

Summary

The keynote speaker was John H. Fitzgerald, III, Vice President of PSG Corrosion Engineering. The title of his paper was "The Future as a Reflection of the Past." Scientists tell us that scientific knowledge doubles every ten years. Taking as his theme the fact that continued growth in scientific knowledge is based on the foundation laid by others, Fitzgerald traced the growth of corrosion control from the early 20th century to the present. He noted that around the turn of the century nearly all underground corrosion was attributed to stray current "electrolysis" from street railways and subways. In 1910, the National Bureau of Standards began a study of this "electrolysis" and by 1920 concluded that soil corrosion was equally as serious as stray current corrosion. So, in 1922 the study was expanded to cover soil corrosion. The parameters responsible for soil corrosion were evaluated through long-term burial tests, and the report was published in 1945.

Fitzgerald went on to discuss engineers and scientists who studied the effects of different soil parameters such as resistivity, acidity, bacterial action, and moisture. He outlined the contribution each researcher made to the understanding of underground corrosion and showed how their work became the building blocks of today's instrumentation, procedures, and technology.

"Soil corrosion is too complex to permit correlation with any one parameter," says the 1945 NBS report. He said that we know today how true this is, and through the use of statistics and other methods of analysis we attempt to establish the effects of a given soil on underground facilities. "But let us remember," he said, that our success today has been made possible by those who have contributed to it over the last 75 years."

Looking to the future, he pointed out the need for further understanding of the interaction of various soil parameters to enable the corrosion engineer to make more accurate predictions of their effect on pipelines, tanks, and the like. "Let us study the work done in the past, reflect on it, and build on it as we go forward into the future," he said.

David Palmer, president of Corrosion Control Engineering, Ltd., presented the second paper, entitled "Environmental Characteristics Controlling the Soil Corrosion of Ferrous Piping." He examined six characteristics of soils controlling the external corrosion of ferrous piping materials, with particular reference to the AWWA rating formula. Under the heading Material Performance, he reported that cast iron (pit-cast and centrifugally cast) has commonly given service life in the 100-year range. He said that 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," he said.

"In the 1960s," he added, "ductile iron was widely used as a replacement for cast iron based on the understanding that its corrosion resistance property was equal or superior to gray cast iron. In the 1950s, steel-coated pipe protected by cathodic protection was introduced for its improved pressure rating and relative economy of installation."

In the section entitled Corrosion Morphology—Ferrous Materials, he mentioned that 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. "On the other hand," he added, "the relationship of the cathodic graphite to the anodic 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 has been examined with-

out firm conclusions reached. Metallurgical tests tend to confirm that the corrosion of cast iron is nucleated by graphite iron galvanic cells and suggest that the graphite/corrosion product deposit's pressure-retaining ability is influenced by the characteristics of the matrix established by the graphite flakes."

A review conducted by Canada's National Research Council concluded that the corrosion rate of all ferrous materials by soils is essentially equal.

In the section entitled Mitigative Action, he stated that to date it consisted mainly of logging clamped leaks and installing sacrificial cathodic protection anodes at each leak.

As for soil characteristics, he reviewed several parameters with respect to their reliability and relevance as corrosion indicators. "Resistivity," he said, "is a function of soil moisture and concentration of current-carrying soluble ions." He stated that the overwhelming majority of field studies show resistivity to be the controlling parameter except for areas with severe micro-biological activity.

In the section entitled pH, he mentioned that this criteria may be useful only in identifying unusual soil conditions.

In the section entitled Redox Potential, he said, "The redox potential parameter attempts to distinguish between aerobic and anaerobic soils," "Kuhlman and others have attempted without success to correlate redox potential with corrosion rate."

In the section entitled "Sulfides," he stated that sulfate levels are of significance where concrete structures are considered.

In the Discussion section he explained the AWWA formula point system. He suggested to limit the parameters to be considered to two, leading to a requirement for protection when a resistivity is less than 1400 ohm-cm.

He concluded that resistivity mapping combined with pipe type/age plotting appears to be the most reliable approach to planning mitigative programs.

