PRELIMINARY CORROSION STUDY
SANTA BARBARA HARBOR
MARINA 1

Prepared for:

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April, 2011
Job 8566

ATTACHMENT

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EXECUITIVE SUMMARY

In 2010 Santa Barbara Harbor implemented a replacement of the power distribution system for Marina 1 (M1). Installed concurrently was a new fresh water distribution system that included non metallic piping/ flex hoses connected with stainless steel collars.

During the month of February 2011 Farwest Corrosion control conducted a series of inspection and test to determine the facts regarding reported corrosion issues that included:.

- Accelerated corrosion of the stainless steel collars used to secure the non metallic water flex hose sections.
- Individual boat owners reports of accelerated corrosion of outdrives and rapid consumption of zinc anodes.

The field survey consisted of:

- Meeting with Santa Barbara Waterfront personnel that included:
  - Review of the past and recent history of the changes in the shore power infrastructure.
  - Physical inspection of the construction methods used for construction of the new shore power and water distribution system.
  - Visual inspection of some of the failed stainless steel collars.
  - Discussion on the basic corrosion mechanisms that would be applicable to the specific corrosion issues.
- Conducting a series of inspections and tests to gather information and data that would be helpful in determining the cause and correction of the reported corrosion issues. Tests were conducted in three areas: a.Stainless Steel hose collars. b. AC power distribution. c. Selected individual vessels.

SURVEY RESULTS
Stainless Steel Pipe Collars-

- Virtually no notable corrosion on the outside of the collars.
- All corrosion was initiated on the inside surfaces of the collars and failures were a result of metal loss from the inside out.
- Results of the structure to water potential tests indicated that the SS collar exhibited a normal potential for 316 SS and no stray currents were detected.
- It is concluded that the corrosion observed on the inside of the collars was clearly and exclusively a classic example of "crevice corrosion".
- Correction of the problem will require a change in installation methodology and or use of materials that are resistant to crevice corrosion.

AC Power Distribution

For safety reasons all AC power systems require a ground circuit. All AC powered equipment is designed to have all exposed metal parts connected to ground to prevent personnel contact with a dangerous voltage if electrical insulation/isolation fails. In theory, in a properly operating AC circuit there should be zero current flowing on the ground wire.

The Marina 1 AC distribution system carries common ground conductors from the source to the shore power connection at each slip. Whenever a boat is connected to shore power, the hull and drive systems are connected to the shore grounding system and to other adjacent vessels (also connected to shore power) via the grounding conductor in the shore power cable. This connection, while required for safety, can create a galvanic corrosion cell involving the dissimilar metals between boats and the shore grounding system.

During the testing of the ground circuits unacceptably high AC currents were found on some of the vessels. These are indicative of a problem on board the vessel. More often the problem is a result of improper wiring or grounding of equipment on the vessel.

Therefore if one vessel has a problem, i.e., faults in the AC system or poor cathodic protection levels, it will likely have an affect on the neighboring vessel(s). Electrical isolation of the vessel from the grounding system is required to prevent these issues. Specific aftermarket products are available to provide the necessary electrical isolation and still maintain the safety of a secure grounding system.

Premature consumption of anodes and or coating systems was one of the issued investigated. There are many variables that can contribute to an individual vessels vulnerability to corrosion. Aside from the electrical problems already addressed, coating systems can fail due to many reasons. Specific issue that can be the cause of premature coating failure are addressed in this document.

It seems common throughout the world that when a vessel owner/operator experiences unusual corrosion, or coating issues, the subject of stray currents come into the conversation with comments of "Hot harbor" or "Hot Slips". It is the opinion of this author that stray currents either AC or DC significant enough to cause notable "stray current corrosion" in a facility like Marina 1 are extremely rare. None of the tests performed during our survey or review of the Waterfront Department data suggest anything that would be considered a "Hot Harbor" or "Hot Slips". Each of the reported corrosion problems have their own unique causes and there are simple tests that can be performed to identify the source of the corrosion. The recommended tests and methods are detailed in this document.

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PROJECT SCOPE

Farwest Corrosion Control Company has been retained to investigate the reported accelerated corrosion issues within the Marina 1- Santa Barbara Harbor. On February 1, 2011 Farwest Corrosion conducted a series of onsite inspections and tests to determine the cause and correction of the reported corrosion issues.

This document includes details on the preliminary field investigation. A separate document (under separate cover) is provided that is to be used as a primer/guide for individual vessel operators to determine if their vessel is at risk for any corrosion issues and provides some options for correction of any known issues.

BACKGROUND

In 2010 Santa Barbara Harbor implemented a replacement of the power distribution system for Marina 1 (M1). The new M1 power distribution system consists of a meter section located on land behind the 132 building with a 3 phase 480 4 wire feed with a 2000 GIFT main. Power to M1 is distributed via 5 submerged cables to a 480V.power board located at the bottom of the M1 ramp. 480 volt power is fed to 5 transformers located on the main walkway. Each transformer steps down the 480 to 208 three phase to each finger and it is then distributed to each slip with either a 30 amp 120V or 50 amp 208V single phase receptacle. It is noted that all grounding is provided by a uffer (driven rod system) ground located at the meter panel behind the 132 building.

