavior. Making simultaneous measurements on ten identical specimens tends to give data on which reasonable confidence may be placed.

Underground Corrosion Field Studies and Surveys

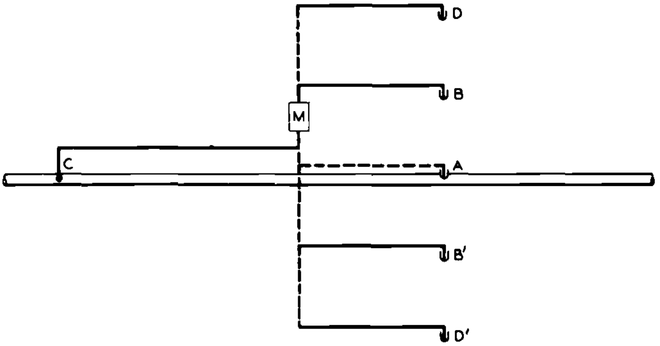
Out in the field, one wishes to know if and where his underground structure is corroding. Other than exposing the structure by digging and making a visual examination, there is no positive way of determining the condition of the structure. The presence of active corrosion can be determined, frequently, by certain electrical measurements or surveys. Similarly, the cause of the corrosion may be determined by electrical measurements. These techniques are not simple, and no single measurement, in most circumstances, will prove or disprove the presence of stray d-c current.

Corrosion on buried structures results from internal forces such as corrosion cells produced by differential aeration, differences in soil composition, the effect of cinders, differences in the surface metal, etc., and by external stray currents, either dc or ac. The worst situation is usually stray dc. In the internal system, the corroding area has a more negative potential than the surrounding surfaces of the metal or other metal equivalents as in a dry cell. In stray d-c situations the corroding area is more positive than its neighbor areas. In the days when stray d-c current from trolley cars was a problem, corrosion engineers looked for areas on their structures that were positive to the grounded negative of the trolley system. Here, they would have serious corrosion problems.

The methods of locating possible areas of corrosion were described by Mudd [*3*], Standring [*4*], Compton [*5*], Logan, et al [*6*], their associates, and others. As indicated by these writers, no potential survey will locate localized small corrosion cells. Primarily, the method consists of measuring the potential of the structure to a reference electrode placed in contact with the nearby earth. Related is the measurement of the fall or difference in potential between two reference electrodes in contact with the earth to determine the presence and direction of current flow. In a well managed survey of a structure such as a pipeline or a cable, the first procedure is to make a series of measurements along the length of the structure of its potential to the reference electrode placed on the earth above it. At points where changes in the potential occur, lateral measurements should be made at close spacing to determine the presence of current. If the cable potential readings become more positive in a somewhat uniform manner as the electrode is moved away from the structure, current is flowing away from that point. If they become more negative, current is flowing toward the structure, and if they change in one direction on one side of the structure but in the opposite direction on the other, current is flowing past the structure and may not affect it. This is shown in Fig. 4. None of these methods reveal local cell corrosion.

Many papers have been written which present, in reality, very limited methods of making field electrical measurements in the study of corrosion. For example, insistence on making potential measurements of the cable or pipe to a half cell (reference electrode) placed on the ground a fixed distance to one side of the structure merely adds an IR voltage drop error to the readings. If the half cell is also placed over the cable or pipe in addition one may discover a current in the earth which cannot be related to the structure.

LATERAL POTENTIAL GRADIENTS



	METER READING IN VOLTS					REMARKS
1	C-A -0.58	C-B -0.64	C-B' -0.63	C-D -0.70	C-D' -0.68	CABLE RECEIVING CURRENT
2	A-B +0.060	A-B' +0.050	A-D +0.120	A-D' +0.100		
3	C-A -0.58	C-B -0.50	C-B' -0.51	C-D -0.42	C-D' -0.41	CABLE DISCHARGING CURRENT
4	A-B -0.080	A-B' -0.070	A-D -0.160	A-D' -0.170		
5	C-A -0.58	C-B -0.64	C-B' -0.51	C-D -0.70	C-D' -0.41	TRANSVERSE CURRENT
6	A-B +0.060	A-B' -0.070	A-D +0.120	A-D' -0.170		

FIG. 4—*Method of measuring pipe or cable potentials in the field.*

Changes in the potential of the structure to a half cell over the structure do not give positive indications of corrosion unless supplemented by other readings as described previously.

Pipelines and lead sheathed cables can be surveyed in a rather simple and straightforward manner compared to the new underground problem confronting corrosion engineers, the buried underground residential distribution (URD) power cables. In addition to those factors in common with pipelines and lead sheathed cables, there is the presence of stray ac, the uncertainty as to the material of the outer surface, and the difference between single-phase and three-phase cables. The stray ac is usually produced by the owner of the cable. Holley [7] demonstrated that if the number of wires in the concentric neutral is reduced to give a conductivity much less than the core or phase conductor, a large portion of the a-c current will be returned from the load to the source through the parallel path in the earth. Where this current passes from cable to earth, a considerable acceleration of corrosion may be produced. The grounding system is at the source, and the load figures into the amount and behavior of the stray ac. In his paper he showed that a particular construction of single phase cable with reduced neutral capacity would return 25 percent of the load current through the earth.

The potential of a "tinned" neutral is about 300 to 400 mV negative to a bare copper neutral, but, in many reports, corrosion engineers appear to have ignored this difference in cables. Again, an "ideally balanced" three-phase cable would have no stray ac returning in the parallel path. Furthermore, corrosion engineers often make little or no distinction between single and polyphase cables. In addition, the current density of the stray ac is unknown, and in many cases its presence is undetected.

Resistivity measurements in the area have some value in judging the corrosion, but one must realize that the resistivity of the soil in contact with or near the cable may be significantly different from that determined by the four pin method. Analysis of the soil and a judgment of its aeration may help in determining the cause of the corrosion but may be misleading if given too much weight.

Recommended Procedure for Surveys

Although individual situations may make variations necessary, the author has found the following procedure to give satisfactory results.

1. Connect the negative terminal of the voltage measuring instrument to the underground structure and the saturated copper sulfate reference electrode (half cell) to the positive terminal with properly insulated test leads of convenient length. Place the half cell over the structure and read the potential. Advance the half cell in measured steps of 1 or 2 m, measuring and recording at each step. Plot the measured potentials against the distance along the structures.

2. At points where a significant change in potential occurs (more than 25 mV), make a lateral survey in steps of 1 or 2 m by either of the following methods.

1. With the negative terminal of the meter still connected to the structure, move the half cell in steps at a right angle to the structure to both sides. If the readings become less negative, current is flowing away from the cable, if more negative, a current is flowing to the cable, if more positive on one side and less positive on the other, a current may be flowing past the cable without affecting it. See Fig. 4.

2. The author prefers to use two matched half cells, placing one over the cable and advancing the other at a right angle to the cable. If the half cell over the cable is positive to the advancing cell, the current is flowing from the cable.

Figure 5 illustrates a situation where this technique could be applied to a cable running along a street. (The cable had failed and had to be replaced). The survey was made on the new cable to aid in planning mitigative measures. Starting at the cable splice at 0 m, a survey of the potentials of the cable to a copper sulfate electrode on the surface over the cable was made using 5-m intervals. These over the cable measurements are shown in Table 1. Based on past experience, it was obvious that potentials between 0 and 40 m were more positive than they should have been. Surface gradient potentials were measured at a right angle to the cable at steps of 3 m from the cable splice location, 0 m, by placing one copper sulfate electrode over the cable and advancing the other measuring the potential between them with the results shown in Table 1. These measurements show that a corrosion current is flowing from the cable into the earth at one side. No surface gradients could be made in the opposite direction due to the wide paved street. The cause of the corrosion current was the presence of a cinder fill in a parking lot to one side of the cable that was in contact with water pipes, which in turn were grounded to the cable. The use of insulating joints and cathodic protection solved the problem.

In power cables where stray ac may be encountered, the a-c drop should be measured laterally and a-c potentials to nearby structures should be made. The potential of the cable to half cell is usually changed by the presence of ac as compared to its absence as shown in Fig. 6. Making an over the cable survey with the power off and then repeating with the cable energized may indicate self generated stray ac in a single phase cable but would not in a well balanced three phase cable.

Mitigation of Underground Corrosion by Cathodic Protection

Impressing a direct current on an underground structure of adequate current density to polarize all of the cathodes to the potential of the anodes would, according to Mears and Brown [*8*], completely suppress corrosion. In

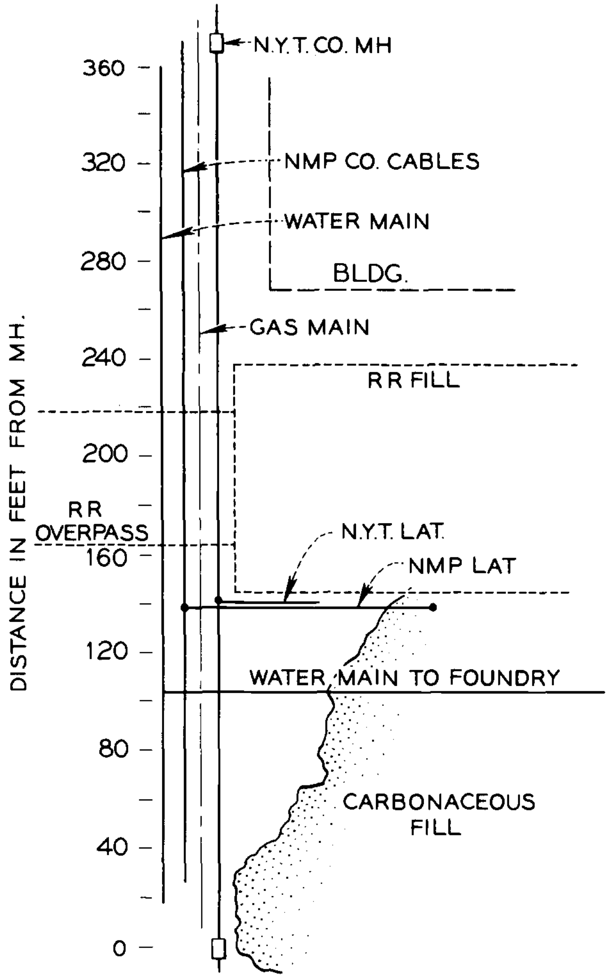


FIG. 5—*Layout of cables etc. at site where data in Table 1 were obtained.*

TABLE 1—*Over-the-cable and right angle to cable measurements.*

Over Cable		Right Angle to Cable				
Distance from Splice along Cable, m		Meters at a Right Angle from the Cable	Distance from Splice Point, m			
			0	3	6	12
	Volts		Volts			
0	−0.30	0	0	0	0	0
3	−0.42	1	−0.03	−0.03	−0.02	−0.01
6	−0.40	2	−0.18	−0.18	0.18	−0.02
9	−0.45	3	−0.32	−0.35	0.35	−0.02
12	−0.55	4	−0.35	...	...	...
15	−0.60	5	−0.30	−0.40	0.41	−0.01
30	−0.62	6	−0.05	−0.28	0.32	+0.005
60	−0.60	7	+0.05	−0.10	−0.14	+0.02
90	−0.55	8	+0.20	+0.10	+0.05	+0.05

the absence of stray ac, this can be achieved if the impressed current can reach the structure and produce the required polarization. The current may be supplied from power sources such as rectifiers or sacrificial anodes. Carbon steel must be polarized to a potential more negative than −0.85 V to the copper sulfate half cell, lead cable sheath to <−0.70 V, and copper to about −0.20 V. The criterion for the cathodic protection of copper has not been established as well as that of the other two metals. In the case of the power cables, the metallic surface to be polarized is something of an uncertainty. Some investigators recommend shifting the open circuit potential 100 mV negative.

There has been lots of discussion in the literature about how to apply these criteria, where to place the half cell, and the effects of excessive polarization. Several bridge methods of eliminating the IR drop in the earth have been used. The author [5] has made use of the Pierson, Logan, Hadley bridge method which was developed jointly by the National Bureau of Standards and the research laboratory of a pipeline company. These bridge circuits are cumbersome in the field and are inoperative in the presence of stray d-c currents. All experienced research workers in the electrochemistry of corrosion know that the potential of interest is that between the structure and the immediate surrounding earth. In other words, the closer the half cell is to the structure, the more reliable or significant the potential measurement. Hence, any measurements to "remote earth" or to a half cell at fixed distances (such as 91 m 300 ft) from the structure may be meaningless.

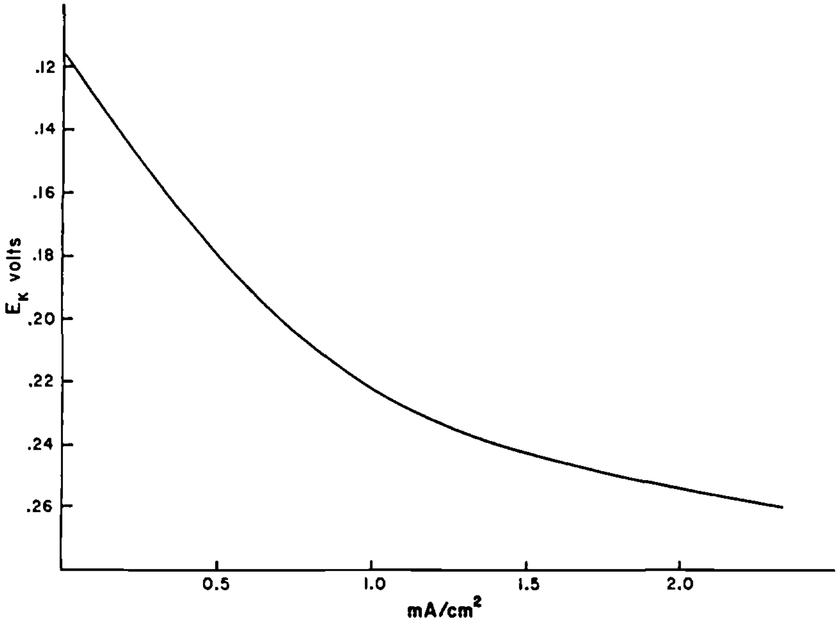


FIG. 6—*Shift of the corrosion potential of copper concentric neutral wires to a copper sulfate electrode in soil with the application of ac at various current densities.*

In the presence of stray a-c current there are indications that the structure cannot be polarized to a potential where protection is obtained. When the positive half wave of the ac hits the structure, the current leads the voltage while the condenser formed by the Helmholtz double layer is being charged. The voltage then builds up and many of the reducing reactions at the surface are changed to oxidizing reactions, making the entire surface strongly anodic and corroding. With the reversal of the current, the charging operation repeats in the opposite direction and reducing reactions take over. The d-c polarization is relatively slow so that it is rapidly reduced when the ac opposes it, and does not buildup fast enough when the ac is aiding. This results in a suppression of polarization in both directions.

Summary

The intention of the author was to cover the general principles, procedures, and some of the pitfalls in the study of underground corrosion. It was pointed up that solutions of salts have little in common with a real soil, that highly precise measurements of composition, pH, resistivity, etc., are unnecessary, and that a steady-state relationship between such things as polarizing current and electrode potential, rarely exist. Further, there is no shortcut to a painstaking examination of all of the parameters if one wishes to solve the cause of an underground corrosion problem.

References

[1] Romanoff, M., "Underground Corrosion," Circular 579, National Bureau of Standards, 1957.

[2] Compton, K. G., *Materials Performance*, Vol. 16, Dec. 1977, pp. 29-33; also see "Project 265 on Underground Corrosion of Copper, etc.," International Copper Research Association, Inc., Dec. 1977.

[3] Mudd, O. C., *Oil and Gas Journal*, May 1942, p. 55, also see *Corrosion*, Vol. 1, 1946, pp. 25 and 193.

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[5] Compton, K. G., *Corrosion*, Vol. 14, 1958, p. 237.

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[10] Stern, M. and Geary, A. L., *Journal of the Electrochemical Society*, Vol. 104, 1957, p. 56.

DISCUSSION

J. B. Lankes[1] (*written discussion*)—During the course of the symposium, the word "polarization" was frequently mentioned and "passivity" was used a few times. I asked the author of this paper if he would define these two words, or perhaps, differentiate between the two. As I understood his answer, the words are used in several senses and one definition would not cover all. I wonder if Dr. Compton, who is widely respected in the corrosion control world, would expand this to give us his personal opinion of what he thinks the definitions should be. Perhaps we need a new word or words. For what little it may be worth, I have the notion that polarization reflects a potential (or electronic) change and passivation represents a film-forming (or chemical) change. All uses of the words do not fit my notion and I could be easily persuaded to change my thinking.

K. G. Compton (*author's closure*)—ASTM defines polarization (overvoltage) as the change in the potential of an electrode during electrolysis, such that the potential of an anode always becomes more noble and that of the cathode less noble than their respective static potentials. This is equal to the difference between the static potential and the dynamic potential.

Passivity is defined as the condition of a metal that retards its normal reaction in a specific environment and associated with the assumption of a potential more noble than its normal potential.

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[1] Corrosion control engineer consultant, Richmond, Va. 23220.

The reviewer is rightly confused by these over-simplified definitions. The author in presenting these electrochemical phenomena to his graduate students uses the broader approach of Vetter[2] who recognizes the following species of overvoltages (polarization).

Charge-transfer overvoltage.
Diffusion overvoltage.
Reaction overvoltage.
Crystallization overvoltage.
Resistance polarization.