Paul A. Burda presented a paper entitled "Differential Aeration Effect on Corrosion of Copper Concentric Neutral Wires in the Soil." Field data showed that extensive localized corrosion cells on concentric neutral copper wires were associated with many failures. Differential aeration is considered by some investigators to be the most probable mechanism for this corrosion deterioration. Burda identified other factors affecting this corrosion phenomena: pH at the metal interfaces, the environment, the ohmic resistance, and the anodic reaction.

He reported that the results of laboratory experiments showed that the differential aeration effect increased the corrosion of copper in soil by 20 times. It was also found that chlorides in soils doubled the rate of copper corrosion. "When pH is between 6 and 8," he stated, "the differential aeration mechanism can control the corrosion of copper." The maximum rate of corrosion of concentric neutral copper wires in the soil was found when the anode to cathode ratio was 1 : 1. He also stated that anodic polarization, which may occur at high corrosion rates, can be neglected in ordinary cases.

Goran Camitz and Tor-Gunnar Vinka presented a paper entitled "Corrosion of Steel and Metal-Coated Steel in Swedish Soils—Effects of Soils Parameters." The paper presented the results of a long-term study being conducted by the Swedish Corrosion Institute. Carbon steel, zinc-coated steel, and aluminum-zinc alloy (trade name Galvalume) specimens in flat bar and plate forms were tested. Since groundwater was only 1 m from the surface, two specimens were used, one placed at about 0.7 m depth, the second at about 1.7 m. The soils tested were clay, muddy clay, silty clay, peat, and sand.

Detailed site locations were reported with several soil parameters measured for each site. Also, the detailed weight loss method was described; the results were presented in graph and table forms.

The study concluded the following:

1. The corrosion rate of carbon steel is higher above the groundwater table; as for zinc-coated steel and aluminum zinc alloy, no obvious effect was observed.

2. There is a higher corrosion rate of carbon steel panels placed in homogeneous sand when compared with native soil. Zinc-coated panels were lower in corrosion rate in sand. Aluminum zinc alloy panels reported a similar tendency as zinc, with a less drastic rate of change as in the case of zinc.
3. The pitting rate of carbon steel panels is considerably high in sand above the groundwater table.
4. In general, the corrosion rate is high in soils with low pH for all tested specimens.
5. Muddy clay and peat have the highest corrosivity rate for all three materials, and sand has the comparatively lowest rate.
6. The corrosion rate is the same in both sample shapes, although the plates have 15 times larger exposed area to the flat bars.
7. The corrosion rates of carbon steel are relatively constant with time.

Robert C. Rabeler presented a paper entitled "Soil Corrosion Evaluation for Screw Anchors." The paper described an evaluation performed over a seven-year period to evaluate corrosion of guy anchors for a transmission power line. Galvanized screw anchors were used. Instantaneous corrosion rates were evaluated using polarization testing techniques, and actual thickness and weight loss measurements were performed to verify the results.

He pointed out that both the linear polarization and polarization break techniques can be used to calculate corrosion current. Faraday's law must then be used to convert from corrosion current to corrosion rate.

The paper described in detail and step-by-step each decision and the reason for it. While the test anchors were in the ground, polarization tests were performed; both linear polarization and polarization break techniques were used. After the removal of the anchors, weight loss and corrosion rates were calculated; pit depth was also measured.

In the Discussion section, Rabeler reported that the galvanized steel bolts indicated weight losses ranging from 0.1 to 0.2% of the original weight. He also indicated loss in total zinc thickness of approximately 0.5 to 2.0 mils after 4.3 years. This translates to an annual average corrosion rate from 0.06 to 0.23 mils per year.

Polarization test measurements accurately predicted the actual measured corrosion rates. The polarization break technique appeared to most accurately reflect actual weight loss measurements. The study did not show a clear trend in corrosion rate with depth. In conclusion, Rabeler confirmed that polarization tests can be performed to accurately predict corrosion rates of buried metallic structures.

Edward Escalante presented a paper entitled "Concepts of Underground Corrosion." He defined underground corrosion as the deterioration of metals, or other materials, brought about by the chemical, mechanical, and biological action of the soil environment.

