



# **CP 4– CATHODIC PROTECTION SPECIALIST COURSE MANUAL**

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| 1                 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1                 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |  |
| 2                 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2                 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |  |
| 3                 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3                 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |  |
| 4                 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4                 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |  |
| 5                 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5                 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |  |
| 6                 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6                 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |  |
| 7                 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7                 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |  |
| 8                 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8                 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |  |
| 9                 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9                 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |  |

| LAST NAME |   |   |   | FIRST NAME |   |   |   | M.I. |   |   |   | CODE |   |   |   |
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| N A C E   |   |   |   | J O E      |   |   |   |      |   |   |   |      |   |   |   |
| A         | A | A | A | A          | A | A | A | A    | A | A | A | A    | A | A | A |
| B         | B | B | B | B          | B | B | B | B    | B | B | B | B    | B | B | B |
| C         | C | C | C | C          | C | C | C | C    | C | C | C | C    | C | C | C |
| D         | D | D | D | D          | D | D | D | D    | D | D | D | D    | D | D | D |
| E         | E | E | E | E          | E | E | E | E    | E | E | E | E    | E | E | E |
| F         | F | F | F | F          | F | F | F | F    | F | F | F | F    | F | F | F |
| G         | G | G | G | G          | G | G | G | G    | G | G | G | G    | G | G | G |
| H         | H | H | H | H          | H | H | H | H    | H | H | H | H    | H | H | H |
| I         | I | I | I | I          | I | I | I | I    | I | I | I | I    | I | I | I |
| J         | J | J | J | J          | J | J | J | J    | J | J | J | J    | J | J | J |
| K         | K | K | K | K          | K | K | K | K    | K | K | K | K    | K | K | K |
| L         | L | L | L | L          | L | L | L | L    | L | L | L | L    | L | L | L |
| M         | M | M | M | M          | M | M | M | M    | M | M | M | M    | M | M | M |
| N         | N | N | N | N          | N | N | N | N    | N | N | N | N    | N | N | N |
| O         | O | O | O | O          | O | O | O | O    | O | O | O | O    | O | O | O |
| P         | P | P | P | P          | P | P | P | P    | P | P | P | P    | P | P | P |
| Q         | Q | Q | Q | Q          | Q | Q | Q | Q    | Q | Q | Q | Q    | Q | Q | Q |
| R         | R | R | R | R          | R | R | R | R    | R | R | R | R    | R | R | R |
| S         | S | S | S | S          | S | S | S | S    | S | S | S | S    | S | S | S |
| T         | T | T | T | T          | T | T | T | T    | T | T | T | T    | T | T | T |
| U         | U | U | U | U          | U | U | U | U    | U | U | U | U    | U | U | U |
| V         | V | V | V | V          | V | V | V | V    | V | V | V | V    | V | V | V |
| W         | W | W | W | W          | W | W | W | W    | W | W | W | W    | W | W | W |
| X         | X | X | X | X          | X | X | X | X    | X | X | X | X    | X | X | X |
| Y         | Y | Y | Y | Y          | Y | Y | Y | Y    | Y | Y | Y | Y    | Y | Y | Y |
| Z         | Z | Z | Z | Z          | Z | Z | Z | Z    | Z | Z | Z | Z    | Z | Z | Z |

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# NACE CORROSION NETWORK (NCN)

NACE has established the NACE Corrosion Network, an electronic list serve that is free to the public. It facilitates communications among professionals who work in all facets of corrosion prevention and control.

If you subscribe to the NACE Corrosion Network, you will be part of an E-mail-driven open discussion forum on topics A-Z in the corrosion industry. Got a question? Just ask. Got the answer? Share it! The discussions sometimes will be one-time questions, and sometimes there will be debates.

The topics will range from questions and answers about cathodic protection to materials and chemical inhibitors and tons more!

What do you need to join? An E-mail address. That's all! Then:

1. Send a blank email message to:  
[Join-nace@nacecorrosionnetwork.com](mailto:Join-nace@nacecorrosionnetwork.com)
2. To Unsubscribe, send a blank e-mail to:  
[Leave-nace@nacecorrosionnetwork.com](mailto:Leave-nace@nacecorrosionnetwork.com)
3. You're done! You'll get an e-mail back telling you how to participate, but it's so easy that you'll figure it out without any help.

## Audience (Who Should Attend)

This course is directed toward those who intend to become certified Cathodic Protection Specialists or engineers who have a need to know the finer points of cathodic protection and the design of cathodic protection systems.

## Prerequisites

To attend this training course, students must meet the following prerequisites:

### Path 1

- 12 years cathodic protection work experience
- 2-year post high school training in Math or Science from an approved Technical/Trade School
- CP 2–CP Technician Certification or equivalent training

### Path 2

- 6 years cathodic protection work experience
- 4-year Physical Science or Engineering degree
- CP 2–CP Technician Certification or equivalent training

### Path 3

- 4 years cathodic protection work experience
- One of the following:
- Bachelor's degree in Engineering or Physical Sciences AND an advanced degree in Engineering or Physical Science that required a qualification exam
- PE, Peng, or equivalent
- CP 2–CP Technician Certification or equivalent training

## Length

The course begins on Sunday at 1:00 pm and concludes on Friday at 5 pm.

## Examination

This course will conclude with a written final examination.

The final examination is open book and students may bring reference materials and notes into the examination room. The final examination will be given on Friday.

Non-communicating, battery-operated, silent, non-printing calculators, including calculators with alphanumeric keypads, are permitted for use during the examination. Calculating and computing devices having a QWERTY keypad arrangement similar to a typewriter or keyboard are not permitted. Such devices include but are not limited to palmtop, laptop, handheld, and desktop computers, calculators, databanks, data collectors, and organizers. Also excluded for use during the examination are communication devices such as pagers and cell phones along with cameras and recorders.

A score of 70% or greater on the examination is required for successful completion.

## Certification Application

Successful completion of the written examination and an approved CP 4–Cathodic Protection Specialist certification application is required to obtain certification.



### Concepts, Definitions and Conventions

#### ***Cathodic Protection***

Cathodic protection is a technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell. The cathode in an electrochemical cell is the electrode where reduction (and no corrosion) occurs. Prior to applying cathodic protection, corroding structures will have both cathodic areas and anodic areas (those areas where corrosion is occurring). It follows, then, that if all anodic areas can be converted to cathodic areas, the entire structure will become a cathode and corrosion will be eliminated.

Classic Definition: Cathodic polarization of all noble potential areas (cathodes) to the most active (anode) site on the metal surface.

Cathodic protection is achieved by making the structure the cathode of a direct current circuit in which the flow rate of charge is adjusted to assure that the polarized potential is at least as active (electronegative) as the most active anode site on the structure.

A glossary, based in part on “NACE International Glossary of Corrosion Related Terms”, is included as Appendix A.

Thermodynamic Definition: The structure must be cathodically polarized to the potential of thermodynamic stability of the specific metal in the specific environment. This corresponds to the area of immunity on a Pourbaix (pH – Potential) diagram described later in this chapter. Cathodic protection current requirement under these two definitions need not be identical.

# Energy

## Pourbaix Diagrams

The concept of energy relationships is fundamental to corrosion control and cathodic protection. Figure 1.1 is a simplified version of a Pourbaix Diagram for iron that relates electrical potential with the pH of a system. It is essentially a diagram of energy versus pH for an element and its compounds. The simplified diagram presented in Figure 1.1 shows three regions of stability for iron: immunity, corrosion, and passivation.

Assuming passivation by films of  $\text{Fe}_2\text{O}_3$  and  $\text{Fe}_3\text{O}_4$

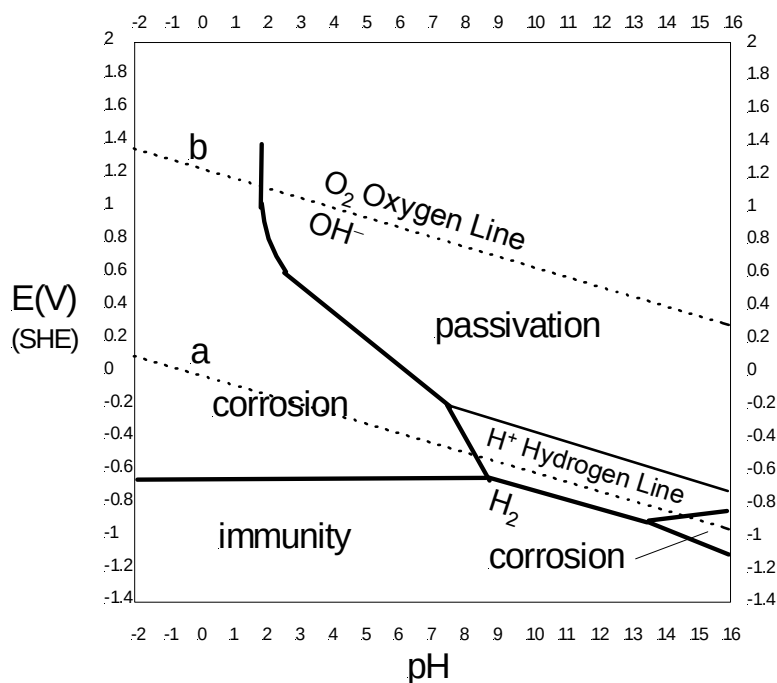


**Figure 1.1 Pourbaix Diagram**

Also shown on the diagram are dashed lines (a) and (b). Line “a” represents the lower limit of stability of water. These are the conditions of pH and potential at which hydrogen ions in the water are in

equilibrium with hydrogen gas at one atmosphere pressure. The chemical equation is:



Line “b” represents the upper limit of stability of water. These are the conditions where oxygen gas can be released from water at an electrode. The equation is:



The lines bounding all the other regions on the diagram represent the area of thermodynamic stability of the product indicated. The potentials given on this diagram (Figure 1.1) are referenced to a standard hydrogen electrode (SHE). To obtain the potential referenced to a saturated copper/copper sulfate reference electrode, subtract 0.316 volts (316 mV) from the SHE potential. Note that the area of stability for immunity lies about -0.60 volts for pH's of -2 through 9. If the pH is greater than 9, the line closely parallels the equilibrium line for hydrogen evolution (Line a). True “thermodynamic” cathodic protection would require that the potential of iron be maintained on or more negative than the line bounding the iron stability region.

