

CHAPTER 16.2

CATHODIC PROTECTION

by

A.W. Peabody

I. INTRODUCTION

Since Volume 1 of the SSPC Manual was first published, general knowledge of cathodic protection and its practical application have increased greatly. Its importance can be seen in the federal regulation that all new construction for hazardous pipelines must include the use of effective coatings and cathodic protection.

Because a comprehensive discussion of cathodic protection would be voluminous, this chapter presents only a general introductory account. Other sources provide more specific treatment^{1,2}.

II. HOW CATHODIC PROTECTION COMPLEMENTS A COATING

Coatings used on pipelines and other underground structures frequently need to protect very large areas of underground metal, especially with major cross-country pipelines. For instance, only 10 miles (16.09 km) of 48" (1219.2 mm) diameter steel pipeline has an exterior surface area of approximately 15.2 acres (6.2 hectares).

Such large areas, when coated and buried, cannot remain permanently free of all pinholes, developed defects, or outside damage. Even though the coating may, initially, be free of holes in the film, pipe movement with temperature variations, soil stresses, and damage from outside sources (such as excavation work on other projects) will ultimately expose bare metal to the corrosive effect of the surrounding environment (soil or water). The amount of metal exposed will be determined by the quality of the coating used and the severity of the hazards working to damage the coating.

Even though 99.9999% of the surface area might remain fully and effectively protected by the coating, the remaining 0.0001% could be a problem. On the 10 miles of 48" pipe mentioned earlier, this represents some 0.6635 square feet of exposed metal. Serious damage could occur on this much exposed surface if corrosive effects are not controlled. To put the 0.6635 square feet in better perspective, it represents in the order of 50 one-half-inch diameter holes in the coating for each mile of the 48" diameter pipe. A lot can happen at these locations.

Although the coating-cathodic-protection combination is used widely on pipeline exterior surfaces, this working team can also be used on the interior surfaces of pipelines carrying electrically conductive materials such as water or other conductive solutions. Although there

may be unique design considerations when planning a cathodic protection system for pipeline interiors, such a system can work very effectively.

Cathodic protection current must be able to reach all of the pipeline's exposed metal. If, for example, a coating material is not bonded to the pipe surface, it may permit water to reach the metallic pipe surface under the disbonded coating around coating holidays.

Where the disbonded coating has a high electrical resistance, cathodic protection current cannot flow through it to reach the pipe surface, and active corrosion may result.

While cathodic protection current can enter the space between the disbonded coating and pipe surface, the thin water film there may prevent the protection current from penetrating in sufficient quantity for adequate protection.

If the space between a disbonded coating and pipe surface remains dry, there will normally not be a corrosion problem. If water does enter the space, however, an electrically insulating coating acts as an "electrical shield" preventing the effective cathodic protection of the pipe at that location. Electrical potential measurements may indicate that the pipe is cathodically protected in accord with an accepted criterion at the disbonded area, whereas it may, in fact, be corroding.

The pipeline operator will normally find that a top grade coating will give the best practicable corrosion control for his metallic pipe when it is complemented by a cathodic protection system which has been properly designed, installed and maintained.

III. RELATION BETWEEN COATING CHARACTERISTICS AND CATHODIC PROTECTION

The characteristics of a coatings system determine the requirements for cathodic protection.

If a coating on a buried or submerged pipeline forms a high electrical resistance barrier between the pipe and surrounding earth or water, the electric current needed to provide cathodic protection will be less than with a coating barrier having a lower effective electrical resistance, and lower current requirements for cathodic protection mean a lower investment for the cathodic protection system.

The designer and operator of the cathodic protection system for a coated pipeline are concerned with three ma-

for coating characteristics:

- 1) Effective coating resistance;
- 2) Bond between coating and protected structure as discussed in the preceding section;
- 3) Coating stability.

Of these three, "coating stability" is perhaps the most important. A stable coating has effective resistance and bond for a long period of time.

