

CORROSION OF HIGHWAY STRUCTURES

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A research study was undertaken with the objectives of evaluating existing corrosion design procedures for corrugated metal pipe and determining if the development of new corrosion test methods for service life designs was indicated and feasible. As a result of the research, a field test method for corrugated metal pipe installations was developed to measure corrosion reaction rates. By utilizing the new test method to measure corrosion rates, it was determined that metal pipes in high-resistivity soils (ρ greater than 3000 ohm-cm) had low corrosion reaction rates. The rate of corrosion in medium-resistivity soils (ρ above 2100 ohm-cm) was high initially but decreased greatly after a few years. However, in low-resistivity soils (ρ less than 1000 ohm-cm) the corrosion reaction continued at a high rate. Also, a linear polarization test method was developed and compared with the conventional resistivity test method with satisfactory results. The study included corrosion protection of corroded steel pilings utilizing magnesium anodes. Research showed that corroded corrugated metal pipes could not be protected as easily because of the large surface area and soil resistance. The use of bituminous-coated corrugated metal pipe was found to be effective for inhibiting corrosion in most cases tested in Arizona.

•A STUDY was undertaken to define the problems of corrosion and its effects on corrugated metal pipe. The primary objective of the research was to evaluate present corrosion design methods and alternatives. In this paper corrosion is defined as the electrochemical reaction between buried metals and soils. The corrosion research study included the following topics:

1. Field corrosion test method (tests on buried metal structures by a voltage measurement method);
2. Laboratory test methods (testing of corrosive soil materials for pH and electrical resistivity and testing of corrosive soil materials by electrical polarization techniques); and
3. Corrosion protection methods (protection of buried highway structures by magnesium anodes and protection of corrugated metal pipe by bituminous coatings).

DEVELOPMENT OF A FIELD CORROSION TESTING METHOD

It was found that reactions between corrosive areas on corrugated metal pipe could be recorded by measuring voltage gradients existing along the length of the buried metal structure. The voltage gradients developed on the surface of the pipe were measured with a high-impedance voltmeter and a constant-voltage reference cell. The most widely used corrosion test cell for this purpose is the copper sulfate reference cell.

By using the reference cell, it was possible to measure voltages on corrugated metal pipe at various points to study corrosion. The reference cell has a constant internal voltage, which allows voltage changes existing on the metal surface to be measured.

When a voltage difference is measured between 2 areas on a buried metal structure, active corrosion has been detected with a relative positive and negative region. The relative positive region is anodic and the relative negative region is cathodic. When a large voltage gradient is detected, it is a direct indicator of corrosion. It produces high corrosion current and accelerated deterioration of the metal.

EQUIPMENT AND PROCEDURE FOR FIELD CORROSION VOLTAGE TEST

The test procedure for measuring corrosion on corrugated metal pipe requires only a few minutes to perform. The negative lead from a high-impedance voltmeter is attached to the metal pipe, and the positive lead is connected to the reference cell. A series of readings are taken as the reference cell is moved at approximately 1-m intervals across the road surface and along the length of the pipe (Figure 1). After the voltage data are taken along the length of the pipe, the arithmetic mean of the voltage data and the statistical variance about the mean are calculated to determine the corrosion rate. Field testing showed that a rapidly corroding pipe usually has a variance of data from 5×10^{-3} to 10×10^{-3} . It was determined that the variance was a representative measurement of corrosion activity (Figure 2).

Buried metal pipes were tested in many locations and conditions throughout Arizona using the new test. After testing a pipe, it was uncovered and the visual appearance was then compared with the voltage test data. The voltage variance test correlated well with visible corrosion on the surface. Several of the culverts exhibited extreme corrosion, and in some cases perforation of the culvert was observed. The voltage variance was highest on extremely corroded pipes and lowest on uncorroded pipes. On uncorroded pipes, the voltage change was 0 to 50 millivolts, and the variance was below 2×10^{-3} . On extremely corroded metal pipes, the voltage change was between 0 and 300 millivolts, and the variance was above 5×10^{-3} . The results indicated that there was a good correlation between predicted corrosion as determined by the voltage survey method and visual inspection of the corrosion. After the test was fully developed to accurately measure underground corrosion reactions, it provided a good comparison for the evaluation of laboratory corrosion tests.