On the Pourbaix diagram, the region (or domain) between Line “a” and Line “b” is the area where water is stable. At potentials more negative than Line “a”, hydrogen ions are reduced to hydrogen gas. The entire stable region for iron lies more negative than Line “a”. It is not possible to “thermodynamically” cathodically protect iron without the possibility of reducing at least some hydrogen ions at the metal surface. Most commonly used cathodic protection criteria do not exceed the potentials for evolution of hydrogen except at a pH below 9.

The Pourbaix diagram suggests that the current needed to protect iron (or other metals) must be sufficient to keep the potential of the metal at least as electro-negative as the region of stability for the metal at a given pH.

More detail can be found on Pourbaix diagrams in the Atlas of Electrochemical Equilibria in Aqueous Solutions by Marcel Pourbaix is available from NACE International.

Corrosion occurs where metal atoms give up electrons that produce electron flow (negative current flow) away from the area and positive ions (corrosion products). The objective of cathodic protection is to force the entire surface to act as a cathode so there is no electrical potential to cause the electrochemical reaction and, therefore no corrosion occurs. The application of direct current to a corroding metal structure can cause it to become

entirely cathodic. Figure 1.2 illustrates direct current associated with the corrosion process on a buried or submerged metallic pipeline.

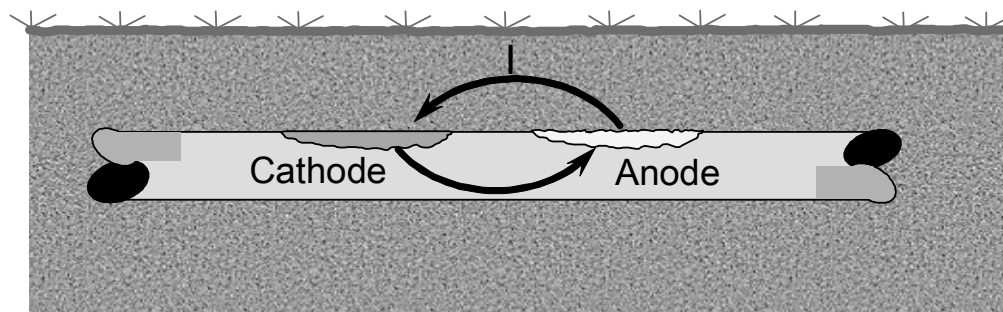


**Figure 1.2 Underground Corrosion Cell**

Positive ions, as corrosion products, pass from the anode areas into the environment. Simultaneously, other positive ions from the environment accept electrons from the metal surface at the cathode of the cell. As positive ions are neutralized (reduced) at the cathode, negative ions move from the cathode vicinity toward the anode. Both positive and negative ions are involved in the charge transfer process. From there, current flow is back through the metal itself to complete the circuit. For a given driving voltage (the open-circuit potential between the anode and cathode), the amount of current is limited by such factors as the resistance of the environment (concentration of ions present in the electrolyte) and the degree of polarization at anode and cathode areas. Figure 1.3 shows an equivalent electrical circuit for a simple corrosion cell. Polarization is a function of the corrosion current density,  $i$ .

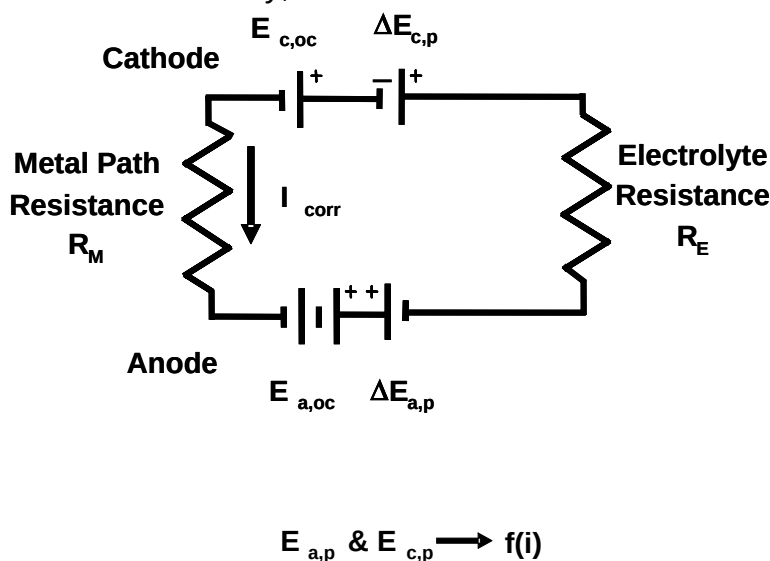


**Figure 1.3 Equivalent Electrical Circuit for Simple Corrosion Cell**

The polarities shown on the symbols representing  $E_{c,oc}$  and  $E_{a,oc}$  represent the polarity of the metal with respect to the electrolyte at the cathodic and anodic sites. The total potential difference between the open circuit potential of the anode and cathode, which is the driving voltage for corrosion, is such that the cathode is positive with respect to the anode as shown in Figure 1-2. The polarities shown on the symbols representing polarization potentials  $E_{c,p}$  and  $E_{a,p}$  represent the polarity of polarization effects. The polarization potentials are opposite to the potentials of the cathode and anode that constitute the cell. The result of polarization is to reduce the total potential difference between the anode and cathode of the corrosion cell.

Figure 1-4 illustrates the basic manner in which cathodic protection is applied. The original corroding section of pipe illustrated Figure 1-2 becomes a cathode. The cathodic protection current must pass into the environment from a cathodic protection anode (usually called a ground bed in underground cathodic protection) established for the purpose. By definition, the materials used in the ground beds are anodes, and conversion of electric current into positive ions occurs at the ground bed.

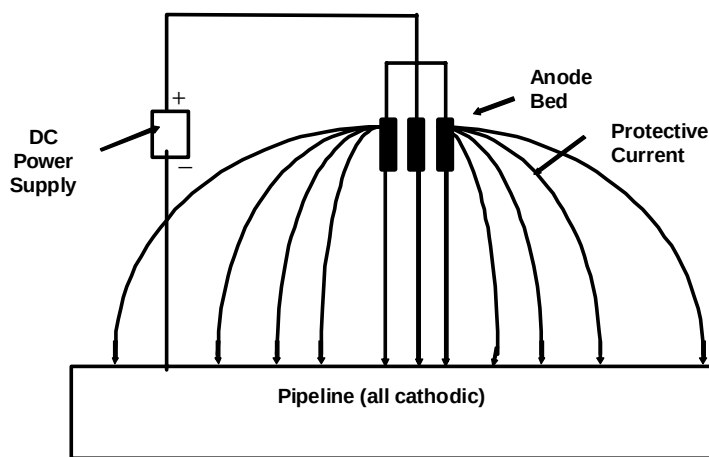


**Figure 1.4 Cathodic Protection of a Buried Pipeline**

## ***Polarity and Sign Convention***

To avoid confusion, it is necessary to adopt a standard sign convention for electrical circuits. The basis for the sign convention is the assumption of positive charge movement. Anytime current direction is assigned, it must be based upon the assumption that the charge carriers are positive. This assumption of positive charge carriers is known as conventional current. The conventional current direction is opposite to negative charge flow di-

rection. Conventional current will always be assumed unless specifically stated otherwise.

With the above convention for current direction in mind, two rules can be utilized to establish the voltage polarity. The rules apply only to circuits external to the power source.

- RULE 1: Conventional (positive) current direction is from the positive voltage terminal of a power-producing device, “source”.
- RULE 2: Conventional (positive) current direction is towards the positive voltage terminal of a power-consuming device, “load”.

Polarity and sign conventions are illustrated in Figure 1.5.

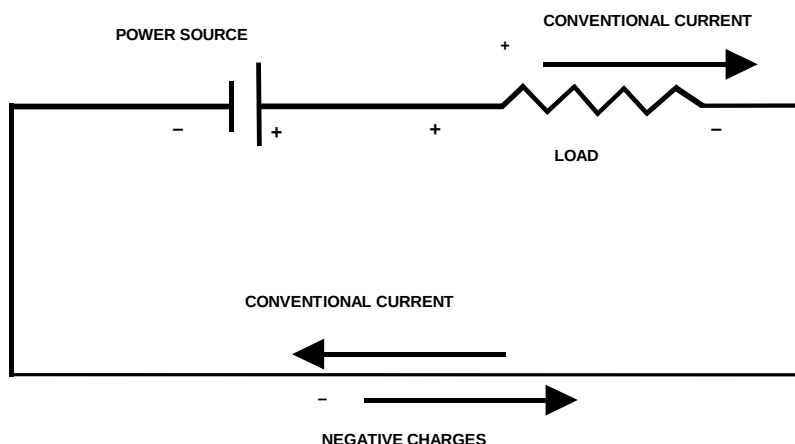


**Figure 1.5 Polarity and Sign Convention**

Resistors are examples of power-consuming devices. Power is consumed by producing heat. Examples of resistive circuit elements found in the corrosion field are lead wires, anode resistance-to-earth, pipeline resistance-to-earth, and lineal resistance of the pipeline itself. Power sources transfer some form of energy into electrical energy within the device itself. Examples of power sources in cathodic protection are rectifiers, solar power supplies, batteries, corrosion cells, and galvanic anode systems.

