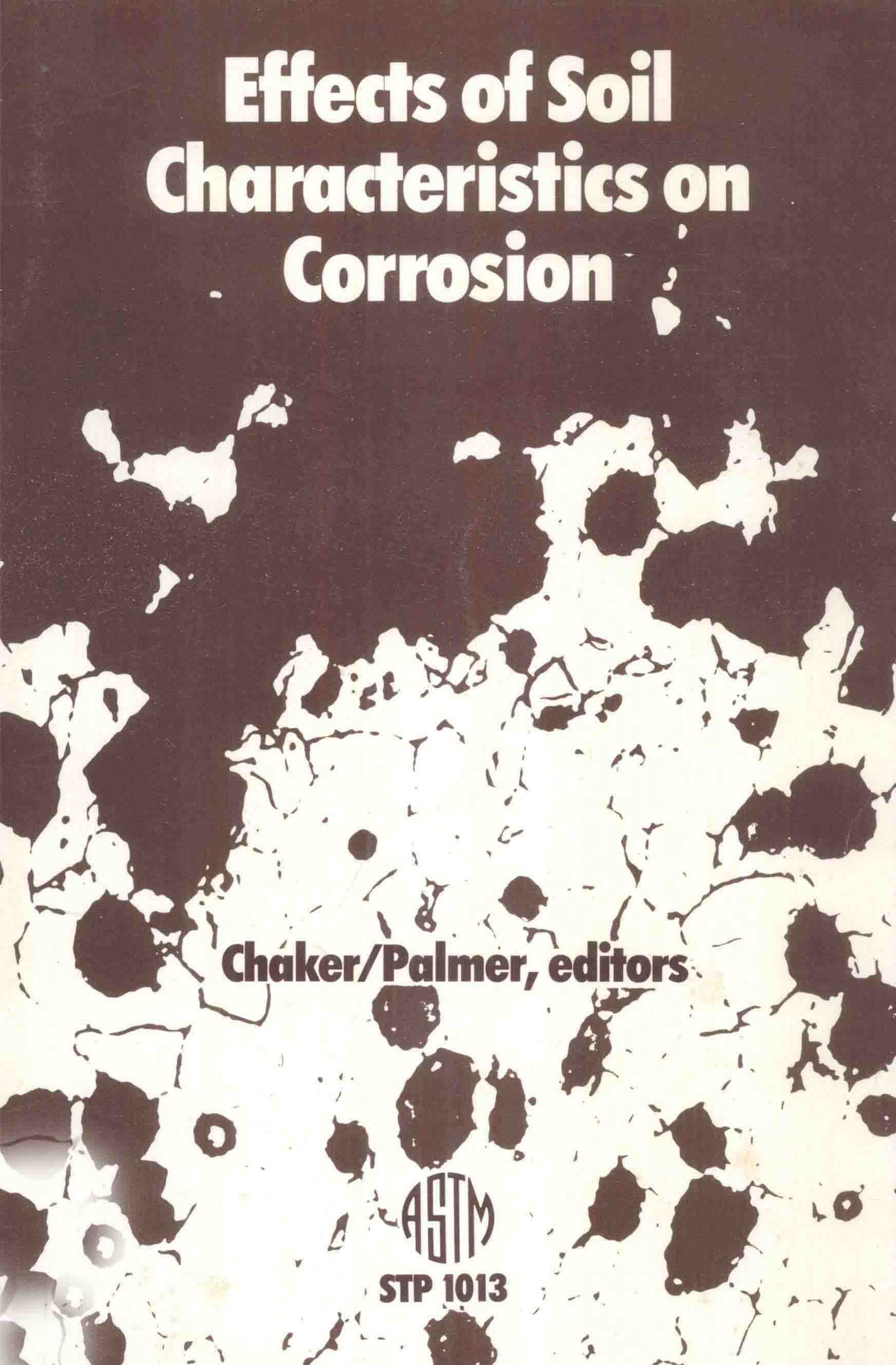
Effects of Soil Characteristics on Corrosion

Chaker/Palmer, editors



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Victor Chaker and J. David Palmer, editors

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Foreword

This publication, *Effects of Soil Characteristics on Corrosion,* contains papers presented at the symposium of the same name held in Cincinnati, OH on 12 May 1987. The symposium was sponsored by ASTM Committee G-1 on Corrosion of Metals. Victor Chaker, The Port Authority of New York & New Jersey, and J. David Palmer, Corrosion Control Engineering, Ltd., presided as symposium chairmen and were coeditors of this publication.

Introduction

Corrosion of metals in soils is responsible for a large percentage of corrosion worldwide. Several individual characteristics have been used to indicate the corrosivity of soils. However, no documentation describes the synergistic effect of several soil characteristics. This led Subcommittee G1.10 on Corrosion in Soils to create a task group to discover the answer. The task group decided to sponsor an international symposium to find the latest activities in the field of corrosion of metals in soils. The symposium was held 12 May 1987 in Cincinnati. Eleven papers were presented, followed by question and answer sessions.