All of these are quite complex and have various subdivisions. The two species of greatest concern to students of underground corrosion are charge-transfer and diffusion overvoltages. A redox electrode involves the transfer of electrons, whereas metal ions are transferred in a metal/ion electrode. Hindrance of either of these charge transfer reactions causes this form of overvoltage. When the supply of reactants at the electrode or the removal of the reaction products is rate determining when current flows, a diffusion overvoltage is produced.

In the early days of the study of passivity Faraday developed the theory of oxide-skin which is still in use. Theoretical studies of passivity cover a broad spectrum and at some times are very complicated. In alloys there is talk of shared electrons, but in general a film theory is pre-eminent. There is some disagreement as to whether gold and platinum are inert or have a very dense thin film. While some of the high-voltage potentio-static work may throw light on mechanisms of passivity and film growth, much of it is unrealistic in the true world of corrosion as these high positive potentials do not exist. The author supports the thin-film concept, having spent many years studying blocking films on aluminum, tantalum, etc. He believes that the film is maintained by an anodic process on the surface of the metal as expounded by Vetter.

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[2] Vetter, K. J., *Electrochemical Kinetics,* Academic Press, New York, 1967.

J. B. Vrable[1]

Eight-Year Evaluation of the sti-P_3 System for Protection of Buried Steel Tanks

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REFERENCE: Vrable, J. B., "**Eight-Year Evaluation of the sti-P_3 System for Protection of Buried Steel Tanks,**" *Underground Corrosion, ASTM STP 741,* Edward Escalante, Ed., American Society for Testing and Materials, 1981, pp. 156–165.

ABSTRACT: A system termed P_3 was developed by U.S. Steel Research to economically reduce the corrosion of carbon-steel tanks used in underground applications. This system combines three established methods for reducing corrosion: (1) the use of sacrificial anodes for cathodic protection; (2) the use of a protective coating; and (3) the use of insulating bushings, which are installed on the tank during manufacture. A subsequent cooperative program with a leading tank manufacturer resulted in the development of fabrication specifications for the design and the initial in-service installation in the latter part of 1969. Shortly thereafter, the Steel Tank Institute adopted the system and since that time approximately 5000 sti-P_3 tanks have been installed.

This paper describes an eight-year evaluation of the system on two 18.9-m^3 (5000-gal) steel tanks buried at a gasoline service station in Chicago, Illinois. Both previous experience with steel tanks used for the underground storage of gasoline at this station, and the results of various soil tests conducted on samples obtained from the tank excavation show that the soil is corrosive to steel. Readings obtained with electrical-resistance probes indicate that after eight years of service, essentially no corrosion is occurring on the sti-P_3-protected tanks. Also, the results of electrochemical measurements show that the tanks are being cathodically protected by the sacrificial anodes and that the anodes should have a long life in this soil.

KEY WORDS: corrosion, underground steel storage tanks, cathodic protection, underground corrosion

In the late 1960s, U.S. Steel Research investigated a system for protecting underground steel-storage tanks that would be installed by the fabricator and would eliminate periodic maintenance. The system, termed sti-P_3,[2] combines three methods for reducing corrosion: (1) the use of magnesium anodes, which are permanently attached to the end of each tank for cathodic protection; (2) the use of a protective coal tar epoxy coating over the entire tank surface; and (3) the use of a nylon bushing in each tank to electrically insulate the tank from contact with other underground metallic structures.

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[1] Section supervisor, U.S. Steel Corporation, Monroeville, Pa. 15146.
[2] Trademark of the Steel Tank Institute.

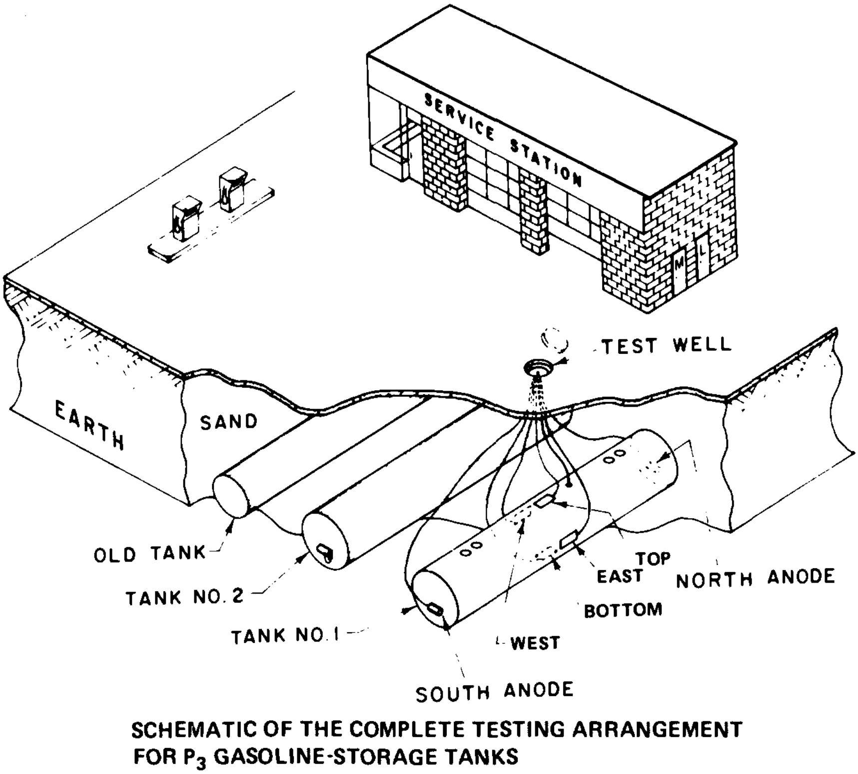

FIG. 1—*Schematic of the complete testing arrangement for P_3 gasoline storage tanks.*

Following a cooperative program with Kennedy Tank and Manufacturing Company, Inc., Indianapolis, Indiana, to develop necessary fabrication specifications for the design, the initial in-service installation was made in the latter part of 1969. Shortly thereafter, the Steel Tank Institute adopted the system, and since that time more than 5000 sti-P_3 tanks have been installed. This paper describes an eight-year evaluation of the system on two 1819-m^3 (5000-gal) tanks installed as replacements for two leaking tanks at a gasoline service station in Chicago, Illinois.

Testing of the sti-P_3 System

Two 2.13-m-diameter (7-ft) by 5.49-m-long (18-ft) 1819 m^3 (5000-gal) tanks were fabricated in accordance with the specification for the sti-P_3 system of corrosion protection of underground steel-storage tanks.[3] These tanks were installed at the gasoline service station in Chicago, Illinois, on 16 Dec. 1969. The testing arrangement at the test site is illustrated in Fig. 1. Several electrical-resistance probes for measuring corrosion rates were at-

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[3] "Specification for sti-P_3 System of Corrosion Protection of Underground Steel Storage Tanks," Steel Tank Institute, Chicago, Ill., Oct. 1978.

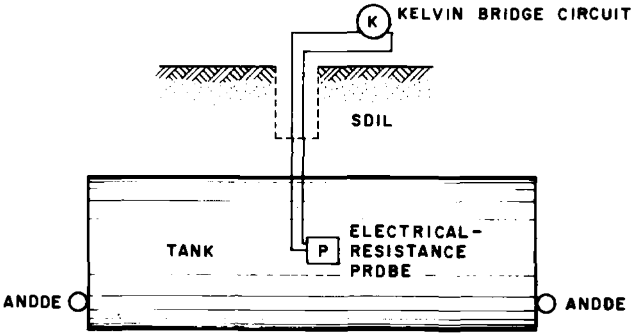


FIG. 2—*Schematic illustrating electrical resistance probe measurement circuit.*

tached with masking tape to the walls of Tank 1 (Fig. 1). The probe metal which had a surface area of about 64.51 cm^2 (10 in.^{2}), was fabricated from AISI 1010 mild steel and was similar in composition to the steel tanks. A multicable test wire extended from each probe to a ground-level test well where the corrosion rate, indicated by changes in electrical resistance, was measured by attaching the cable to a special instrument which utilizes a Kelvin bridge circuit as illustrated in Fig. 2.

Four probes were installed midpoint at the top, bottom, and sides of Tank 1 (Fig. 1) and simulate large coating flaws on the tank body. During the exposure period, the probe test leads were connected to the tank and received cathodic protection current from the sti-P$_3$ system anodes. Because these locations are the most remote on the tank, relative to the anodes, they are the most difficult to protect. As long as the sti-P$_3$ system is effective, no change in the resistance reading from the probe will occur.

The circuit used to measure the tank-to-soil potential is illustrated in Fig. 3. This potential was measured with a high-resistance voltmeter and a cop-

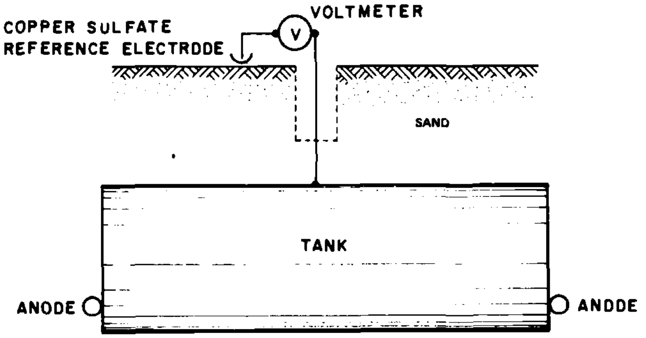
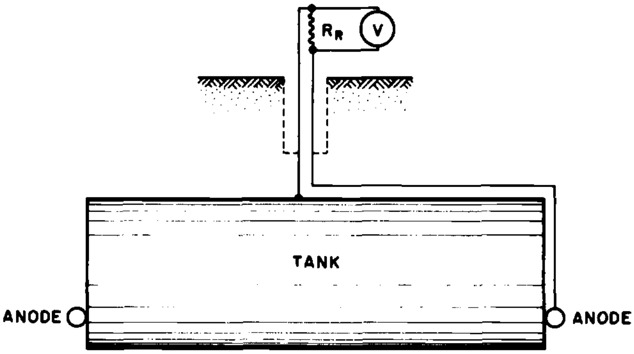


FIG. 3—*Schematic illustrating tank potential measurement circuit.*



SCHEMATIC ILLUSTRATING MAGNESIUM-ANODE-CURRENT MEASUREMENT CIRCUIT

FIG. 4—*Schematic illustrating magnesium anode current measurement circuit.*

per/copper sulfate reference electrode placed on the ground over the center of the tank. The potential measurements on Tank 1 were made by using the "instantaneous off" method. With this method, the flow of protective current is momentarily interrupted and the potential is measured the instant the current ceases to flow. The potential measurements on Tank 2 were made with the anode current flowing.

Note that in addition to the sti-P$_3$ tanks (1 and 2) in Fig. 1, a third tank is illustrated (old tank). This tank, which was in service at the test site at the time the sti-P$_3$ tanks were installed, was not leaking and therefore was not replaced. Because this tank is not protected, it provides a useful voltage reference for comparison with the protected tanks.

Figure 4 shows a minor modification of the anode-to-tank circuit that was necessary to obtain data relative to the performance of the magnesium anodes. This modification was made on Tank 1 only and consists of placing an 0.1-Ω shunt in series between each magnesium anode and the tank. All test connections were made with No. 12 Awg insulated copper wire and extended to the ground-level test well.

Electrical-resistance-probe readings, anode-current measurements, and tank-potential measurements were made at various times during the test.

Exposure Conditions

Reportedly, the three existing tanks at the test site, two of which were leaking, were installed in the late 1940s and never received corrosion protection in any form. Figure 5 shows the condition of one of the tanks removed from the excavation. The fact that the tank had developed leaks and appeared to be extensively corroded confirmed the corrosiveness of the site environment.

Representative specimens of soil, sand backfill, and groundwater in the excavation were obtained and tested in the laboratory. On-site tests of electrical resistivity were made on undisturbed soil, sand, and groundwater in

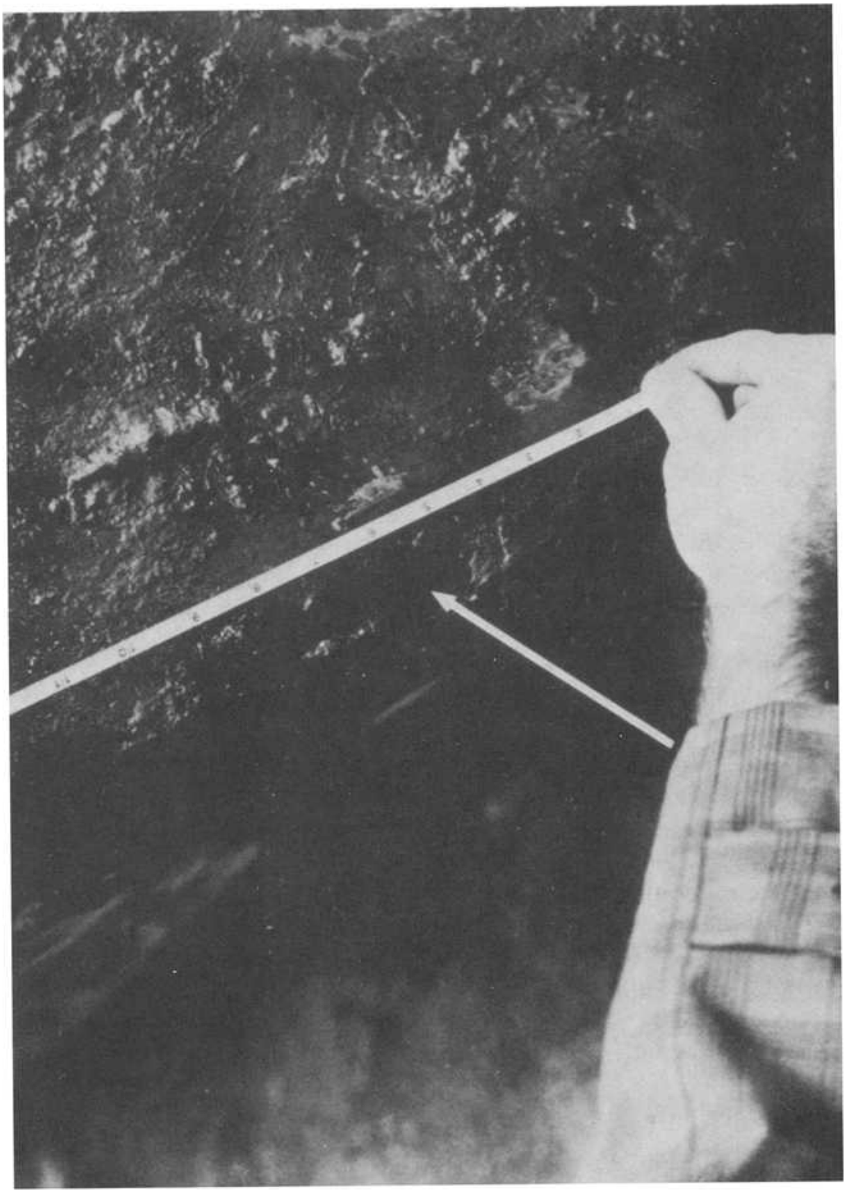


FIG. 5—*Corroded region on the steel tank removed from the test station. Note large hole.*

TABLE 1—*Electrical measurements on sti-P$_3$-protected tanks.*

		Potential, −mV[a] (dc)			Anode Current,[b] mA(dc)		
Date	Days in Test	Tank 1	Tank 2	Old Tank	South	North	Total
1/02/70	16	1500	1500	570	60	34	94
1/16/70	30	1500	1550	540	65	32	97
1/30/70	44	1500	1520	600	66	25	91
2/06/70	51	1500	1550	580	62	20	82
2/18/70	63	1600	1650	780	63	19	82
3/18/70	91	1550	1600	720	68	20	88
4/25/70	126	1430	1530	710	70	32	102
6/01/70	161	1400	1500	690	68	30	98
6/23/70	183	1375	1500	680	65	28	93
8/26/70	247	1300	1500	680	63	29	92
12/10/70	357	1250	1500	635	36	23	59
5/27/71	527	1240	1510	630	34	24	58
2/23/72	824	1210	1320	540	24	21	45
6/18/73	1390	1020	1205	545	21	17	38
5/02/74	1713	980	1150	480	17	15	32
9/10/74	1844	950	1120	565	22	22	44
2/20/76	2372	1024	1030	690	20	15	35
5/26/77	2832	900	1150	600	. . .[c]	35	35
5/27/77	2833	960	1150	600	4[d]	35	39

[a] Potential measurement made to Cu-CuSO$_4$ reference located over midpoint of tanks.

[b] Current measurements made between tank and anodes mounted on north and south tank ends on Tank 1 only. Measurement made by using an 0.1-Ω shunt in series with the anode and tank.

[c] South anode was not connected to Tank 1.

[d] Twelve hours after reconnecting south anode to Tank 1.

the excavation, as well as tests to determine the presence of stray current in the earth. The results of these tests were presented previously.[4] Briefly, it was determined that the environmental conditions are moderately to severely corrosive. No underground stray currents were found at the site.