## ***Electrode Potential Measurement and Reporting Conventions***

Two electrodes each consisting of a metallic element surrounded by a continuous electrolyte and joined by an electronic conductor form a galvanic cell. The electrolytes may be chemically different but have a common boundary or the electrodes may be immersed in a common electro-

lyte. Each of the electrodes together with the electrolyte surrounding it is called a half-cell. A metal structure in contact with soil or other electrolyte is in fact a half-cell even though there may be many local cells (anodes and cathodes) on the surface of the metal. In order to obtain a measurement of the half-cell potential of the structure, a second half-cell with a known stable half-cell potential is required. The potential of the structure measured with respect to the stable reference half-cell provides the desired information.

In order to report a half-cell potential measurement properly, four components are required: polarity, magnitude, unit of measurement, and reference. For example, "-0.850 volts CSE" means "a negative value of 0.850 in the units of volts when measured with respect to a copper/copper sulfate (CSE) reference cell." If any of the four components of the potential measurement are ignored or not reported, confusion regarding the measurement is possible.

All half-cell potentials must be measured relative to a standard or reference, such as the copper/copper sulfate reference (CSE). Therefore, it is always necessary to report the specific reference used to measure the half-cell potential. For example, a protective potential measured for a buried steel pipeline could be reported as -0.850 volts "relative to a saturated copper/copper sulfate reference (CSE)." Often this potential is reported as -0.850 volts "pipe-to-soil."

Although this might not be the best reporting method, it is widely understood in the corrosion field that "pipe-to-soil" actually means "the potential of the pipe relative to a saturated copper/copper sulfate reference in contact with the soil." Table 1.1 lists the most common reference electrodes with their standard half-cell potentials and conversion factors.

***Table 1.1 Standard Reference Potentials and Conversion Factors<sup>1</sup>***

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<sup>1</sup> NACE Corrosion Engineer's Reference Book, Second Edition, R. S. Treseder – Editor, NACE International, Houston, TX



### REFERENCE POTENTIALS

| Electrode                                        | Potential (V) @ 25°C<br>$E^0$ | Temp.Coeff.<br>(mV/°C) |
|--------------------------------------------------|-------------------------------|------------------------|
| $H_2/H^+$ (SHE)                                  | 0.000                         | +0.87                  |
| Ag /AgCl/1MKCl                                   | +0.235                        | +0.25                  |
| Ag /AgCl/0.6MKCl<br>(seawater)                   | +0.25                         |                        |
| AgAgCl /0.1M KCl                                 | +0.288                        | +0.22                  |
| Hg/Hg <sub>2</sub> Cl <sub>2</sub> /sat.KCl(SCE) | +0.241                        | +0.22                  |
| Hg/Hg <sub>2</sub> Cl <sub>2</sub> /1MKCl        | +0.280                        | +0.59                  |
| Hg/Hg <sub>2</sub> Cl <sub>2</sub> /0.1MKCl      | +0.334                        | +0.79                  |
| Cu/CuSO <sub>4</sub> sat                         | +0.316                        | +0.90                  |

In all cases, the potential of interest is the potential of a given electrode relative to a specific reference at 25°C. Notice it is not the potential of the reference relative to the given half-cell that is of interest. At first glance, it might appear that these two potentials are exactly the same. They are not the same. Although both potentials have the same magnitude, one potential is the negative of the other potential. Therefore, in order to report the potential of interest with proper polarity, it must be reported as the electrode potential of interest relative to the specific reference.

To measure the potential of the half-cell of interest relative to a specific reference, the reference must be connected to the negative terminal of the voltmeter in order for the meter display to indicate the correct polarity. This fact is confirmed by the markings found at the negative terminal of many voltmeters indicating "common" or "reference." Since most digital displays can indicate either a positive or a negative value, always connecting the reference to the negative terminal presents no difficulties. However, since most analog displays can only indicate a positive or upscale value, always connecting the reference to the negative terminal results in an attempted down scale pointer deflection if the measurement value is negative. Since the pointer is prevented from moving down scale, the reference lead must be moved to the positive terminal of the voltmeter in order to determine the magnitude of the potential in this case. The value should then be reported as negative. See Figure 1.6.



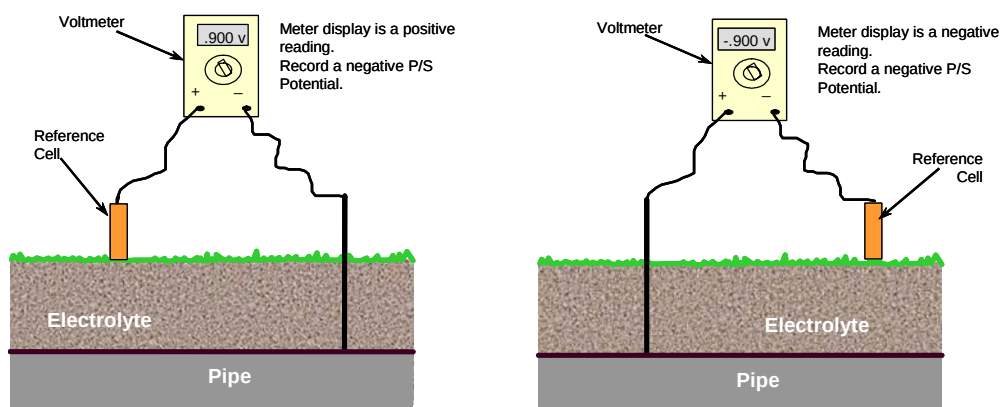


**Figure 1.6 Pipe-to-soil potential measurement**

In summary, when using a digital meter capable of displaying both positive and negative values, if the reference is connected to the negative terminal, the correct polarity to be reported will be indicated by the display. When using analog meters capable of displaying only upscale or positive values, connect the reference to the terminal necessary to produce an upscale measurement. If the reference must be connected to the positive terminal to produce an upscale reading, the measurement should be reported with a negative polarity.

With the assumption of conventional current and potentials reported as the electrode of interest versus a specific reference, the sign of all potentials will be in agreement with the reporting policy of the International Union of Pure and Applied Chemistry (IUPAC) known as the Stockholm Convention.<sup>2</sup> This reporting standard is also the generally accepted sign convention used in the corrosion field.

Remember, electron flow is in the opposite direction of current flow.

## Polarization

As current flow continues over time, polarization occurs at both the anode and cathode. Polarization lowers the potential difference between the anode and cathode areas and, by Ohm's Law, the current,  $I$ , drops and the corrosion rate decreases until an equilibrium is reached between polarization and depolarizing effects. Depolarizers include:

- dissolved oxygen
- changes in ion concentration

<sup>2</sup> David J. G. Ives and George J. Janz, ea., *Reference Electrodes: Theory and Practice*, (New York: Academic Press, 1961), p. 26 - 28.

- water flow
- temperature
- low pH.

Polarization always occurs in the direction to oppose current flow causing it. When the anode and cathode of a corrosion cell are connected, current flows between the two. This current will cause the potential of the anode to approach the potential of the cathode. Also, the potential of the cathode will approach the potential of the anode. The voltage difference between the polarized electrodes decreases approaching a steady-state mixed potential ( $E_M$ ) when the polarizing effect of the current is exactly balanced by external depolarizing effects. The mixed potential is somewhere between the polarized potentials of the two electrodes. The difference between the polarized potentials of the anode and cathode is the driving voltage of the corrosion cell. The current at this steady-state condition is defined as the corrosion current ( $I_{corr}$ ) of the system. The polarization or Evans diagram Figure 1.7, may better illustrate the concept of corrosion cell polarization.

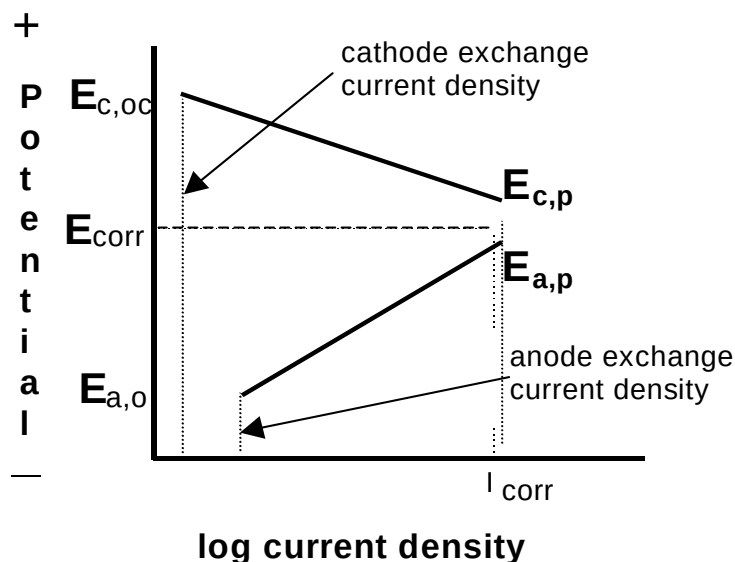


**Figure 1.7 Polarization (Evans) Diagram for a Corrosion Cell**

The electrode potentials prior to current flow are referred to as the open-circuit potentials. These potentials ( $E_{c,oc}$  and  $E_{a,oc}$ ) are the potentials of the cathode and anode before they are connected (short circuited). Under open circuit condition, the only current flowing to or from an electrode is the exchange current. The exchange current is the rate at which either positive or negative charges are entering or leaving the surface when an electrode reaches dynamic equilibrium in an electrolyte. Under equilibrium conditions, there is no net current flow at the electrode. The magnitude of the exchange current density is a function of the specific electrode mate-

rial and the electrolyte and is generally small. Examples are given under Activation Polarization in Table 1.3.

In general, polarization is related to the depletion of the reactants and the build-up of reaction products. Anything that favors the build-up of reaction products or the depletion of reactants increases polarization. Conversely, anything that causes the removal of reaction products or the replenishing of the reactants will reduce polarization.