The symposium revealed specific projects that are being carried on. Several papers expanded the knowledge of one parameter: oxygen concentration cells and their effect on concentric neutral cables. The most promising work was in a paper in which many soil characteristics were correlated using statistical analysis. The technical contributions of each paper are highlighted in the Summary in the back of the book.

More work is needed in the field of corrosion of metals in soils. Such information could be very important in identifying the synergistic effect of all the synergistic parameters, leading to more technically and economically effective methods of corrosion control.

On behalf of ASTM Committee G-1, Subcommittee G1.10, and the Task Group, I wish to express my sincere gratitude to the authors and technical reviewers who made this publication possible.

Victor Chaker

The Port Authority of New York & New Jersey, Jersey City, NJ 07310-1397; symposium co-chairman and editor

Contents

John H. Fitzgerald, III[1]

The Future as a Reflection of the Past

REFERENCE: Fitzgerald, J. H., III, **"The Future as a Reflection of the Past,"** *Effects of Soil Characteristics on Corrosion, ASTM STP 1013,* V. Chaker and J. D. Palmer, Eds., American Society for Testing and Materials, Philadelphia, 1989, pp. 1-4.

ABSTRACT: This symposium will deal with the various parameters that affect soil corrosivity and the methods used to measure those parameters. Each soil characteristic has been used at some time in the past to indicate corrosivity, and methods were developed for its measurement. This talk will delve into the background of these parameters and measurements methods and show how past studies affect future understanding. Where did the 10 000 ohm centimeter plateau come from? What was the contribution of the National Bureau of Standards? How did Starkey and Wight affect modern thinking on bacteriological corrosion? What did we learn from the Shepard cane, Columbia rod, and Putman's apparatus? Who was Wenner, anyway?

KEY WORDS: acidity, bacteriological corrosion, history, redox, resistivity, soil corrosion, soil maps, statistical analysis

How It All Started

Alvin Toffler, in his book *Future Shock,* states that scientific knowledge doubles every ten years. When one considers the increase in knowledge since the beginning of the industrial revolution, that statistic becomes somewhat overwhelming. Even if we look back over the relatively short history of corrosion control, we find that about 65 times as much is known today about corrosion as was known in 1930.

And we keep on learning. But we also build upon knowledge gained in years gone by. So, before we begin this symposium, let us pause for a moment and consider the activities and contributions of those who have gone before us. How is their work reflected in what we are doing today?

At the turn of the century, all corrosion was attributed to stray current from rail traction systems—trolley cars and subways [*1*]. In 1910, Congress authorized the National Bureau of Standards to begin a study of this "stray current electrolysis" that was causing so much damage. In the course of its study, however, the Bureau discovered that corrosion would also occur in soils where no stray current was present. By 1920, NBS had concluded that soil corrosion was equally as serious as corrosion caused by stray current. So the study was expanded in 1922 to determine the causes of soil corrosion; finding that some soils were more corrosive than others, the Bureau went on to determine just what soil parameters were responsible for the corrosion of metals.

What NBS found out is something that we have all come to appreciate in later years, that the corrosivity of a particular soil is based upon the interaction of several parameters—resistivity, dissolved salts, moisture content, pH, presence of bacteria, amount of oxygen, and others. No one parameter can be taken as indicative of the corrosivity of a given soil. The results of the

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studies were presented in Circular C450, *Underground Corrosion* [*2*] in 1945. In it, the Bureau states succinctly that soil corrosion is too complex to permit correlation with any one parameter.

The Bureau's burial tests had established the severity of corrosion to be expected on various metals in various soils. The data were very useful if one were working with a soil similar to one in which tests had been made. But what if one were working with a different soil? It obviously would not be feasible to wait for the outcome of a burial test. It became apparent, therefore, that perhaps one could obtain data on soil parameters and compare those data with NBS test results and thereby come up with an estimate of the soil's corrosivity.

This is where it all began. Today, we are able to measure the pertinent soil parameters and indeed make reasonable estimates about the corrosivity of a particular soil to a buried metallic structure. But who laid the groundwork for the tests we so commonly perform in the field and laboratory today? How is their work reflected in today's terminology and instrumentation?

Resistivity

In 1916, F. Wenner [*3*] demonstrated that the resistivity of a volume of earth could be measured by inserting four pins into the earth in a straight line, passing a current between the two outer two pins and measuring the resultant resistance between the inner two pins. Known as the "Wenner four pin method," this technique is one of the most common methods of measuring soil resistivity today. Early instruments used with this setup were the McCollum earth current meter and the hand-cranked Megger. Modern, solid state instruments may be faster and more accurate, but they perform about the same function as the old timers did!