Installed concurrently was a new fresh water distribution system that included non metallic piping/ flex hoses connected with stainless steel fittings that consist of a barb style fittings with stainless steel crimped ferrule (sleeve/collar) at the end fittings.

Reported corrosion issues include:

- Accelerated corrosion of the stainless steel collars used to secure the non metallic water flex hose fittings.
- Individual boat owners reports of accelerated corrosion of outdrives and rapid consumption of zinc anodes.

METHODS AND PROCEDURES

- Meeting with Santa Barbara Waterfront personnel that included:
    - Review of the past and recent history of the changes in the shore power infrastructure.
    - Physical inspection of the construction methods used for construction of the new shore power and water distribution system.
    - Visual inspection of some of the failed stainless steel collars.
    - Discussion on the basic corrosion mechanisms that would be applicable to the specific corrosion issues.
- Conducting a series of inspections and tests to gather information and data that would be helpful in determining the cause and correction of the reported corrosion issues. Tests were conducted in three areas: a.Stainless Steel hose collars. b. AC power distribution. c. Selected individual vessels.

  Tests on the Stainless Steel hose fittings included:
    - Measure structure to water potentials to determine the native potential of the stainless steel fitting.
    - Conduct "AC cell-to-cell" voltage drops to determine the presence of any stray AC currents.
    - Measuring "DC cell-to-cell" voltage drops at selected locations to determine the presence of any stray DC currents.

  Tests on the AC supply system included:
    - Measuring AC & DC current on the ground legs at the distribution transformers.
    - Conduct "AC & DC cell to cell voltage drops at selected locations to determine the presence of any stray AC currents.

  Tests on selected vessels included:
    - Measuring structure to water potentials (both DC & AC) to determine the effectiveness of any existing cathodic protection system and the presence of any stray AC currents.
    - Measure AC& DC "hot", "neutral" and "ground" currents.
    - Measure the effectiveness of any "Galvanic Isolators" if equipped.
    - Utilizing a " GalvanAlert Shore Power Corrosion Detector" to determine the proper polarity of the AC wiring and possible galvanic corrosion issues.

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SURVEY RESULTS & ANALYSIS

STAINLESS STEEL PIPE COLLARS

Visual inspection of the collars reveal the following corrosion patterns:

- Virtually no notable corrosion on the outside of the collars.
- All corrosion was initiated on the inside surfaces of the collars and failures were a result of metal loss from the inside out.
- Corrosion patterns on the inside of the collars were inconsistent, i.e., some were very localized and some were spread over a large area. But all on the inside in areas where the seawater was able to migrate between the collar ID and the OD of the non metallic pipeline.
- Results of the structure to water potential tests indicated that the SS collar exhibited a normal potential for 316 SS.
- Results of the stray AC & DC current tests indicated that no notable currents were detected.
- It is concluded that the corrosion observed on the inside of the collars was clearly and exclusively a classic example of "crevice corrosion". The following is a brief discussion on the characteristics of stainless steel and some of the unique corrosion problems is suffers:

Stainless Steel
The basic corrosion resistance of stainless steel occurs because of its ability to form a protective coating on the metal surface. This coating is a "passive" film which resists further "oxidation" or rusting. The formation of this film is instantaneous in an oxidizing atmosphere such as air, or moving water, or other fluids that contain oxygen. Once the layer has formed, it is said that the metal has become "passivated" and the oxidation or "rusting" rate will slow down to less than 0.002" per year.

Crevice Corrosion on Stainless Steels
Crevice corrosion on stainless steels is a geometrically controlled form of corrosion. It occurs below rivet heads, between ***lap joints***, in threads and anywhere a small crevice is formed in which at least one side is a metal. It is an important point to note that only one side of the crevice is required to be a metal. This means that interface between the stainless steel and the other material (in our case the non metallic hose) must fit properly and not be loose enough to allow water to enter the crevice.

Mechanism of Crevice Corrosion
The general conditions for crevice corrosion include a stagnant solution and a gap between two surfaces, one of which is metal. Initially, the usual anodic and cathodic reactions occur over the surface of the metal. However, once the oxygen is consumed the passivation is lost and the metal continues to corrode and can exhibit aggressive corrosion rates.

In many cases crevice corrosion is not detectable by visual inspection as it occurs in the lap joints or threads and is hidden from view. The hidden nature of the corrosion also makes inspection very difficult.

AC POWER DISTRIBUTION

For safety reasons all AC power systems require a ground circuit. Typically driven rods in the earth that will provide a relative low resistance/alternate path to a common ground.

Typically AC powered equipment is designed to have all exposed metal parts connected to ground to prevent personnel contact with a dangerous voltage if electrical insulation/isolation fails. In theory, in a properly operating AC circuit there should be zero current flowing on the ground wire. However, there will always be some capacitive couple current between the hot wire(s) to the ground wire. This capacitive couple current is caused by the fact that the wiring and transformers all have some capacitance between the ground and hot wire(s). Therefore even with a properly functioning AC system, there will be some current flowing on the ground circuit. However, it is important to note that the amount of current is typically very low (between 0.006 amperes to 0.010 amperes. As a result this very low current does not cause any safety concerns or functional problems with the equipment being powered by the AC.