There are three types of electro-chemical polarization: resistance, activation and concentration.

### ***Resistance Polarization***

Resistance polarization, also called IR drop in soil, is very similar to the concept of resistance in an electronic circuit. Charge transfer in an electrolyte is by means of ions present in solution. The more ions of whatever species, the easier the transfer of charge and the lower the magnitude of the electric field due to charge transfer. The potential difference in the electrolyte and across the boundary layer films caused by charge transfer (equivalent to current flow through a resistor) is called resistance polarization. Resistance polarization is important because it becomes part of the IR drop, which must be considered in the measurement of structure to reference cell potential.

Mathematically resistance polarization is given by the following equation, which is essentially ohm's law.

$$\eta_r = IR_p \quad \text{Eq. 1.1}$$

where:

- $\eta_r$  = resistance polarization (volt)
- $I$  = current flowing in the cell (A)
- $IR_p$  = the resistance included in the measurement (ohms)

For a more complete review of the subject of resistance polarization see Klaus J. Vetter "Electrochemical Kinetics Theoretical and Experimental Aspects", Academic Press, New York, London, 1967, pp 385-395.

## Activation Polarization

Activation polarization is caused by retarding factors inherent in the reaction itself.

For example, consider the evolution of hydrogen gas at the cathode. The rate at which hydrogen ions are reduced to hydrogen gas is a function of several factors, including the speed of electron transfer to the hydrogen ion at the metal surface. Thus, the rate is inherent for this reaction and depends on the particular metal and the temperature of the system. In fact, there are wide variations in the ability of the various metals to transfer electrons to hydrogen ions, and as a result, the rate of hydrogen evolution from different metal surfaces is quite different.

Activation polarization usually predominates in electrolytes where there are abundant reactants and/or an ease in the removal of products involved in the electrochemical reaction is rapid.

The equation for activation polarization is:

$$\eta_a = \pm \beta \log \frac{i}{i_0} \quad \text{Eq. 1.2}$$

where:

- $\eta_a$  = activation polarization (volt)
- $\beta$  = the Tafel constant (volt)
- $i$  = current density at electrode surface ( $\text{A/m}^2$ )
- $i_0$  = exchange current density ( $\text{A/m}^2$ )

Figure 1.8 is a plot of activation polarization on a cathode with an exchange current density of  $1.0 \times 10^{-6} \text{ A/cm}^2$  and a  $\beta$  (slope) of  $-120 \text{ mV/decade of current}$ .

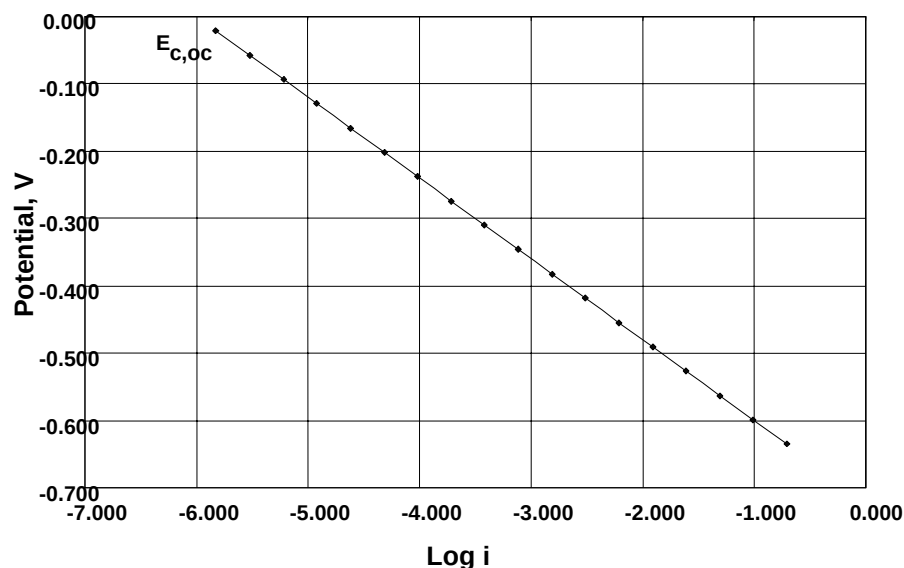


**Figure 1.8 Activation Polarization Plot for a Reduction Reaction**

Remember:  $\log x^n = n \log x$   
 For example,  $\log 10^{-2} = -2 \log 10 = -2 (1) = -2$

In this equation (commonly termed the Tafel equation), the Tafel constant (slope of the line) is positive if conventional current is flowing from the electrode to the electrolyte. That is oxidation is occurring at the surface and the site is an anode. The polarization potential moves in a positive direction with increase in current density on the surface of the electrode. Conversely, the Tafel constant is negative when conventional current is from the electrolyte to the electrode. In this case, reduction is occurring at the surface. The value of the Tafel constant varies with the specific electrochemical reaction, the electrolyte chemistry, and the surface of the electrode. Several examples of the value of the Tafel constant are given in Table 1.2.

**Table 1.2 Examples of the Tafel Constants for Hydrogen Evolution from Aqueous Solution<sup>3</sup>**

| Metal | Electrolyte | Temp. (°C) | $\beta$ (mV) |
|-------|-------------|------------|--------------|
|       |             |            |              |
| Ni    | 0.01N HCl   | 20         | – 91         |
| Ni    | 0.001N NaOH | 20         | –103         |
| Cu    | 0.01N HCl   | 20         | –122         |
| Cu    | 0.02N NaOH  | 20         | –114         |
| Fe    | 0.01N HCl   | 20         | –118         |
| Fe    | 0.01 N NaOH | 20         | –117         |

The exchange current density is also a function of the specific electrochemical reaction, chemistry of the electrolyte, and of the surface of the electrode. The value indicates the ease with which a specific reaction can take place. The larger the value the more readily the reaction takes place. The exchange current densities for the hydrogen evolution reaction in dilute sulfuric acid are given in Table 1.3<sup>4</sup>. The  $-\log i_0$  for hydrogen evolution on iron in 0.01N HCl is 6.29 A cm<sup>2</sup> and in 0.01N NaOH is 6.62 A cm<sup>2</sup>.

**Table 1.3 Exchange current densities  $i_0$  for the hydrogen evolution reaction in approximately 1 mol/dm<sup>3</sup> H<sub>2</sub>SO<sub>4</sub>**

| Metal | $i_0$ [A cm <sup>-2</sup> ] | $-\log i_0$ [A cm <sup>-2</sup> ] |
|-------|-----------------------------|-----------------------------------|
| Pt    | $8 \times 10^{-4}$          | 3.1                               |
| Ni    | $6.3 \times 10^{-6}$        | 5.2                               |
| Ti    | $6 \times 10^{-9}$          | 8.2                               |
| Pb    | $1 \times 10^{-12}$         | 12.0                              |
| Hg    | $5 \times 10^{-13}$         | 12.3                              |

<sup>3</sup> Data after Parsons, *Handbook of Electrochemical Constants*, Butterworths, London (1959)

<sup>4</sup> L. L. Shreir, *Corrosion, Volume 2*, Newnes – Butterworth, London (1976)

## Concentration Polarization

Concentration polarization refers to the retardation of an electrochemical reaction as a result of concentration changes in the solution adjacent to the metal surface.

Using hydrogen ion reduction as an example, assume the concentration of hydrogen ions in the solution is relatively low and the reaction proceeds at a fairly rapid rate. The region very close to the metal surface will become depleted of hydrogen ions because they are being consumed by the cathodic reaction. Under these conditions, the reaction is controlled by the diffusion rate of the hydrogen ions to the metal reaction surface.

Concentration polarization usually predominates in electrolytes where the concentration of the reactants is low, as with dilute solutions, or there is a build-up of reaction products, such as in stagnant environments.

The equation for concentration polarization is:

$$\eta_c = 2.3 \frac{RT}{nF} \log \frac{(i_L - i)}{i_L} \quad \text{Eq. 1.3}$$

where:

- $\eta_c$  = concentration polarization (volt)
- $R$  = universal gas const. (1.98 cal/gm. equiv., °K)
- $T$  = absolute temperature (°K)
- $n$  = number of electrons taking part in the reaction
- $F$  = Faraday constant (96,500 coulombs/equiv.)
- $i_L$  = limiting diffusion current density (A/cm<sup>2</sup>)
- $i$  = current density to/from surface (A/cm<sup>2</sup>)

From the equation, it is evident that a large limiting current density will result in minimal concentration polarization. Figure 1.9 illustrates the effect that limiting diffusion current density has on polarization.

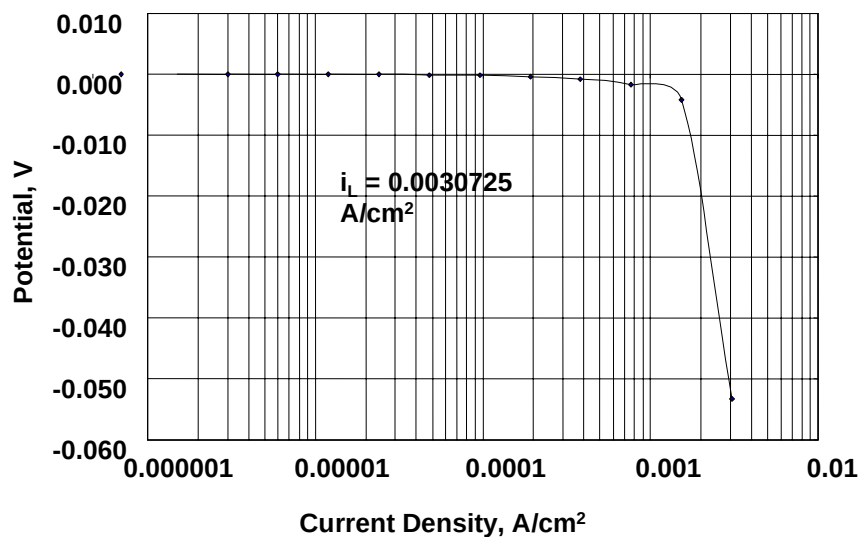


**Figure 1.9 Plot showing the effect of current density on concentration polarization  $i_L = 0.0030725 \text{ A/cm}^2$**

Figure 1.10 shows the combined effects of activation and concentration polarization.

