CATHODIC PROTECTION

Consequences and standards from using CP systems to prevent corrosion

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CORROSION HAS BEEN AROUND FOR ALL OF RECORDED history. Cathodic protection is the electrical solution to the corrosion problem. In this article, the history of cathodic protection (CP) is traced, and the design fundamentals are developed, including the three components of a corrosion system, the three elements of an electric circuit, and the three configurations causing potential difference. CP is the process of forcing a metal to be more negative (cathodic) than the natural state. Case studies investigate unintended side effects from CP. One is from a pipeline crossing a lake. Another is a pipeline in very rocky soil. Technical ramifications are involved when bonding of electrical grounding systems to metal protected by CP. Installation and maintenance requirements are identified. A compendium of applicable standards and recommended practices is presented.

Corrosion is not exactly a new topic. It has been around since the beginning of time. Corrosion is simply the loss of material resulting from current leaving a metal, flowing through a medium, and returning to the metal at a different point, as shown in Figure 1 [1].

Corrosion takes many forms and has various names, such as oxidation, rust, chemical, and bacteria action. Regardless of the agent, all corrosion is the result of electrical current flow. Various methods are used to treat corrosion or to try to prevent it. Some of these include chemical treatment, coatings, and electrical current [2]. Proper impressed current can stop corrosive action on the protected surface; nevertheless, this may not be practical in some environments.

The concept of CP has been around for quite some time. Marine vessels have used CP for almost 200 years The first recorded use of CP occurred in the early 1800s. In 1824,

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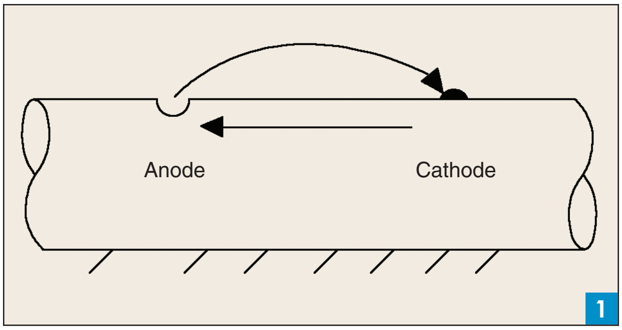
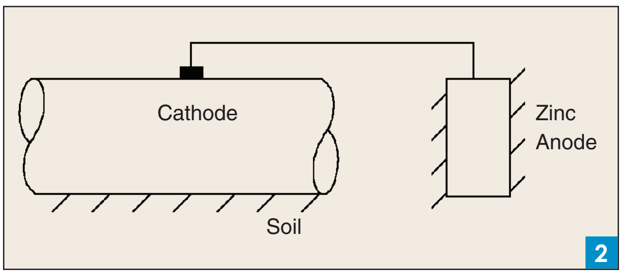
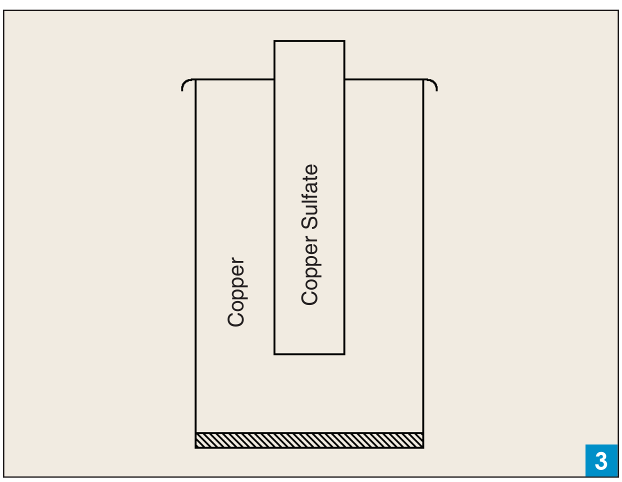


Cathodic cell on pipe.



Cathodically protected pipe.



Half-cell.