Another early instrument that helped in obtaining soil resistivity, particularly in relatively confined areas, was the Shepard cane. Developed by E. R. Shepard [*4*] about 1930, the instrument consisted of two rods about three feet long, each tipped with a iron electrode. The rods were inserted in holes in the ground about 8 or 10 in. apart, and a current from a 3-V battery was passed between them. The instrument contained an ammeter that was calibrated in ohm centimeters. From the Shepard cane has come several probe-type instruments for the measurement of soil resistivity.

Soil resistivity is relatively easy to measure and, being an electrical quantity and thus related to corrosion current flow through Ohm's law, is probably the parameter most often looked upon as indicative of a soil's corrosivity. Even today we see codes that state that corrosion protection is not required in soils of resistivity above 10 000 ohm centimeter or some similar figure. Where did that plateau come from? It goes back to 1940s; it had been found that, in soils of resistivity above 10 000 ohm centimeter, the rate of corrosion on pipelines was generally slow enough that it was less expensive to repair leaks when they occurred than to provide corrosion protection. That may have been all right in the political atmosphere of those days, but it is no longer valid. Bacteria, dissimilar metals, or oxygen concentration cells, for example, may create severe corrosion in high-resistivity soil; we are concerned today about safety, pollution, and economics and can no longer rely on simple measurement as a basis for determining the need for corrosion control.

Acidity

Often attempts are made to relate corrosivity to the pH of the soil; people worry about "acid" soil. The question goes back to 1924 when J. W. Shipley, I. R. McHaffie [*5*], and H. D. Holler [*6*] observed that there appeared to be a relationship between soil acidity and the rate of corrosion of iron. It remained for I. A. Denison and R. B. Hobbs [*7*] in 1934, however, to determine that corrosion was related to the total acidity of the soil rather than just the pH. In 1935 I. A. Denison and S. P. Ewing [*8*] discovered a relationship between total acidity and soil resistivity in tests in northern Ohio. The complexity of soil corrosion was beginning to be appreciated as experimenters began to realize that no one soil parameter could tell the whole story.

Bacteriological Corrosion

Bacteriological corrosion, a serious concern in many parts of the country today, came under investigation as early as 1923 when R. Stumper [9] reported on the corrosion of iron in the presence of sulfur. Early concern centered around the corrosion of pipes having joints caulked with sulfur-bearing compounds. The matter came under further investigation along about 1940. R. L. Starkey and K. L. Wight [10] came to the conclusion that oxidation-reduction (redox) potential was the most reliable indicator of bacteriological action. They developed what was later to become known as the redox probe. Consisting of two units, one containing a platinum and calomel electrode and the other a calomel and a glass electrode (to measure pH), the instrument was later refined into a single probe for improved mobility and field use.

Interest in bacteriological corrosion began to grow in the succeeding two decades as a possible cause of corrosion failures in high-resistivity or other soils that would otherwise be thought of as only mildly corrosive. Extensive research was undertaken by J. O. Harris [11], who studied the action of bacteria under both aerobic and anaerobic conditions. He also did some rather controversial work on the effect of bacteria on coatings. Harris' work, combined with that of earlier researchers, helped pave the way to a modern understanding of the phenomenon of bacteriological corrosion.

Interrelation of Soil Parameters

All of this so far has dealt with the development of understanding of the contribution to corrosion of various soil parameters. There remains the question of how the parameters react together to produce corrosion. The question was pondered as early as 1930 when B. B. Legg [12] developed the Columbia rod. This was a probe-type instrument having a steel and a copper electrode at its tip, connected through a milliammeter. It was an attempt to correlate soil resistivity, potential differences pH, and polarization. The data obtained gave an indication of corrosivity when compared against observed pipeline conditions in soils of known resistivity. J. F. Putman [13] in 1917 developed a device to measure soil resistivity and modified it in 1935 in an attempt to combine pH and resistivity as a measure of what he called the "potential corrosivity" of the soil. The complexity of soil corrosion was indeed beginning to be realized.

Today, one method of evaluating soil corrosivity is through statistical analysis of soil characteristics and pit depths on pipelines. Here we look back on a heritage developed in the hydroelectric industry over what would be the maximum flood level or water flow over the expected lifetime of a generating plant or dam. Engineers spoke of the "hundred year flood" and added arbitrary safety factors such as perhaps double the size of the largest flood that had occurred during the past 50 years. In the mid-1950s, E. J. Gumbel [14] applied extreme value statistics to flood evaluation and was able to predict the probability of a major flood occurring every so many years. G. G. Eldridge [15] applied this concept to pitting of oil well tubing in the late 1950s and his work has been expanded into the procedures used today to evaluate pipe condition. Also in the late 1950s, G. N. Scott [16] used extreme value statistics to evaluate soil resistivities, furthering our understanding of the chances of encountering low-resistivity soil at a given site.