One of the tests performed by Farwest as well as the Waterfront Department was to measure AC & DC currents on the various system ground wires. In review of the data of over 50 vessels tested, AC ground wire currents were typically 0.020 amperes or less which would be considered a non issue. Two vessels measured 0.400 amperes with one vessel with a high of 2.840 AC amperes. These are indicative of a problem on board the vessel. More often the problem is a result of improper wiring or grounding of equipment on the vessel. It is noted that where elevated AC currents were detected, elevated DC currents were found as well. The measured currents may be only a portion of the total current flowing to the system ground. There can be and typically is an alternate (parallel) path to ground. The alternate path would include the current that is flowing from any metal that is connected to the vessel ground and is in contact with the water, i.e., props, shafts, rudders, coolers, outdrives, etc. The amount of current being discharged off the underwater structures is impractical to measure but can have significant detrimental corrosion.

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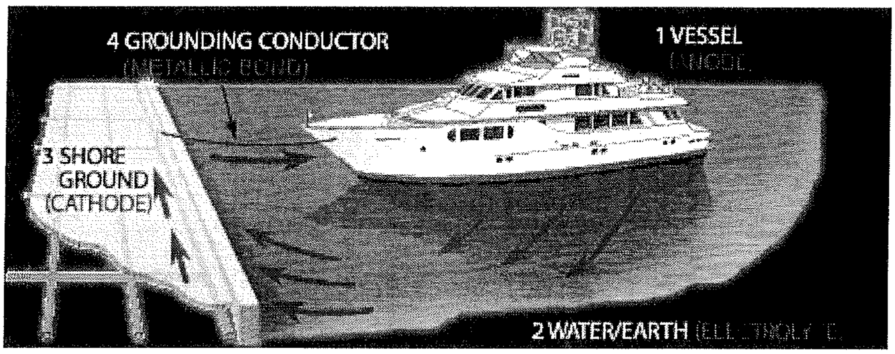
Whenever a boat is connected to shore power, the hull and drive systems are connected to the shore grounding system and to other adjacent vessels (also connected to shore power) via the grounding conductor in the shore power cable. This connection, while required for safety, can create a galvanic corrosion cell involving the dissimilar metals between boats and between a boat and the shore grounding system, as shown in the following diagram below:



Four Components are needed for Corrosion:

1) **Anode** – a metal surface which gives up metal ions (corrodes).
2) **Electrolyte** – a medium which conducts ionic current between the anode and cathode.
3) **Cathode** – a metal surface that picks up metal ions.
4) **Metallic Bond** – a metallic path that allows current to flow from cathode to anode.

With the vessel "hard wired/bonded" to the shore power ground, both AC and DC currents will flow as illustrated above. Of the two the DC current is the most destructive. Currents as small as 0.250 Amps DC flowing off a propeller/rudder or outdrive system can create serious damage in as little as a year if not corrected.

To comply with local and national electrical codes it is mandatory that a dedicated current path to an approved grounding system be provided for each vessel. One way to eliminate DC galvanic corrosion but still provide a path for AC current to flow is the installation of a Dielectric Isolator in the ground circuit. This is a solid state device that is designed specifically for this purpose. See the attached web link at the end of this document for more information.

AC current in high levels can also be an issue. It is rare that magnitudes of AC current flowing on a small vessel would reach levels that would be a corrosion problem.

Recent studies have found that AC current densities can have the following effects:

- Less than 20 Amperes per square meter = No notable AC corrosion

- Greater than 20 Amperes per square meter but less than 100 Amperes per square meter = Corrosion is unpredictable and influenced by many environmental factors
- Greater than 100 Amperes per square meter = AC corrosion is likely to occur.

An effective method of determining current densities is to install a steel coupon of a known surface area adjacent to the structure under investigation and connect it to the structure through a current measurement shunt. With the known area and current magnitude, a current density per unit area can be measured. This test would normally be conducted by a corrosion professional.

COMMENTS

The design of the AC shore power system will electrically bond neighboring vessels together through the common ground conductor. Therefore if one vessel has a problem, i.e., faults in the AC system or poor cathodic protection levels, it will likely have an affect on the neighboring vessel(s). The actual magnitude of the interaction is dependant on the quality of interconnect through the common ground. This would be a function of the actual circuit resistance between the vessels. This would likely be a large range due to the variations of the wiring of the individual vessels. Electrical isolation of the vessel from the grounding system is required to prevent these issues.

As you can see there are many variables that can contribute to an individual vessel's vulnerability to corrosion. A corrosion issue can be self imposed or the result of being interconnected to a problem vessel. The vast majority of corrosion issues are from improper monitoring and maintenance of the coating and cathodic protection system. Coating systems on hulls and outdrives can fail due to many reasons. Some are: a. Poor surface preparation prior to coating application. b. Disregard for monitoring temperature and humidity requirements as required by the specific coating system. c. Improper application, i.e., too thin, too thick, exceeding the pot life of the coating. d. Cathodic disbondment (rare) which is blistering and disbondment of the coating due to excessive high cathodic protection levels or discharge of AC current of high current densities.

CONCLUSIONS

Stray currents either AC or DC significant enough to cause notable "stray current corrosion" in a facility like Marina 1 is rare. None of the tests performed during our survey or review of the Waterfront Department data suggest anything that would be considered a "Hot Harbor" or "Hot Slips". Each of the reported corrosion problems have their own unique causes and there are simple tests that can be performed to identify the source of the corrosion.