Sir Humphry Davy was consulted by the British Admiralty, which was concerned about "the rapid decay of the copper sheeting of His Majesty's ships of war and the uncertainty of the time of its duration." Davy proposed the attachment of a small piece of zinc to nullify electrochemical action on the copper sheathing similar to Figure 2. Davy also investigated using an impressed current system; however, reliable batteries had not then been developed [3].

Currently, CP is mandatory for underground, metallic pipelines of hazardous gas and liquids [4], [5], and for water storage tanks with a 250,000 gallon capacity or greater [6]. Cathodic protection also is recommended for underground piping systems located within ten feet of steel reinforced concrete. Galvanic corrosion will occur between the steel rebar and the pipeline if the two systems are too close [6], [7].

Fundamentals

Components

There are three components to a corrosion system. 1) An anode sacrifices metal in a corrosion circuit and is the positive electrode on a battery; 2) a cathode receives current in a corrosion circuit and is the negative terminal of a battery; and 3) an electrolyte is a nonmetallic medium, with some moisture content, which supports flow of electric current.

Circuit

For corrosion to exist, there must be an electric circuit composed of 1) a metal conductor, 2) an electrolyte, and 3) a potential difference. This forms a cell, much like a simple battery. The first two conditions exist anytime pipe is placed in soil or when water is placed in contact with a vessel. The potential difference is caused by environmental circumstances or by differences in electrochemical properties.

Differential

Three possible configurations create the potential difference.

- two different metals in the same electrolyte
- the same metal in two different electrolytes
- outside interference.

For example, corrosion occurs in splices between aluminum and copper wire because of different metals in the same electrolyte.

Half-Cell

A half-cell is a reference electrode consisting of a copper conductor immersed in a copper sulfate electrolyte, as shown in Figure 3.

Cause and Mitigation

The same elements that cause corrosion can be used to control it or to protect a different material. Aluminum will corrode if placed in contact with iron products. Aluminum has an electronegativity of 1.61, while iron's electronegativity is 1.83 [8]. Therefore, aluminum molecules have an ionic charge that is less negative than the steel. This causes an electrochemical attraction between the two metals. Aluminum molecules will flow from the aluminum, through the electrolyte, and deposit on the iron. This fact can be used to protect steel pipe if the aluminum is sacrificed.

Were the aluminum forced to a more negative potential through some outside energy, iron molecules would travel in the opposite direction and deposit on the aluminum. Cathodic protection, then, is the process of forcing a metal to be more negative (cathodic) than the natural state. If the metal is forced negative enough, then corrosion will stop.

This phenomenon creates problems when a cathodic system is no longer performing as expected. A metal surface can be protected at the undesired expense of causing other metal to fail. The remainder of the article describes the problems and discusses the issues using actual case studies.

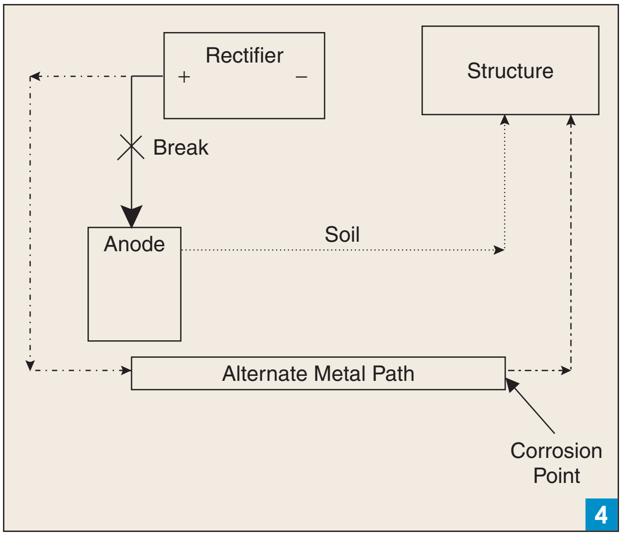
Problem

In addition to protecting vessels and wells, CP is a common practice and regulatory requirement on cross-country petrochemical pipelines [4], [5]. By the nature of pipelines, these pass through a variety of terrain and earth conditions. The change in soil conditions is one of the three elements that affect corrosion.