A coating with a high effective resistance will be chosen for pipeline application. This effective resistance per average square foot depends upon the basic resistivity of the coating material itself, the coating thickness, number and size of holidays in the coatings, deleterious effect of the environment on the coating, the resistivity of the conducting environment in which the pipeline is buried or submerged, and the bond between pipe surface and coating. If effective resistance is unstable, the electric current needed for cathodic protection may double every few years, causing increased costs for installation of new cathodic protection facilities, maintenance, and energy.

Resistance almost always declines as additional coating defects are generated through environmental effects. While the cathodic protection engineers are able to measure the effective resistance of a coating on a pipeline, this measurement can be misleading if the pipe has been installed in dry earth and not given time enough for the backfill to settle and for moisture to permeate all existing coating pinholes and holidays. Measurements made under these conditions will normally indicate a higher effective resistance (possibly *much* higher) than what actually exists. Thus, experience is required to judge the validity of coating resistance measurements and to use them for calculating the design of cathodic protection systems.

There is a great difference between the resistance of a perfect pipeline coating and one with even just a very few small pinholes. To illustrate: the resistance across a 3/32" (2.38 mm) thick completely pinhole-free coal tar enamel coating having a volume resistivity of 10^{13} ohm-centimeters on a ten-mile (16.09 km) length of 36" (914.4 mm) diameter pipeline in a 1000 ohm-cm environment would be approximately 5148.2 ohms. This is equivalent to an effective coating resistance of 2.56×10^9 ohms per average square foot. However, if there were *just one* 1/16" (1.59 mm) diameter pinhole filled with the 1000 ohm-cm environment, the resistance across the 3/32" (2.38 mm) length of the pinhole would be 12,026 ohms. This resistance in parallel with the 5148.2-ohm coating resistance would be approximately 3605 ohms, which is equivalent to an apparent coating resistance on the ten-mile (16.09 km) section of 1.79×10^9 ohms per average square foot — a 30% reduction from the "perfect coating" condition.

Under practical conditions, the chances are that there would be many more than one pinhole in a ten-mile pipeline section. Assuming there were fifty pinholes of the size stated in the example, the parallel resistance across the fifty pinholes would be 240.52 ohms. This figure, in

turn, in parallel with the 5148.2-ohm coating resistance would give a net resistance across the ten-mile (16.09 km) length of 229.8 ohms which is equivalent to an apparent coating resistance on the ten-mile (16.09 km) section of 114.3×10^8 ohms per average square foot. Although this is still a high resistance figure (and indicates a very low electrical energy requirement for cathodic protection), it nevertheless represents a 95.5 reduction from the "perfect coating" condition.

Coating bond also effects resistance particularly adjacent to any pinholes or holidays in the in-place coating. Any lifting of the coating because of disbondment at such openings in the coating increases the amount of pipe metal exposed to the surrounding environment, reduces the effective coating resistance, increases the electrical current requirements for cathodic protection and introduces the possibility of under-film corrosion that is electrically shielded from the beneficial effects of cathodic protection.

It doesn't take much disbondment to double the area of exposed metal at the usual small coating defect. For example, doubling the exposed metal area at the base of a 1/4" (6.35 mm) diameter hole in a pipe coating involves a disbondment lifting of only approximately 52 mils (1.32 mm) from the edges of the hole. Disbonding effects can be far worse than this.

IV. BASIC THEORY OF CATHODIC PROTECTION

To understand how cathodic protection works, it is necessary to understand corrosion. On a pipeline, corrosion causes a flow of direct current between the elements of a corrosion cell on the pipeline or between the pipeline and some external entity which may be affecting the pipeline. Fig. 1 illustrates this. As shown by the figure, areas where corrosion is occurring are called "anodic", which means that they are discharging corrosion current to a conductive electrolytic environment, earth or water. When direct current leaves the surface of pipe metal to enter such an electrolytic environment, it takes the metal with it, and the pipe suffers corrosive deterioration. On the