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RECOMMENDATIONS

STAINLESS STEEL COLLARS

Use the original 316 SS sleeves, and install them with a sealant between the sleeve and non metallic pipe to eliminate the ingress of seawater, thus eliminating the crevice corrosion issues. Some caulks are very good, however many depend on acetic acid evaporation to cure, i.e., silicone sealants. These should not be used as they possibly will initiate crevice corrosion by creating a local acidic environment.

In the event that the above recommended sealant proves unsatisfactory, changing to a different alloy would be a method to preclude the crevice corrosion. Hasteloy or AL-6XN are both stainless steel alloys that are well known for their resistance to crevice corrosion. They are also much more expensive. However, consider the costs of continually replacing 316L stainless steel components, downtime and labor costs associated with those replacement, the long term operating costs could likely be less.

TESTS TO DETECT POSSIBLE CORROSION ISSUES ON INDIVIDUAL VESSELS - See attached "Vessel Corrosion Evaluation Testing Form" Data from the following test procedures should be entered on this form.

1. CATHODIC PROTECTION SYSTEM TESTS - To test the operational effectiveness of the on board cathodic protection system, structure(Hull/drive system) to water potential readings shall be measured. This test will require the use of a digital multimeter and a silver chloride reference electrode with a submersible adapter. The digital meter should be set on DC volts. Negative of the meter connected to the reference electrode. Positive of the meter connected to the common bonding/ground within the vessel. This point of connection can often be accomplished by connecting to a fuel fill cap from the outside without boarding the vessel. Lower the silver chloride reference electrode into the water adjacent to the vessel under test. Multiple readings should be obtained for comparison by moving the point of connection to different locations on the vessel.. A reading of -0.800 volts or greater is indicative of a cathodic protection system that is providing adequate protection. Readings greater (more negative) than -1.200 volts indicate that the Cathodic Protection system is operating at a higher than required level. Readings greater than -1.200 volts have the potential of damaging hull or outdrive coating systems. Concurrently while obtaining the DC potentials, it is advisable to switch the meter over to AC volts and record the AC to structure to water potential. Both DC and AC potential tests should be performed with the vessel connected to shore power and also identical tests with the vessel disconnected from shore power.

   The higher (more negative) the structure to water potential means that there is a higher cathodic protection current density being applied to the underwater metallic structures. Typically a higher reading is achieved with more anodes, bigger anodes, more efficient coating system or a combination of all of these.

NOTE: Vessels with known coating problems should be surveyed using the method described in this document BEFORE they are hauled out. Results of these tests may yield clues as to the root cause of the coating problem.

2. SHORE POWER CURRENT TESTS - Measure AC & DC currents on power and ground cables. Disconnect the shore power cable from the power pedestal. Plug in a "Break out" patch pigtail assembly. This is a short power cord that allows access to each of the individual power cables. The Waterfront Department already has this device. Using a clamp on current meter, measure and record the AC & DC current on the Black (hot), White (neutral) and Green (Ground) cables. The AC currents on the hot and neutral lines can be anything from zero to maximum rating of the supply system. However they should be of equal values. Both AC & DC currents on the ground cable should be less than 0.050 amperes. Any current measurement above 0.100 indicates that a problem may exist onboard the vessel and further investigation is advised.

3. GALVANALERT TEST - The "GalvanAlert Shore Power Corrosion Detector" if available should be used per instructions. As shown in our tests. If an AC polarity problem is found it will quickly indicate this as well as potential galvanic corrosion issues. Typically if a higher than normal ground current is detected the device will indicate a high galvanic activity.

Any of the above tests that do not meet the specified minimum requirements should be followed up with similar tests on adjacent vessels. As noted, vessels connected to the shore power system are in effect electrically bonded together unless special isolation equipment is installed.

If it is determined that an "offending" vessel has be identified. Comparative tests should be performed at least three vessels on each side.

TESTS OF THE SHORE POWER GROUNDING SYSTEM

1. Measure and record the ground current (AC & DC) at each of the distribution transformers. Preferred test results would yield consistency from transformer to transformer.

2. Any transformer with atypical ground currents can be an indicator of possible issues with individual vessels assigned to the transformer.

3. Further investigation would include testing of individual vessels assigned the that transformer.

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Note that a separate stand alone document will be issued that will be used to distribute to individual vessel owner/operators. The document will provide a primer on the basics of corrosion and testing methods and procedures that can be performed to assess if their vessel is at risk for any corrosion issues and provides some options for correction of any known issues.

We trust that the enclosed information is adequate for your needs. If you have any questions, or if we can assist you in any way, please do not hesitate to call.

Respectfully,

Farwest Corrosion Control Company

John C. Bollinger
PE #CR 937

References and Attachments:

Please review the "DEI Marine Galvanic Isolator Resources" section for a wealth of technical information. This can be found at the following link:http://www.farwestcorrosion.com/fwst/marine/galvanic_isolators.htm

Individual Vessel Corrosion Evaluation Form (Double click on Excel Icon to open file)

8566A Santa Barbara Harbor Test :

APPENDIX

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DEFINITIONS:

Anode: The electrode of and electrochemical cell at which oxidation occurs. (Electrons flow away from the anode in the external circuit, which is normally metallic. The anode is usually the electrode where corrosion occurs and metal ions enter solution.)