The current flow resulting from CP is designed and intended to protect the metal pipe or vessel. Under some conditions of poor maintenance, soil conditions, and proximity of other metal structures, the current does not flow on the preferred path. The results on surrounding structures can be very dramatic. Electrical shock and corrosion are just two of the observed effects.

The unintended results of two different pipeline systems operated by different companies are illustrated, along with an investigation into a deep well application. The terrain for the installations was very diverse. One was a lake crossing, another was in very rocky soil, and the third was in a dry, clay location.

Although the particular projects involved petroleum pipelines and wells, the information is appropriate for any engineer concerned with safety, corrosion, and CP.



Unintended return path.

Case 1 Residential Corrosion Caused by Pipeline CP Ground Failure

Three pipelines passed through a rural residential area on the shores of a lake. Two of the pipelines carried petrochemical products and had CP installed. The third pipeline was a former products line that had been converted to other, nontransportation use, and as a result did not have protection.

All 16 residences in the area had complained of unexpected corrosion on underground steel and copper lines. An investigation of the extent of the problem and the possible causes was undertaken.

Visual inspection of the wiring at several of the residences and at adjacent commercial installations revealed that ground wires at many facilities had corroded to the point of complete failure. This created a potentially hazardous situation. In fact, there were reports of some residents receiving electric shock from water exiting faucets. This indicates that the ground system was severely compromised.

Voltage tests on various pieces of metal at the residences, a communications tower, an abandoned water tower, and three pipelines were taken and compared. The pipe to soil voltage readings showed a shift in the positive direction. These readings were higher than could be explained by simple galvanic action of the metal. Potential shifts of this type indicate that corrosion was caused by external sources.

Soil measurements using copper/copper sulfate half-cells were made in several locations throughout the immediate area. There were small swings in the order of 30–50 mV positive at several locations. These were in the direction that can cause corrosion but were not considered significant.

Measurements were made at the two homes closest to the pipeline rectifier station. At these locations, very dramatic voltage swings in the positive direction were observed. This is indicative of a strong corrosion potential.

Rectifier readings were routinely made on each of the protected pipelines. Even though this was done, no indication of improper operation was observed. There was a complete path allowing current to flow; however, this path was not through the intended ground circuit.

After recognition and identification of the problem source, it was necessary to investigate the root cause. Examination of the pipeline rectifier stations revealed a break in the lead between the rectifier and the ground bed.

For corrosion to occur, there must be an electrical circuit. Without a direct connection to the sacrificial anode, a path will be found through any adjacent metal. In this case, the unintended path was through the metal in the residential and commercial structures, as shown in Figure 4.

Although corrosion of water and sewer pipes can be inconvenient and costly, more serious safety issues were raised. In at least two locations, ground wires had corroded to the point that no ground connection existed at the meter site. Additionally, corrosion could be found in natural gas and propane lines, a potentially catastrophic situation.

Case 2 Residential Shock Hazard Caused by Pipeline CP Failure

Four pipelines passed within 150 feet of a residence. Three of the pipelines carried petrochemical product, and one had been converted to other, nontransportation uses. The three petrochemical pipelines each had CP installed. The fourth line had no CP. Each of the three lines with CP had –1.45 V pipe to soil measurement.

Over an eight-month period, residents in the area had experienced several problems. Each of these was indicative of a serious situation.

All copper tubing under the concrete floor of one house had required replacement. The 3/4-in copper supply line into the residence had been replaced on two separate occasions. Both a television screen and a computer failed prematurely due to voltage problems. Multiple 120 Vac motors in the residence had burned out. On several occasions, fluorescent lights would not ignite.