LABORATORY TEST METHODS

Resistivity and pH Test Methods

For electrochemical corrosion to occur, the electrolyte that is in contact with the anode and cathode surface must conduct electricity. The rate of corrosion caused by an electrolyte depends on a number of factors. Two important factors affecting the corrosion rate of corrugated metal pipe are pH and resistivity. The pH is a measure of acidity or alkalinity of the electrolyte. A neutral pH is the least corrosive, while an excessive concentration of either acidity or alkalinity accelerates the rate of corrosion. Moist soil that is in contact with buried corrugated metal pipe acts as an electrolyte characterized by a particular pH and resistivity that directly affect corrosion reactions.

The resistivity (ρ) of a substance determines the amount of electrical current that passes through a given volume of material. Resistivity is a natural characteristic of a material, independent of dimensions. It is not the resistance (R) but is related by the equation, $R = \rho \times L/A$ (ohms). For example, a copper wire has a constant resistivity, but the resistance of the wire increases as it is made longer or as the cross-sectional area is made smaller.

By rewriting the equation for resistivity we have $\rho = R \times A/L$. In the equation the

Figure 1. Corrosion voltage testing equipment.

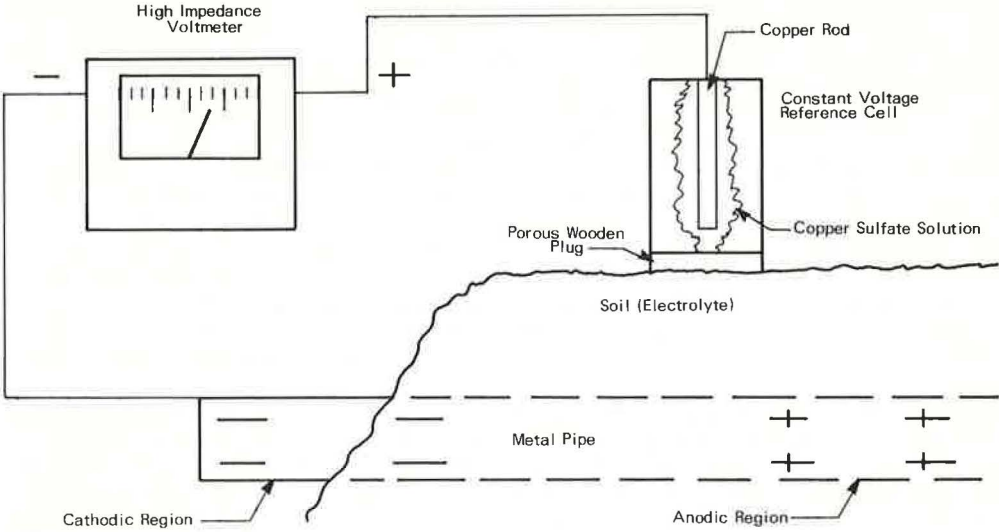
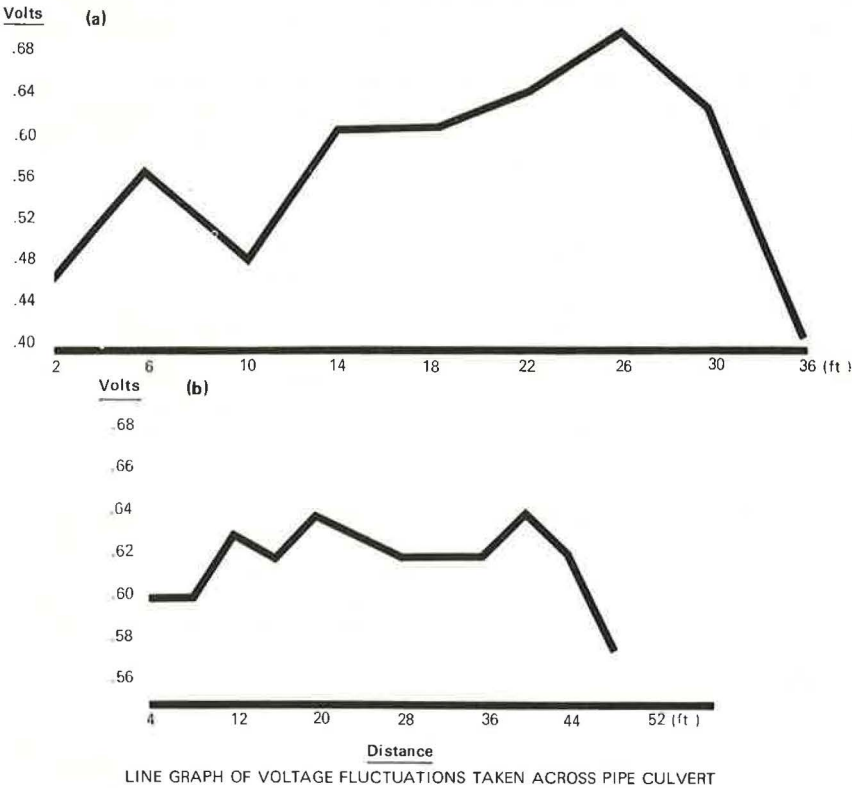