Bond: A method to provide electrical continuity between two structures. The bond may be through a dedicated electrical cable or by direct metal to metal contact.

Cathode: The electrode of an electrolytic cell at which reduction occurs. The cathode is the NON corroding element in a corrosion cell.

Cathodic Polarization: The change of electrode potential in the electronegative direction resulting from the flow of current between the electrolyte and electrode.

Cathodic Protection: A technique to control the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

Cell: Two metallic elements in a common electrolyte that generates an electromotive force by an irreversible conversion of chemical to electrical energy. See also "Half Cell"

Cell to Cell Voltage: The electrical voltage/potential between half cells electrodes in a common electrolyte. The electrodes can be reference electrodes as used when testing cathodic protection systems. See also "Half Cell".

Corrosion Coupon: An isolated piece of metal (specific alloy) buried or submerged in the electrolyte to serve as a relative indicator as to the freely corroding potential of the specific metal. Each coupon will have an insulated wire terminated at an above ground test box for monitoring purposes.

Corrosion Potential: The mixed potential of a freely corroding structure surface with reference to an electrode in contact with the electrolyte.

Corrosion Rate: The rate at which corrosion proceeds, expressed as either weight loss or penetration, per unit time.

Current Density: The sum of the electrical current applied or discharged per unit area.

Electrical Isolation: The condition of being electrically separated from other metallic structures or the environment.

Electrode: An electronic conductor used to establish electrical contact with an electrolyte part of a circuit. See also "Cell", "Galvanic Cell" & "Half Cell"..

Electrolysis: A chemical decomposition reaction of metallic structures produced by passing an electric current through a solution containing ions.

Electrolyte: A chemical substance or mixture containing ions that migrate in an electric field. For the purpose of this discussion, electrolyte refers to the soil or liquid adjacent to and in contact with a buried or submerged metallic structure, including the moisture and other chemical contained therein.

Galvanic Anode: A metal which, because of its relative position in the galvanic series, provides protection to metal or metals that are more noble in the series, when coupled in an electrolyte.

Galvanic Corrosion: An electrochemical process in which one metal corrodes preferentially to another when both metals are in electrical contact and immersed in an electrolyte. The same galvanic reaction is exploited in primary batteries to generate a voltage.

Galvanic Series: A list of metals and alloys arranged according to their relative potentials in a given environment.

Half Cell: Either of the two connected electrodes of an electrochemical cell. OR one electrode in a conductive fluid (electrolyte). Reference electrodes used in testing and monitoring corrosion control systems are referred to as "Half Cells". Typically Copper-Copper Sulfate half cell is used for soil applications where a Silver-Silver Chloride half cell is used in salt water applications..

Impressed Current: Direct current supplied by a cathodic protection system utilizing an external power source.

IR Drop: The voltage across a resistance in accordance with Ohm's Law.

Mixed Potential: A potential resulting from two or more electrochemical reactions occurring simultaneously on one metal surface.

Structure-to-Electrolyte Potential: The potential difference between the metallic structure surface and electrolyte that is measured with reference to an electrode in contact with the electrolyte (typically soil or water).

Polarization: The deviation from the corrosion potential of an electrode resulting from the flow of current between the electrode and the electrolyte.

Polarized Potential: The potential across the structure/electrolyte interface that is the sum of the corrosion potential and the cathodic polarization.

Reference Electrode: A reversible electrode with a potential that may be considered constant under similar conditions of measurement.

Shielding: Preventing or diverting the cathodic protection current from its intended path.

Sound Engineering Practices: Reasoning exhibited or based on thorough knowledge and experience, logically valid and having true premise showing good judgment or sense in the application of science.

Stray Current: Current in paths other than the intended circuit.

Stray Current Corrosion: Corrosion resulting from stray current transfer between the metallic structure and electrolyte.

INTRODUCTION TO CORROSION

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Excerpts from:

"CONTROL OF PIPELINE CORROSION"

By

A.W. Peabody

WHAT IS CORROSION?

Ask ten different people and you will get as many different answers. Some say corrosion is oxidation. Others will say it is a chemical attack. Still others will say it is an electrical phenomenon, electrolysis. Each is partially true. Aside from unusual types of corrosion such as bacterial or direct chemical attack, we can say that the corrosion process is basically electrochemical in nature.

A metallic structure buried or submerged is essentially a length of metal embedded in an electrolyte. For many different reasons, electrical potentials may vary from one spot to another with the result that anodic areas and cathodic areas will exist. These different electrical potential areas are the basis for an electrolytic "corrosion cell".

There are certain conditions which must be present before an electrolytic corrosion cell can function:

1. There must be an anode and a cathode.
2. There must be an electrical potential between the anode and cathode. (This potential can result from a variety of conditions on buried or submerged metallic structures.)
3. There must be a metallic path electrically connecting the anode and cathode.
4. The anode and cathode must be immersed in an electrically conductive electrolyte. The usual soil moisture or water surrounding the structure normally fulfills this condition.