In the section Basic Concepts, Escalante stated that underground corrosion is electrochemical in character; thus, the corrosion process can be examined by electrical means. He said the process is very similar to the electrochemical action that takes place in an ordinary dry cell. In his explanation he mentioned that the anode goes into solution in the electrolyte; this dissolution is referred to as an oxidation reaction. On the other hand, reduction reactions occur at the cathode, leading reduced ions such as hydrogen to adhere to the cathode surface and stop further reaction. The driving force for any galvanic cell is the potential difference between the anode and the cathode. The difference in potential developed between two metals and their relative chemical performance can be judged by examining a galvanic series. Differences in grain orientation can cause some grains to act as anodes while others act as cathodes with excellent electrical continuity existing in the bulk material. Inhomogeneities in the electrolyte can also cause potential difference on a metal surface.

In the section Corrosion in Soil, Escalante gave the Department of Agriculture definition of soil as the loose surface material on the earth consisting of disintegrated rock with an admixture

of organic material on which plants grow. The corrosion behavior of structural steel in soil can be divided into two categories, corrosion in disturbed soil and corrosion in undisturbed soil.

In the section Corrosion in Disturbed Soil, Escalante identified some of the factors the National Bureau of Standards (NBS) has evaluated over a period of years from the seven underground corrosion test sites in the United States:

1. *Soil texture*, which is determined by the proportions of sand, silt, and clay that make up a soil. It has an important influence on the diffusivity of soluble salts and gases.
2. *Internal drainage* is the property that describes the water retention of a soil.
3. *Soil resistivity* is a measure of how easily a soil will allow an electric current to flow through it.
4. *Temperature of soil*; it does not have as large an effect on underground corrosion as one might expect.
5. *Soil pH* is the acidity or alkalinity of the soil media. It has little effect on corrosion of steel.
6. *Redox potential or oxidation*—reduction potential is the potential of a platinum electrode versus a reference half-cell converted to the hydrogen scale. It is an indication of the proportions of oxidized and reduced species in a specific soil.

In the Summary section, Escalante concluded that corrosion in disturbed soil is a function of the soil environment, but soil pH and redox potential are poor indicators of a corrosive soil. A soil with a resistivity below 500 ohm-cm is corrosive. Above 2000 ohm-cm, the relation of soil resistivity to soil corrosivity is less reliable.

He noted that the corrosion of steel piles in undisturbed soil is independent of the soil environment. Even with low soil resistivities, the corrosion observed is very low. Coating the cathodic area of the pile in the disturbed soil zone above the water line or in the concrete cap will further reduce corrosion effects.

Richard A. Corbett and Charles F. Jenkins presented a paper entitled "Soil Characteristics as Criteria for Cathodic Protection of a Nuclear Fuel Production Facility." They used leak frequency curves from other nearby plant sites, extensive soil resistivity surveys, and geochemical analyses to evaluate the onsite soil characteristics for corrosion susceptibility.

The paper recounted the steps taken to investigate soil corrosivity and to determine the extent of the necessary corrosion control measures.

The Defense Waste Processing Facility is designated to receive radioactive wastes from the Savannah River Plant nuclear fuel production in a liquid slurry form and encapsulate it into a permanent solid glass form. The wastes from the chemical separations process and tank form storage areas will be transferred through underground piping systems up to five miles. Because of the radioactive nature of the slurry, special care utilizing conservative design and installation approaches are applied throughout. Public safety demands assurance that no failures occur during the reasonable design life of the entire system.

The paper stated that the soil represents the last controllable means of protection against contamination of the water table and nearest aquifer. Low permeability, impervious clay provides the slowdown of percolation, which is desired. This is due to the characteristics of clay, namely absorption of water, swell, and ion exchange. There is a negative effect in the tendency of wet clay to hold moisture in the vicinity of buried lines. If the soil is high in soluble salts or if it has high total acidity and is alternately wet and dry, it may be especially corrosive.

The result of the leak frequency curve for the site under investigation is classical in nature, he noted, and follows general experience with underground corrosion. This means that once leaks start, an increase in their rate of development can be anticipated.