More critical safety issues arose. On several occasions, individuals were shocked by water from a shower. Persons were shocked when metal walls of a preengineered building on the premises were touched. Finally, a hole had burned in a metal wall where it had been exposed to an energized ground wire.

An electrician had measured 40 Vac on ground wires at the service entrance and at the meter location. The local utility measured 90 V on the ground conductor at an adjacent pump location.

A pipeline in the area had undergone recent repairs over a distance of several hundred feet. There had been an additional leak repair on the lines at a distance of 1/4 mi from the rectifier stations. Additionally, the rectifiers had received very recent maintenance.

An investigation of the rectifier location showed numerous problems. The most severe was that the ground resistance of the connection to earth was 178 Ω. This value was more than seven times that recommended in the National Electric Code (NEC) [9].

Additionally, there was an inadequate ground connection on the power system to the rectifier. The ground wire on the meter pole was completely corroded. A new ground rod was driven about five feet into the ground. The rest of the rod was left sticking in the air. The NEC requires eight feet of rod be placed in the earth [9]. The ground resistance on this connection was 48 Ω, which is nearly twice the NEC value, and contributed greatly to the energized ground wire at the residence.

Finally, there were several pump facilities in the area. One of these pumps was running a 277 Vac, single-phase system with no ground connection whatsoever. Each of the other locations had ground connections with ground resistance measurements from 750–1,000 Ω. The purpose of a ground is to return any stray currents safely back to earth potential. Without a proper ground connection, the excess voltage will travel on an unintended path back to earth.

The failed CP system caused the corrosion problems to the plumbing and electrical ground circuits in the area. Once the facility ground was corroded, a scenario was set up for stray currents. The pumping system was the primary source of the energy for electrical shocks, damage to electrical equipment, and damage to the structure. When the pump was turned off, those problems ceased.

The system did not have adequate ground protection to keep the stray potential from seeking alternate paths. Without adequate grounding, the electric current sought the lowest resistance route. This was through the metal in the pipeline. This graphically emphasizes the need for proper system maintenance.

Case 3 Well Casing

The third case involved CP of a well casing rather than a pipeline. The pipe had a diameter of 5.5 in and was 6,500 ft deep. The casing penetrated a variety of soil conditions as it passed through several production zones. Cathodic protection was used because of known corrosion problems and because the casing was carrying substantial internal pressure from gas.

The CP system included a rectifier with five anodes. The system was designed for eight amps impressed current. A similar design had been used literally hundreds of times for similar installations. Other structures in the area included tanks with steel bottoms and metal framework for pumping equipment. The casing was isolated from these other steel structures. An insulating flange was installed between the casing and the pipeline.

As with most cathodic installations, the rectifier current was read and reported regularly. Throughout the short life of the project, all rectifier reports appeared proper. However,

TABLE 1. INSPECTION REQUIREMENTS FOR PIPELINES AND TANKS [4], [5].

Device	*Inspection Requirements*
Protected Pipelines	a) Conduct tests for corrosion at least once each calendar year, with intervals not exceeding 15 months. b) Determine by 29 Dec. 2003 the interval practical and necessary for close internal survey to accomplish objectives of NACE standard RP0169-96. c) Whenever any pipe is removed from the pipeline, the internal surface must be inspected for corrosion. If any is found, the adjacent pipe must be internally inspected and corrective measures taken.
Unprotected Pipe	Conduct electric survey for corrosion at least once every three calendar years, with intervals not exceeding 39 months.
Rectifier	Electrically check for proper performance at least six times each calendar year, with intervals not to exceed two and one-half months.
Reverse Current Switch	Electrically check for proper performance at least once each calendar year, with intervals not to exceed 15 months.
Diodes	Electrically check for proper performance at least once each calendar year, with intervals not to exceed 15 months.
Critical Interference Bonds	Electrically check for proper performance at least six times each calendar year, with intervals not to exceed two and one-half months.
Interference Bonds	Electrically check for proper performance at least once each calendar year, with intervals not to exceed 15 months.
Breakout Tanks	Inspect each CP system to ensure that operation and maintenance are in accordance with API RP 651.

in less than three years, the casing experienced extensive damage from corrosion. Repairs could not be made. It was necessary to drill a new well and install new casing. The replacement cost was in excess of US$350,000.