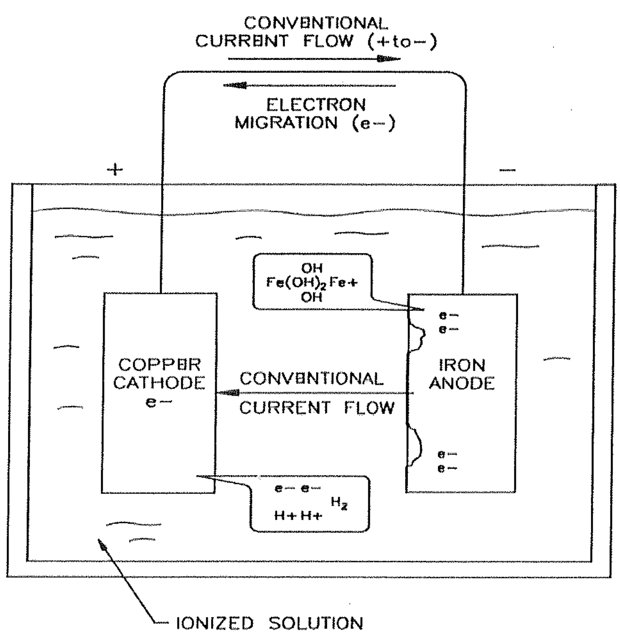
Once these conditions are met, a "corrosion cell" is created and an electric current will flow and metal will be consumed at the anode. Remove any one of the above four items and the corrosion is stopped. Refer to Figure 1.

The anode and cathode of a corrosion cell may be a fraction of an inch apart or many feet apart depending upon the cause of the potential difference between the two locations. The **rate of corrosion** is directly proportional to the rate of current flow. The rate of current flow is affected by many factors -- soil/water resistivity, structure coating efficiency, etc.

The electrical pressure between the anode and the cathode results in a migration of electrons from the anode to the cathode along the metallic path. At the anode, with the loss of electrons, positively charged iron atoms remain which combine with negatively charged (OH-) ions in the environment to form a ferrous hydroxide, which in turn usually reacts further to form ferric hydroxide (RUST).

At the cathode, a surplus of electrons has arrived from the anode. These surplus negatively charged electrons combine with positively charged hydrogen ions from the environment to form hydrogen (H_2). This hydrogen at the cathode is the basis of the "polarization film" which will be discussed later.

For practical use, current flow is defined in terms of the conventional concept which is opposite to actual electron flow. Figure 1 shows the conventional direction for + (more positive) to - (more negative) in the metallic portion of the circuit. The circuit is completed through the electrolyte.



DIAGRAMATIC REPRESENTATION
BIMETAL CORROSION CELL

FIGURE 1

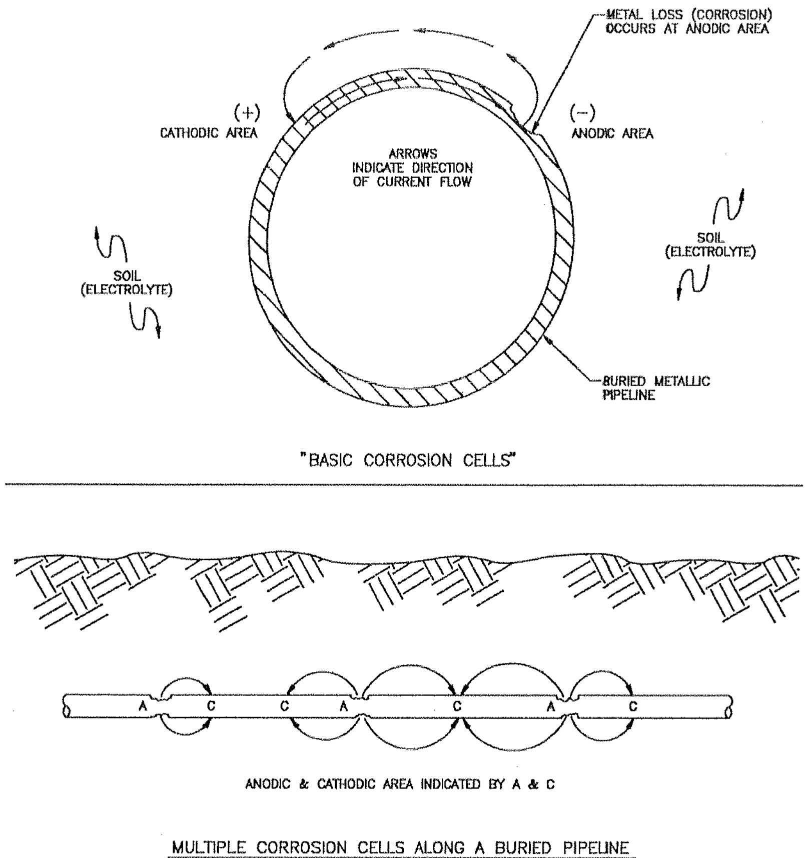


FIGURE 2

Figure 2 is a diagrammatic presentation of corrosion with conventional current direction shown.

The following points should be remembered in terms of conventional current flow:

1. Conventional current flow will be from the cathode to the anode in the metallic circuit.
2. Conventional current flow from the anode to the cathode in the electrolyte.