Soil Maps

We would be remiss if we didn't mention soil maps. From time to time various maps have appeared purporting to show areas of "corrosive" and "noncorrosive" soils. It all began in 1899 when the U.S. Department of Agriculture began mapping the soils of the United States. While not addressing corrosivity, the U.S.D.A. reports do cover aeration, drainage, and other soil characteristics useful to the corrosion engineer. C. F. Marbut [17] in 1935 classified the soils of the United States into eight great groups and identified many subgroups.

These maps can be helpful in preliminary planning, but we still must recognize that soils of similar types in different areas may not exhibit the same corrosion characteristics. The corrosion engineer still needs to get out in the field and evaluate what is to be expected at a given site or along a specific right of way. There may also be a considerable amount of corrosion data available to assist in the investigation which, when combined with newly acquired field data, will give a good indication of the corrosivity of the soil.

Epilogue

Much has been accomplished in the past; much remains to be learned in the future. Ten years from now we will know twice as much as we do now. Perhaps we will have instrumentation that can combine all the soil parameters and give us a good indication of the effect of soil on various metals. But let us not forget that many investigators have postulated equations and formulae over the past years in attempts to do the same thing!

Thomas a'Kempis, a German monk of the fifteenth century, said, "Today I pray for the wisdom to build a better tomorrow on the mistakes and experiences of yesterday." Let us apply that same philosophy to corrosion engineering, and as we go forward in our understanding of soil corrosion let us remember and apply the contributions of those who have labored in the past to bring us to where we are today.

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J. D. Palmer[1]

Environmental Characteristics Controlling the Soil Corrosion of Ferrous Piping

REFERENCE: Palmer, J. D., **"Environmental Characteristics Controlling the Soil Corrosion of Ferrous Piping,"** *Effects of Soil Characteristics on Corrosion, ASTM STP 1013,* V. Chaker and J. D. Palmer, Eds., American Society for Testing and Materials, Philadelphia, 1989, pp. 5–17.

ABSTRACT: The characteristics of soils controlling the external corrosion of ferrous piping materials are examined with particular reference to an American Water Works Association (AWWA) rating formula. The relationship and reliability of the following characteristics as corrosion predictors are examined: resistivity, pH, redox potential sulfides, moisture, and chlorides. Metallurgical test results illustrating the mechanism of attack on cast iron and ductile iron are presented and the apparently different performance of the two materials is reviewed. Mitigative and preventive measures are mentioned and the organization of a corrosion control program outlined.

KEY WORDS: underground corrosion, piping materials, parameters, resistivity, pH, redox, moisture, surveys, mitigation

Over the last century the material used for water (and gas) mains has changed from wood to pit-cast iron to centrifugally cast iron to ductile iron to plastic with occasional introduction of wrought iron, plain and galvanized steel, coated and cathodically protected steel, asbestos cement, and reinforced concrete. Customer service piping has been made from all of the above materials as well as from copper. Current interest is focusing on the performance of ductile iron, which largely replaced cast iron beginning in the 1960s. Ductile iron failure rates of 0.5 leaks/km/year are common, with Winnipeg recording even higher rates beginning in the 1950s [*1*].

Material Performance

Wood must be considered a primitive material with the early butt-joint and strapped wood stave piping limited in pressure and subject to rot and attack by fungi.

Cast iron (pit-cast and centrifugally cast) has commonly given service life in the 100-year range, and post-World War II studies showed percentages of installed pipe still in service in the 90% range, increasing with increased pipe size [*2*]. Studies conducted in the early 1960s did not show the exponential increase in leak (break) rate commonly associated with corrosive attack, but later studies have shown this effect, suggesting that the corrosivity of the soils has increased since the 1960s.

The interpretation of cast iron failure data is difficult because most failures are described as "breaks," whether due to purely mechanical effects or partially due to the weakening effect of corrosion. Usually the only leaks attributed to corrosion are those where there is an obvious blowout of the graphitized part of the pipe wall without an accompanying mechanical failure.

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The later failure mechanism is more commonly found in ductile iron piping. As subsequently noted, specific inspection procedures are necessary for the identification of iron corrosion.

Increasing failure rates coincided with the tremendous increase in the use of road deicing salts in North America, most immediately evident on automobiles beginning with the 1955 model year. The effects were first evident in areas where deicing salt use was common, where the natural salt content of the soil was high, or where the local soil had natural corrosive and mechanical characteristics conducive to early failures. Winnipeg falls into the later classification, and the poor performance of cast iron in Winnipeg was well documented in the 1950s [*3*].

Asbestos cement was recognized as an alternative in the 1950s, but mechanical considerations resulted in rather limited use and it is subject to destructive leaching in some soils and waters.