Eight-Year Exposure Tests Results

The results of electrical measurements on the sti-P$_3$-protected tanks are shown in Table 1 and summarized in Figs. 6 and 7. The results in Table 1 and Fig. 6 show that the sti-P$_3$-protected tank potentials were more negative than the −850-mV value needed for complete corrosion prevention of buried steel.[5] The voltage difference between the protected tanks reflects the different measurement methods employed. With the "instantaneous off" method

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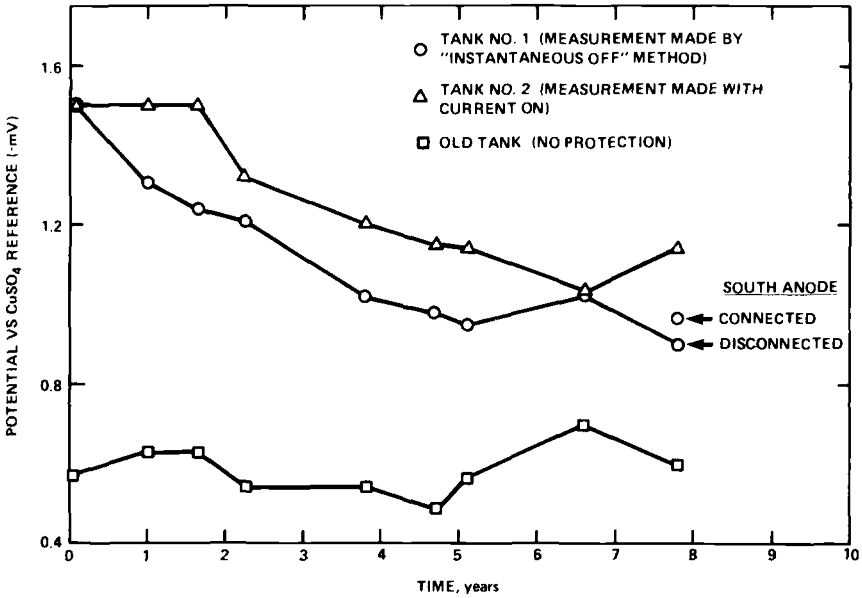
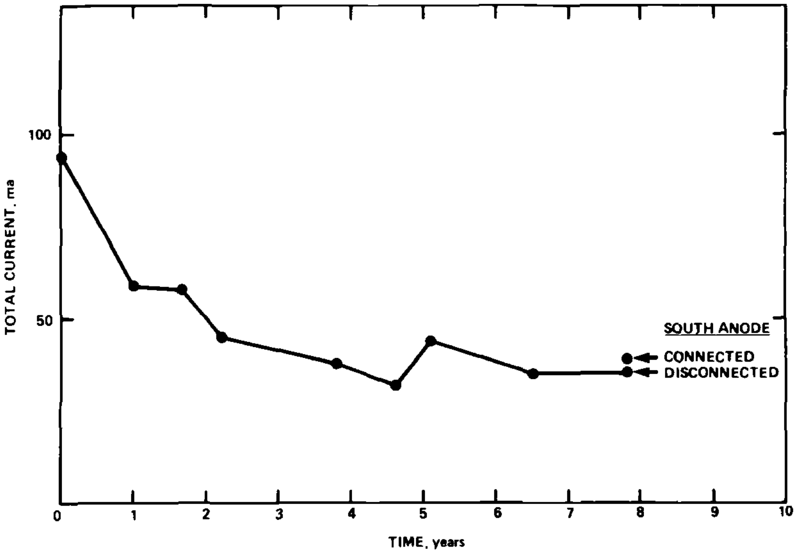
[4] Vrable, J. B., *Materials Protection and Performance,* Vol. 10, No. 5, May 1971, pp. 45–47.

[5] "Control of External Corrosion on Underground or Submerged Metallic Piping Systems," NACE RP-01-69, National Association of Corrosion Engineers, 1969.



POTENTIALS FOR UNDERGROUND TEST TANKS

FIG. 6—*Potentials for underground test tanks.*



TOTAL ANODE CURRENT OUTPUT FOR UNDERGROUND TEST TANK NO. 1

FIG. 7—*Total anode current output for underground test, Tank 1.*

(Tank 1), the value reported does not include the increment of voltage required to force the anode current through that portion of the circuit resistance spanned by the tank to the reference electrode point (earth-potential gradient). The "current on" measurement (Tank 2) includes this earth-potential gradient and, as expected, usually gave more negative (cathodic) polarized potential values than did the "instantaneous off" method (Fig. 6).

The voltage difference between the protected tanks and the "old tank," Fig. 6, shows that a negative (cathodic) voltage shift of at least 300 mV occurred with application of cathodic protection, this complies with the protection criterion of voltage shift.[6] In addition, the 300 mV difference also proves that no electrical contact existed between the tanks, thereby confirming that the nylon bushings effectively insulated the piping which connected the tanks.

Figure 7, a plot of total anode current output for Tank 1, shows that the total current significantly decreased during the first two years and then stabilized at a value of about 40 mA. It is interesting to note that after the 6.5-year on-site test, the south anode was inadvertently disconnected. When this was discovered nearly 1.5 years later, testing revealed (Table 1) that the current output of the north anode nearly doubled to offset the loss of current from the south anode and that the tank was being effectively protected by one anode (Fig. 6).

Based on the average total current output over the last six years (Fig. 7), the useful life of the anodes has been calculated from the following equation.[7]

$$L = \frac{K \times W \times E \times U}{I}$$

where

L = anode life, years,
K = 0.116 constant based on the electrochemical equivalent for magnesium (1.24×10^{-4} g/coulomb),
W = anode weight, kilograms (pounds),
E = anode efficiency, decimal percent,
U = anode utilization, decimal percent, and
I = anode current, amperes.

The anode efficiency is based on a theoretical A/h/kg value of 1000 and an estimated value of 500 at the actual current density. This results in an anode efficiency of 50 percent. The anode utilization value is normally placed at 85 percent, meaning that when the anodes are 85 percent consumed they should be replaced because the current output will be less than required

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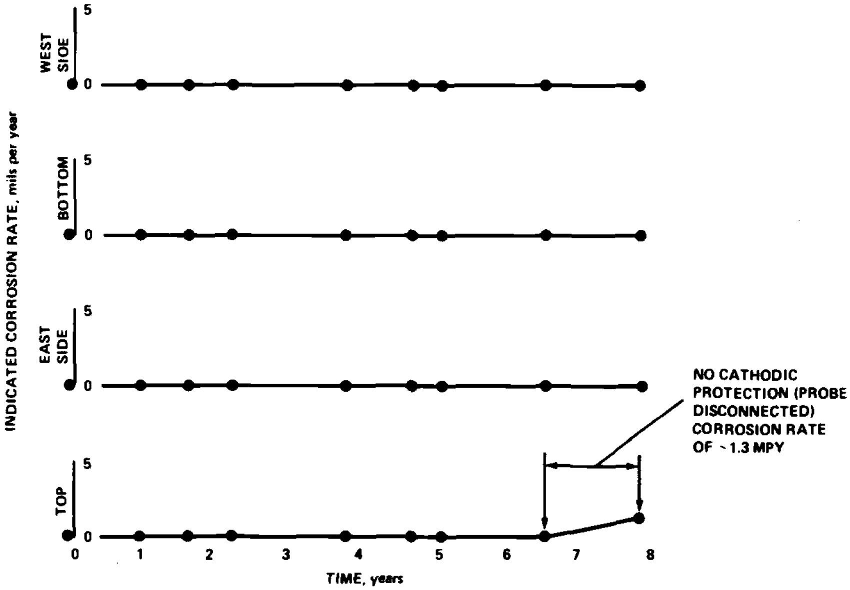
[6] "Control of External Corrosion on Underground or Submerged Metallic Piping Systems," NACE RP-01-69, National Association of Corrosion Engineers, 1969.

[7] Peabody, A. W. in *Control of Pipeline Corrosion*, National Association of Corrosion Engineers, Houston, Tex., 1967, p. 120.



NO CATHODIC PROTECTION (PROBE DISCONNECTED) CORROSION RATE OF ~1.3 MPY

CORROSOMETER CORROSION READINGS, TANK NO. 1

FIG. 8—*Corrosometer corrosion readings, Tank 1.*

for cathodic protection of the tank. When this equation is used, the calculated useful life is 40 years for this installation.

Figure 8 gives the plots of the corrosion rates recorded for the electrical-resistance probes and shows that the system has been 100 percent effective in preventing corrosion of the probes. This indicates that the cathodic protection is reaching areas on the tank most difficult to protect. Also from Fig. 8, it can be seen that when the top probe was disconnected from the tank, and therefore received no cathodic protection for a period of about 1.5 years, corrosion occurred at a rate of 1.3 mils per year (mpy). This confirms that the probes continued to function over the 8-year underground exposure and that as determined by the soil tests, the environmental conditions at the site are moderately corrosive.

This test was scheduled to last for more than 20 years, however, an economic decision to terminate service at the test station resulted in the unannounced removal of the tanks shortly after eight years of service.

Summary

The results of the eight-year exposure testing show that the sti-P_3 system is a practical means of extending the service life of underground steel-storage tanks in corrosive soil. Readings obtained with electrical-resistance probes indicate that during the 8-year exposure, essentially no corrosion had occurred. Also, the results of electrochemical measurements showed that the tanks were being cathodically protected by the sacrificial anodes and that the anodes should have a long life in this soil.

DISCUSSION

J. B. Lankes[1] (*written discussion*)—A question was asked about protective current flow to each of the four 10-in.^{2} bare plates at top, bottom, and sides of tank, the intent of the question being to learn something about current distribution. The answer, as I understood it, was that flows to these plates were so small that they could not be measured with available instrumentation. This is surprising, in view of my memory of 40-mA anode output. Could it be that the bare plates polarized so well that practically all protective current flow was through the excellent protective coating?

J. B. Vrable (*author's closure*)—Yes, with the possible exception of the current flow to unintentional holidays in the coating.

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[1] Consultant, Richmond, Va. 23220.

A. C. Toncre[1]

The Relationship of Coatings and Cathodic Protection for Underground Corrosion Control

REFERENCE: Toncre, A. C., "**The Relationship of Coatings and Cathodic Protection for Underground Corrosion Control,**" *Underground Corrosion, ASTM STP 741,* Edward Escalante, Ed., American Society for Testing and Materials, 1981, pp. 166–181.

ABSTRACT: External corrosion control for buried pipelines and other metallic underground structures is accomplished industry-wide by using dielectric coatings supplemented by cathodic protection. Relationships between these two corrosion control methods are outlined to show how effective corrosion control can be achieved.

The long-term changes of protective coatings in relation to their porosity, permeability, and osmotic action under electrical potentials are discussed. Evaluation of existing criteria for adequate cathodic protection of underground metals with poor or disbonded coatings, in conditions conducive to stress corrosion cracking and other localized corrosion phenomena, indicates a need to consider revisions in corrosion control measurement techniques and criteria.

KEY WORDS: underground corrosion control, coatings, cathodic protection, underground corrosion

The practice of using coatings and cathodic protection against corrosion attack of metals extends to antiquity. In his brief history of corrosion protection, Baeckmann [*1*][2] cites evidence that the earliest metal pipes were often surrounded by lime or gypsum backfill, apparently for sealing against leakage and protection against soil corrosion. One of the oldest underground pipes was found by the archeologist Borchardt at a temple complex near the pyramid of King Sahu-Re. The estimated age of the 47-mm-diameter copper pipe was 4500 years. It was set into a hewn rock channel and covered with lime mortar.

Protective Coatings Development

Asphaltic materials obtained from petroleum seeps were used for protection and sealing of pipes in Babylon about 4000 years ago. With the Industrial

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[1] Engineering consultant, Arabian American Oil Company, Dhahran, Saudi Arabia.

[2] The italic numbers in brackets refer to the list of references appended to this paper.

Revolution came improvements and developments in pipe coatings. Formulations of coal tar and asphaltic materials were begun about 1830 in England and a mineral-filled asphalt mastic pipe coating material was developed about 1884. In the early 1900s other reinforcements such as mineral wool or jute were used with molten coal tar or asphalt. Rapid development of the pipeline industry in the first third of the 20th century brought major innovations in pipeline protective coatings. These included the use of primers, glass wool, and felt wrappings in conjunction with the asphaltic or coal tar coating materials.

With the expansion of pipeline transmission networks after World War II, alternative materials and techniques became available. Newly developed "plastic" materials such as poly(vinyl chloride) and polyethylene, both products of the diversification of the petrochemical industry, were made available as tape wrappings, with adhesive backings and primers. These could be applied to pipelines during construction using machines which moved along the pipeline as it was being constructed.

In the 1960s a process was developed to apply polyethylene directly to piping. The factory process applied an asphaltic-rubber adhesive to the pipe over which a sheath of polyethylene was extruded from a ring shaped die. Later, in Germany, a sintering process was developed in which the polyethylene resin material was directly adhered to the pipe. In the United States of America a concurrent similar development was the development of application of an epoxy resin formulation directly to the pipe. Called "fusion bonding" the process applies an air suspension of epoxy resin formulation onto the shot blast cleaned and preheated pipe. The heat causes the resin mix to melt, fuse, and catalyze onto the pipe surface.

Cathodic Protection Development

Although Roman ship builders solved the problems associated with galvanic corrosion of lead sheathed ships by using copper nails instead of iron nails, Sir Humphrey Davy was the first investigator to elucidate the electrochemical nature of corrosion and the use of cathodic protection. In 1824, the Man-of-war "Sammarang" was equipped with zinc bars to protect the copper cladding of the hull. Michael Faraday, Davy's pupil, continued investigations in electrolysis and related the basic connection between corrosion and electric currents. Gibbs and Nernst further developed the chemical and electrochemical nature of corrosion, the dissolution of a metal by its environment. The Nernst equation is basic to galvanic corrosion and electrical methods of corrosion prevention, the most common of which is cathodic protection. Practitioners of cathodic protection utilizing impressed currents instead of galvanic anode methods include Thomas Alva Edison who tried cathodic protection of ships in 1890. In 1906 direct current generation was used in Karlsruhe Germany to protect 300 m of buried gas and water pipelines. The first documented application of cathodic protection in the United States was done by Robert J. Kuhn in 1928. Protection was applied to a gas pipeline in New Orleans. McCollum used the copper sulfate reference electrode in 1910 for field potential measurements and Kuhn reported in 1933 that buried steel pipe could be considered protected at a potential of −0.85 V copper/copper sulfate ($Cu/CuSO_4$) [*2*]. Kuhn and others engineered cathodic protection installations in the 1930s, but widespread applications did not begin until the 1940s, concurrent with the general growth of the petroleum and pipeline transportation industry.

In 1943 mutual interest led to the formation of the National Association of Corrosion Engineers in Houston, Texas, a group dedicated to the mitigation and control of corrosion. During the 1950s and 1960s corrosion research, engineering application, and formation of associations accelerated. Today, several national corrosion societies conduct periodic meetings and seminars, and there are several annual international conferences and many corrosion subgroups within other engineering societies such as Society of Petroleum Engineers (SPE), American Society of Mechanical Engineers (ASME), American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME), and the American Society for Testing and Materials (ASTM). Government involvement is exemplified by the United States Department of Transportation Office of Pipeline Safety. This agency has promulgated regulations for corrosion protection of pipelines based on the social justification for public safety [*3*].

Theory of Corrosion Protection of Underground Metallic Structures by Coating and Cathodic Protection

Corrosion is defined as the chemical or electrochemical destruction of a metal by its environment and as such has been subject to widespread investigation in laboratory and field studies. The electrochemical parameters of corrosion have been extensively expressed by M. Pourbaix [*4*]. Based on thermochemical relationships, he has constructed potential − pH diagrams which indicate the regimes of corrosion and passivity for most metals. The thermodynamic relationship for iron in a water-oxygen system is shown in Fig. 1. Although affected by the specific chemical ions present, this diagram is applicable to general soil corrosion of buried steels. To control or mitigate the corrosion which may occur in corrosive environments, as defined by the stated electrochemical reactions, modifications of environmental parameters are required. Most obvious is the isolation of the metallic structure from the environment by the use of coatings, as practiced by the ancients. To supplement the protection supplied by the coating, particularly at any flaws in the coating, the application of cathodic protection is most common, as shown in Fig. 2. Cathodic protection is based on the electrochemical theory that dissolution will cease at the anodic (corroding) areas on a metal surface when the

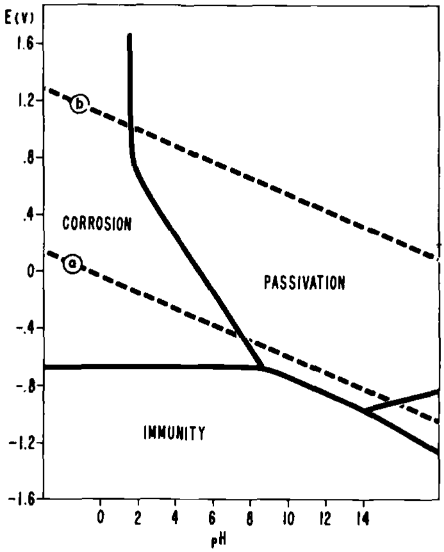


FIG. 1—*Potential pH diagram for iron in oxygen water system. Pourbais (after Pourbaix* [4]).

potential of all cathodic areas is changed by application of an external current, to the open circuit potential of the anodic areas. This regime is indicated by the area labeled "immunity" on the Pourbaix potential/pH diagram, Fig. 1. The definition of cathodic protection accepted by the National Association of Corrosion Engineers is "Reduction or elimination of corrosion by making the metal a cathode by means of an impressed d-c current, or attachment to a sacrificial anode (usually magnesium, aluminum, or zinc)."