3. Metal is consumed where current leaves the structure to enter the surrounding electrolyte.
4. That metal receiving sufficient current from the surrounding electrolyte does not corrode.

CATHODIC PROTECTION

Cathodic protection is, very simply, the use of direct current electricity from an external source to oppose the discharge of corrosion current from anodic areas that would be present naturally. When a cathodic protection system is installed for maximum effect, all portions of the protected structure collect current from the surrounding electrolyte and the entire exposed surface becomes a single cathodic area--hence the name.

DISSIMILAR METAL CORROSION CELL

The simplest cell to visualize is the dissimilar metal corrosion cell. Such a cell can be established whenever different metals are used in construction provided there is an electrical contact between them and provided they are in contact with a common electrolyte (soil or water). Under such conditions, any two dissimilar metals may be expected to have an electrical potential between them. The magnitude of this potential, and which one of the two metals will be anodic, will normally depend on the position of the metals in the electromotive force series.

The relative position of these metals are shown in the "Practical Galvanic Series". All potentials are measured with respect to a copper-copper sulfate reference electrode (or "half cell") commonly used in corrosion control testing of buried structures..

TABLE 1 - PRACTICAL GALVANIC SERIES

Metal	Volts *
Commercially pure magnesium	-1.75
Magnesium alloy (6% Al, 3% Zn, 0.15% Mn)	-1.60
Zinc	-1.10
Aluminum alloy (5% Zn)	-1.05
Commercially pure aluminum	-0.80
Mild steel (clean and shiny	-0.5 to -0.8
Mild steel (rusted)	-0.4 to -0.55
Cast Iron (not graphitized)	-0.50
Lead -0.50	
Mild steel in concrete	-0.20
Copper, Brass, Bronze	-0.20
Mill scale on steel	-0.20

*Typical potentials observed in neutral soils and water, measured with respect to copper sulfate reference electrode.

The Practical Galvanic series is arranged with the most active metals uppermost so that, of any two metals selected, the one uppermost normally will be the anode and the lower one the cathode.

As an example of how the table works, assume that an underground plain steel pipeline is built with copper branch lines. Unless the copper lines are electrically insulated from the steel pipe, conditions for dissimilar metal corrosion exist. It can be seen from the Table 1 that iron (or steel) appears in the series above copper, indicating that steel will be the anode and would corrode. This is, in fact, the case and in a low resistivity soil, the copper lines would produce aggravated and rapid corrosion of the steel pipe.

CORROSION CONTROL METHODS

With some of the conditions that cause corrosion understood the techniques used to control corrosion can be better understood. The three basic methods for mitigating electrolytic corrosion on metallic structures are the following:

1. Electrical isolation
2. Coatings
3. Cathodic protection

ELECTRICAL ISOLATION

The basic first step in corrosion control is to isolate the structure from foreign metallic structures. A foreign structure can be other pipelines, boats, electrical conduits, and electrical grounding systems.

Electrical isolation obviously will not prevent localized corrosion cells on the primary structure. Electrical isolation reduces the corrosion control problem to the soil or water environment effects on the primary structure, itself.

COATINGS

Coatings normally are intended to form a continuous film of an electrically insulating material over the metallic surface to be protected. A coating would be completely effective as a means of stopping corrosion if:

1. The coating material is an effective electrical insulator.

2. It can be applied with no breaks whatsoever and will remain so during shipping, installation and backfilling.
3. It provides an initially almost perfect film which will remain so with time.

Coatings vary in quality as initially installed and in resistance to damage during handling and installation.

A coated structure installed can be expected to have points of damage or coating imperfections (holidays) that allow electrolyte to contact the metal. Any corrosion cell must be within a holiday area or consist of two holidays--a cathodic holiday and another anodic holiday.

Longevity of coating is a complex subject. Dielectric strength and permeability are affected with time.. This along with additional physical damage will in effect increase the surface area required to protect.

A structure with a new coating should initially have a coating efficiency of better than 99%.

A well coated structure will typically have some coating defects or holidays. A cathodic protection system need only protect the minute areas of steel exposed to the earth at the holidays rather than the whole surface of an uncoated structure. The electrical energy required to cathodically protect a bare structure may be thousands of times greater than the energy required to protect the same structure when well coated.

PRACTICAL APPLICATION OF CATHODIC PROTECTION

In order for a cathodic protection system to work, current must be discharged from a ground electrode (anode). The current is forced to flow onto the structure at areas which were previously anodic. When the proper amount of current flow is discharged from the anodes, it is collected onto the structure and overpowers the natural corrosion currents that were discharging from the anodic areas and as a result there will be a net current flow onto all areas of the structure surface. The entire surface then will be cathodic and the corrosion protection complete.

Actually a cathodic protection system does not necessarily eliminate corrosion. It does, however, transfer the corrosion from the surface of the protected structure and concentrates the corrosion at another location--the installed anode. At the end of the anode's useful life it can easily be replaced and at no time has the protected structure suffered any corrosion.