Figure 2. Corrosion test for corrugated metal pipe.



expression of area/length is derived from the testing cell dimensions. It is called the effective cell constant and has dimensions in centimeters. The effective cell constant is used as a fixed multiplication factor for a testing apparatus such as a soil box. For example, the reading (ohms) of the ac ohmmeter is multiplied by the effective cell constant of the soil box (cm) to determine the value of resistivity (ohm-cm).

As part of the corrosion study, buried corrugated metal pipes were tested in the field for corrosion by the voltage test method and soil samples were taken from the backfill material around each pipe. The soil samples were then tested for resistivity and pH in the laboratory (1). To determine whether significant relationships might exist between soil parameters and field tests, data were analyzed by graphical means and by numerical calculations on a digital computer. A rough correlation was developed between the pH-resistivity test and the voltage test method results from the field. For a wide range of resistivity values, the corrugated metal pipe corrosion data could not be correlated accurately. When the resistivity data were classified into categories of low, medium, and high values, more significant relationships were developed.

When the corrosion rate was plotted against time in the soil, an interesting relationship was found for medium- and high-resistivity soils. By analyzing the corrosion voltage test data, it was determined that nearly all the galvanized steel pipes demonstrated high reaction rates for the first few years. However, for medium- and high-resistivity soils (rho greater than 2100 ohm-cm) the rate of reaction decreased rapidly after 5 years (Figure 3).

When the corrosion data were plotted for low-resistivity soils, no definite relationship could be found. Sometimes the initial high reaction rate was found to continue, and in other instances the initial reaction rate decreased greatly. A variable such as moisture content may affect the rate of corrosion for soil of the low-resistivity classification.

It is interesting to note that the findings of the corrosion research study from the voltage test parallel the findings of Schwerdtfeger (2). Results from the research demonstrated low corrosion rates for non-saline soils with resistivities greater than 2100 ohm-cm. Similarly, Schwerdtfeger reports:

In higher resistivity soils greater than 500 ohm-cm, there appear to be no regular variations between maximum pit depth and soil resistivity. For soils with resistivities over 2000 ohm-cm, and assuming the absence of stray currents or contact with more noble metals, the extrapolated data indicate that perforation of 8 inch diameter (0.322 inch wall thickness) steel pipe in 30 years is rather unlikely. However, the data definitely showed the need for protective measures, such as coatings, cathodic protection, or both, on wrought materials exposed to soils with resistivities less than 2000 ohm-cm, and even in some soils of higher resistivity, all depending on the hazard involved should a perforation occur . . .

Concerning low-resistivity soils, the Schwerdtfeger report states, "For periods of exposure up to 5 years, the maximum pit depths are on the average deeper in soils with resistivities up to 500 ohm-cm than in soils with higher resistivities" (Figure 4). Schwerdtfeger found that "perforation of a pipe wall ranging in thickness from 0.172 inch to 0.322 inch is predicted in almost all soils having resistivities less than 1000 ohm-cm." In Arizona perforated corrugated metal pipes were found in soils with resistivities of 20 to 1400 ohm-cm.

The voltage survey test showed that corrosion rates were higher in medium- and high-resistivity soils immediately after burial of corrugated metal pipes than 5 years later. Schwerdtfeger states, "For periods longer than 5 years, the rate of maximum penetration decreases as the soil resistivity increases." From these findings a similarity in both studies can be seen, even though different testing methods were incorporated. Results from this research study indicated that when a metal pipe is first buried there is a high rate of corrosion in most moist soils. In high-resistivity soils, the rate decreases after a few years, whereas low-resistivity soils continue corroding at a high rate.

Figure 3. Corrosion reaction of corrugated metal pipe in non-saline soils.