Investigation revealed the tank bottoms were like new. The pipeline was pristine. Yet, the well casing was literally eaten up. It was found that the insulating connection between the casing and the pipeline was damaged. Therefore, the impressed current took the preferential path to the metal that was closer to the anode circuit. This path was through the pipeline and the metal tanks.

Electrical Bonding

According to the NEC, the grounding electrode is preferentially in the following order: metal underground water pipe, metal frame of structure, concrete-encased electrode, ground ring, rod electrode, plate electrode, or other local metal underground systems. Specifically, the electrodes that shall not be grounded are metal underground gas piping systems and aluminum electrodes [9].

It is useful to note that the preference of underground water pipe as the grounding electrode is most valid when applied to a copper line. Steel, ductile, or cast iron water pipes can corrode and become a sacrificial anode to protect copper in the area. In addition to connecting the electrical components to the single point ground electrode, it is desirable to bond pipe and well casings to the grounding electrode [10]. The pipe is not the grounding electrode. By definition, the grounding electrode is at the source and the metal is simply a location to bond. Without bonding, there would be voltage build-up, uncontrolled arcing, and potential shock.

However, when CP is connected to pipe and structures, the electrical bonding must be removed. If a ground bond were connected, it would drain off the cathodic impressed current and defeat the protection. This creates concern among some electrical practitioners that they are precluded from using the large metal surface of a cathodically protected pipe as a ground conductor.

A CP system has inherent personnel protection. CP systems are typically designed to drive the potential to about 1 V negative. Potentials more negative than 2.5 V can be damaging to coatings. Equipment properly connected to a CP system has a very low resistance path to ground ($<2\ \Omega$). This provides an adequate path for dissipation of current in a fault condition.

Standards

All of the aforementioned cases emphasize the importance of full, proper CP system maintenance. This goes well beyond monthly current readings. Additional steps must be undertaken to preserve the integrity of the CP system and to avoid costly and potentially dangerous situations.

Department of Transportation (DOT) regulations dictate the periodic maintenance requirements of pipelines and

TABLE 2. APPLICABLE CORROSION STANDARDS.

Org	*Number*	*Name*
DOT [4]	49 CFR Part 192	Transportation of Natural Gas and other Gas by Pipeline
DOT [5]	49 CFR Part 195	Transportation of Hazardous Liquids by Pipeline
EPA [12]	40 CFR Part 280	Technical Standards and Corrective Action Requirements for Owners and Operators of Underground Storage Tanks (UST)
UL [13]	1746	External Corrosion Protection Systems for Steel Underground Storage Tanks
NACE [14]	RP0169	Control of External Corrosion on Underground or Submerged Metallic Piping Systems
NACE [15]	RP0177	Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems
NACE [16]	RP0193	External Cathodic Protection of On-Grade Carbon Steel Storage Tank Bottoms
NACE [17]	RP0285	Corrosion Control of Underground Storage Tank Systems by Cathodic Protection
NACE [18]	RP0286	Electrical Isolation of Cathodically Protected Pipelines
NACE [19]	RP0388	Impressed Current Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks
API [20]	RP 1632	Cathodic Protection of Underground Petroleum Storage Tanks and Piping Systems
API [21]	RP 651	Cathodic Protection of Aboveground Storage Tanks
STI [22]	R892	Recommended Practice for Corrosion Protection of Underground Piping Networks Associated with Liquid Storage and Dispensing Systems
STI [23]	R972	Recommended Practice for the Installation of Supplemental Anodes for STI-P3 USTs

tanks [4], [5]. These requirements have become quite stringent for the period beginning 29 December 2003. Table 1 shows the required frequencies of inspection for each component of the piping system.