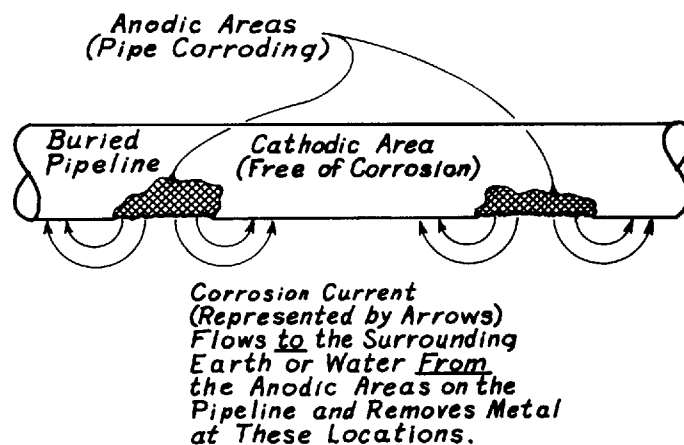


FIGURE 1
Typical Components of Pipeline Corrosion Cell.

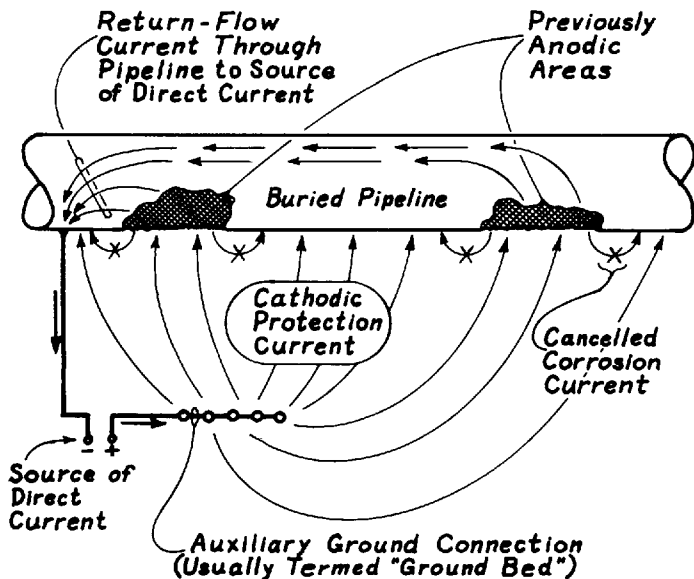


FIGURE 2
Basic Concept of Cathodic Protection.

other hand, when direct current flows from a surrounding electrolytic environment onto the pipe surface at cathodic areas, there is no corrosive damage.

If there were a way to convert all anodic areas on a buried or submerged pipe surface to corrosion-free cathodic areas, corrosive damage would be eliminated. This is exactly what is accomplished with a properly designed, installed and maintained cathodic protection system. Basically, this is done by using some external source of direct current to neutralize and counteract the natural corrosion currents discharging from anodic areas.

Figure 2 illustrates the concept of cathodic protection. The figure shows a ground connection established separate from the pipeline. A source of direct current metallically connected between the pipe and ground connection forces the ground connection to discharge current. The system is designed to regulate the amount of current discharged (cathodic protection current) so that it eliminates the flow of corrosion cell current from anodic areas by converting them to cathodic areas. A net flow is established from the conductive environment onto the previously anodic areas.

Because the cathodic protection system ground connection (also known as "ground bed" or "anode bed") is discharging current to do its job, it is subject to corrosion.

Thus, a cathodic protection system, although it renders a protected structure surface free of corrosion, does not eliminate corrosion — it transfers the corrosive effect from critical operating structures such as pipelines to known locations (the ground connections) where replacements may be made periodically (10 to 15 years or more) without making it necessary to take the protected operating pipeline out of service.

V. CRITERIA USED FOR EVALUATING CATHODIC PROTECTION

Criteria have been developed to determine that a structure has been made completely cathodic, or in other words that it is fully protected from corrosion. These criteria are set forth in National Association of Corrosion Engineers (NACE) Standard RP-01-69 (use latest revision) titled, "Recommended Practice — Control of External Corrosion on Underground or Submerged Metallic Piping Systems." These criteria are also contained in Section I, Corrosion, of Part 192 (Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards), Title 49 of the Code of Federal Regulations, which was prepared following the passage by the Congress of the Natural Gas Pipeline Safety Act of 1968.