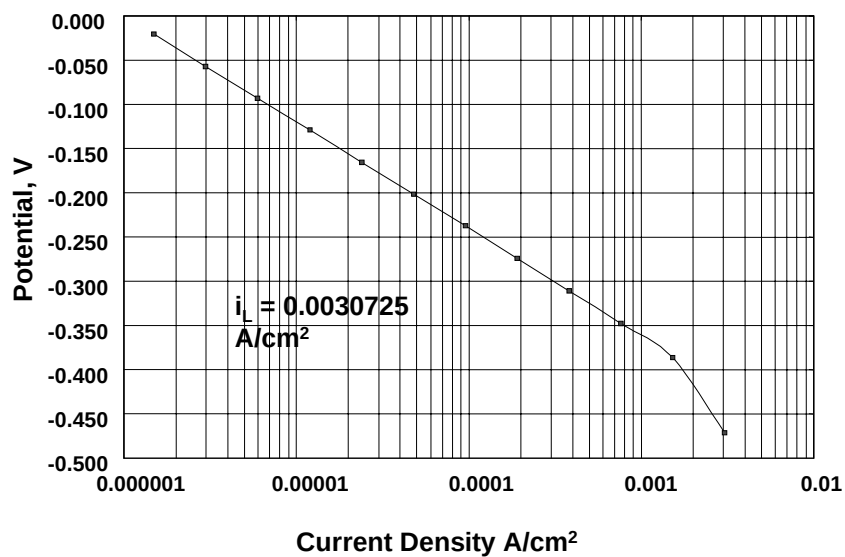


**Figure 1.10 Combined effect of activation and concentration polarization  $i_L = 0.0030725 \text{ A/cm}^2$**



## Polarization as it Relates to Cathodic Protection

Cathodic protection involves polarization. Remember that polarization is a change in potential caused by current flow. As current flows from the electrolyte to the metal, reduction reactions occur. Products from these reactions change the chemical composition of the electrolyte at the structure/electrolyte interface. The chemistry difference and consequent potential change at the interface is referred to as polarization. When cathodic protection current is interrupted, the polarization will dissipate similar to the voltage dissipation of a capacitor.

As a structure polarizes, its potential changes in an electronegative direction. Polarization occurs in a step-like manner with the more positive or cathodic sites polarizing first. As the potential of the first cathodic sites equals the potential of other sites, polarization begins at other sites. A better understanding may be gained from the simplified illustration in Figure 1.11 below.

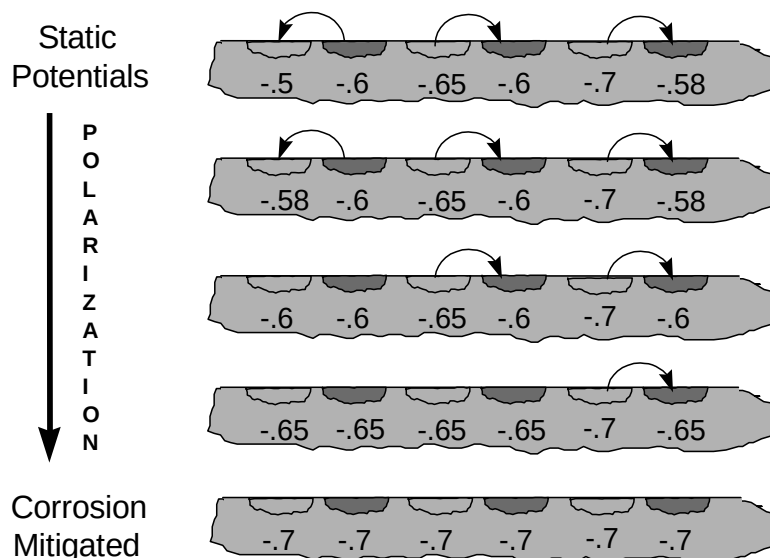


**Figure 1.11 Polarization of a Structure**

To stop corrosion, all existing cathode sites must be electronegatively polarized to a potential equal to the most negative open-circuit potential existing on the structure. Polarization of a structure is accomplished by the application of an external current, the magnitude of which depends on the cathodic polarization behavior. Discussed later are factors that affect current requirements for adequate cathodic protection of a structure. The following Evans diagram, Figure 1.12, represents the polarization of the

cathode to the open-circuit potential of the anode of a corrosion cell on a structure using a cathodic protection anode.

Polarization of the cathodes to the open-circuit potential of the anodes is the true criterion for eliminating corrosion. However, for all practical purposes, it is impossible to determine the open-circuit potential of the most active anodic site. Because corrosion cells are usually microscopic and the measured potentials are corrosion potentials, the initial measurements are most likely to be an average of corrosion potentials for several corrosion cells. Therefore, several surrogate criteria, which will be discussed later, were developed to assist in meeting the true criterion.

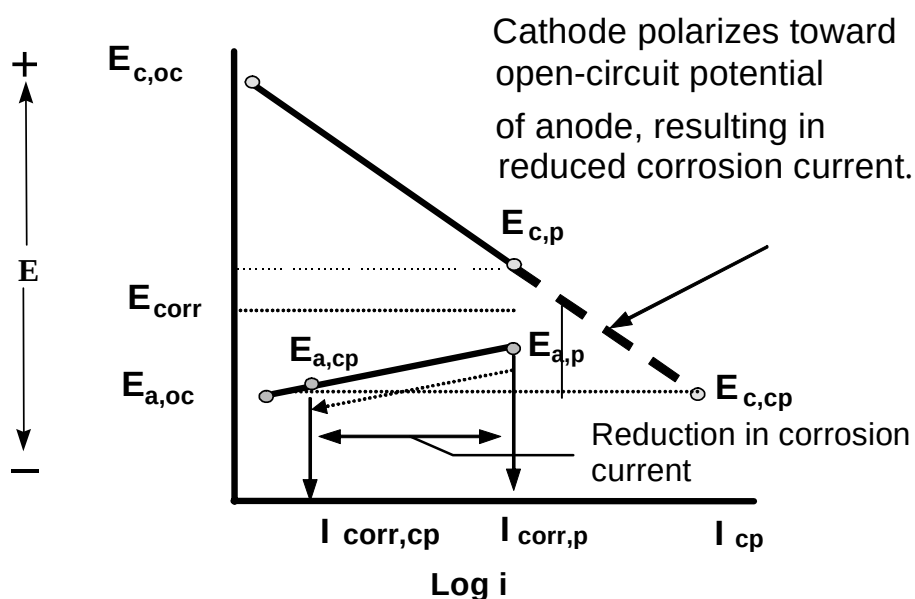


**Figure 1.12 Polarization of the Cathode to the Most Active Anodic Site**

## Factors Related to Current Requirement

The amount of current required to provide adequate protection depends on the surface area to be protected and the polarization behavior of the structure in its environment. The subject of current requirement and criteria will be encountered many times in this course.

### Surface Area

In a given environment, current requirement is directly proportional to surface area: the more surface area to protect the higher the current requirement. For example, a coated structure requires less current than a bare structure. A coated structure only needs protective current at coating defects (holidays). To consider an actual example, look at the following calculations involving an imperfect coating.

Given Information:

|                                                 |                                                              |
|-------------------------------------------------|--------------------------------------------------------------|
| Pipeline dimensions                             | Length = 16,100 meters (10 miles)                            |
| Pipeline OD                                     | 21.90 cm (8.625 in.)                                         |
| Coating efficiency                              | 98% (percent of surface completely protected by the coating) |
| Required current density (based on environment) | $i = 32\text{mA/m}^2$ (3 mA/ft <sup>2</sup> )                |

Calculations:

Surface Area:  $A_S = \pi dL$  Eq. 1.4

where:

$$\begin{aligned} A_S &= \text{Pipeline Surface Area} \\ d &= \text{Pipeline OD (m)} \\ L &= \text{length of pipeline (m)} \\ A_S &= \pi(0.2190\text{m})(16100\text{m}) \\ A_S &= 11,100\text{m}^2 \end{aligned}$$

Current Required  $I = i A_s$

where:

$I$  = Current Requirement (Bare)

$A_s$  = surface area ( $m^2$ )

$I = (0.032A/m^2)(11,100m^2)$

$I = 355 \text{ A}$

Current Requirement (Coated)

$I = i A_s \%bare$

$I = (0.032A/m^2)(11,100m^2)(0.02)$

$I = 7.1 \text{ A}$

## ***Polarization Response to Current***

In the case of a corrosion cell, an increase in polarization is desired whether it is anodic, cathodic, or both, because it decreases corrosion current. For a cathodic protection system, factors that tend to depolarize a metal surface will increase the demand for cathodic protection current.

## Cathodic Protection Criteria, Maintenance and Management

In a continuous electrolyte, polarizing the cathodes in the electronegative direction can mitigate corrosion. Corrosion will be completely arrested when the cathodes are polarized to a potential equal to or more negative than the potential of the most negative anode on the metal surface being protected.

It is also known that many factors affect the corrosion rate and, correspondingly, the current required to achieve cathodic protection. The more important factors are listed in Table 1.4.