Ductile iron was inserted into this situation in the 1960s and was widely used as a replacement for cast iron on the understanding that its corrosion resistance was "equal or superior to grey cast iron" [*4*]. Unexpectedly, early failures were first identified in the Metropolitan Toronto area in the 1970s, apparently due to the acceleration effects of stray d-c currents produced by the area transit systems. Area pipeline people had been active in combatting stray d-c effects for some years and were then joined by the waterworks people—only recently achieving appreciable mitigation. During this period there was considerable debate concerning the relative performance of cast and ductile iron. Currently, many municipalities have instituted extensive programs for the identification of high-risk piping and mitigation by a combination of cathodic protection supplemented by bonding where stray dc is a contributing factor. Most new transit systems use insulated rail systems which greatly alleviate the stray current situation.

Although the hydrocarbon-transportation industry quickly introduced cathodically protected coated steel pipe beginning in the 1950s because of its improved pressure rating and relative economy of installation, only limited installations were made by waterworks people. In general, these installations were of limited success because of the failure to maintain the electrical isolation necessary for effective cathodic protection.

Plastic piping took over an appreciable percentage of the market in the 1970s in spite of the insufficiency of long-term service data. Isolated instances of early failures have begun to appear and a judgement on suitability cannot yet be made. Reinforced concrete pipe has been used for high-pressure transmission systems, and failures have been experienced in high-salinity soils. In view of the disastrous performance of reinforced concrete in highway and parking structures, the performance of reinforced concrete in deicing salt-contaminated soil must be considered suspect.

Corrosion Morphology—Ferrous Materials

The corrosion of mild steel produces no particularly significant behavior other than the usual lowering of corrosion rate with time as the corrosion products introduce additional resistance in the corrosion cell electrical circuit. Cast iron has been characterized by the significant pressure-retaining ability of the corrosion product, with perforated pipe retaining appreciable pressure capacity [*4*]. This characteristic has also been attributed to ductile iron by some sources [*5*].

The relationship of the cathodic (noncorroding) graphite to the anodic (corroding) iron in cast and ductile iron pipe has long been of interest, and the size and shape of the graphite particles in relation to corrosion resistance have been examined—without firm conclusions being reached.

An extended series of physical inspections and metallurgical tests of Metro Toronto gas mains examined this aspect [*2*]. The in-the-ditch inspections and laboratory examination of pipe samples confirmed that the cast iron corrosion products were hard and dense—often resembling the natural pipe surface and requiring chipping or sandblasting for identification. Our examinations of ductile iron pipe have revealed similar characteristics.

Older cast iron pipe is typified by considerable variation in graphite flake size, covering the complete range of ASTM size classification (Fig. 1) [ASTM Method for Evaluating the Microstructure of Graphite in Iron Castings (A 247-67)]. Reflecting improved technology and individual foundry practice, newer centrifugally cast pipe tends to have smaller and more uniform graphite flakes (Fig. 2). Ductile iron appears to be produced with more uniform procedures, producing uniform graphite nodules (Fig. 3).

Metallurgical tests tend to confirm that the corrosion of cast iron, a form of "dealloying corrosion," is nucleated by the graphite-iron galvanic cell and suggested that the graphite/corrosion product deposits pressure retaining ability is influenced by the characteristics of the matrix established by the graphite flakes [*2*]. There was also a suggestion that the deposit formed becomes increasingly dense as soil resistivity increased, perhaps due to the reduced ability of the iron ion to migrate away from the corrosion site. Neither of these effects were firmly established and are not covered in the published literature.

Where cast and ductile iron corrosion is accelerated by stray d-c currents, it would appear that the corrosion products are transported away from the corrosion site, and the classical in-place graphitic corrosion product is not evident to the same degree as with normal corrosion.

Ductile iron has been reported to have better corrosion resistance than cast iron, but the exposures were generally conducted over relatively short periods in very low (<500 ohm-cm) resistivity soil [*6*]. A review conducted by Canada's National Research Council concluded that the corrosion rate of all the ferrous materials by soils is essentially equal [*7*]. The high early failure rates for ductile iron can then be explained by the lower thickness for the same pressure rating as shown in Fig. 4. Assuming the normal exponential reduction in penetration rate, if cast iron perforates in 50 years, the equivalent pressure rating ductile iron would perforate in 18 years. The even thinner schedule 40 mild steel would perforate in 15 years.

Mitigative Action

To date, mitigative action for ductile iron has consisted mainly of logging leaks and installing sacrificial cathodic protection anodes at each leak. A preventive program based on historical leak data can be established and anodes installed on a planned basis in augered holes using cleaning and attachment techniques which permit the work to be done in a small hole, working from grade. Such programs have been described at many ASTM, AWWA, and NACE (National Association of Corrosion Engineers) meetings and a number of proprietary approaches have been developed.