Probably the most used criterion is the one based on a simple measurement of the electrical potential between the pipeline and adjacent earth or water. The wording of this criterion is as quoted below from the NACE Standard RP-01-69:

A positive indicator for steel and cast iron structures is "A negative (cathodic) voltage of at least 0.85 volt as measured between the structure surface and a saturated copper-copper sulphate reference electrode contacting the electrolyte. Determination of this voltage is to be made with the protective current applied."

This is all based on the fact that when a pipeline is under cathodic protection, direct current flows from the conducting environment onto the pipeline as shown by Figure 3. This current flow through the environment and coating resistance forces the pipeline to assume a negative electrical polarity with respect to the environment. The question, then, is just how negative the pipe should be to serve as an indication that full protection has been attained. The value of -0.85 volt is used for steel pipe as measured using a standard copper-copper sulphate reference electrode to contact the environment. If other types of reference electrodes are used, the values will be different.

Figure 4 illustrates how the protective potential is measured. The reference electrode (used to assure stable and repeatable readings) is normally placed on the earth surface directly above the pipeline as shown. This position

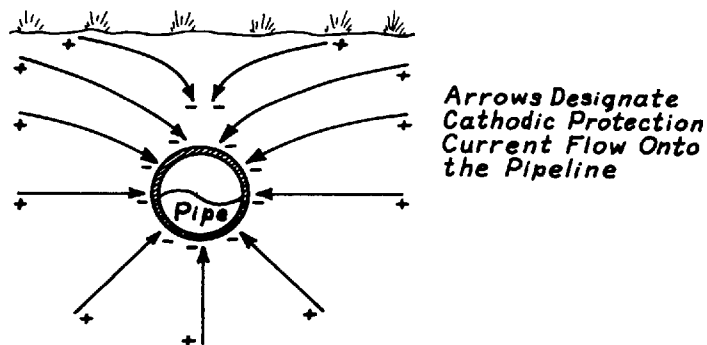


FIGURE 3
Current Flow Pattern at Cathodically Protected Pipe.