**Table 1.4 Factors Involved in the Current Required to Achieve Cathodic Protection**

| Factors Affecting Current Requirement                                            |
|----------------------------------------------------------------------------------|
| Surface Area                                                                     |
| Moisture                                                                         |
| Environmental pH                                                                 |
| Temperature                                                                      |
| Degree of Aeration in the Environment                                            |
| Relative Movement at Metal Environment Interface (e.g., vibration and agitation) |
| Microbiological Activity                                                         |
| Metal Alloy Involved                                                             |

The true criterion for the achievement of complete cathodic protection is the potential of the most negative static anodic site on the structure to be protected. Unfortunately, this potential ( $E_{a,oc}$ ) cannot be meaningfully measured or calculated. Furthermore, it will vary in value and location with time and environmental conditions. Various alternative criteria for protection have been developed; some of which are listed in Table 1.5.

**Table 1.5 Types of Cathodic Protection Criteria**

| Types of CP Criteria                    |
|-----------------------------------------|
| Potential                               |
| Polarization Shift                      |
| E log i                                 |
| Structure/Electrolyte Current Direction |

Each of these criteria has advantages and limitations that the corrosion engineer must carefully consider if the desired level of cathodic protection is to be achieved. There are variations in these criteria and there is not universal agreement as to validity or effectiveness.

NACE International has developed consensus standards for cathodic protection of underground or submerged metallic systems, internal surfaces of water storage tanks, above grade reinforced concrete structures, offshore platforms, and various specialized processing equipment.

Table 1.6 lists a number of NACE standards that are available. These standards include criteria applicable to specific types of structures and environments.

American Water Works Association (AWWA) D104 “Automatically Controlled, Impressed Current Cathodic Protection for the Interior of Steel Water Tanks” is a standard that specifies a criterion of  $-850$  to  $-1050$  mV polarized potential relative to a copper-copper sulfate reference electrode.

The American Petroleum Institute, API Recommended Practice 651 “Cathodic Protection of Aboveground Petroleum Storage Tanks” refers to NACE Standard RP0169 for external cathodic protection and NACE Standard RP0575 and RP0388 for internal cathodic protection. The standard does provide additional information.

API Recommended Practice 1632 “Cathodic Protection of Underground Petroleum Storage Tanks and Piping Systems” includes criteria similar to NACE Standard RP0285.

**Table 1.6 NACE International Standards for Cathodic Protection Application**

|        |                                                                                                   |
|--------|---------------------------------------------------------------------------------------------------|
| RP0169 | Control of External Corrosion on Underground or Submerged Metallic Piping Systems                 |
| RP0176 | Corrosion Control of Fixed Offshore Platforms Associated with Petroleum Production                |
| RP0180 | Cathodic Protection of Pulp and Paper Mill Effluent Clarifiers                                    |
| RP0186 | Application of Cathodic Protection for Well Casings                                               |
| RP0193 | External Cathodic Protection of On-Grade Metallic Storage Tank Bottoms                            |
| RP0196 | Galvanic Anode Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks    |
| RP0285 | Corrosion Control of Underground Storage Tank Systems by Cathodic Protection                      |
| RP0290 | Cathodic Protection of Reinforced Steel in Atmospherically Exposed Concrete Structures            |
| RP0388 | Impressed Current Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks |
| RP0575 | Internal Cathodic Protection Systems in Oil-Treating Vessels                                      |

There are other international and industry criteria published in the literature. The following are summaries from some of these standards:

- **Norwegian**

Cathodic Protection Design, RP B401, Det Norske Veritas Industrie Norge AS (DNV). Criteria listed are:

1. Carbon and low alloy steel in aerated seawater:  $-800$  mV to a silver-silver chloride reference
2. In anaerobic environments:  $-900$  mV to a silver-silver chloride reference.

Norsok Standard Common Requirements Cathodic Protection, M-CR-503

$-800$  mV to  $-1050$  mV vs Silver-silver chloride seawater reference electrode

- **Petroleum Development of Oman (PDO-65-12)**

–850 mV min. to CSE instant-off. Avoid potentials more negative than –1200 mV CSE (off)

- **Abu Dhabi National Oil Company (ADNOC)**

Steel in soil: –950 to –1150 mV instant off CSE  
 –900 to –1100 mV instant off SSC  
 Steel in concrete: –700 to –1100 mV instant off CSE  
 –650 to –1050 mV instant off SSC  
 Steel in water: –850 to –1050 mV instant off CSE  
 –800 to –1000 mV instant off SSC

- **British**

Cathodic Protection, Part 1. Code of Practice for Land and Marine applications, Part 1: 1991, BS 7361, BSI Standards (British Standards Institution).

Criteria listed in this standard are:

|                                         | <b>Potential, CSE<br/>Soils and Fresh<br/>Water</b> | <b>Potential,<br/>Silver-silver Chloride<br/>Seawater</b> |
|-----------------------------------------|-----------------------------------------------------|-----------------------------------------------------------|
| Iron and steel<br>Aerobic environment.  | 850 mV                                              | 800 mV                                                    |
| Iron and steel<br>Anaerobic environment | 950 mV                                              | 900 mV                                                    |
| Lead                                    | 600 mV                                              | 550 mV                                                    |
| Aluminum                                | 950 mV                                              | 900 mV                                                    |
| Not to exceed                           | 1200 mV                                             | 1150 mV                                                   |
| Copper Alloys                           | 500 to 650 mV                                       | 450 to 600 mV                                             |

The criterion for steel in atmospherically exposed concrete is a 100 mV minimum polarization decay in 4 hours or less.

Code of Practice for Protective Coating of Iron and Steel Structures Against Corrosion, BS5495-1977

Protection of Structures Against Lightning, BS 6651: 1985



- **Canadian**

CSA Standard Z662-96, "Oil and Gas Pipeline Systems" references CGA Recommended Practice OCC-1 "For the Control of External Corrosion on Buried Or Submerged Metallic Piping Systems" for criteria and methods. The criteria are the same as the NACE International Recommended Practice.

CSA Standard Z169 covers cathodic protection of aluminum.

- **Australian**

Australia Standards Institute Standard No. 2832. This standard has three parts – Part 1 is concerned with Pipes, Cables and Ducts, the subject of Part 2 is Compact Buried Structures, and the topic of Part 3 is Fixed Immersed Structures. The criteria listed are the same as NACE RP0169.

- **German**

DIN 30676 lists the cathodic protection criteria as follows:

| Material                                    | Temperature, °C or Electrolyte            | Protective Potential, V vs. CSE |
|---------------------------------------------|-------------------------------------------|---------------------------------|
| Unalloyed and low alloy ferrous materials   | Below 40                                  | –850                            |
| Same                                        | Greater than 60                           | –950                            |
| Same                                        | Anaerobic media                           | –950                            |
| Same                                        | Sandy soils, $\rho > 500 \Omega\text{-m}$ | –750                            |
| Stainless steels with $\text{Cr} \geq 16\%$ | Soil or fresh water and less than 40      | –100                            |
| Same                                        | Soil or fresh water and higher than 40    | –300                            |
| Stainless steels with $\text{Cr} \geq 16\%$ | Salt water                                | –300                            |
| Copper, copper-nickel alloys                |                                           | –200                            |
| Lead                                        |                                           | –650                            |
| Aluminum                                    | Fresh Water                               | –800                            |
| Same                                        | Salt water                                | –900                            |
| Steel in contact with concrete              |                                           | –750                            |
| Galvanized steel                            |                                           | –1200                           |

- **Japanese**

*Corrosion Protection and Repair Manual for Port and Harbor Steel Structures*, The Overseas Coastal Area Development Institute of Japan, 1998. This document lists the criteria for the cathodic protection of steel in seawater as:

- 770 mV vs. saturated calomel electrode
- 780 mV vs. silver-silver chloride
- 850 mV vs. copper-copper sulfate reference

The document further lists the protective current density as:

|            | <b>Clean Areas,<br/>mA/m<sup>2</sup></b> | <b>Polluted Areas,<br/>mA/m<sup>2</sup></b> |
|------------|------------------------------------------|---------------------------------------------|
| Seawater   | 100                                      | 130 to 150                                  |
| Sea rubble | 50                                       | 65 to 75                                    |
| Sea mud    | 20                                       | 30                                          |
| Soil       | 10                                       | 10                                          |

Japanese Port Authority Association, Part 1, *Harbor Facility Technology Criteria and Discussion*. This document lists the same criteria and current requirements as those listed in the table above.

Japanese Water Piping Association, *Cathodic Protection Manual for Coated Steel Water Pipe*, WSP-050-95. This document lists the criterion as –850 mV to a copper-copper sulfate reference cell.

As with all standards, the user must contact the governing authority to obtain the latest version.

## Potential Criteria

A potential criterion assumes that the value selected is slightly more negative than the most negative static anode potential that is likely to exist on the structure. Accordingly, the potential criterion is a function of the metal and environment as indicated in Table 1.7. Because potential criteria depend so heavily on environment, there is little agreement regarding the potential criteria for cathodic protection of metals other than iron and steel in aerobic environments.

**Table 1.7 Potential Criteria from the Literature on Cathodic Protection of Some Metals and Alloys at 25 °C**

| Metal/Alloy                           | Potential Criterion, mV vs CSE |
|---------------------------------------|--------------------------------|
| Iron or Steel in aerobic conditions   | –850                           |
| Iron or Steel in anaerobic conditions | –950 to –1020                  |
| 300-Series Stainless Steel            | –650                           |
| Lead                                  | –600 to –650                   |
| Copper                                | –500                           |

The potential criteria stated in Table 1.7 are not to be used without regard to environmental circumstances. Other sources report different values and, in fact, a range of protection criteria. For example, Japanese sources report the protection potential for lead as –710 mV and for steel as –1,000 mV referenced to copper/copper sulfate. British investigators believe that the protection potential for aluminum can be expected to vary between –950 mV and –1,200 mV vs. CSE. American investigators have suggested that “negligible” corrosion occurs on steel exposed to various soil conditions when the steel has been cathodically polarized to –850 mV referenced to CSE. These potential criteria have decreasing validity with increasing temperature. Normally, the potential criterion must be more electronegative to compensate for temperature increases. More electronegative potentials are also required if sulfate-reducing anaerobic bacteria (SRB) activity exists.