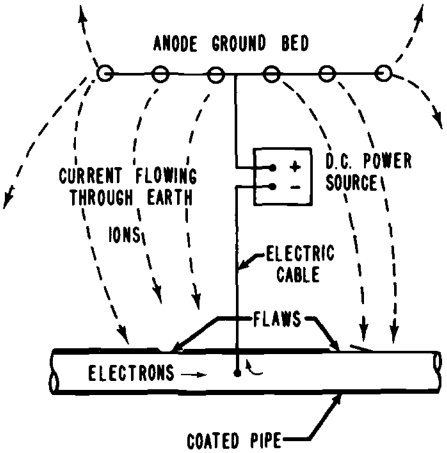


FIG. 2—*Corrosion protection of underground pipe by coating and cathodic protection.*

Coating Characteristics

The primary purpose for coating a pipeline with an inert material is to reduce the area of metal in direct contact with the corrosive environment. Coating efficiency depends on the quality of surface preparation of the metal to be protected, the coating application techniques, the coating thickness, chemical and physical qualities of the coating material, the method of installing the coated structure, and the long-term changes in the coating material. Factors which inter-relate to cathodic protection of coated pipelines are the number of "holidays" or flawed areas of the coating on the buried structure, and the electrical resistance of the coating material. Damage to the coating can be controlled during the coating process and minimized by construction practices, but there is always a requirement for cathodic protection to supplement the protection offered by the coating. The amount of cathodic current required for protection is related to the initial amount of bare metal exposed at holidays, to the future amount exposed due to in-service rock damage, soil stress damage, and coating deterioration; and to the conductance characteristics of the coating material. Electrical conductance of materials used for coatings may be determined by ASTM Test for d-c Resistance or Conductance of Insulating materials (D 257-78). Long-term changes in resistivity are caused principally by water and ion absorption into the coating. Water absorption characteristics are determined by ASTM Test for Water Absorption of Plastics (D 5-73 1978) and water transmission by MIL-I-16923E. Typical electrical resistivity values for commonly used pipe coating materials are shown in Table 1.

Perfect pipe coatings are never achieved in practice, and quality is related in part to the type of surface preparation. Mechanical cleaning such as done by the over-the-ditch coating machines leaves mill scale and residue on the pipe surface. Even with shot blast cleaned pipe, oxides form quickly on the steel surface, and the adhesion of the coating depends on the presence of oxides. For instance, a commercial hot applied thick film coating or a mastic type coating will tolerate more of a flash oxide film on the pipe surface than

TABLE 1—*Characteristics of pipe coating materials.*

Material	Resistivity,[a] Ωcm	Water Absorption,[b] percent	Water Transmission,[c] g/h/cm/cm^2
Asphalt/coaltar	10^{13} to 10^{16}	. . .	. . .
Epoxy	10^{14} to 10^{15}	0.01 to 0.5	4×10^{-7}
Polyethylene	10^{15} to 10^{17}	0.01 to 0.06	. . .
Polyvinyl chloride	10^{11} to 10^{15}	0.15 to 0.75	. . .

[a] ASTM D 257-76.
[b] ASTM D 570-63.
[c] MIL-I-16923E.

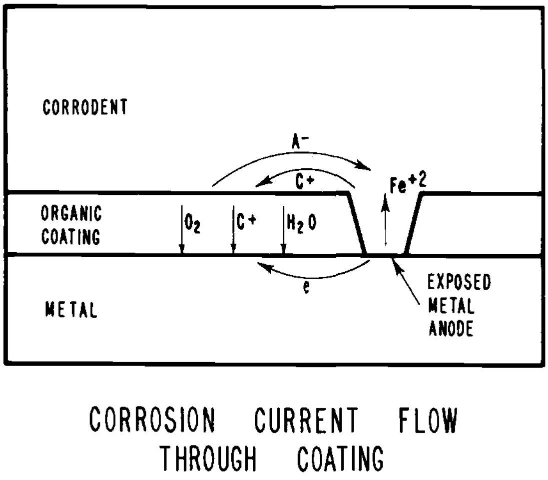


FIG. 3—*Corrosion process representation through a coating* (*after Koehler* [5]).

will a fusion-bonded thin film. In the worst case there may be completely unbonded coating with no adhesion to the surface.

Koehler [5] has summarized investigation of corrosion under thin film organic coatings in relation to their basic properties. Organic films have membrane qualities and as such allow penetration by water or gas molecules as well as ionized substances as illustrated in Fig. 3. Several factors affecting the rate of transfer through a membrane, the most important being that of film thickness. Water absorption is related to osmotic pressure as shown in Fig. 4. Diffusion of water through the coating is related to water absorption and

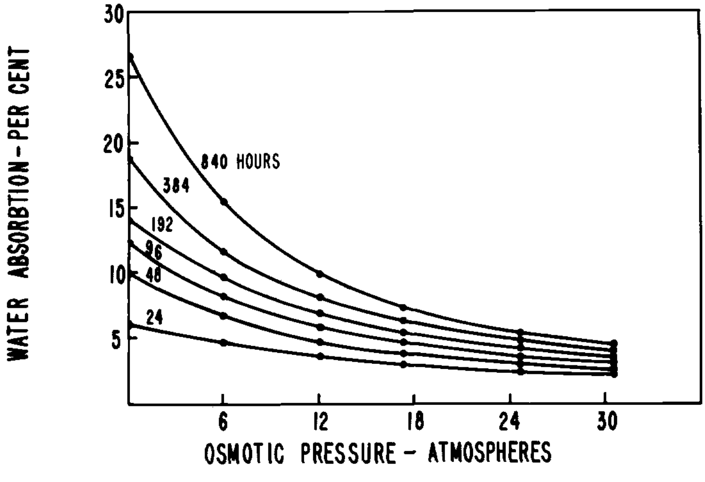


FIG. 4—*Water absorption ratio of organic coating as a function of osmotic pressure of immersion solution. Numbers of curves show immersion time in hours* (*after Kittleberger and Elm* [23]).

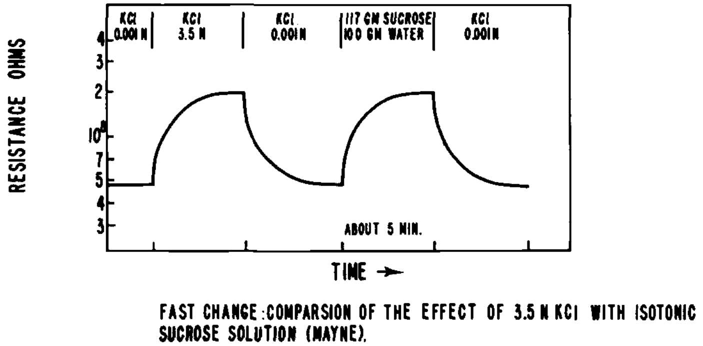


FIG. 5—*Resistance change of organic coating in differing solution strengths* (*after Mayne and Cherry* [24]).

the concentration gradient of the water both within the membrane and between the pipe surface and surrounding soil. These relationships are shown in Fig. 5. Ionized substances moving into and through organic coatings do so by virtue of a potential gradient as well as a concentration gradient. Most organic coatings tend to be cation selective [*5*]. The fact that the metal under the coating is usually cathodic to the metal at a flaw or holiday in the coating increases the cationic effect but current can be carried by either anions or cations. Water found under disbonded films has been found to have pH values from 9 to 11 indicating that the cathodic reaction of oxygen reduction and formation of hydroxide has occurred [*6*].

Water absorption tests show that organic coatings have two rates, fast and slow. The slow rate depends on ionic movement (Fig. 6). Long-term changes

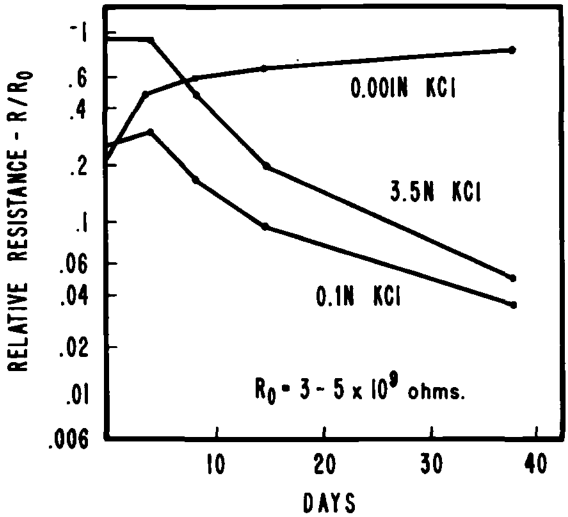


FIG. 6—*Resistance change of organic coating with time* (*after Brasher and Nurse* [25]).

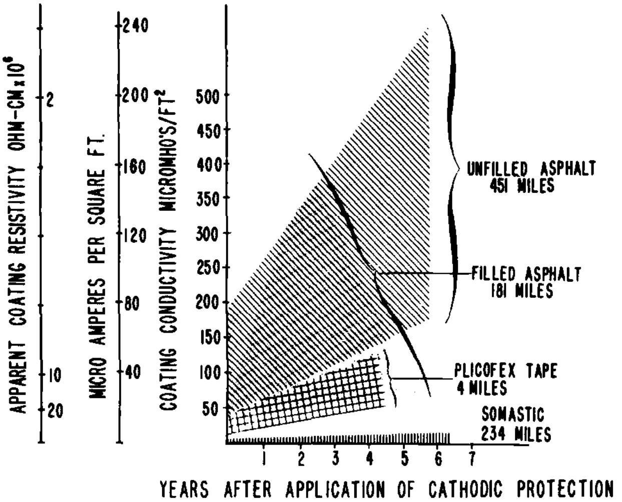


FIG. 7—*Change of resistivity of pipelines with time.*

in apparent coating resistivities on underground structures have been observed in the field. Hewes [7] surveyed over 30 000 km of buried pipelines and reported large variations of coating resistivities. The change of apparent resistivity with time is shown in Fig. 7.

Consider a buried pipeline 100 km in length, 75 cm in diameter, which has a coating 1 mm thick. The coating has a laboratory measured resistivity of 10 Ωcm [*10*]. The equivalent electrical resistance of the coated pipeline in a cathodic protection circuit may be calculated using Kirchoff's law for *n* branches of parallel circuit.

$$Rp = \frac{R1}{n}$$

where

Rp = equivalent resistance,
R_1 = resistance of one element, and
n = number of elements.

Solving for the conditions of the given buried pipeline the equivalent resistance is about 0.43 Ω. To change the natural potential of the pipeline by 0.5 V would require about 1.1 A, and this potential change would be considered by most cathodic protection engineers to provide protection. However, field measurements show that 10 to 30 times this amount of current is required on a newly buried coated pipeline to change potentials to the desired level. Using the actual field current requirement, the calculated average specific resistivity of the coating is about 10^6 or 10^7 Ωcm rather than the 10^{10} Ωcm assumed from laboratory tests. Thus, it may be inferred that even the initial permeability and absorption characteristics of the pipeline coatings

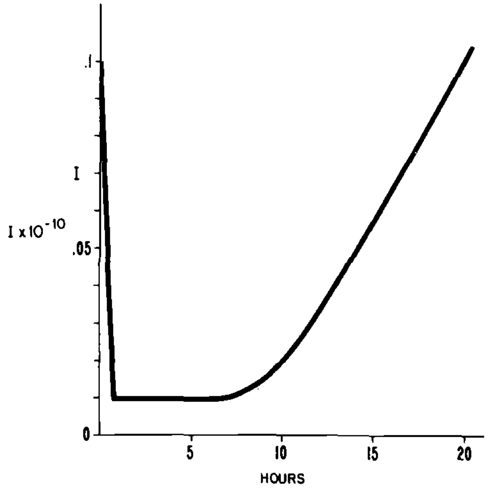


FIG. 8—*Galvanic current flow at a coating holiday (after Craig and Olson* [8]). *Numbers on curves are hours of immersion.*

are much greater than evidenced by the laboratory evaluation of coating characteristics.

Even where cathodic protection is not used and an organic film or coating is the only corrosion prevention method, many investigators, including Koehler [*5*], Craig and Olson [*8*], have shown that the metal under an organic coating is cathodic to metal exposed at voids or discontinuities. A galvanic current carried by ions flows between the anodic metal at the void through the electrolyte and thence the coating to the cathodic metal surface under the coating. Results of laboratory tests have shown that the galvanic current begins to flow in a matter of hours after the specimen is immersed in the 3.5 percent sodium chloride test solution (Fig. 8). This implies that active galvanic corrosion cells initiate soon after a structure is buried underground, and that cathodic protection should be energized immediately to prevent corrosion attack.

Flaws in coatings may have undercutting or film disbondment evidenced away from the damaged spot as shown in Fig. 9. There has been much con-

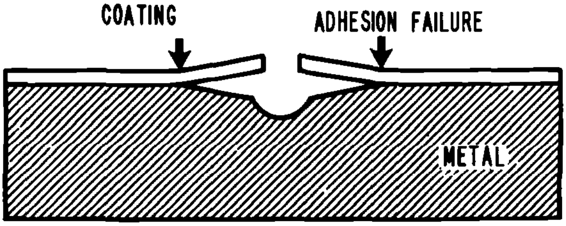


FIG. 9—*Coating flaw illustration possible crevice formation under disbonded coating.*

cern that the area of metal under the disbonded coating is shielded from the cathodic protection current. However, Peterson and Lennon [9] showed that cathodic protection was effective on stainless steel and copper in saline water in crevices which had a ratio of opening to crevice depth of 12 000 to 1 as shown in Fig. 10. Similar results were reported by Toncre and Ahmad [10] on plain carbon steels in saline and brackish waters (Figs. 11 and 12). In both investigations, the potential at the tip of the crevice was less negative than at the opening of the crevice, but more alkaline pHs were found within the crevice compared to the bulk solution. Hewes [6] has reported on field inspections which indicated that no serious corrosion was found under disbonded coatings on buried pipelines which were cathodically protected.

Cathodic Protection Criteria

The definition of a criterion for the protection of a metal in a corrosive environment and the techniques to measure this state in the field have been subject to much study. Investigation by Kuhn [2], Ewing [11], Sudrabin and Ringer [12], and Schwerdfeger [13], among others, indicate that polarized steel to soil potential of −0.85 V to a copper sulfate reference cell may be considered a minimum level of protection for structures buried in moist aerated soils. Although a large number of cathodic protection practitioners favor this criterion, the recommended practice of the National Association of

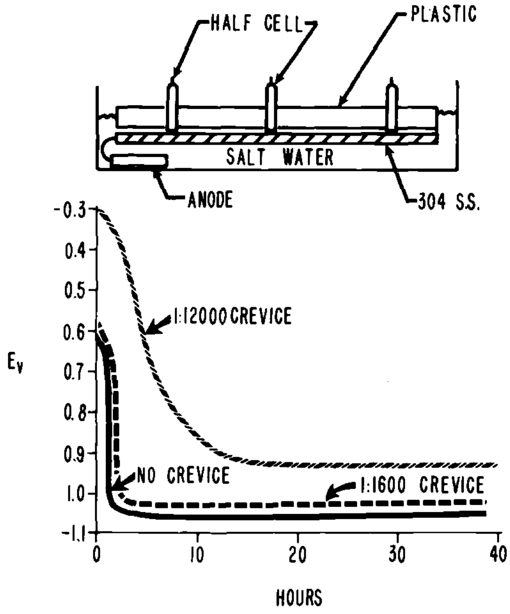


FIG. 10—*Cathodic polarization of crevices in Type 304 stainless steel in saltwater (after Peterson and Lennox* [9]).