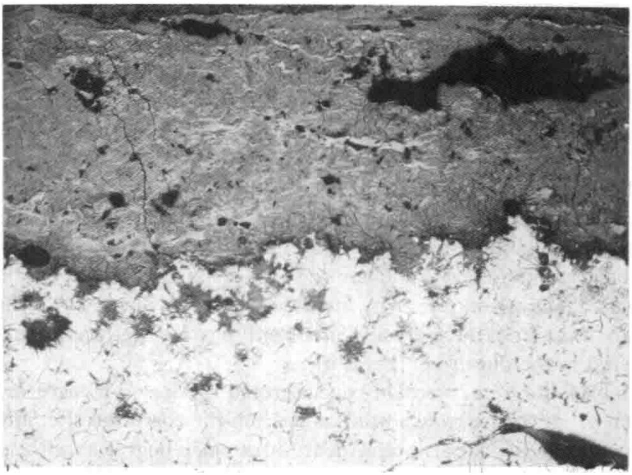
At repair costs which may exceed $2,000 Canadian/leak, there is considerable economic advantage in the early initiation of preventive programs involving a combination of soil mapping, pipe size-age plotting, and the planned installation of sacrificial anodes based on risk of a leak.

Soil Characteristics

A large number of variables has been given consideration in AWWA Standard C 105-72 (Table 1), proposed by the Cast (Ductile) Iron Pipe Research Association (CIPRA) and widely used by waterworks departments in selecting pipe materials and protective measures. Each of these parameters is reviewed with respect to its reliability and relevance as a corrosion indicator.

Resistivity

Resistivity, the reciprocal of conductivity, indicates the ability of an environment to carry corrosion currents. Most pipe corrosion cells tend to be local, and the resistance of the pipe is very much lower than the resistance of the soil path. Resistivity is a function of the soil moisture and the concentration of current-carrying soluble ions. Measured in ohm-cms, resistivity can



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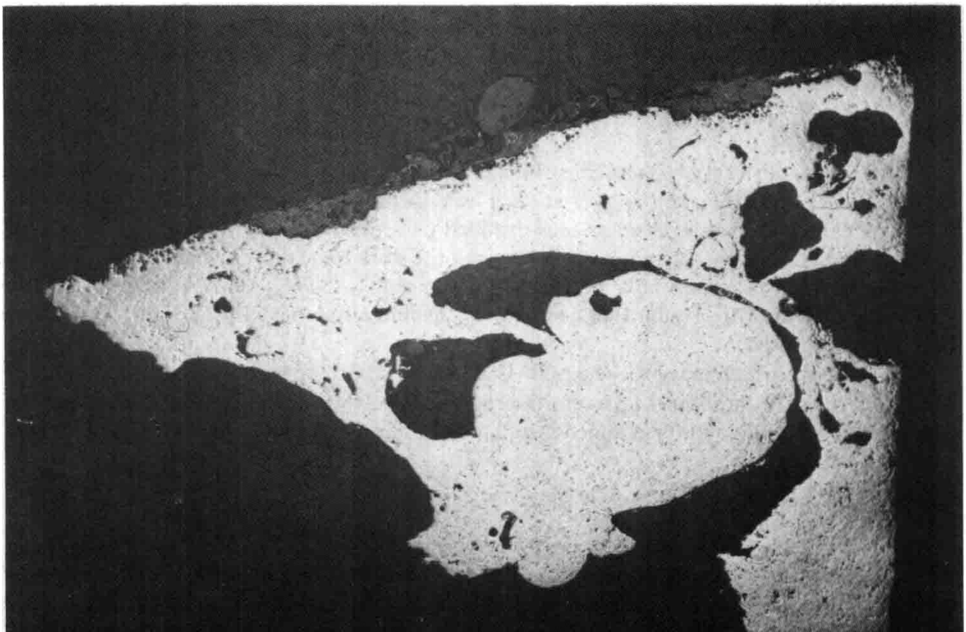

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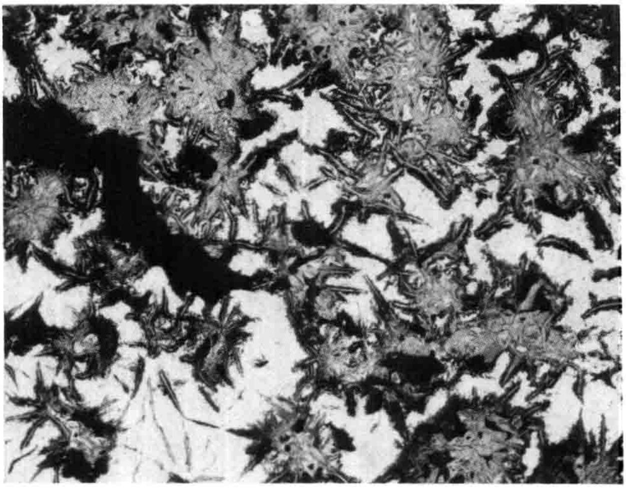
FIG. 1—*Fifty-one-year-old CI pipe—resistivity >10 000 ohm-cm—showing casting defects and corrosion nucleation around fine graphite flakes.*