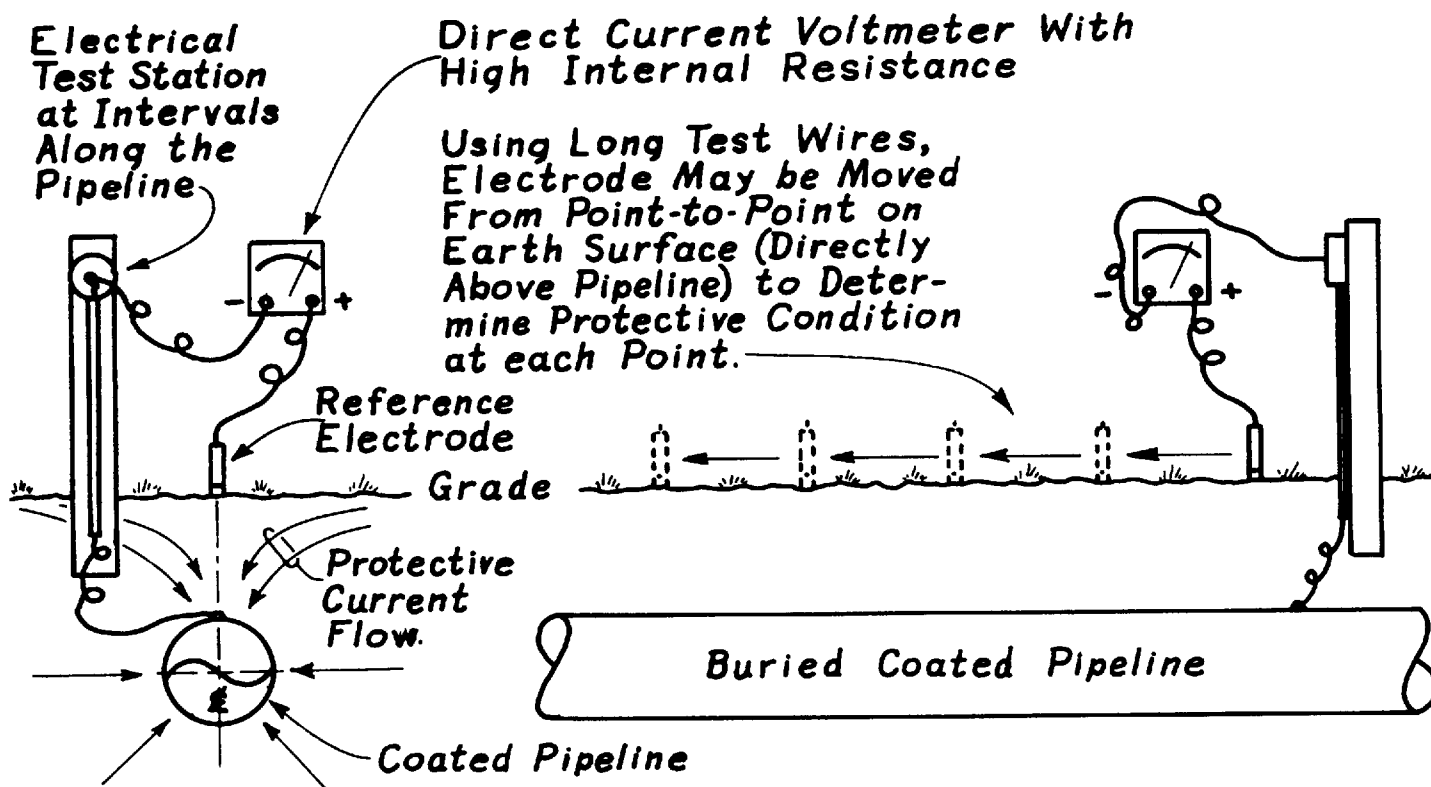


FIGURE 4
Measurement of Pipeline Protective Potential.

tends to be a neutral zone where there is the least net concentration of cathodic protection current flow between the electrode and the pipe surface. When working with submerged pipelines, suitable submersion electrodes may be lowered to a position just above the pipeline.

Potentials on steel pipe which are less negative than -0.85 volt to copper-copper sulphate electrode indicate less than full cathodic protection. On the other hand, potentials more negative than -0.85 volt to copper-copper sulphate electrode indicate wasted energy — since once corrosion is stopped at -0.85 volt, there is no real need to carry more negative potentials at a given point as far as corrosion control at that point is concerned. In actual practice, however, it is usually necessary to maintain more negative potentials at drainage points of cathodic protection current along a pipeline in order to maintain the minimum of -0.85 volt at locations remote from the drainage points. This is primarily a result of attenuation — voltage drops caused by cathodic protection current on the pipeline flowing through the longitudinal resistance of the pipeline steel in order to return to the drainage point. In this respect, large diameter coated lines are much easier to protect cathodically than are small diameter coated pipes because the larger cross sectional steel area in a large pipe means lower longitudinal electrical resistance with resulting lower attenuation.

Where there are more negative than necessary cathodic protection potentials on coated pipelines, gaseous hydrogen is generated at coating defects in the

steel surface. Hydrogen bubbles may cause mechanical lifting of paint around defects, increasing the current requirements for cathodic protection. This effect is most likely to occur in environments of low resistance.

Avoiding coating damage by excessive cathodic protection is best accomplished by avoiding over-protection in the first place although coatings that are resistant but not immune to this effect can be selected.

Normally, cathodic protection design engineers will strive to keep the polarization potential on their protected pipeline below the hydrogen over-voltage potential, which is the point at which free hydrogen starts to evolve. The "polarization potential" is the potential measured between the pipe and adjacent earth immediately (within a fraction of a second) after cathodic protection current flow to the pipe is interrupted. The reading must be taken very quickly because the polarization potential decays very rapidly at first. Although its rate depends upon environmental conditions, free hydrogen evolution on steel pipe can be looked for when the polarization potential approaches a value in the order of -1.2 volt as measured to a copper-copper sulphate reference electrode.

Other accepted criteria for steel (and cast iron) structures which may be used are given below based on the NACE Standard RP-01-69 and are supplemented by explanatory notes as appropriate.