Record-keeping is also required under the DOT regulations. According to Article 192.491 of 49 CFR, the operator must maintain records or maps that show the location of CP piping, CP facilities, anodes, and neighboring structures bonded to the CP system [4]. These maps must be retained for the life of the pipeline.

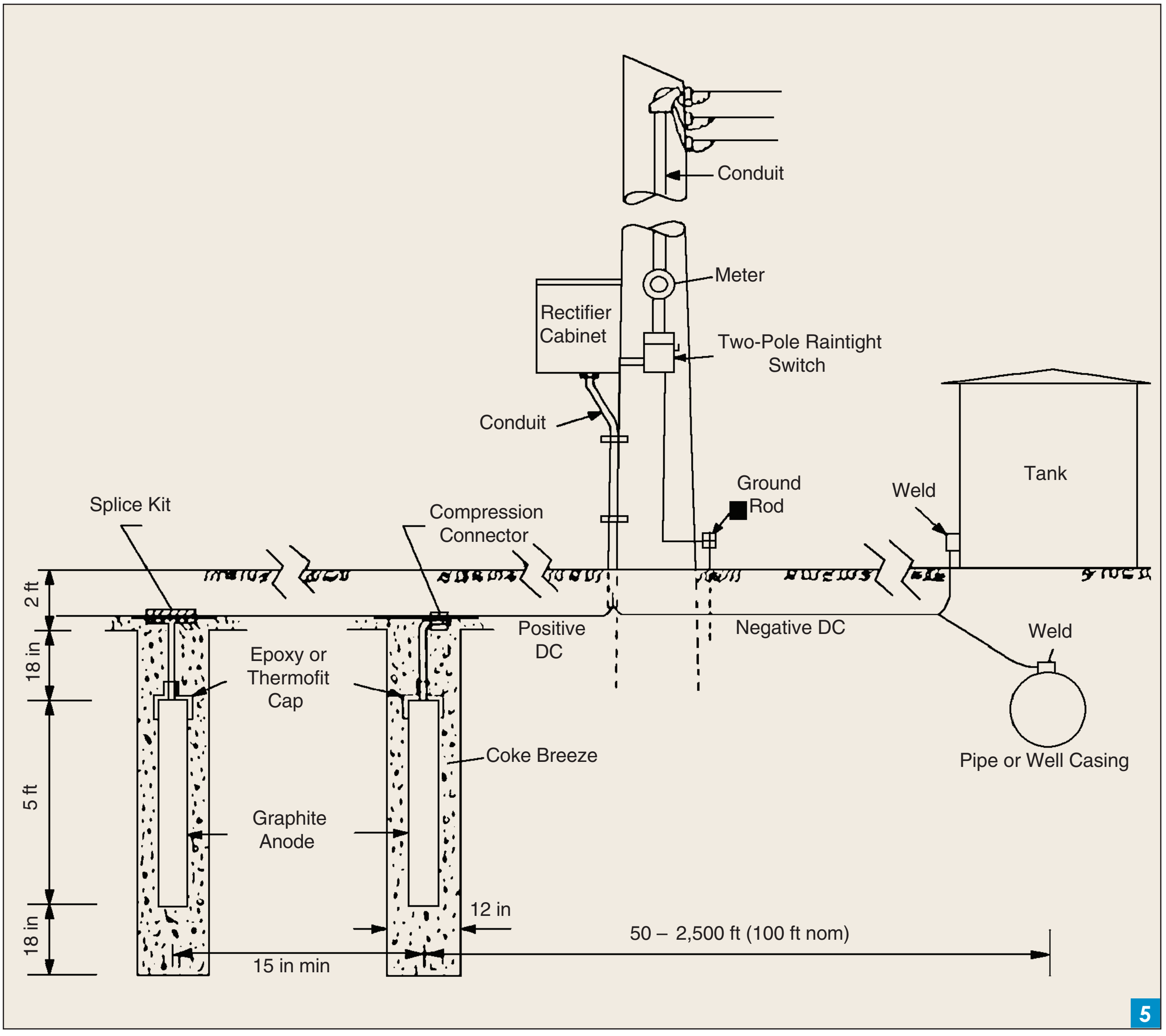
Test records must include a record of each test, survey, or inspection required in Table 1, in sufficient detail to demonstrate the adequacy of the CP system, or that corrosive conditions do not exist. These records must be maintained for at least five years. Records for inspections of the protected pipelines and critical interference bonds must be retained for the life of the pipeline. Critical interference bonds are defined as bonds whose failure would jeopardize structure protection [4], [5].