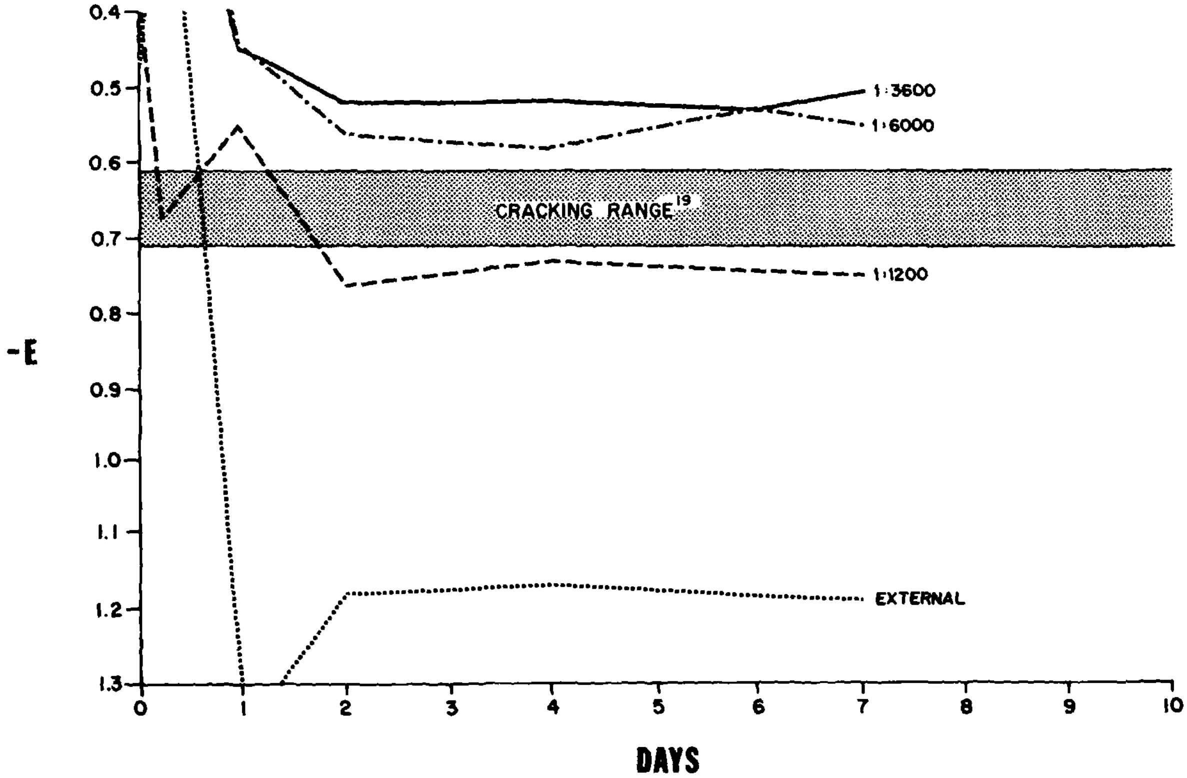


FIG. 11—*Cathodic polarization of crevices in mild steel in natural seawater (after Toncre and Ahmad* [10]). *Specimen with mill scale.*

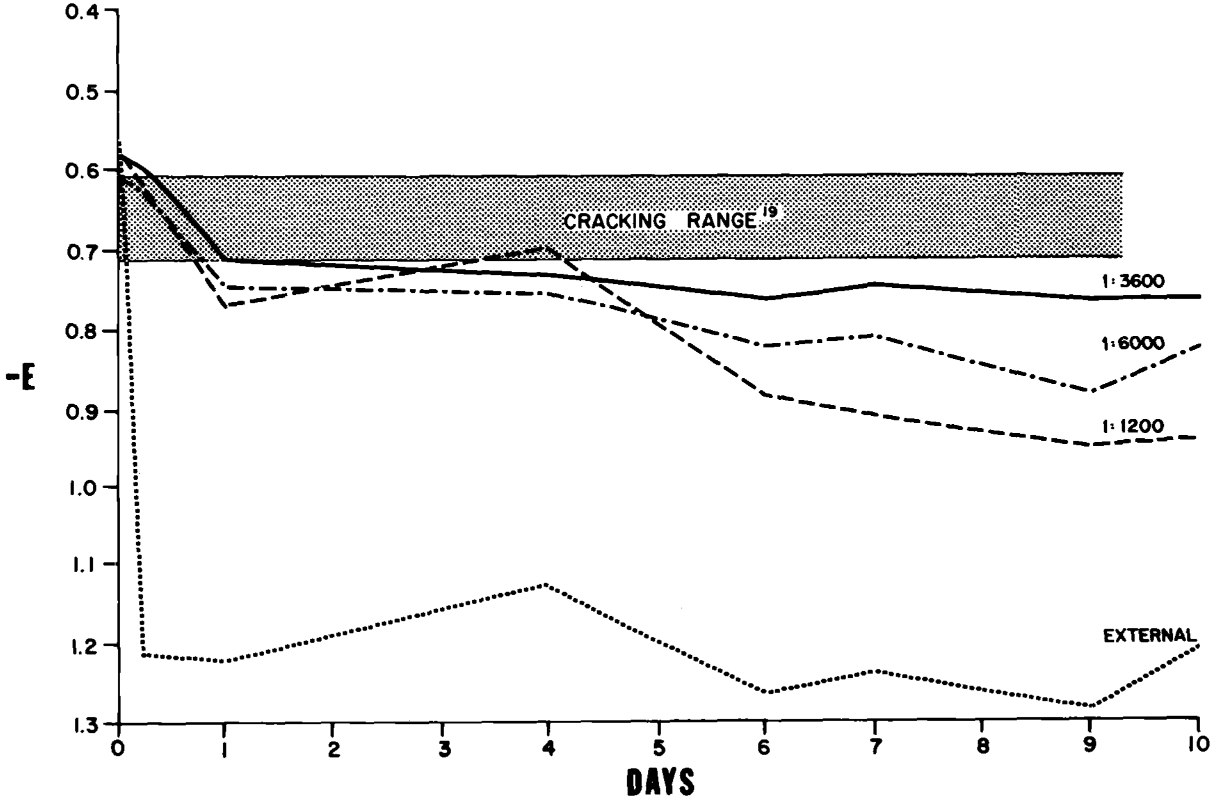


FIG. 12—*Cathodic polarization of crevices in mild steel in natural seawater (after Toncre and Ahmad* [10]). *Specimen sandblasted.*

Corrosion Engineers includes alternatives for application, where the −0.85 V criterion could not be used, due to practical or economic considerations, and where bacteriological corrosion is a factor, a −0.95 V criterion is recommended [*14*]. Theoretically, the passive potential calculated by electrochemical theory ranges from −0.78 to −0.91 V CuSO4 depending on the conditions, ions species, and concentrations used. The investigations by Ewing [*11*], Schwerdfeger [*13*], and Bechmann [*1*] show that even at these potentials, some dissolution of metal continues (Fig. 13). In the investigations reported [*11–13*] all authors stressed the need for careful measurements of the polarized potential without ohmic or IR drop errors. The methods of elimi-

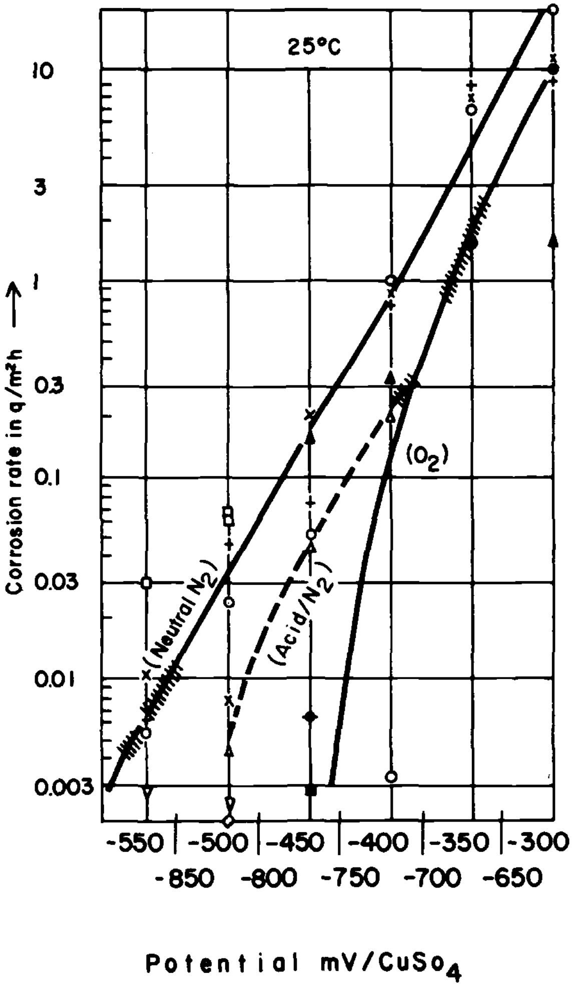


FIG. 13—*Corrosion rate for mild steel in aqueous solutions versus potential (after Bechmann and Schwenk* [1]).

nating or reducing this error have been discussed by Rizzo [*15*]. Other measurement errors have been previously stated by Husock [*16*], Compton [*17*], among others, and have been summarized by the author [*18*].

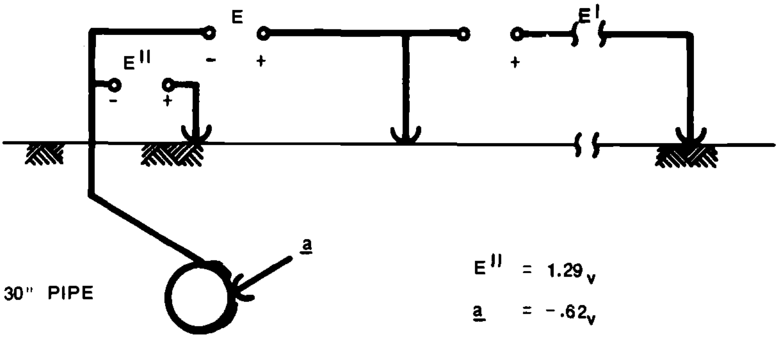
Controlled field investigations of protective potentials of underground metals have generally used specimens or short sections of uncoated pipe [*11, 12*]. Determination of small anodic areas on bare pipe requires careful techniques. On a buried coated pipeline the large cathodic area can completely mask a corroding area from monitoring potential measurements made during periodic surveys. This is not only true of anodic areas at coating flaws, but also at flaws which have disbonded segments of coating associated with the flaw, in a crevice fashion. Investigations [*19*] of stress corrosion cracking (SCC) of pipeline grade materials indicate that the SCC occurs in the range of about -0.67 to -0.77 V $CuSO_4$, but does not occur outside that range. Based on measurements of potentials within crevices [*8–19*], the SCC range could be expected to exist under a disbonded coating even though the polarized potential at the coating flaw or crevice opening was -0.85 V $CuSO_4$ (see Figs. 10, 11, 12).

Analysis of pipeline failures reported to the United States Department of Transportation for the period 1970 to 1973 indicated that 76 percent of the failures caused by external corrosion were due to pitting corrosion. Investigations of pitting corrosion phenomenon were reported by McBee and Kruger [*20*], Pickering and Frankenthal [*21*], among others. Potential differences up to 0.6 V have been observed, and current densities up to 2 A/cm^2 were reported. Although there is little agreement on the initiation mechanism, pitting potentials, or current density at the active anodic area of a pit, the reported values all indicate that higher current densities and larger potential differences exist in pits than those measured in the field investigations of corrosion which have large anodic areas. However, there is general agreement that cathodic protection will stop both pitting and cracking.

As shown by Sudrabin [*22*], the usual survey technique of measuring pipe-to-soil potentials with all cathodic protection installations operating, and with no determination of IR drop or other errors, is incapable of detecting pitting attack on a buried metallic structure in spite of the high local current density, and the large potential differences at an active pit on a pipeline (Fig. 14).

Conclusions

1. When applied properly and maintained at adequate levels, the use of dielectric coating materials and supplemental cathodic protection provides a practical and economical system for controlling or mitigating corrosion of underground structures.
2. Dielectric coating materials absorb and transmit water at rates dependent on coating characteristics, environmental conditions, and time.



$$E_p = E - IR = E - \left(\frac{E'i}{e'}\right)\left(\frac{e}{i}\right) = E - \frac{E'e}{e'}$$

$e' = \Delta E'$ when I + i

$e = \Delta E$ when I + i

I = applied protective current

$$\begin{array}{llll} & \text{I} & \text{I+i} & \\ E \rightarrow & -1.405 & -\ 1.495 & e = 0.09 \\ E' \rightarrow & 0.16 & 0.177 & e' = 0.017 \end{array}$$

$$E_p = 1.405 - \frac{0.16\ (0.09)}{0.017} = 0.558$$

FIG. 14—*Ohmic drop error in field cathodic protection measurement* (*after Sudrabin* [22]).

3. Conductivity of dielectric coatings increases with service time and requires additional cathodic protection current to maintain desired structure-to-soil potentials.

4. Corrosion attack under disbonded coatings can be mitigated by the application of a protective criterion more negative than the usual polarized −0.85 V criterion. Corrosion under disbonded coatings is not a general problem.

5. Corrosive attack of underground structures by pitting and stress corrosion cracking mechanisms can be mitigated by potentials more negative than the usual −0.85 V.

6. Field monitoring measurements of cathodic protection potentials of underground metallic structures are not usually corrected for ohmic drop or other measurement errors, and may lead to misinterpretation of the state of protection of the structure.

7. Cathodic protection potential criterion for underground structures in known or suspected SCC environments, or in populous areas should be increased above the −0.85 V polarized level to reduce the possibility of fracture rupture failures.

Acknowledgments

Acknowledgment is made to the Arabian American Oil Company for permission to publish this paper and to F. E. Hewes, F. E. Rizzo, F. W. Schremp, and R. F. Weeter for sharing their experiences and opinions concerning cathodic protection techniques.

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J. F. Tatum[1]

Replaceable Deep Groundbed Anode Materials

REFERENCE: Tatum, J. F., "**Replaceable Deep Groundbed Anode Materials,**" *Underground Corrosion, ASTM STP 741,* Edward Escalante, Ed., American Society for Testing and Materials, 1981, pp. 182–203.

ABSTRACT: The replaceable deep anode groundbed design is described in detail. Each component of the groundbed is shown along with complete details covering the installation thereof, with design factors and other parameters.

The various types of anode materials are described, and configurations of graphite anodes are discussed in detail with particular emphasis on the use of a center-tapped anode to prevent premature anode failure from end effect. Other anode materials are described, such as platinized titanium, platinized niobium, and platinum clad niobium. The use of platinum anode materials are covered in detail along with various anodically passive substrates.

Wire insulations are covered, such as high molecular weight polyethylene, and the dual jacketed insulations involving fluoropolymers along with their performance in downhole environments.

Calcined petroleum coke backfills are presented with information as to their resistivity and the various material specifications available.

The interference characteristics of deep groundbeds versus surface beds are shown in detail. The superiority of the deep groundbed in eliminating anodic interference is described, with data as to causes of cathodic interference.

KEY WORDS: replaceable deep groundbed, deep groundbeds, calcined petroleum coke dual jacketed wire insulations, platinized titanium, platinized niobium, platinum clad niobium, acrylonitrile-butadiene-styrene, center-tapped anode, graphite, metallurgical coke, high molecular weight polyethylene, polyvinylidene fluoride, polyolefin jacket, ethylene chlorotrifluoroethylene, wire anodes, rotary rig, end effect, underground corrosion

Replaceable Deep Anode[2] Groundbed

The writer during the early 1970s served on the task group of the National Association of Corrosion Engineers Committee T-10A-7b to prepare a recommended technical practice for the installation of deep anode groundbeds [*1,2*].[3] In writing the technical practice, it became quite apparent that our technology had not advanced to the point that a deep groundbed could be

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[1] Chairman of the board, Cathodic Engineering Equipment Co., Hattiesburg, Miss. 39401.

[2] U.S. Patent No. 3725669.

[3] The italic numbers in brackets refer to the list of references appended to this paper.

designed for a specified life of 10, 15, or 20 years with a degree of certainty that the groundbed would render the designed service life to the purchaser. It was highly improbable to design a groundbed which would operate over the design life, and it became apparent that the best and most sufficient answer would be to design a deep groundbed that could be replaced. The term "replaceable" being defined as preparing a deep anode groundbed in which the discharging mechanism (anodes along with their attendant conductor wires) could be replaced without loss of the original hole, thereby saving a large amount of money because the hole could be used repeatedly for the life of the structure it was desired to protect, be this a pipeline, tank bottom, building foundation, sheet piling, etc. The design shown in Fig. 1 accomplishes this purpose. This design of a replaceable deep anode groundbed has now accomplished a service life of over seven years. Numerous installations have had the expended anodes removed and replaced with new anode materials. Some of these have been the result of material failure, and some have been the result of an ongoing material evaluation program.

With the development of the replaceable deep anode groundbed, an effective field research tool was developed. It became possible to test different types of anodes, different types of wire insulations, and different types of backfills by installing them in the replaceable deep groundbed, and, upon removal, the materials could be evaluated for service life. This has led to the development of higher quality anode materials, different methods of connection, and superior backfills. The use of the replaceable deep groundbed for material and design evaluation, as might be expected, has resulted in a more efficient design and one that results in predictable design life.

This particular installation (Fig. 1) had a hole drilled approximately 20.3 cm (8 in.) in diameter and 76.2 m (250 ft) deep. The reason for the choice of the 76.2 m (250 ft) depth is arbitrary, and is not the same for all deep groundbeds. Obviously, in the installation of a deep groundbed, it behooves the designer to place the discharge area of the bed in the lowest resistivity stratum available in the particular geographical location. It is not within the scope of this paper to go into the many factors that have to do with the selection of the recommended depth of a deep groundbed installation. It should be noted that there are times in which the low resistivity stratum may be split in different strata levels and this, of course, depends upon the stratigraphy of the particular area. In such cases, the anode discharge area may be split by moving the perforated area of the casing up or down and separating it with solid plastic casing in the high resistivity areas. The only additional requirement is that more backfill anodes and wire are necessary in a split section discharge installation. It should be noted here, also, the particular installation described is one that is in an area where significant caving of the hole might occur if left open without casing.