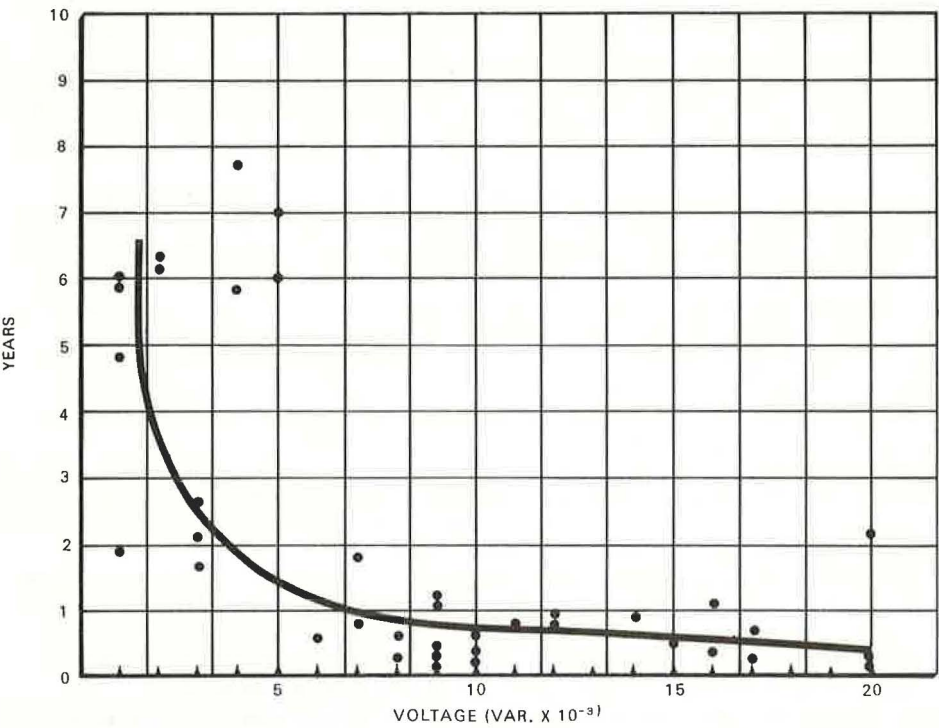
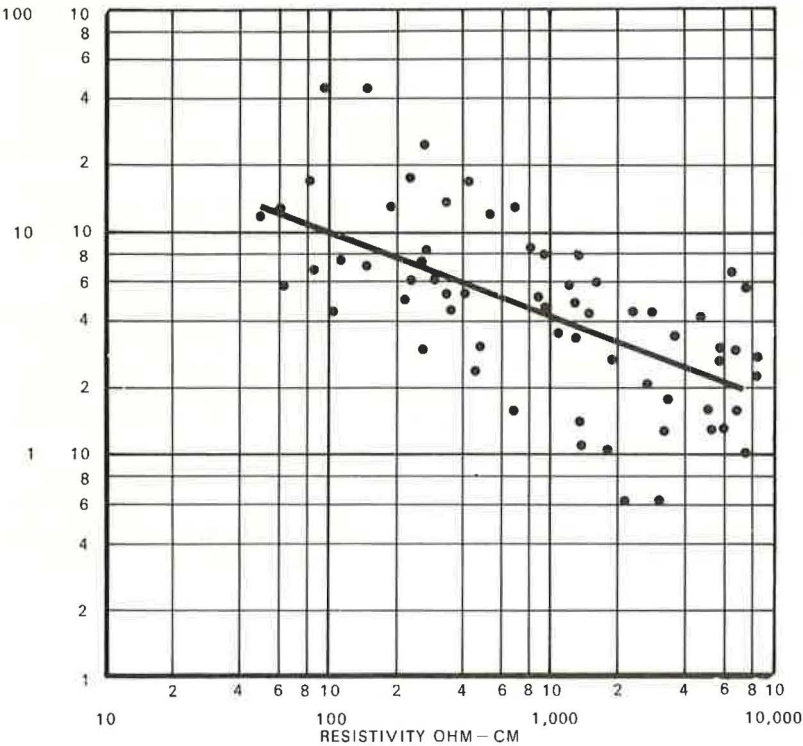


Figure 4. Rates of penetration based on maximum pit depth (National Bureau of Standards).



Polarization Test Method

Polarization is a method that tests corrosion reactions directly and has been widely used by corrosion engineers to measure instantaneous corrosion rates. The voltage of a metal surface in an electrolyte is a function of the corrosion reaction. When external energy in the form of direct current is applied to the metal in the electrolyte corrodent, a change in the corrosion rate is brought about and is reflected by a voltage change on the surface.

The metal surface becomes polarized when a voltage change occurs and reflects a corrosion behavior change. Voltage polarization is the change of voltage in either the positive or negative direction due to changing conditions of the corrosion system. The corrosion surface voltage is measured with a constant-voltage reference cell and is termed the corrosion potential. Normally the corrosion potential remains constant unless some change in the reaction occurs either externally or internally. For example, if an external direct current is applied to a rapidly corroding metal, the corrosion potential will not change greatly because the internal reaction is too intense. In the opposite case, when the corrosion rate is not rapid, the corrosion potential at the metal surface changes greatly for an applied external current.