Another interesting factor mentioned was that disturbance of soil, disturbance of compaction, and use of heavy equipment all contribute to failures in cast iron piping and can sometimes be related to later corrosion occurrences in an area.

The paper stated that the most commonly agreed-upon criteria to rank the degree of corrosiv-

ity among soils are resistivity and total acidity. Large variations in soil resistance provide for a possibility of galvanic couples.

Long line corrosion usually occurs when the pipe traverses soils of different composition (for example, one section of the pipe becomes anodic with respect to another).

The paper points out that cathodic protection was recommended for the Defense Waste Processing Facility project based on a conservative approach, including:

1. Heterogeneous soil resistivities that could lead to galvanic corrosion.
2. Soil chemistry leading to a corrosive tendency.
3. A leak frequency history in adjacent areas.

The cathodic protection system was an impressed current of closely distributed anodes to limit the amount of current discharge per anode to reduce voltage gradients around the anodes, leading to a minimum of detrimental effects of stray currents occurring on electrically discontinuous structures.

James B. Bushman and Thomas E. Mehalick presented a paper entitled "Statistical Analysis of Soil Characteristics to Predict Mean Time to Corrosion Failure of Underground Metallic Structures."

The paper started by identifying Ohm's law as the law that corrosion rate of buried or submerged metallic structures follows. Corrosion current is directly proportional to the voltage of the corrosion cell and inversely proportional to the resistance of the corrosion cell.

The authors mentioned that for a number of years corrosion engineers have been using structure-to-electrolyte and other electrical potential measurement techniques to analyze corrosion patterns on underground pipelines. These did not help determine the rate of time to future failure.

The paper enumerated research work using statistical analysis starting with Gordon Scott, who determined that soil resistivity was "normally" distributed if the logarithm of the resistivity was used in the analysis. This was followed by the Husock and Wagner evaluation, the probability of corrosion leaks versus the logarithm of soil resistivity. This, in turn, was followed by Warren Rogers, who developed a computer model which could predict the mean time to corrosion failure (MTCF) for each site. The paper identified some eleven soil characteristics that impact the corrosion rate of buried metallic structures and eight structure factors.

The authors used multivariate and nonlinear regression analysis to develop a mathematical model for predicting the MTCF, which is the average age at which each location will leak due to corrosion. When the model was tested in a pipeline study, it resulted in a coefficient of determination value in excess of 0.95, which is considered to be extremely high. The authors also showed by their newly developed model the inability of using any single soil characteristic to predict MTCF.

K. P. Fisher and O. R. Bryhn presented a paper entitled "Corrosion and Corrosion Evaluation of Superficial Sediments on the Norwegian Continental Shelf."

The purpose of the paper was to report the methodology used in evaluating the corrosivity of the Norwegian soil below sea water to a depth of 500 m. They said that geotechnical properties of the soil can be considered reasonable data to determine the corrosivity of the soil. For more accurate information and corrosion rates, detailed electrochemical studies are necessary. The authors stated that "the marine sediments are mainly anaerobic and the activity of the sulphate reducing bacteria has been considered to be the main cause for free corrosion." They followed King's scheme for corrosion prediction, which is based on sediment type, organic content, water depth, sea water content of nitrogen and phosphorous, and temperature. They found that the main part of the Norwegian sector of the North Sea is low in corrosivity with the exception of the southern coastal area of Norway, where sulfate-reducing bacteria can be expected.

The authors described in detail the method of sampling soil, the differences which can be

encountered between laboratory versus in situ for exposure of metal samples, and several other factors important to collect reliable data. The factors they considered in their study were:

1. Corrosion caused by sulfate-reducing bacteria.
2. The influence of precipitated ferrous sulfides on the cathodic and anodic reactions.
3. Formulation of protective or nonprotective ferrous sulfides on the cathode.
4. Formation of galvanic cells due to the presence of ferrous sulfides.