The hole described was drilled with a rotary mud rig, washed reasonably clean, and reamed to approximately 20.3 cm (8 in.) in diameter, being made

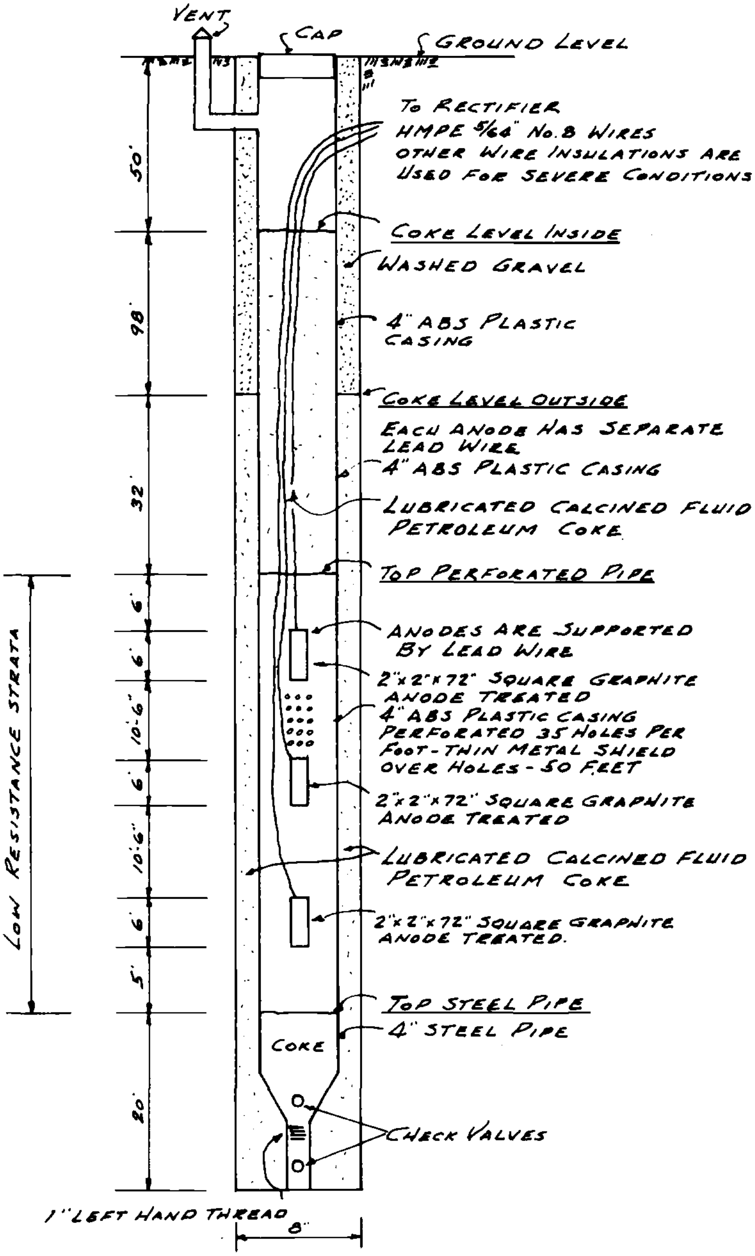


FIG. 1—*Replaceable deep groundbed.*

as straight as possible by drilling in a slow, progressive manner. At the time the installation of the casing is begun, the hole is completely full of mud. At the bottom of the casing string, there is provided a 6.1 m (20 ft) or 3.1 m (10 ft) steel section of standard weight steel pipe. On the bottom of this steel section, there is provided a check valve with a left-hand 2.5-cm (1-in.) threaded coupling. The check valve operates to allow the fluids to pass out of the casing, but to stop the return of the fluids from the outside up into the casing itself.

The 10.2-cm (4-in.) pipe then is attached to the perforated plastic casing and, in this particular installation where it expected to have sodium chloride contamination, acrylonitrile-butadiene-styrene (ABS) casing of extra thickness was used. The casing had previously been perforated in the discharge area to the extent of thirty-five 2.5-cm (1-in.) holes per 30.5 cm (1 ft). These holes are placed in the casing on a 45 deg angle so that the material within the casing may flow out of the hole and create pressure against the hole sidewalls; that is, the holes are on a 45 deg angle looking up into the casing. These holes are then covered with a thin conductive shield that is riveted in place to prevent the passage of fluids through the holes from the inside of the casing to the outside, or vice-versa.

This perforated casing is attached to the steel pipe and lowered into the hole. At the top of the discharge section, solid ABS casing is installed to the top of the ground. At the same time as the ABS casing is being placed with the steel lead at the bottom, there is inserted inside of the casing a 2.5-cm (1-in.) pipe with a left-hand thread screwed into the top of the check valve in the bottom of the steel lead. This 2.5-cm (1 in.) pipe is fabricated within the casing to the top of the ground and the pipe protrudes therefrom. More often than not, the casing must be filled on the inside with water, otherwise, it has a tendency to float and not sink to the bottom of the hole. At this particular stage of the installation, we have the solid casing, perforated section, and steel lead installed in the hole surrounded by mud.

With the casing in place and the 2.5-cm (1 in.) pipe sticking out at the top, the backfill material mixture (lubricated treated calcined fluid petroleum coke—specifications will be covered later) is mixed in a tank to a heavy constituency of 18.9 litre (8 gal) of water per 45.4-kg (100-lb) dry coke weight. The pump is then connected to the top of the 2.5-cm (1 in.) pipe, and this heavy backfill mixture is pumped down the inside of the 2.5-cm (1 in.) pipe through the bottom check valve and up around the outside of the casing to approximately 45.7 m (150 ft) from the top of the ground, as indicated by (Fig. 1). It should be remembered that this is an approximate level, and the reason for making the outside backfill 9.1 m (30 ft) over the perforated section is because, more often than not, there are washed-out areas within the hole that cause more backfill to be used than had been calculated.

When the pumping of the backfill is completed, it is followed by 378.5 to 577.8 litre (100 to 150 gal) of clear water to remove the backfill from inside the check valve at the bottom of the steel lead, another ball check valve is dropped in the top of the casing. It immediately goes to the bottom and rests adjacent to the 2.5-cm (1-in.) pipe where it is to be unscrewed. The 2.5-cm (1 in.) pipe is then unscrewed and the ball check valve drops into place. This prevents the passage of fluid through the check valve in either direction because there is a ball check valve on the bottom as well as on the top. This is necessary because the static fluid weights inside and outside the casing will vary, thereby, causing some undesirable directions of flow. In this particular instance, inside the casing around the 2.5-cm (1-in.) pipe, often becomes filled with heavy mud because the metal shield is not completely watertight. With this mud inside the casing, and backfill water mixture on the outside, the flow would be down inside the casing and will displace the coke at the bottom of the hole. This is the reason for the second check valve.

The 2.5-cm (1-in.) pipe is then raised approximately 3.1 m (10 ft) from the bottom of the casing, and clear water is pumped down through the pipe to clean the mud from inside the casing. It is sometimes necessary to lift the pipe as much as 6.1 m (20 ft) to 12.2 m (40 ft) above the bottom in order to lift the mud column up the casing without rupturing the conductive shield because of the weight of the mud column. As soon as the mud column is lifted to the point where clear water will begin to appear at the surface, then the 2.5-cm (1-in.) pipe is lowered to the bottom of the inside of the casing. Washing is continued until the fluid inside the casing is reasonably clear.

At this stage of the installation, the casing is in place. Clear water is inside the casing, and the outside is backfill, up to the level of 45.7 m (150 ft) from the top of the ground (Fig. 1). The anodes are then lowered into place with each one hanging on its individual lead wire. The number of anodes are determined by the amount of current to be discharged from the groundbed. With the anodes in place, a pipe is positioned down the hole, and the backfill mixture (the same that is on the outside of the casing) is pumped to the bottom of the casing and surrounds the anodes. The backfill will be placed to within 15.2 m (50 ft) of the top of the surface within the casing. The reason the backfill level is placed high inside the casing is to give a significant material particle pressure to the backfill at the bottom of the hole contacting the anodes and the earth. This creates intimate surface contact and is necessary to maximize electronic current flow. Electronic current flow will reduce consumption of anode material. As a practical matter, no anode materials subjected to a positive electromotive gradient will be completely immune from some electrolytic current flow, and this electrolyte ion conduction will cause some anode dissolution or deterioration and result in eventual anode replacement.

At this point, the installation is virtually complete, with the exception of washed gravel (or equivalent) which is placed in the annulus between the casing and the earth from the top of the backfill column to the top of the ground. The gravel serves two purposes; to prevent foreign matter from fall-ing into the hole and to provide a high porosity path for the relieving of any gases which may be generated by the groundbed current. Quite often a vent is provided from the top of the casing to relieve any gases that may be generated inside the casing. Experience has shown that, generally, there is very little gas generated inside of the casing because of the electronic flow between the anodes and the backfill, and most gassing occurs at the periphery of the backfill column to the earth. The periphery of the backfill column is a large area, and the generated gases distributed over this are usually absorbed by the underground strata, therefore, not venting to the ground surface. However, a path is provided by this means if it is needed for gas relief. One of the advantages of a replaceable deep groundbed system is, should you develop some gas blocking through some peculiar formations that will not absorb any gas generated, it is quite easy to fluidize the hole and provide a tube for gas relief.

To complete the installation, a cover should be provided to prevent casing damage and protect the public. The anode wires are left with slack around the top of the casing so, should they need to be replaced, it is necessary only to fluidize the backfill and remove the anodes. Ample wire will then be available to reconnect the anodes.

The replacement is a very simple operation. A water pump is used to pump clear water down the inside of the casing through a pipe and rubber tube down and around the anodes. Then the anode materials remaining and the lead wire are removed. If the anode has become separated from the lead wire because of consumption, then the anode material is washed loose so it may settle to the bottom of the hole in the 6.1-m (20-ft) steel pipe. As the backfill is fluidized, some backfill will return with the water. This backfill mixture is carried into a settling pan provided at the top of the casing and the backfill settles out into the pan and is available for reinstallation in the hole. After the wire and the expended anodes have been removed, the new anodes are placed in the proper location, and the backfill that has been accumulated in the pan is mixed and pumped back into the hole. Any additional backfill required is added at that time. It is important to have the backfill level within 15.2 m (50 ft) of the top of the casing, and the groundbed should be reinspected after a month to be sure the backfill level is at the proper point.

Anode Construction and Materials

Any type of impressed current anode material can be used in a replaceable deep groundbed, such as high silicon cast iron, steel, graphite, and platinized or platinum clad anodes. Most replaceable groundbed installations are made with graphite and platinized or platinum clad anodically passive substrate materials. The graphite anodes used may be either round or square type (which gives more surface area per unit length) and are designed with a current loading not to exceed 0.16 A/dm^2 (1.5 A/ft^2). Laboratory experiments indicate that graphites will function quite well in low resistivity carbonaceous backfills with loadings up to 0.5 A/dm^2 (5 A/ft^2), but when the anodes are installed in a deep groundbed installation, end effect causes the loading on the ends to approach a much higher figure than the design. For this reason, the anodes are loaded to a much lower current concentration. The phenomena of end effect causing higher current concentrations on anodes has been documented in a paper presented before the National Association of Corrosion Engineers in 1979 [*3*]. The paper states that one of the solutions to anode end effect is to provide segregated insulating strips on the anode surface. This causes the anode to have multiple ends rather than two. The paper shows by experimentation that segregating the anode with insulating strips causes the current discharge to spread over the anode surface and thereby reduce anode attack for the same apparent surface current density. This is done with a small increase in anode-to-backfill resistance.

A recent development in the graphite field is to provide the anodes with a current connection at the center (Fig. 2). This ensures a longer anode life because the center remains intact around the connection, and, therefore, a larger percentage of the anode is consumed before it must be replaced.

A square shaped graphite anode (Fig. 3) has additional surface in contact with the backfill. A 5.0 by 5.0-cm^2 (2 by 2-in.^{2}) anode has 27 percent more surface then a 5.0-cm (2-in.) round anode. The 5.0 by 5.0-cm^2 (2 by 2 in.^{2}) square anode has 27 percent more weight than the 5.0-cm (2-in.) round anode.

The other anode materials are platinized titanium and platinized or platinum clad niobium. Titanium and niobium are commonly called passive substrate materials, having reference to their ability to build a passive film under anodic voltage gradients under some conditions (Fig. 4). These anode materials have been used in Great Britain for over 15 years and have been in applications in the Continental United States for over three years at the present time [*4,5*]. They generally consist of low resistivity core material, such as copper, surrounded by a passive substrate, titanium or niobium, with an extremely thin coating of platinum on the surface. The principle is, as the passive material is exposed to the corrosive environment with an anodic gradient, it forms a very thin molecular barrier at the surface which restricts the passage of electrons. In the case of titanium, where predominant chlorides are present, the passive film breaks down at 7 or 8 V. This does not limit the use of titanium because the resistance contact between the anode and the backfill is so small that with the normal current density loading of the platinum anode surface to the backfill, usually 2.2 A/dm^2 (20 A/ft^2), the interface voltage between the anode and the backfill becomes negligible. Difficulty would arise if titanium was, by some error in installation, not surrounded by backfill. Being in contact with the aqueous electrolyte or soil, the entire anodic voltage would then develop across the passive film and cause it to break down (7 V with chloride ion dominance). However, if phosphate or

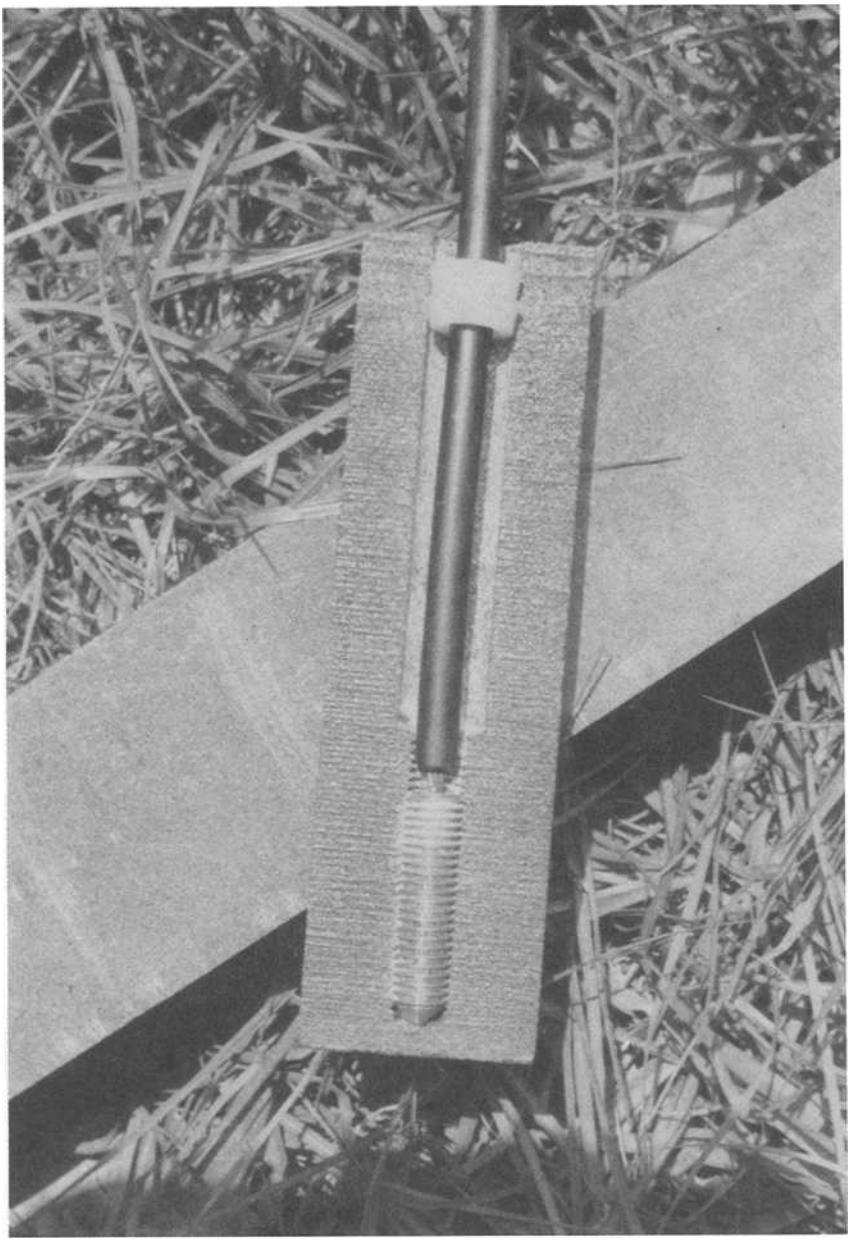


FIG. 2—*Anode center-tapped connection.*

FIG. 3—*Square graphite anodes.*

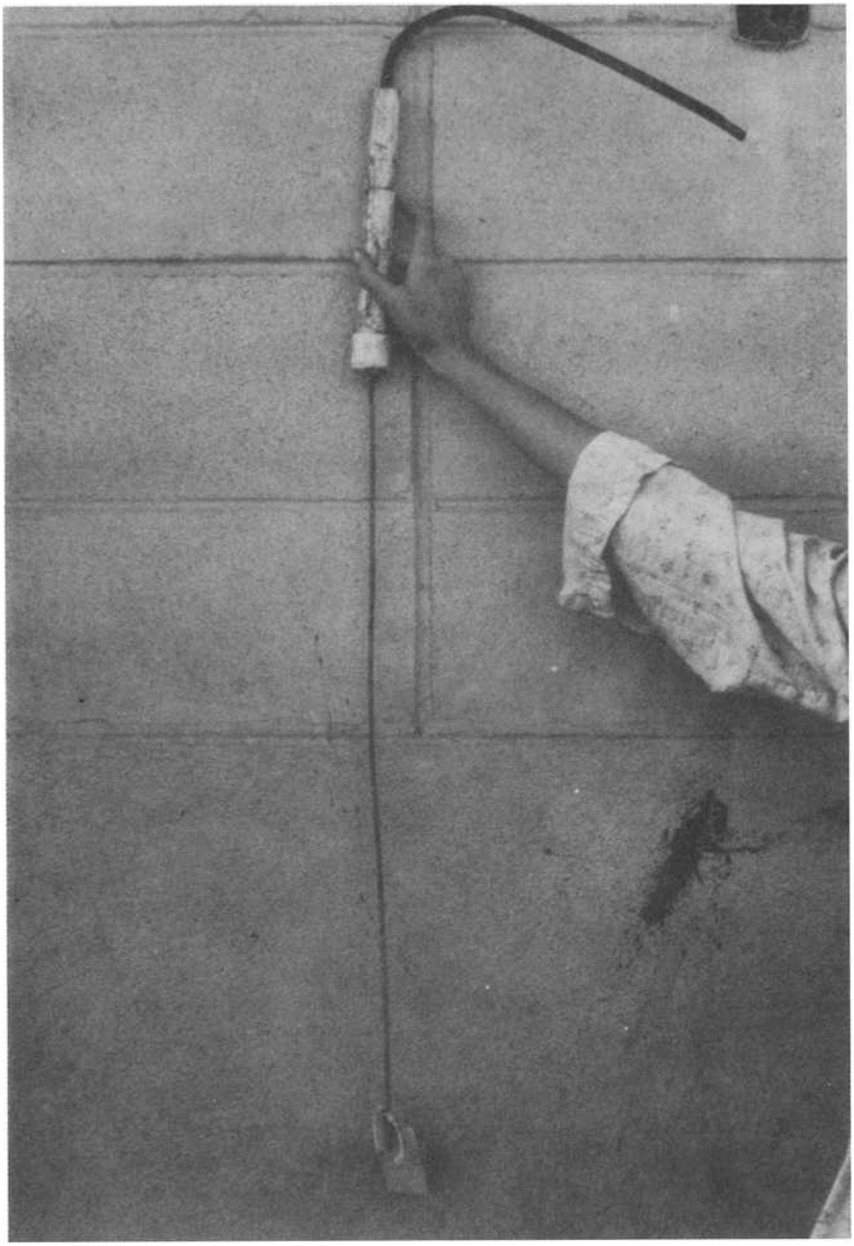


FIG. 4—*Platinized titanium anode.*

sulphate ions are dominant, experimentation indicates that the breakdown voltage of titanium will approach 60 to 70 V.