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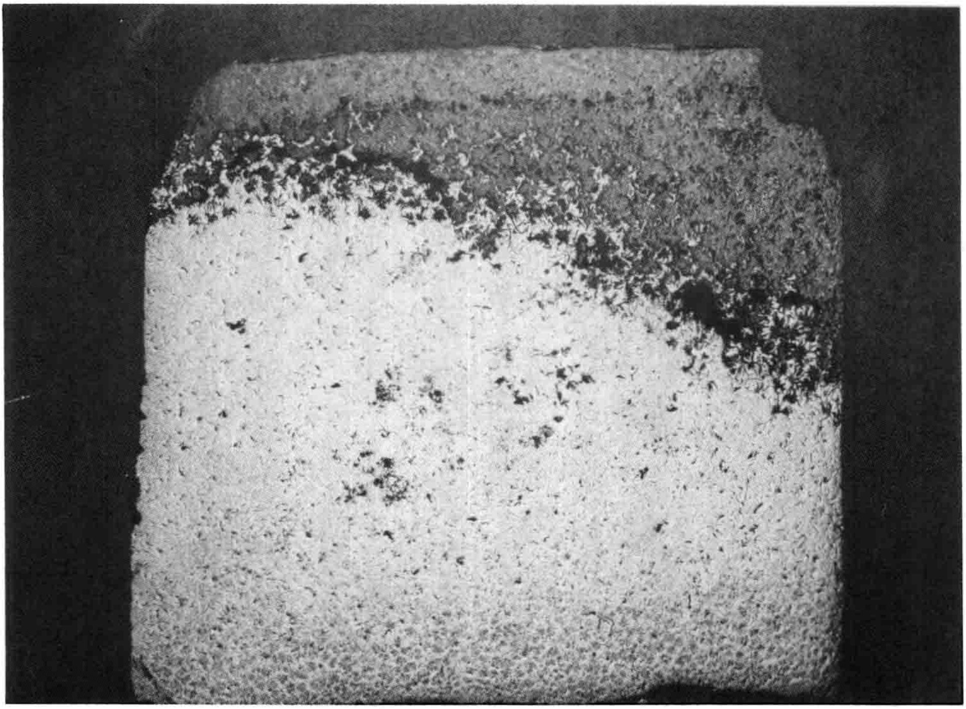

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FIG. 2—*Fifty-five-year-old cast iron pipe—resistivity 500 ohm-cm—showing corrosion nucleation around coarse graphite flakes.*