In the application of potential criteria, regardless of structure material, the potential must be interpreted as a polarized value. Structure-to-electrolyte measurements for comparison to the chosen criterion must be free of IR error. Sometimes this can be achieved by placing the reference electrode immediately adjacent to the structure or, alternatively, by measuring the potential shortly after the cathodic protection current is interrupted i.e., after spiking due to current interruption has disappeared but before significant depolarization has occurred.



Where the static anodic potentials on the structure are less electronegative than usual, the adoption of a potential criterion can result in a measure of overprotection. Conversely, a residual corrosion current, albeit small, can exist even when the structure has been polarized to the chosen criteria. In either case, once the criterion has been chosen, structure polarized potentials need only be compared to the criterion value for ease of monitoring.

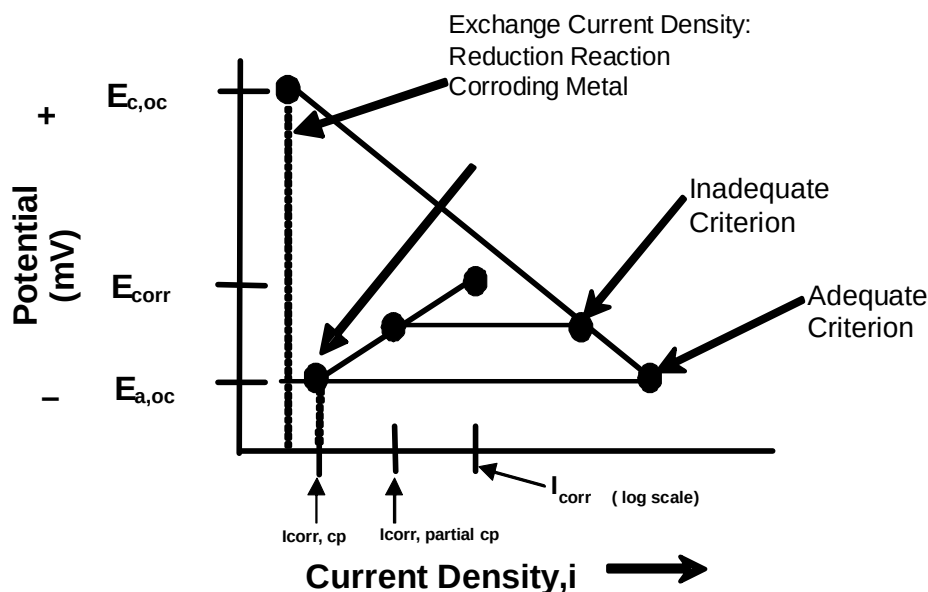


**Figure 1.13 Potential Criterion Somewhat More Positive than the Potential Required for Complete Protection**

## NACE International Potential Criteria

NACE Standard RP0169 (copy included as Appendix L) recognizes a potential criterion as one of the criteria that can be used to evaluate the performance of a cathodic protection system. The recommended practice, 6.2.2.1.1, gives the following voltage criterion: "A negative (cathodic) potential of at least 850 mV with the cathodic protection applied. This potential is measured with respect to a saturated copper/copper sulfate reference electrode contacting the electrolyte. Voltage drops other than those across the structure-to-electrolyte boundary must be considered for valid interpretation of this voltage measurement."

Consideration of other voltage drops may include the following: "Measuring or calculating the voltage drop(s)"; "Reviewing the historical performance of the cathodic protection system"; "Evaluating the physical and electrical characteristics of the pipe and the environment"; and "Determining whether or not there is physical evidence of corrosion."

RP0169 also gives a second definition of the potential criterion, 6.2.2.1.2: "A negative polarized potential of at least 850 mV relative to a saturated copper/copper sulfate reference electrode." A polarized potential is defined as follows: "The potential across the structure/electrolyte interface that is the sum of the corrosion potential and the cathodic polarization."

NACE Standard RP0285 gives similar potential criteria.

When measuring a structure-to-soil potential, the potential measured is the sum of the corrosion potential, the polarization level, and the IR drops. If the IR drops are removed from the measurement either through interruption of the current or any other valid means, the remaining value represents the polarized potential of the structure. The polarized potential (as defined in RP0169) is "the potential across the structure/electrolyte interface that is the sum of the corrosion potential and the cathodic polarization." In other words, since paragraph 6.2.2.1.1 of NACE RP0169 requires that "voltage drops other than those across the structure-to-electrolyte boundary *must be considered* for valid interpretation" and paragraph 6.2.2.1.2 requires determination of the "polarized potential", these two criteria are simply two different statements of the same criterion.

## ***Polarization Shift Criteria***

Presently, one polarization shift criterion, 6.2.2.1.3, is accepted for ferrous structures: the -100 mV polarization potential shift. In applying this criterion, it is assumed that the corrosion cells on the structure are operating under cathodic control; therefore, the structure corrosion potential ( $E_{\text{corr}}$ ) is close in value to the anode open-circuit potential ( $E_{\text{a,oc}}$ ) (i.e. less than 100 mV) as indicated in Figure 1.14.

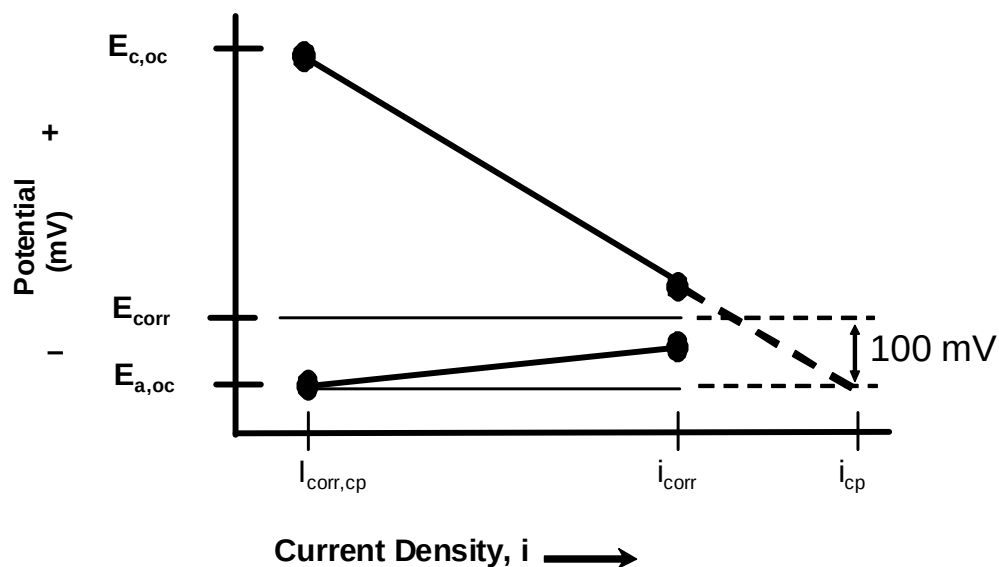


**Figure 1.14 Corrosion Cell Under Cathodic Control (Corrosion Potential Close to Open-Circuit Potential of the Anode)**

If the corrosion potential is polarized electronegatively by 100 mV, protection is considered achieved. Applying this criterion requires recording structure corrosion potentials prior to energizing the cathodic protection system and then measuring polarized potentials at the same locations after the system is placed in operation. Since polarization is a function of time, it is sometimes advantageous, especially on bare structures, to allow the cathodic protection system to operate for a period of time before conducting the polarized-potential survey. All potentials measured after energization must be free of IR drop so that a valid comparison to the base corrosion potentials can be made. If baseline corrosion potential data were not recorded prior to energization, the cathodic protection system can be turned off to allow the structure to depolarize so that baseline data can be obtained. A disadvantage to using this method is that the structure could remain unprotected for an extended period of time. If the structure's corrosion cells operate under anodic control, it is possible that neither of the shift criteria is valid.

### ***E log i Criterion***

Although NACE Standards RP0169 and RP0285 do not recognize  $E \log i$  criteria for cathodic protection, these criteria have been effectively used in the past and may still be useful in specific situations where other more direct methods cannot be applied.

To apply the  $E \log i$  criterion, a cathodic polarization curve for the structure must be constructed. Data for the curve are obtained by applying test currents of increasing magnitude and measuring the structure's polarized potential at each discrete test current value.

In conducting the test, several factors are important. The time interval between measurements should be kept as consistent as possible to eliminate distortions due to the change of polarization with time. The range of test current must extend to at least a factor 10 times greater than the estimated current required for protection. In addition, the measured potential must be corrected for IR-drop error to obtain a polarized potential. The test data are then plotted on semi-logarithmic paper, as shown in Figure 1.15 that is a plot of actual data from a test on an oil well

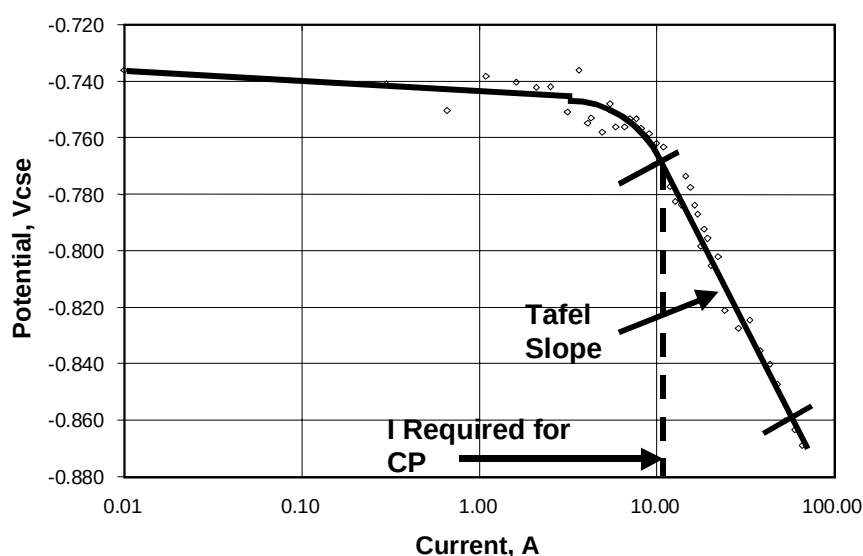


**Figure 1.15  $E \log i$  Polarization Showing Tafel Behavior**

In relatively deaerated environments, such as well casings, the polarization curve often exhibits linear (Tafel) behavior with increased test current. A straight line is normally drawn tangent to the Tafel portion of the curve and extended towards the ordinate. From this Tafel extension, a wide number of interpretations are commonly in use. The most common interpretation of the  $E \log i$  curve is that where the tangent to the Tafel slope breaks away from the data, the current at the break-away point is considered to be the current required to achieve complete protection. In Figure 1.16, this break occurs at a current of approximately 11 A. Note that the Tafel slope is approximately  $-0.115 \text{ V/dec.}$ , in good agreement with values reported for reduction of  $\text{H}^+$  on iron. As noted, the indicated current required for protection by the  $E \log i$  criterion is about 11 A.