The corrosion potential of the metal in the electrolyte can be measured by a calomel reference electrode. By using current and potential measurements, the corrosion rate can be quickly evaluated. In this manner, electrical measurements permit instantaneous testing of the actual metal in its corrosive environment.

With polarization testing methods, either the anodic or cathodic corrosion behavior of a corroding metal can be determined rapidly and accurately. As corrosion occurs on a metal surface, the current density and corrosion potential can be directly measured with polarization testing techniques. Once the value of corrosion current is calculated, the rate of corrosion of a particular reaction can be determined.

A constant-voltage reference cell is used to measure the corrosion potential in conjunction with a high-impedance voltmeter. The reference cell most widely used in the laboratory is the calomel electrode (Figure 5). The auxiliary electrodes must be platinum to remain inert and not interfere with the corrosion reaction. Also, platinum has repeatable and reproducible electrochemical properties. Two auxiliary electrodes were found to be preferable, one on each side of the test specimen to allow an even current distribution. The spacing of the electrodes was fixed and equal in relation to the metal plate (Figure 6).

In order to have the most corrosive soil conditions for the test, distilled water was added to the soil to reach saturation conditions. Approximately 100 to 200 milliliters of water was required for 400 grams of soil. Care should be taken to prevent a surplus water layer from forming above the soil level in the beaker.

After the metal sample is placed in the moist soil and the voltages have stabilized, a small positive direct current is transmitted through the auxiliary electrodes. The current supply must be well regulated, producing a constant current that will not vary under changing load conditions. When a small current is transmitted to the metal specimen, the voltage is changed to another value slightly above the corrosion potential and then remains constant. Once the value is recorded, an incremental current is added and another voltage value is reached by the system. This procedure continues until the voltage has changed about 10 millivolts above the corrosion potential. After the points have been plotted, a line is drawn on linear graph paper and the slope of the line is determined (Figure 7). By using techniques of polarization, the corrosion rate was determined from average slopes calculated from several tests. Measurements were obtained for small voltage changes with an incremental current every 30 seconds.

The equation for the corrosion current is $I = K/R$, where R is the polarization slope. The average value for the constant K is 26 millivolts. Once the value of I is found, Faraday's Law is used to determine the corrosion rate (3).

Thus:

$$\text{Rate} = 0.13 (I) (e/d)$$

Figure 5. Apparatus for polarization measurements.

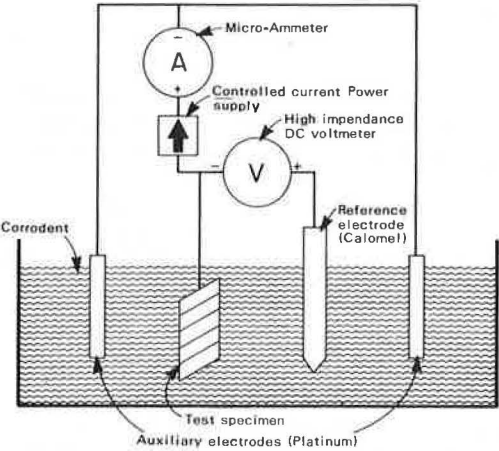


Figure 6. Fabricated polarization testing cell.