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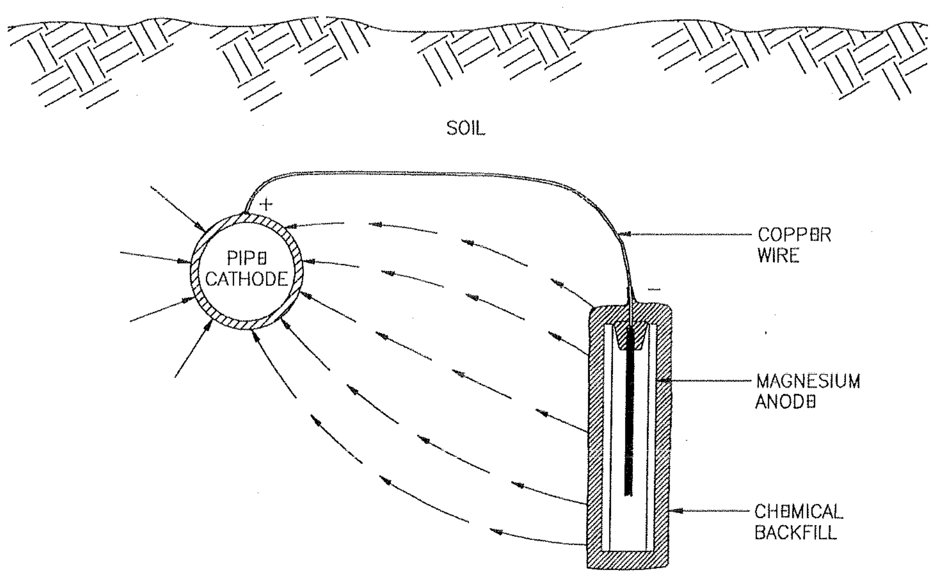
Cathodic protection systems can be divided into two categories.

1. "Galvanic Anode" Systems
2. Impressed Current (Rectifier) Systems

GALVANIC ANODE SYSTEMS

Galvanic anode systems are the simplest and probably the most reliable (Figure 3). We know that when two dissimilar metals are in contact in an electrolyte the more anodic metal corrodes. In a cathodic protection system utilizing galvanic anodes, advantage of this effect is taken by purposely establishing a dissimilar metal cell strong enough to counteract the corrosion cell normally existing on the pipeline or structure that is to be protected. This is accomplished by selecting a material that is strongly anodic to the structure metal.

The galvanic anodes used in soil applications are usually made of a magnesium alloy. In low resistivity soils and in seawater applications, zinc and aluminum anodes would be the material of choice. Table 1 shows us that the driving voltage between the steel and the magnesium is typically less than one volt. Therefore, if the anodes are to generate a useful amount of current, the contact resistance between the anodes and the earth must be low. This means that galvanic anodes are normally used in relatively low resistivity soils or water.



TYPICAL MAGNESIUM ANODE INSTALLATION

FIGURE 3

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Corrosion Control Products Company

IMPRESSED CURRENT
Impressed current cathodic protection systems free us from the limited driving voltage of the galvanic anodes. A D.C. Voltage from an outside source is "impressed" on the circuit between the protected structure and the anodes. The most common source of power is the cathodic protection rectifier or D.C. power supply.

This device simply converts alternating current electric power (from the power distribution system) to low voltage direct current. The output voltage of the unit is usually adjustable. Cathodic protection rectifiers are available in output capacities of from less than one ampere to many hundreds of amperes. Impressed current systems (Figure 4) are inherently more complex than galvanic systems and typically require more maintenance.

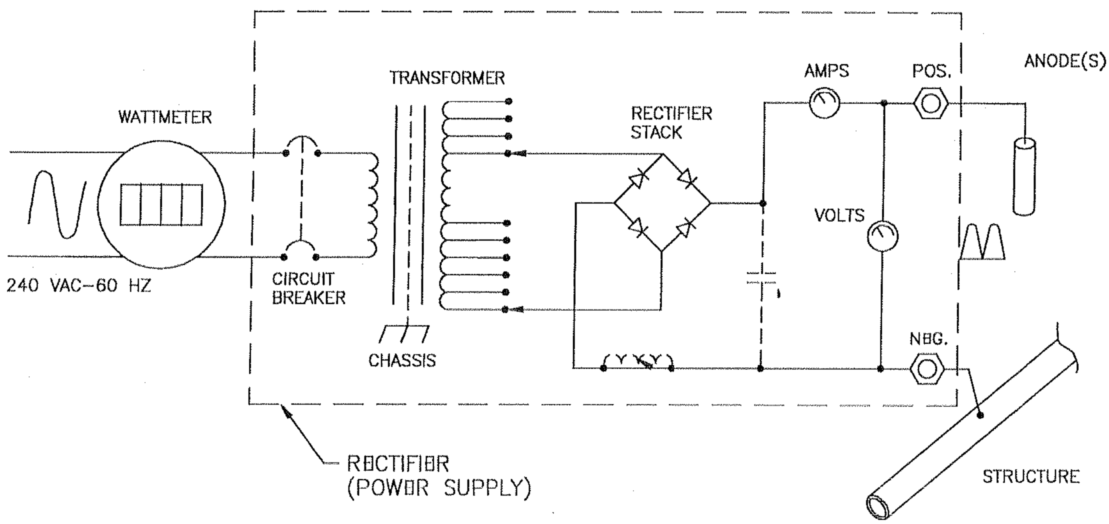

FIGURE 4

BASIC IMPRESSED CURRENT CATHODIC PROTECTION SYSTEM