The reported results were as follows:

1. No simple relationship between resistivity and the corrosion rate was found.
2. Steel surfaces prepared by grinding showed lower corrosion rates when compared with gritblasted surfaces.
3. The corrosion rate obtained by the galvanostatic polarization method was found to be two to three times higher than the one obtained by weight loss.
4. The laboratory evaluation produces much lower corrosion rates when compared to the in situ tests in cases of high activity of sulfides and/or hydrogen sulfide (H_2S).
5. The average value of current demand for cathodic protection in a marine sediment was found to be 17 mA/m^2 .
6. A general trend was found of decreasing activity of sulfate-reducing bacteria with increasing water depth and distance from land.
7. The results of the in situ corrosion exposures performed have generally given very low corrosion rates.
8. The corrosion rate of steel in the Norwegian Continental Shelf can be expected to be very low in most areas. In some areas, it could be very corrosive due to organic material, which can be distinguished by a strong smell of amines.

Thomas V. Edgar presented a paper entitled "In-Service Corrosion of Galvanized Culvert Pipe." The paper showed clearly that minimum resistivity and soil pH, the two most commonly used soil parameters for culvert pipe selection, may be inappropriate values to use in practice.

The author stated that "the most common reason for a culvert pipe to fail is due to a gradual weakening caused by corrosion."

Minimum resistivity of the soil and the pH of the soil and water are the two parameters used by many states to estimate the years to perforation of 16-gauge steel culvert. These and other parameters were studied both in situ and in the laboratory for twelve 35 to 40-year-old culvert pipes from four highway reconstruction sites in Wyoming to determine corrosion protection criteria.

Under general observations, Edgar reported that the corrosion was usually found in local areas on the pipe, indicating that small corrosion cells damaged the most pipe. He added that the most corroded area was found in the center of the culvert and the most anodic area in an oxygen concentration cell under a roadway. He also observed that the band joining two sections of pipe in the centerline of the road experienced the worst corrosion. The invert of the pipe, considered anodic to the crown, suffered the worst corrosion.

The author developed a mathematical relationship to predict weight loss using the field resistivity. He confirmed previous findings that pH of the soil has little or no effect on the corrosion when it is between 6.0 and 9.0. He found that the data indicate a reasonable correlation between the percent of soluble salts and minimum resistivity.

Edgar concluded by stating that "the most obvious defect in practice was the poor backfill material used." He recommended the use of a clean, coarse, cohesionless backfill material.

Gardner Haynes, Gregory Hessler, Reiner Gerdes, Kenneth Bow, and Robert Baboian presented a paper entitled "A Method for Corrosion Testing of Cable-Shielding Materials in Soils." The paper identified mechanical strength, electrical conductivity, and corrosion resistance as important criteria for cable-shielding materials. It also identified the following for

proper function: provide mechanical protection to the cable core during and after installation; prevent ingress of moisture into the cable core; and provide electrical conductivity for the life of the cable.

A previous study was conducted by NBS-REA; however, the study did not evaluate the comparative behavior of idle cable versus cable-carrying alternating current. The present study determined the corrosion behavior and the associated effects of alternating current that is present in service or in commonly used shielding materials.

The paper said that continuous 500-ft lengths of cable with different shielding materials were prepared by shielding manufacturers with damage sites at 30-ft intervals, as well as individual 2 1/2-ft lengths of cable with damage sites. The damage site pattern was intended to simulate possible construction, lightning, or rodent damage to the cable's outer jacket. The paper described in detail the installation of cables and marking for ease of retrieval. The test program called for retrieval of a control cable (static) and a section of test cable (dynamic) of each type of shielding at intervals that varied from 0.5 to 6 years. The soil was tested for pH, electrical resistivity, Ca, Mg, Na, CO₃, HCO₃, SO₄, Cl, and NO₃. The a-c current in shields was measured at the beginning and at the end of determined test time.

The specimens were rated by a panel using a rating system with a scale of 0 to 10 with 10 being no indication of corrosion and 0 being electrical discontinuity due to corrosion. Results are reported, but since the ratings were the consensus opinion of a panel, explanatory notes were required.

The intent of the paper was to record these results in the literature without bias, and, therefore, no discussion or interpretation of these results is included.

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