Numerous additional standards address corrosion and CP in different situations. Table 2 shows a compendium of the major standards and recommended practices. While not all standards are applicable for each situation, the prudent engineer would be familiar with each of the criterion that would be pertinent to his facilities.

Other standards may be applicable to specific geographical regions and jurisdictions. Complete bibliographies can be found in the following references.

Installation and Maintenance Recommendations

Figure 5 shows a complete, properly constructed CP system [11]. At initial construction, it is imperative that the protected piping be isolated from all other metallic parts. This involves both visual inspection and testing. A simple test can be accomplished using a hand-held multimeter. In a plant or pumping station, resistance can be checked between the protected equipment and the local ground. Any reading other than an open circuit indicates a problem. In more remote locations, resistance readings must be made between the protected system and all other pipes or metallic system in the vicinity.



Cathodic protection system.

In addition, at initial construction, it is necessary to check all bonding between protected pieces of equipment. Again, this is a relatively simple, but necessary, procedure. Before the system is energized, resistance readings should be taken between pieces of protected equipment, close to the bonding jumper. These readings should be nominally 0 Ω (shorted). Any readings substantially above this indicate that the bonding jumper is not working correctly, and some pieces of equipment are not being protected.

Resistance bonds between the protected equipment and other metallic equipment in the vicinity should be checked. These are most often encountered when a protected pipeline runs within five feet horizontally of electric gear, or between the protected pipeline and other pipelines on a different CP system.

Periodic current readings will show any drastic changes in the system as a whole and will allow issues such as a failed rectifier or a broken connection from the rectifier to the protected equipment to be addressed quickly.

Additionally, if the readings are recorded and trended over time, much information can be gleaned. Continuously decreasing readings can indicate either a failing anode, a failing connection to the ground bed, or some other electrical equipment failure. Continuous increases in the voltage supply required to maintain current density indicate similar type problems.

Annual tests should be done on an 11-month or 13-month cycle. Over time, the system will be inspected and readings taken through all seasons and climatological conditions.

It is necessary to do a complete inspection of the CP system on a regular basis. The first step is to repeat the inspections of isolation and bonding system discussed previously. Since the system is now energized, tests are done on a voltage differential rather than resistance.

Next, half-cell measurements should be taken between the structure and soil and between the ground bed and soil. Finally, a visual inspection of all rectifier to ground and rectifier to structure connections should be made where these connections are visible.

These procedures, though mandated by federal law and good engineering practice, are often not well known and seldom fully implemented. The results of not adhering to these maintenance procedures can be dramatic.

Conclusions

Corrosion of metal equipment in contact with the earth is a natural phenomenon. To control this corrosion, CP systems intentionally sacrifice one material to protect another. This is primarily done by impressing a certain current density onto the protected equipment. For this system to work, there must be a complete electric path from a negative source, to the protected structure, through the electrolyte, via the ground bed, to the positive side of the source.

Not only do CP systems fail due to component failure, they can also be affected by the addition of metal structures in the vicinity without regard to the CP system. When CP systems go awry, unintended corrosion of external metal equipment can occur. This can lead to costly repairs. In some circumstances, continued problems can lead to serious electrical safety concerns.

With proper, regular maintenance of the CP, including rectifier current readings, half-cell measurements of the pipe and ground bed, and inspection of bonds and isolators, CP systems can be used safely and efficiently.

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