The platinum covering the passive substrate is normally 1 or 2 μm (40 to 80 μ in.) thick. The passive substrate anode makes contact with the backfill through the thin platinum coating, thereby establishing predominant electronic flow. Electronic current flow occurs when electrons move inside a conductor, and electrolytic current flow occurs when electrons are moved through an electrolyte by ions. Field time experience (three years) to date verifies that this type of anode will give good service.

Backfills

Replaceable deep groundbeds require a specialty type of carbonaceous backfill material. The basic carbon used is a calcined fluid petroleum coke which is mixed with low resistivity carbon additives and surface tension reducing agents to provide the desired physical and electrical characteristics.

Figure 5 is a resistivity versus coke pressure curve. This curve shows the contrast between the two types of carbonaceous backfill materials most commonly used in impressed current anode beds. The first figure is a metal-

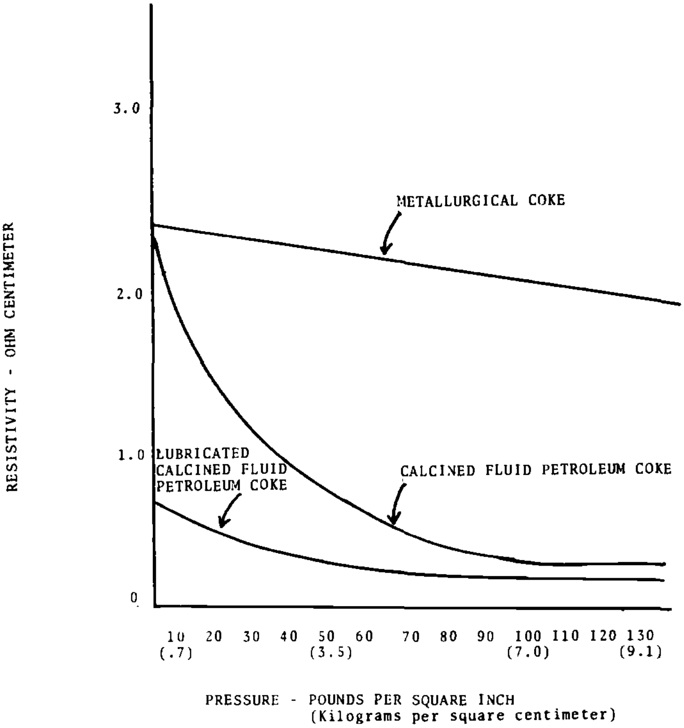


FIG. 5—*Resistivity versus pressure curves.*

lurgical coke and indicates that when pressured from 0 to 914 kg/dm^2 (0 to 130 psi), it approximates a resistivity of 2 Ωcm. Contrasting this, the use of a calcined fluid petroleum coke gives a curve from approximately 2 Ωcm down to about 0.2 Ωcm when subjected to the same pressure. Further, if this material is mixed with low resistivity carbon additives and subjected to the same pressure, the resistivity will start off at 0.8 and will approach 0.1 Ωcm at 703 kg/dm^2 (100 psi). The lubricated calcined treated fluid petroleum backfill is adaptable to a replaceable deep groundbed because it is easily fluidized. It is made up of round, hard balls of carbon, which enable it to separate readily and be fluidized up the hole for removal of the anodes (Fig. 6). In addition to this, the hard, round shaped carbon settles faster and denser than the sharp edged, irregular sized metallurgical coke backfills. The calcined fluid petroleum coke backfills are manufactured with a surface tension reducing agent, as well as the lubricants. This gives them the further property of reducing the

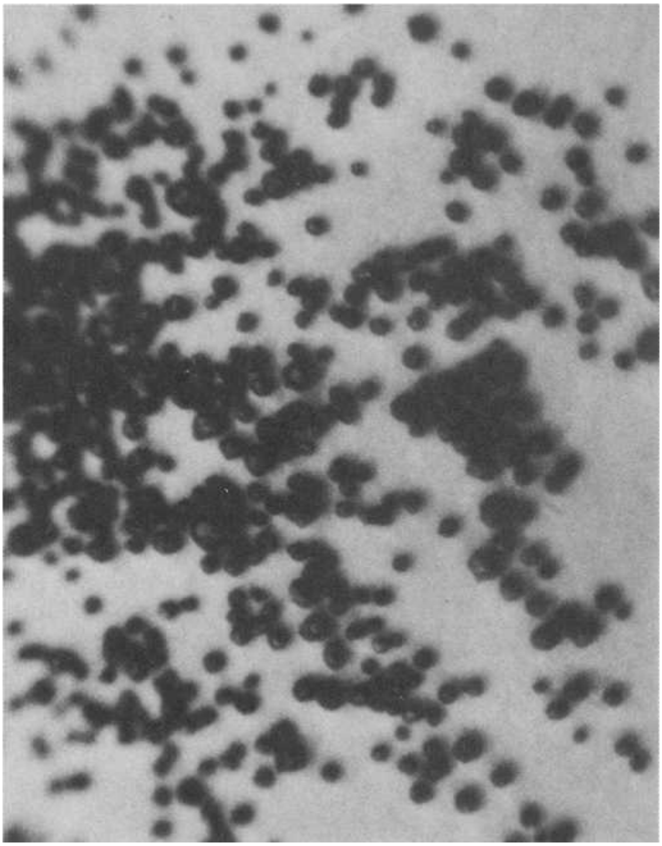


FIG. 6—*Calcined fluid treated petroleum coke.*

surface tension of water, causing the backfill materials to wet faster and settle quicker, to a more dense compaction than heretofore possible.

One other property of the calcined fluid petroleum cokes, making them especially adaptable for replaceable deep groundbeds, is they contain very few voids within the coke particles themselves, and have a specific gravity of two, enabling the particles to put pressure on the anode and on the earth downhole. This pressure reduces the electrolytic current transfer at the anode and causes most of the current to pass into the coke particles electronically, thereby reducing anode consumption. Note Fig. 7 showing the void in a metallurgical coke particle.

The particle size uniformity is a definite advantage in the lubricated treated calcined petroleum backfill. This is shown in Fig. 8, when compared with Fig. 6. This uniformity results in better compaction, lower resistance contact, and more kilograms of carbon per cubic meter. The additional carbon ensures longer life for the groundbed installation.

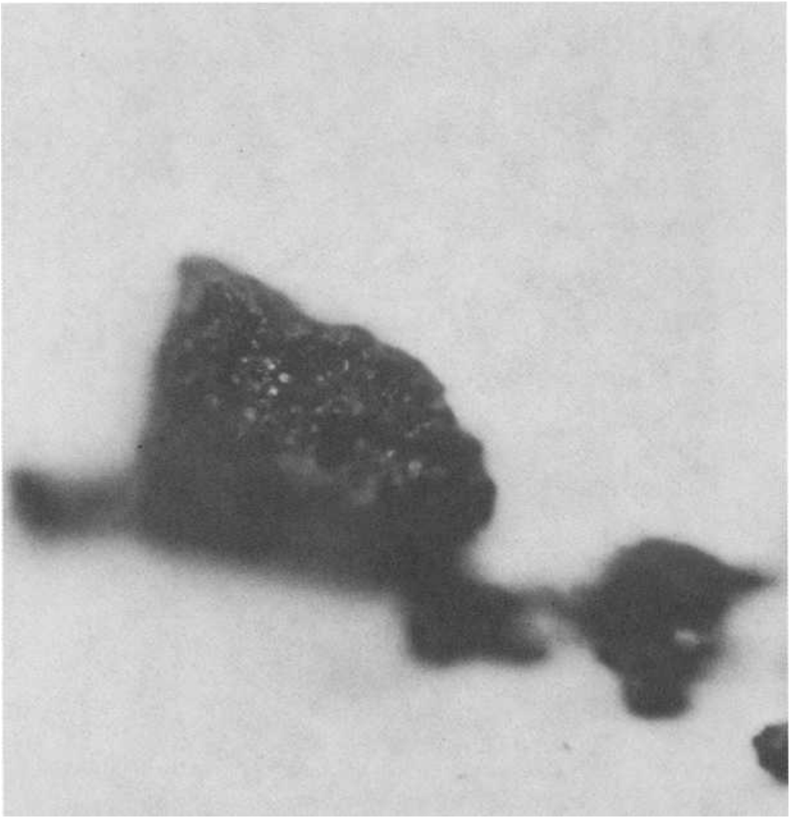


FIG. 7—*Metallurgical coke void.*

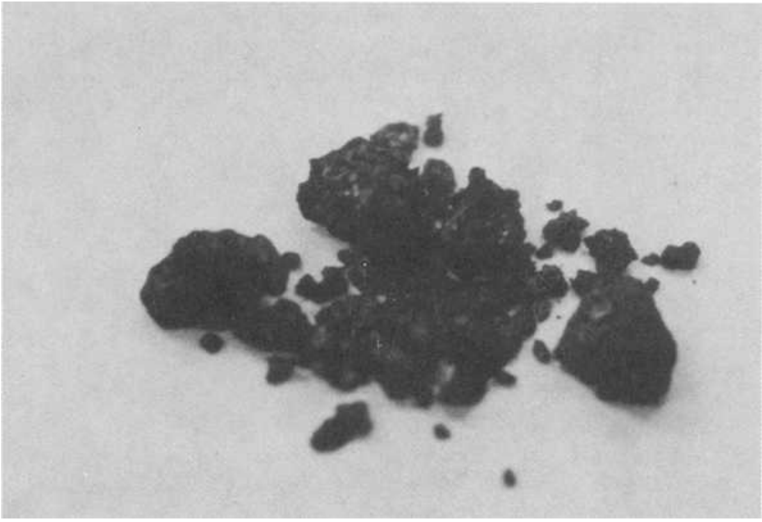


FIG. 8—*Metallurgical coke particles.*

Wire Insulations

At the present time, three types of insulation are used on the wire installed in deep anode groundbeds:

1. High molecular weight polyethylene (HMPE) Single Extrusion (Fig. 9).
2. Polyvinylidene fluoride-primary polyolefin jacket (Fig. 10).
3. Ethylene chlorotrifluoroethylene-primary high molecular weight polyethylene jacket.

The HMPE single extrusion insulations have proven to be satisfactory in all installations with the exception of the more hostile ones. The more hostile involvements are those having a very high concentration of halogens. The hostile environments evolve when anodic discharges take place in deep groundbeds where the water is more or less static. In those areas where there is considerable flow of groundwater, the concentrations of the corrosive halogens are kept to a tolerable level. Installations of deep groundbeds under these conditions will require HMPE 0.27 cm (7/64 in.) thick.

In those installations where a high concentration of chlorides or bromides is expected, the specification should call for the wire insulation to be the double jacketed type of either the numbers 2 or 3, listed previously. The reason for the double jacketed cable is that the primary insulations are susceptible to scratching and notch propagation. The HMPE over the outside of the primary insulation provides the physical properties necessary to protect the primary insulation. These insulations are offered commercially by various companies supplying the corrosion mitigation industry [*6,7*].

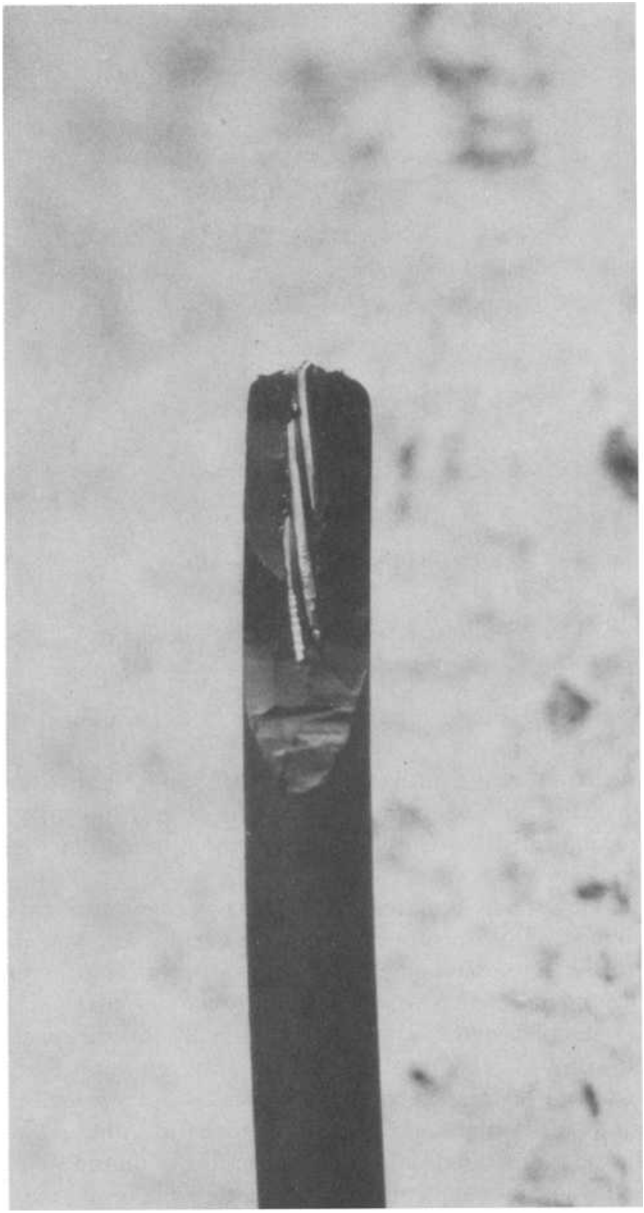


FIG. 9—*HMPE 0.27 cm (7/64 in.) insulation.*

FIG. 10—*Double jacketed fluoropolymer wire insulation.*

Foreign Structure Interference

The deep groundbed has a very distinct advantage in that it does not require any additional surface right-of-way for its installation. In addition to that advantage, it also has the property of not producing any anodic ground potentials at the surface of the earth. The anode bed, by definition, discharges its current 15.2 m (50 ft) or more below the earth's surface, and, therefore, as the current leaves the anode, anodic equipotential lines are established around the bed in more or less a concentric fashion horizontally and in an elliptical fashion from both ends of the anode column. These equipotential lines are altered by the resistivity of the various strata carrying the current. Naturally, we would expect where the current moves through a higher resistivity stratum, the equipotential lines would be closer together. If one views the strata of the earth and observes the overlay between the high resistivity area and the medium and low resistivity areas, it is easy to visualize that the current moving through these various resistivity strata will naturally crowd into the lower resistivity, leaving the higher resistivity areas to carry less current. Therefore, the equipotential lines would be deformed. There is also the interchange of currents between the layers as they equalize their equipotential lines, because more current would crowd into the lower resistivity stratum than the high one until the potentials at the boundaries balance.

One other thing detectable with deep groundbeds is, if there is a high resistivity stratum above the discharge area, the current will spread out below this high resistivity area, thereby increasing the transfer of the current to more distant parts of the line or structure being drained.

Contrasting this to a surface bed, where the groundbed is installed within the first 6.1 m (20 ft) of the earth surface (Fig. 11) [*8*], the current will crowd on the surface. Any foreign structure crossing the equipotential lines will be affected by a potential gradient to force current on the foreign structure, and if the line is bare or coating faults exist, current will pass thereon and will discharge at some remote point. The current enters the structure through faults in the coating, or, in the case of a bare surface, it will be forced thereon and travel the structure because it is the easiest path for the current to follow. The longitudinal resistance of the structure is very low compared to the earth, and the current will travel in the structure discharging at an area where there is another fault in the coating or where the earth potential is low. In the case of Fig. 11, the current traveled down the pipeline and discharged to the protected pipeline at the crossing point. This is not necessarily true, because if it is coated, it might discharge at the crossing point, but, on the other hand, it might travel 6.4 or 8.0 km (4 or 5 mile) before it found a fault in the coating and there discharge into the earth.