- 1) A minimum negative (cathodic) voltage shift of at least 300 millivolts, produced by the application of protective current. (Notes: The "voltage shift"

is from cathodic protection current ON to the value read immediately — within a fraction of a second — after turning the cathodic protection current OFF. Does not apply to all structures; not applicable to structures in contact with dissimilar metals. Used where -0.85 volt to copper-copper sulphate electrode not readily attained. Not always feasible to simultaneously interrupt all cathodic protection current sources on a protected section of pipeline.)

- 2) A minimum negative (cathodic) polarization voltage shift of 100 millivolts measured between the structure surface and a saturated copper-copper sulfate reference electrode contacting the electrolyte. (Notes: This is a measurement of the cathodic protection-OFF decay in the polarization potential. This decay must be to a point at least 100 millivolts less negative than the polarization potential measured immediately — within a fraction of a second — after first turning the cathodic protection current OFF. Full decay may take excessively long on some pipelines. Not always feasible to simultaneously interrupt all cathodic protection current sources on a protected section of pipeline.)
- 3) A structure-to-electrolyte voltage at least as negative (cathodic) as that originally established at the beginning of the Tafel segment of the E-Log-I curve. (Notes: The E-Log-I curve is developed, using specific techniques, by applying increasing increments of cathodic protection current to an initially unprotected pipeline and measuring the pipeline-to-reference electrode potential at each value of applied current. These potentials are plotted against the logarithm of applied current. Typically, starting from the minimum applied current value, the plot will appear as initial and final straight line portions connected by a curved section or "break." It is the indicated pipeline-to-reference electrode potential at the beginning of the final straight line portion that is used as the criterion of protection. Effective, but a slow procedure.)
- 4) A net protective current from the electrolyte into the structure surface as measured by an earth current technique applied at predetermined current discharge (anodic) points of the structure. (Notes: Simplest evidence of compliance is a definite indication that reference electrodes placed on each side of the pipeline opposite the previously anodic spot are electrically positive with respect to a reference electrode placed directly above the pipeline at the previously-anodic spot. This indicates that direct current is flowing onto the pipeline from the environment on each side.)

While the criteria discussed above are the accepted

working tools used by pipeline corrosion engineers to evaluate the effectiveness of their cathodic protection systems, the ultimate criterion is whether or not the development of pipeline corrosion leaks has been effectively stopped.

VI. TYPES OF CATHODIC PROTECTION

There are two general types of cathodic protection systems widely used on pipeline facilities. These are: galvanic anode systems that generate their own electrical energy for protection and impressed current systems that require energy from an outside source. These two systems are discussed below.

A. CATHODIC PROTECTION WITH GALVANIC ANODES

A particularly troublesome source of corrosion damage can be the dissimilar metal corrosion cell. If, for example, copper and steel are in electrical contact with each other and both are in contact with a corrosive (low resistivity) earth or water, the steel is anodic and corrodes faster than is the case if the copper is not present. The copper in the case cited, being cathodic, shows little or no attack.

But the negative effect of dissimilar metal corrosion cells can be reversed if the "right" material is in contact with the steel pipe. The "right metal" is higher than steel in the electromotive series of metals and, as a result, anodic while the steel in the dissimilar metal corrosion cell becomes cathodic and is thereby protected from corrosion.

Materials used for galvanic anodes include zinc, magnesium and (in certain applications) aluminum. The material is usually cast into various commercial shapes (called "anodes") with lead wires attached. Particularly for anodes to be buried in earth, they are commonly purchased with a "package" of a compatible chemical backfill surrounding the anode. This permits more uniform performance and better anode efficiency.

Galvanic anodes generate their own current through "galvanic action" or "battery action" when they are in electrical contact with the pipe metal. This permits a simple construction method which is illustrated in its simplest form by Figure 5. The two dissimilar metals of the anode and the pipe, when electrically connected with a wire as shown, constitute a simple battery causing current to flow from the anode through the earth to the pipe and back to the anode through the interconnecting wire.

Anodes may be installed individually or in groups. Their size, material, intervals between installations along a pipeline, and other details are designed by the corrosion engineer. Design determinants include pipe material and physical size, type and condition of the coating, resistivity of the earth or water surrounding the pipe, presence of stray earth currents from other sources, available construction sites, weather, and other similar factors.

Although galvanic anodes can control pipeline corro-