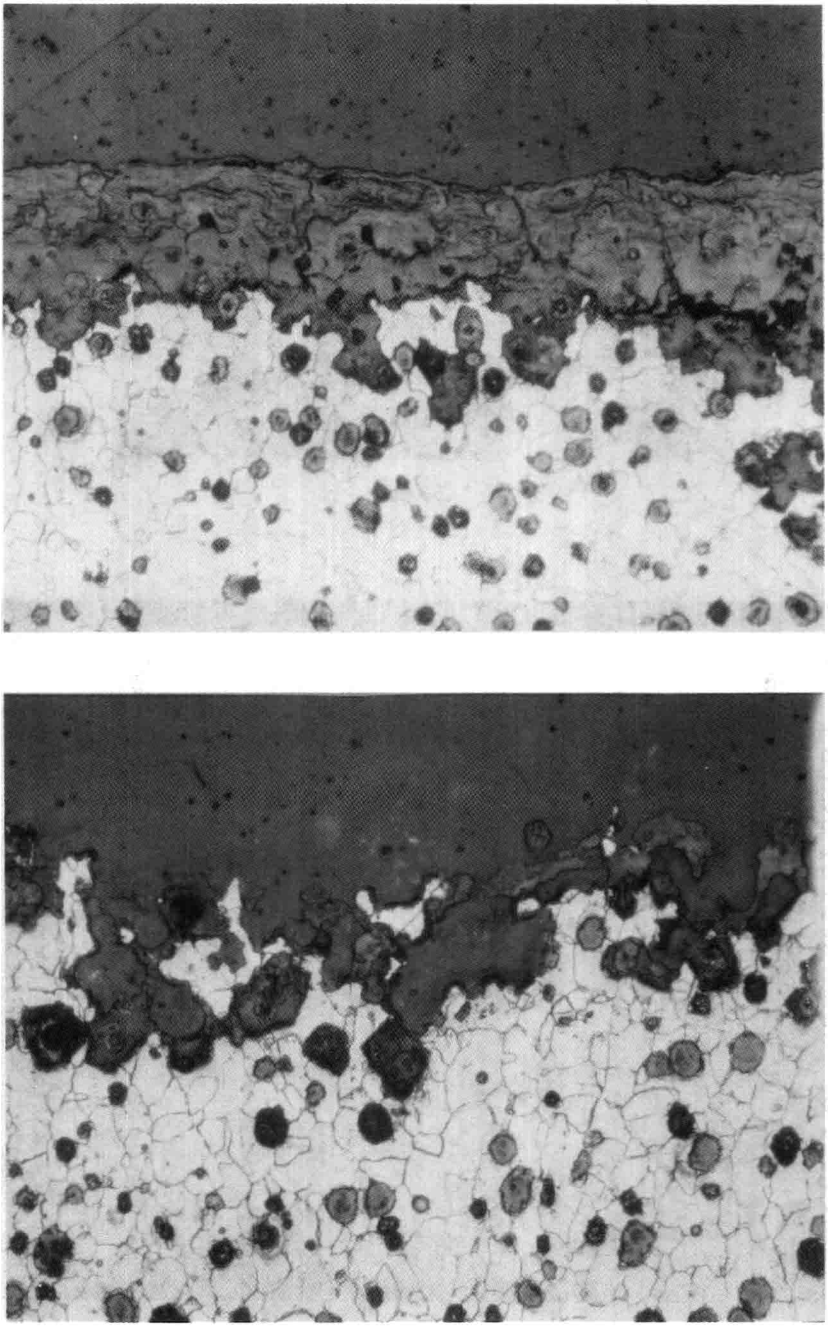

FIG. 3—*Five-year-old ductile iron pipe—230 ohm-cm soil showing corrosion nucleation around graphite nodules (X250) of ductile iron.*

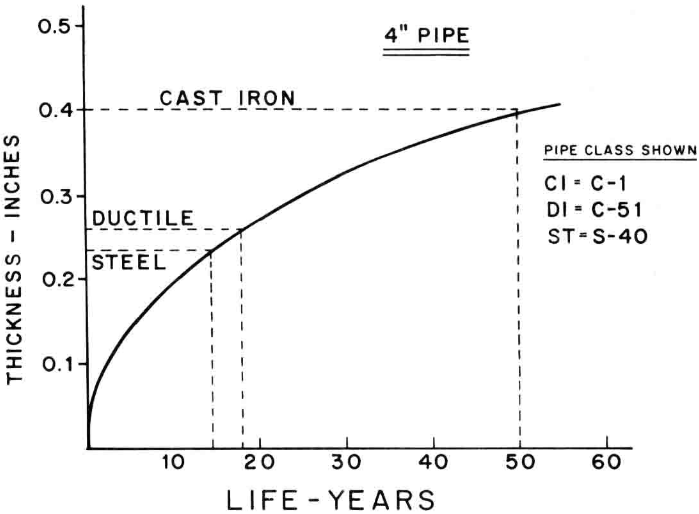

FIG. 4—*Typical exponential corrosion rate relationship for ferrous pipe* [1].

vary from 30 ohm-cm in seawater to in excess of 100 000 ohm-cm in dry sand or gravel. The AWWA formula considers less than 700 ohm-cm to be severely corrosive, while the steel pipeline industry considers anything less than 1000 ohm-cm to be "very severely corrosive" (Table 2) [*8*]. This difference may reflect the tendency for pitting rates to be higher at the defects in coated pipe than on bare pipe as a result of the decreased anode/cathode area ratio. Using the AWWA formula, if the pipe is to be wet, the rating points are the same. The overwhelming majority of field studies show resistivity to be the major controlling parameter except for areas with severe microbiological activity [*9*].

Resistivity may be measured at grade, but, as pointed out in ASTM Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method (G 57-78), contamination effects may be missed and the most relevant resistivity measurement is obtained from a sample taken from the pipe ditch (Fig. 5). Where a volume of at-grade and in-the-ditch data has accumulated, at-grade measurements from undeveloped areas can be adjusted to reflect the effect of future contamination. Our experience has shown that single-probe measurements are totally unreliable. Only the Wenner four-pin method can be recommended. Statistical analytical techniques best display the significance of the data obtained [*8*]. In deicing salt areas, chloride contamination appears to be the main factor in increased soil corrosivity with levels in excess of 0.01% considered indicative of accelerated corrosion. As well as reducing resistivity, the chloride ion tends to break down otherwise protective surface deposits and can result in the cracking of stressed stainless steel hardware such as leak clamps.

pH

Acidity, indicated by the pH value, is given considerable weight in the CIPRA formula, but only when lower than 4 or higher than 8.5. In the pH range of 4 to 8.5, iron can be immune (not corroding), passive (corroding very slowly), or corroding actively, depending on its potential, as shown by a simplified Pourbaix diagram (Fig. 6). Due to the leaching effect of rainfall and the presence of acid rain, most eastern soils tend to be somewhat acidic, but rarely with a pH lower