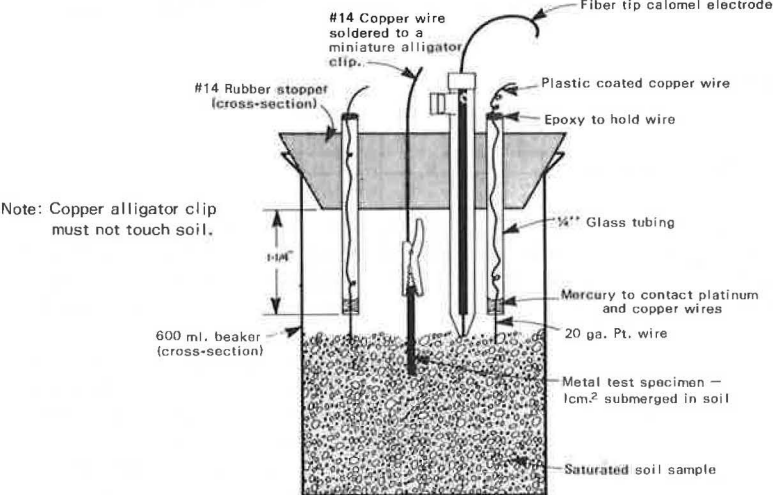
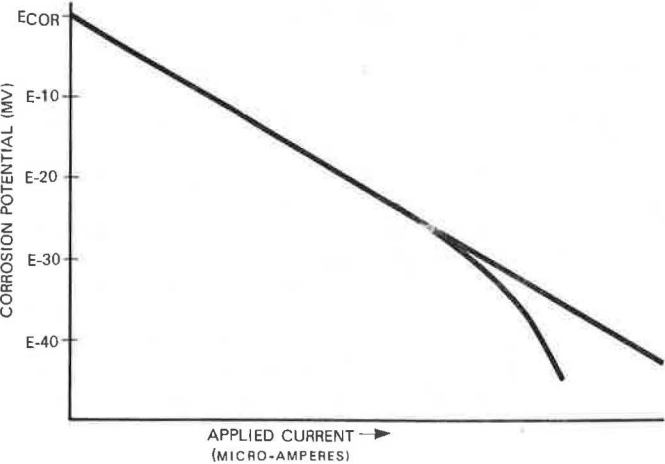


Figure 7. Linear polarization curve.



where c is the equivalent weight and d is the density.

When the thickness of the metal structure is known, the service life can be calculated based on the predicted corrosion rate (4).

After the voltage test was made to determine the corrosion of the corrugated metal pipe, a polarization test was made on the soil to see if a relationship existed between the tests. A good correlation was found between the corrosion predicted by the polarization method and actual corrosion in the field (Figure 8). A satisfactory coefficient of correlation and standard deviation were found for the tests (Figure 9). It would appear that a useful new direct test method was developed from the research study. The time required for the polarization test is approximately 15 minutes. The electrical test equipment needed is costly, but commercial test equipment is available. The complete test equipment costs approximately \$1,000 to \$2,000.

To determine the rate of corrosion for corrugated metal pipe from the polarization test results, the polarization slope is found for the sample. It was found that the corrosion rate of corrugated metal pipe was less than the predicted value by the polarization test. Since the test was made in saturated soil, it stands to reason that the predicted lifetime would be short unless the pipe soil was always in a saturated condition. To compensate for the difference in moisture conditions of the field and laboratory conditions, the test results may need to be adjusted to meet expected field conditions based on field-testing results. However, more research is needed to develop an accurate design for service life of corrugated metal pipe predicted by the polarization test.

CORROSION PROTECTION METHOD

Cathodic Corrosion Protection by Magnesium Anodes

Because galvanic corrosion is electrochemical in nature, it seems reasonable that there should be an electrochemical method for preventing corrosion. Corrosion takes place at anodic areas where current leaves the structure. If the entire structure is made a cathode it should be free of corrosion. Through the use of an anode to change the voltage, corrosion can be prevented.

To protect underground structures, the anodes are buried a distance from the structure. For even current distribution, the anodes are separated and located so the current will flow to all parts of the structure and cause it to be totally cathodic. Copper wires are connected between the structure and the anodes to conduct current.

Under most conditions that usually occur in low-resistivity soils, protective anodes made of magnesium can be used. These anodes drive current through the resistance of the soil to protect the structure. In this manner, the anodes, moist soil, and structure form a large galvanic protection circuit that operates continuously until the anodes have completely deteriorated.

If the soil between the anode and the structure has a high resistance, the sacrificial magnesium anodes do not supply enough current to adequately protect the buried structure. In this case, an impressed current power supply must be applied to overcome the soil resistance. The anodes used with the direct current power supply system are usually inexpensive graphite.

The current required to protect a structure depends on many factors. In general, at least 22 milliamperes per square meter of surface area are required. To determine the proper current, tests should be made on the structure. Anodes in most cases can be used to provide the necessary current if properly designed.

Magnesium anodes were installed on bridge pilings, and tests were made to determine if cathodic protection could be used on highway installations and how effective the protection would be against corrosion. Corroded steel bridge pilings in northern Arizona were protected with magnesium anodes. The pilings were wired together and connected to the magnesium anodes, which were spaced about 3 m apart. The bare steel pilings were adequately protected because of the voltage difference between magnesium and iron. Adequate current output was generated a few weeks following installation,

Figure 8. Pipe corrosion reaction versus polarization test.