In Fig. 12, there are two curves. The No. 1 curve (surface groundbed) indicates where a half-cell is placed on the surface of the ground for reference, and then another was moved away from the groundbed. Note that the potentials rise quite rapidly over the groundbed until it reaches a point of approximately 76.2 m (250 ft) away. This will vary with the resistivity of the soil at the surface of the ground. The deep groundbed surface potential curve is No. 2. In this case, the groundbed was 15.2 m (50 ft) below the surface of the ground and a very slight potential rise is noticed as the reference cell is moved away from the groundbed location. It reaches a point of no change at approximately 30.4 m (100 ft) away. The change in potential over the surface of the ground at no point exceeds 250 mV. Therefore, we can say that with

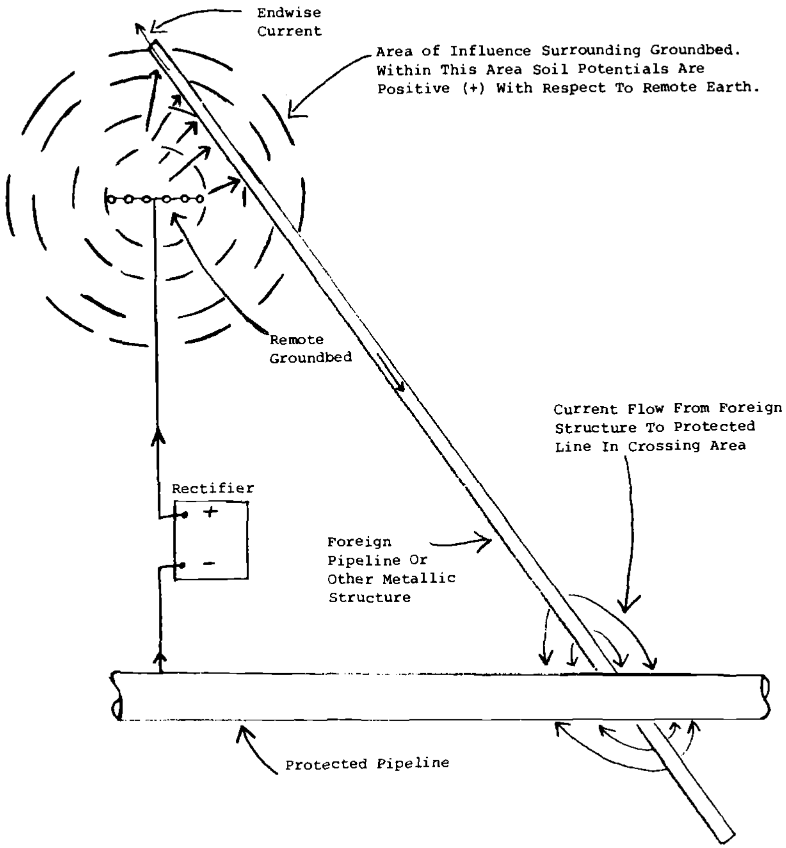


FIG. 11—*Anodic interference.*

the deep groundbed impressed current installation, the possibilities of anodic interference are very sharply reduced.

Anodic interference [*9*] is caused by artificially elevated soil potentials, and cathodic interference is caused by soil potentials being reduced in the vicinity of a cathodically protected pipeline or structure. In Fig. 13 [*10*] the protected pipeline is bare, the foreign pipeline is either poorly coated or bare, and cathodic ground currents are moving toward the protected structure (there is created in the earth a series of equipotential lines which are more often concentric than not). The equipotential lines are deformed by the proximity of the ground surface or by other structures in the vicinity. These equipotential lines crossing the foreign pipeline or structure will cause the current to leave the foreign pipeline or structure at any coating faults. In a bare pipeline, the current will leave from the surface at the vicinity of the protected line and return to it through the earth. Since this is an electrolytic path, cor-

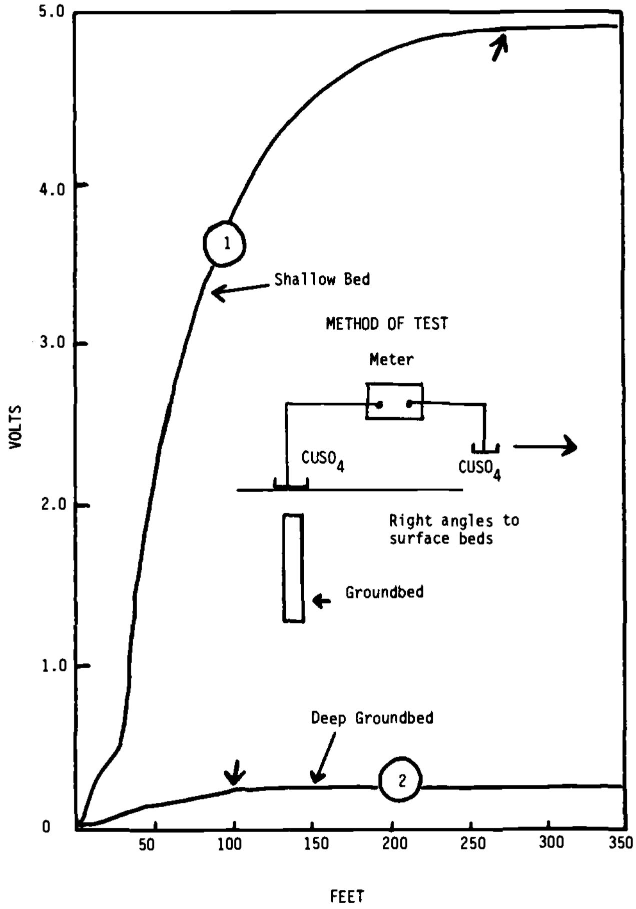
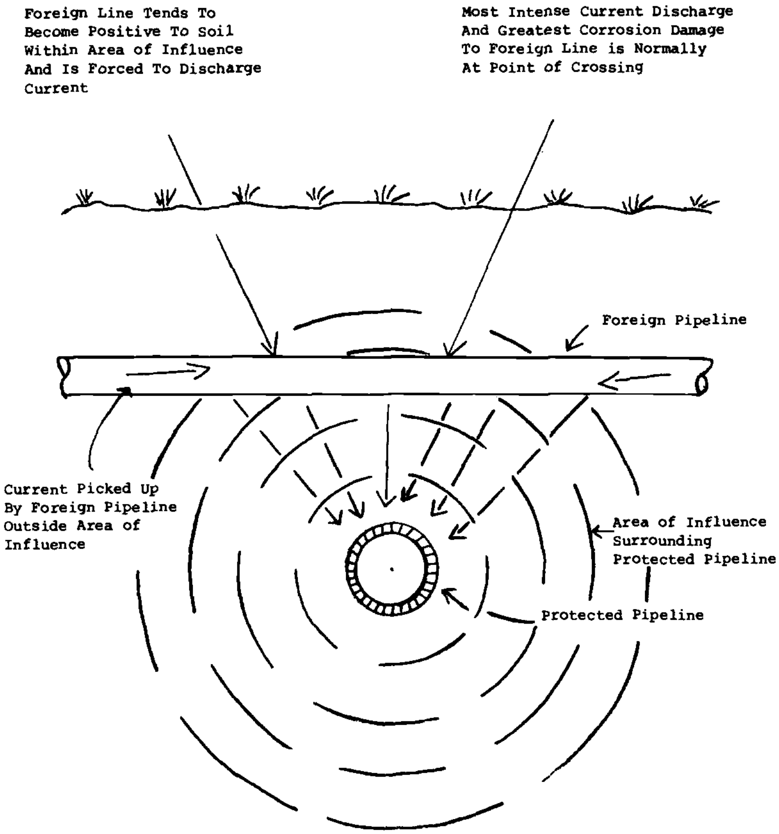


FIG. 12—*Surface potentials of two groundbed types (shallow and deep).*

rosion will occur. This reduction in voltage at the affected crossing will cause the foreign pipeline or structure to pick up current in some other area which may be some distance from the point of interference. This would manifest itself by a more positive potential on the foreign pipeline or structure at the point of discharge, and a more negative potential in the area of current pickup.

In Fig. 14, there are four curves developed in a detailed manner. A reference half-cell was placed over the structure being investigated and another half-cell was moved horizontally and at right angles therefrom. The half-cells were connected to a high impedance voltmeter. The curves indicate the potential difference existing between the two half-cells as they are separated. The No. 1 curve was measured in 30 000-Ωcm soil. This curve indicates that the area of influence from a bare pipeline under cathodic protection would



EFFECT ON FOREIGN PIPELINE PASSING THROUGH EARTH POTENTIAL GRADIENTS AROUND CATHODICALLY PROTECTED BARE LINE.

FIG. 13—*Cathodic interference.*

be in excess of 7.3 m (24 ft) from the protected structure before no interference would occur. Curve No. 2 was developed in soil of 5000 Ωcm resistivity, and the point of zero interference would occur approximately 6.1 m (20 ft) from the structure. Curve No. 3 represents measurements in 1000 to 1500-Ωcm soils and the spacing between the two lines would have to be 1.2 m (4 ft) or less for a point of no interference. Curve No. 4 shows that with a coated pipeline without faults in the coating at the adjacent foreign pipe crossing, no interference will occur of any consequence. We would expect separation of the lines to be at least 0.6 m (2 ft) or more in normal installations. It should be restated, if a fault occurs in the pipeline coating, a very serious interference problem would arise if the lines were no more than 0.6 m (2 ft) apart.

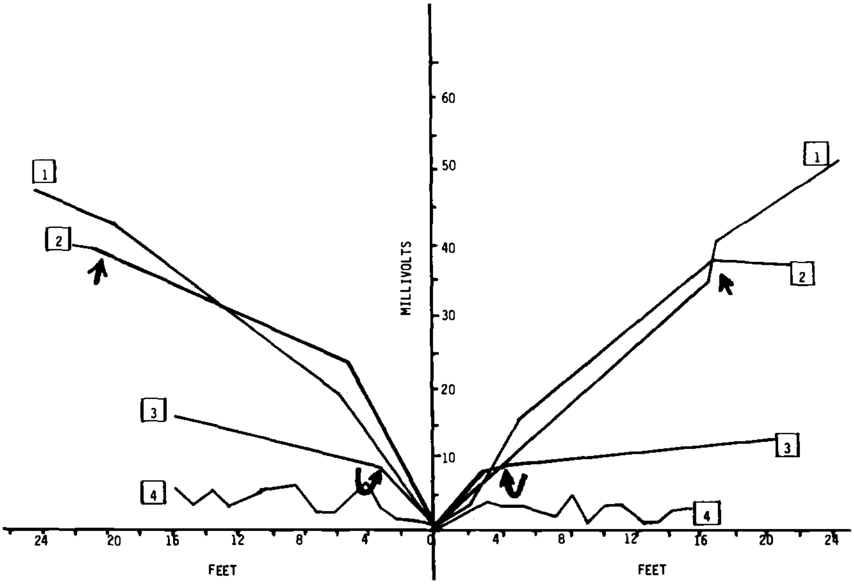


FIG. 14—*Surface potentials—cathodically protected pipelines.*

Conclusions

1. The replaceable deep groundbed is a practical means of providing cathodic protection currents with a minimum of interference.
2. The use of double jacketed cable insulations represents a significant improvement in the operation and dependability of deep groundbeds in chemically hostile environments.
3. The use of platinized passive substrate anode materials has proven to be successful in deep groundbed installations, as well as surface installations.
4. Using properly designed backfills improves impressed current anode performance and life.
5. Center-tapped anodes will give improved anode life in deep groundbeds.
6. Replacing anode materials in properly designed deep groundbeds is effective and economical.

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Summary

The papers have been divided into three broad categories as the following table indicates:

Category	Author(s)
The underground environment	Miller Fischer and Bue Iverson
Resistivity	Husock Chaker Arcone
Evaluation techniques	Serra and Mannheimer Jones Lankes Compton Vrable Toncre Tatum

As is true of most attempts at categorizing, some of these papers fall into their category very well, others fit into more than one, etc.; but all are pertinent to the subject of underground corrosion and are included.

The first paper is presented by Miller, a soil scientist, in which he describes the soil environment from a point of view rarely seen by a corrosion engineer. He describes the process of gathering and assessing data used in the soil survey manuals which show detailed maps and information about the makeup of soil for most counties in the United States. Also included is his discussion of a relatively new section on an evaluation of the "Risk of Corrosion" of soil. This information provided by Dr. Miller is invaluable to engineers concerned with soil corrosion.

The work of Fischer and Bue on the evaluation of causes of corrosion in disturbed and undisturbed soil for pipelines and foundation piles indicates that differential aeration plays an important role in pipeline corrosion, and that corrosion of piles in undisturbed soil is very low. They describe two electrochemical probes for evaluating soil corrosivity. The first, a galvanic probe, is generally used to estimate soil resistivity. The second, the amperostatic polarization probe, is a three-electrode probe for measuring the corrosion rate of a mild steel electrode by polarization techniques. These studies, carried out in Norway, are pertinent to present needs for more soil corrosivity information.

Iverson addresses the problem of microbial corrosion in soil where he not only describes their corrosion effects but, on the basis of his observations, proposes a new mechanism which more accurately explains results obtained in the laboratory and in the field. His suggestions, on actions that can be taken to identify and combat this form of corrosion are included. It is very likely that microbial corrosion is far more widespread than we realize.

Husock points up that soil resistivity measurements are widely used to determine soil corrosivity. Therefore it is imperative that the resistivity data gathered be valid, especially where there are large variations in soil. He describes a statistical technique for evaluating resistivity data that reveals the distribution of the data and what the probability is of finding a given value in the field. This method of data analysis makes it possible to detect soil resistivity changes, if any, with time or after soil excavations.

Chaker describes a special cable and switching device which allows him to obtain soil resistivity data over varying distances of electrodes using Wenner's four-pin method. Furthermore, by applying computer analysis to Barnes' method of determining resistivity layering, he is able to plot soil resistivity as a function of depth. A comparison of these results to actual borings is discussed. This is a significant step in reducing the time necessary for manual resistivity measurements.

Surveys of soil resistivities for large areas or long distances is a laborious time consuming task. Arcone describes two electromagnetic methods for measuring ground resistivity which require that a primary magnetic field be transmitted into the ground. This field interacts and is modifed by the earth to produce a secondary magnetic field which is detected by a hand held receiver loop which is carried as the surveyer walks over the ground. He describes how these changes in the induced magnetic field are related to soil resistivity, and shows data comparing soil resistivity measurements made by the electromagnetic methods to more conventional d-c electrode methods.

Serra and Mannheimer describe their work in which they have used the polarization resistance method to determine the corrosion rate of steel, galvanized steel, aluminum, and copper in various soils in a laboratory setting. They also describe the effect on the measurement of different positions of the counter electrode. They conclude that laboratory polarization data can be used to estimate soil corrosivity.

Jones presents a brief introduction to mixed potential theory and its application to the development of polarization resistance for measuring the corrosion rate of metals in the laboratory and in the field. The limitations that exist in applying these techniques to field measurements are included along with his description of how polarization measurements can be used to determine the degree of cathodic protection needed for a structure. This paper is of invaluable assistance to those using polarization techniques to measure corrosion rates of metals in soil.

Lankes discusses a variety of very practical problems faced by an engineer working in the field along with suggested remedies to subjects ranging from underground residential distribution (URD) systems to buried tanks and cathodic protection systems. His plea for further investigations on several items including magnesium anodes and the protection of cast iron pipe can serve as a guide to some laboratory research.

Using his experience in research and field work, Compton describes the influence of soil composition, materials, stray d-c and a-c signals to underground corrosion. He directs his interest at gaslines and underground residential distribution cables discussing methods of survey and proposed methods for reducing soil corrosion.

The development and application of strict standards of protection in manufacturing steel tanks for underground use is described by Vrable. Though electrochemical measurements indicate the soils to be corrosive, no failures were observed in two 5000 gal tanks buried for ten years. The corrosion data was obtained using electrical resistance probes and polarization techniques, and is of particular significance because of its long-term exposure.

Toncre gives a very interesting description of the historical development of coatings and cathodic protection as applied to underground pipelines. He discusses the effects of water absorption on the coating electrical resistance and shows that these coated regions are cathodic to holidays and voids. He stresses the need for proper cathodic protection and discusses criteria for achieving this protection. He concludes by stating that in some cases a potential more negative than -0.85 versus $CuCuSO_4$ may be necessary in some instances.

Tatum has developed a solution to the problem of removing and replacing deep underground anodes in cathodic protection systems. He discusses in detail the techniques used in placing and retrieving deep groundbed anodes and describes various types of backfills used and their characteristics. Included is information on impressed current anodes of high silicon cast iron, steel, graphite and platinized, or with platinum cladding. Though this paper could not be included in the symposium, it was certainly important enough to be included in this publication.

Acknowledgment

I wish to thank the many individuals that made the symposium and this publication possible; the authors who gave their time and effort in presenting their work, in particular our colleagues who came from outside the United States, Bente Bue of Norway, Eduardo Serra from Brazil, and Art Toncre

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Edward Escalante
National Bureau of Standards, Washington D.C. 20234; symposium chairman and editor.

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