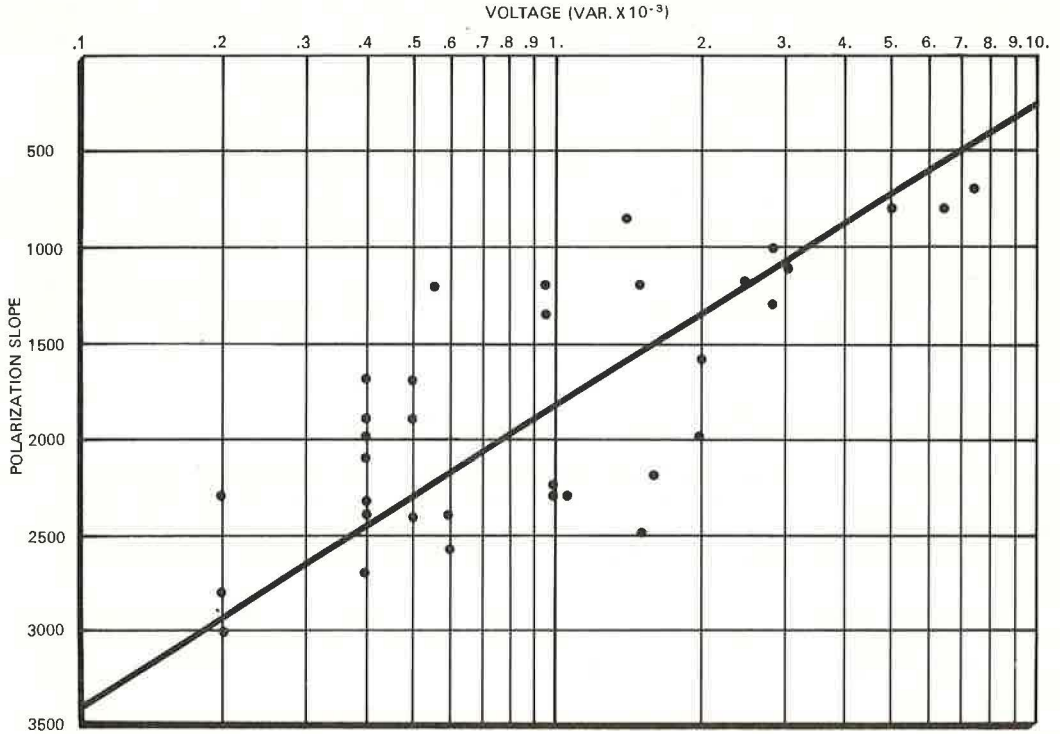
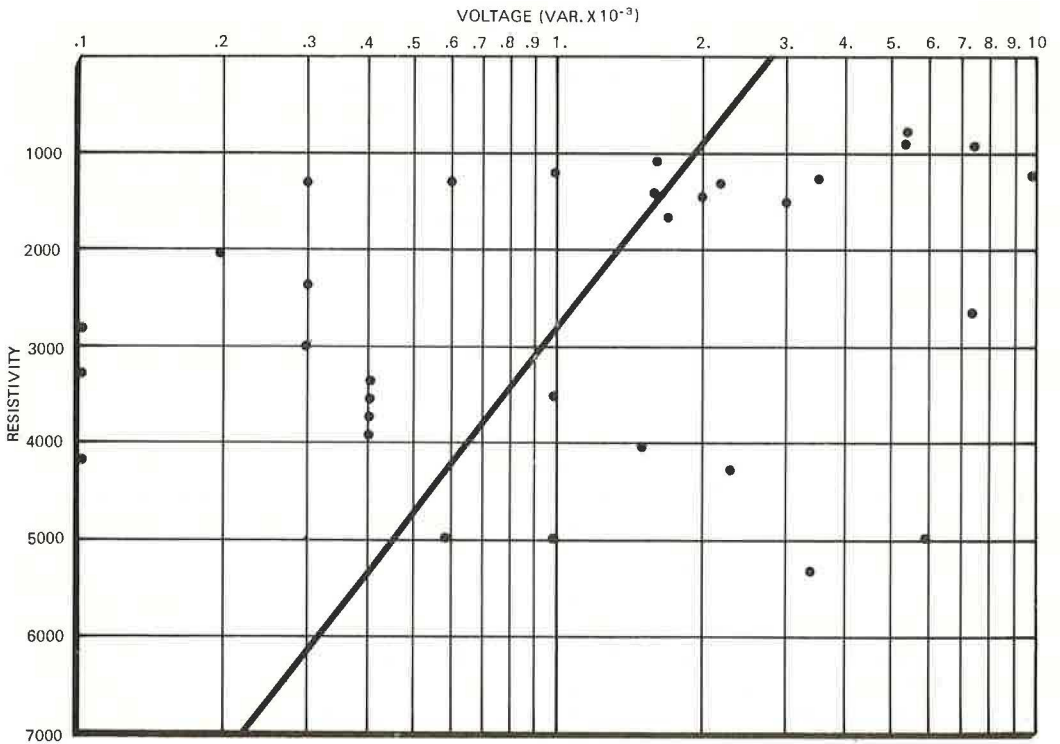


Figure 9. Corrosion reaction versus resistivity test.



and effective protection of the piling was achieved.

Cathodic protection of corroded corrugated metal pipe was also tested. Magnesium anodes were tested because in most locations power was not available near pipe culvert installations.

Test results indicated that the protection was not adequate to prevent corrosion. One possible explanation for the lack of protection of pipe culverts is that the large surface area of the pipe requires a sizable protection current to flow evenly over the entire pipe. In addition, to provide protection the anode conductivity through the soil must be sufficient to permit a large current to flow to the pipe. Even in low-resistivity soils, the current output to the galvanized pipe from the anodes was insufficient because the voltage generated by the zinc galvanizing opposes the driving voltage of the magnesium anodes. However, the use of high-output magnesium anodes may increase the driving potential enough to solve the problem. Further research is needed to develop improved methods for protection of corroded corrugated metal pipe.

Protection of Corrugated Metal Pipe by Bituminous Coatings

In saline areas of Arizona, where the soil usually has a low resistivity, corrugated metal culvert pipes are bituminous-coated to prevent corrosion. Test sites were selected in these regions for corrosion research studies to compare the effectiveness of bituminous-coated galvanized metal pipes with that of uncoated galvanized metal pipes.

The culvert metal pipes were located in a variety of soils and moisture conditions. Culvert metal pipes at these test sites have been installed for 5 to 25 years in corrosive soil conditions. The range of soil resistivity was 50 to 1300 ohm-cm, and the pH was 7.4 to 8.4.

The bituminous coatings on these pipes were visually inspected and usually were found in satisfactory condition. The asphalt coating in most cases demonstrated excellent adhesion to the metal surface, with no peeling or cracking beneath the soil. When exposed to the air, the asphalt surface coating was usually cracking and peeling from the metal surface because of weathering.

Voltage survey tests and polarization tests were performed to evaluate the corrosion activity on bituminous-coated metal pipes. These test results showed that (a) the voltage on bituminous-coated pipes was significantly lower on coated pipes in most cases and (b) the average corrosion current of coated pipes was a fraction of the current density on uncoated metal pipes.

The results of the study showed that bituminous-coated galvanized culvert pipes had a greatly reduced corrosion rate. In nearly all cases tested, bituminous coatings extended the predicted service life of corrugated metal pipe by at least 15 years.

CONCLUSIONS

As a result of the corrosion research study (5), the following new findings and testing methods were developed:

1. Corrosion behavior on buried corrugated metal pipe can be evaluated by measuring voltages along the length of the pipe and then computing the statistical variance of voltage readings. A high corrosion reaction rate has a variance of voltage data greater than 5×10^{-3} . Low reaction rates have a variance below this value, and therefore the pipe is not damaged by corrosion.
2. The corrosion voltage tests made on galvanized pipe show that most buried pipes have high reaction rates for the first few years in any soil. In medium- and high-resistivity soils (resistivity greater than 2100 ohm-cm), the rate of reaction decreased rapidly after the first few years. In low-resistivity soils (resistivity below 2100 ohm-cm), the corrosion rate usually continues at a high rate even after several years.
3. The linear polarization method was used for laboratory soil testing to directly

measure corrosion rates of metal samples in corrosive soils. The estimated corrosion rates compared well with the actual observed corrosion on buried corrugated metal pipes in the field.

4. A comparison of the polarization and resistivity testing methods was made. The polarization method had a better correlation to field corrosion than the resistivity test but is more complicated to perform.

5. In low-resistivity soils, magnesium anodes were used to inhibit corrosion on bare steel pilings. Tests were made to try to protect galvanized corrugated metal pipe with magnesium anodes. These attempts were unsuccessful because the large surface area of the corrugated metal pipes requires a large protection current.

6. The use of bituminous-coated corrugated metal pipe is effective for preventing corrosion in saline soils. In most cases where bituminous-coated galvanized pipes were tested in Arizona, the coating was very effective for prevention of corrosion. No measurable corrosion was found on bituminous-coated galvanized pipes in Arizona. In most cases, the bituminous coating extended the predicted service life of corrugated metal pipe by at least 15 years.

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