The validity of the  $E \log i$  criterion depends on obtaining Tafel behavior. This behavior most often occurs on structures exposed to deaerated environments where the corrosion-cell kinetics is governed by activation polarization from the reduction of hydrogen ions ( $H^+$ ). Tafel behavior is not to be expected for structures exposed to aerated environments because the corrosion-cell kinetics are controlled by concentration polarization (e.g., the diffusion of oxygen to the cathodic sites where reduction occurs). This criterion is sometimes applied to deep well casings where the soil is clearly deaerated. If this criterion can be shown to have been used successfully, it may continue to be used. In many cases where the  $E \log i$  criterion has been used to establish an initial current setting for cathodic protection, both the polarized potential to a standard reference and the 100 mV shift criteria will also be met after a short period of operation.

### ***Structure/Electrolyte Current Direction Criterion***

While NACE Standards RP0169 and RP0285 do not recognize structure-to-electrolyte current direction criteria for cathodic protection, these criteria have been used in the past and are recognized under the category of special conditions.

The structure-to-electrolyte current direction criterion for cathodic protection requires that all of the anodic sites in the structure be initially identified. Subsequently, cathodic protection is reportedly achieved when it can be shown that there is a net (protective) current from the electrolyte onto the structure at all of these predetermined anodic sites. Current is measured using a meter connected to two electrodes, one of which must be positioned as close as possible to the anodic site as illustrated in Figure 1.16.

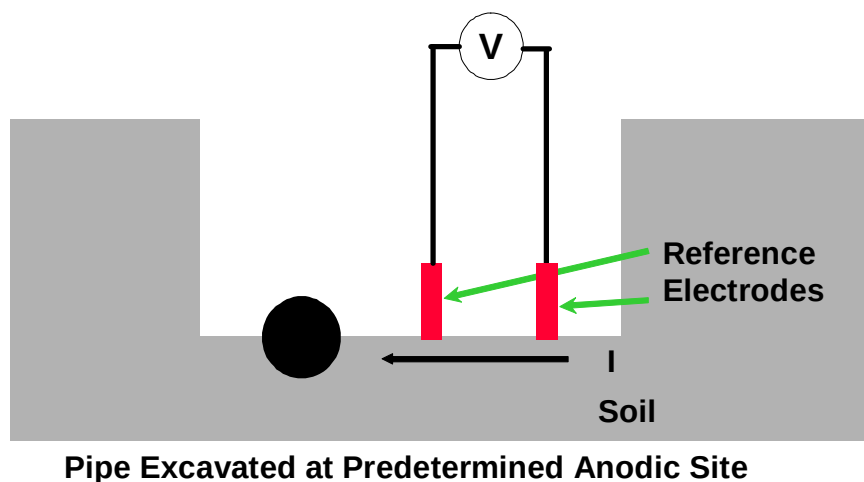


***Figure 1.16 Use of Two Reference Electrodes to Establish There Is a Net Current to the Structure From the Electrolyte at a Predetermined Anodic Site***



This criterion has questionable merit because of the difficulty in locating all of the anodic sites on the corroding structure. Furthermore, the location of anodic sites is known to change with time, and is typically necessary to excavate in order to facilitate proper testing.

Regardless of the criterion used, the important factor is to ensure that adequate cathodic protection has been achieved (i.e., the structure is no longer corroding at an unacceptable rate). For some structures, such as water storage tanks and condenser boxes, coupons can be employed to periodically evaluate the relative success of the cathodic protection criterion. When using coupons, they should be representative of the metal used for the structure.

## ***Other Criteria***

### ***Aluminum***

Aluminum is an active metal that in the absence of a passive oxide surface film, will react directly with water. It is the rapid formation and durability of the oxide film that allows aluminum to be used in many common applications where it is exposed to aqueous environments.

The criterion for cathodically protecting aluminum based on NACE RP0169 is:

A minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte.

Aluminum is amphoteric, that is, the metal corrodes under both acid and alkaline conditions. The polarized potential should not exceed –1200 mV measured between the pipe surface and a saturated copper/copper sulfate reference electrode in order to prevent a buildup of alkali on the surface that could *increase* corrosion rate. Likewise, if the pH of the environment is above 8.0, the situation should be evaluated before cathodic protection is applied. Amphoteric metals should be isolated from all other metal in the system and protected separately.

### ***Copper***

The criteria for the cathodic protection of copper based on NACE RP0169 is:

- A minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte.

- In the case of dissimilar metal piping – a negative voltage between all pipe surfaces and a stable reference electrode equal to that of the most anodic metal.

## Reinforced Concrete Structures

NACE Standard RP0100 “Cathodic Protection of Prestressed Concrete Cylinder Pipelines”, calls for 100 mV polarization development/decay with a cathodic potential limit of  $-1,000$  mV CSE to prevent hydrogen generation, and possible hydrogen embrittlement of the high strength steel. The 100 mV polarization criterion is generally accepted for protection of most reinforced concrete structures.

## Criteria Summary

Cathodic protection requires that the corrosion potentials ( $E_{\text{corr}}$ ) on a structure be polarized in the electronegative direction. Complete protection is achieved when the structure potentials are polarized to the most electronegative open-circuit anodic potential on the structure ( $E_{\text{a,oc}}$ ). Because  $E_{\text{a,oc}}$  cannot be meaningfully measured or calculated, it has been necessary to establish measurable criteria for cathodic protection. Several criteria for cathodic protection exist and each of these has advantages and limitations. These criteria are summarized in Table 1.8.

**Table 1.8 Advantages and Limitations for Cathodic Protection Criteria**

| Criteria                                  | Advantages                                                                      | Limitations                                                                                                                                       |
|-------------------------------------------|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
| Potential                                 | Easy to apply.                                                                  | Assumes potential selected is at least as negative as $E_{\text{a,oc}}$ . <sup>(1)</sup><br>Typically requires IR drop correction.                |
| Polarization Shift<br>100 mV polarization | Measures polarized potential (free of IR-drop error).<br>Avoids overprotection. | Requires measurement of corrosion potential and polarized potential.<br>Probably not valid for local-action corrosion cells under anodic control. |
| E log i                                   | Gives relatively low current requirements.                                      | Invalid in aerated environments.<br>Requires careful test procedures.                                                                             |
| Structure-to-Electrolyte Current          | Theoretically would provide complete protection.                                | Difficult to locate and test pre-existing anodic sites.<br>Anodic sites may change location with time.                                            |

<sup>(1)</sup> The open-circuit anode potential on a freely corroding surface.

## IR Drop Consideration

### ***IR Drop Error Determination and Correction***

Potential measurement for comparison with criteria often involves errors caused by IR drops, particularly in the electrolyte, as was briefly discussed in the previous chapter. Furthermore, the magnitude of IR-drop errors must be determined and appropriately compensated for when measuring and evaluating field data. Accordingly, there are a number of common methods of determining and correcting for IR drop:

- Place the reference electrode close to exposed metal surface of the structure being measured. On a coated structure the reference must be placed next to a coating fault (holiday).
- Place the reference electrode at remote earth to include maximum IR-drop error and then subtract this error from potentials measured with the reference located nearer the structure.
- Interrupt the current and measure the potential before significant depolarization occurs (often called the "instant off" potential).
- Decrease the current in steps while measuring the change in structure-to-electrolyte potential and the resultant surface voltage gradient. The curve created from this data is extrapolated to zero current to identify total IR-drop error in the structure-to-electrolyte potential at full current.
- Use of coupons and probes.

In some situations, the IR-drop error can be neglected if the current and/or the resistance is small. The resistance of a current path is a function of the path's cross-sectional area, resistivity and length. Before neglecting the IR drop, the magnitude of IR drop should be determined in order to verify its insignificance.

## Reference Electrode Near the Structure

Placing the reference electrode close to the structure minimizes the IR drop error in the electrolyte in proportion to the electrode's closeness of the electrode to the surface. Unfortunately, for underground structures, this is not a practical technique except at points of structure-to-soil entry and exit. Also, on coated structures the electrode cannot normally be placed any closer to the structure than a point immediately outside the coating, and it is across the coating where much of the IR drop exists.

## Reference Electrode at Remote Location

With the reference electrode remote from the structure, the potential reading includes the maximum total IR-drop error when the current is applied. Accordingly, by identifying the maximum value between a reference electrode placed at the pipe surface and the remote reference, this value can be subtracted from subsequent pipe-to-soil potential readings as long as the current density and path resistivity remain relatively constant. When constant conditions are present, this technique would probably result in overcorrection of the potential reading, thus erring on the safe side.

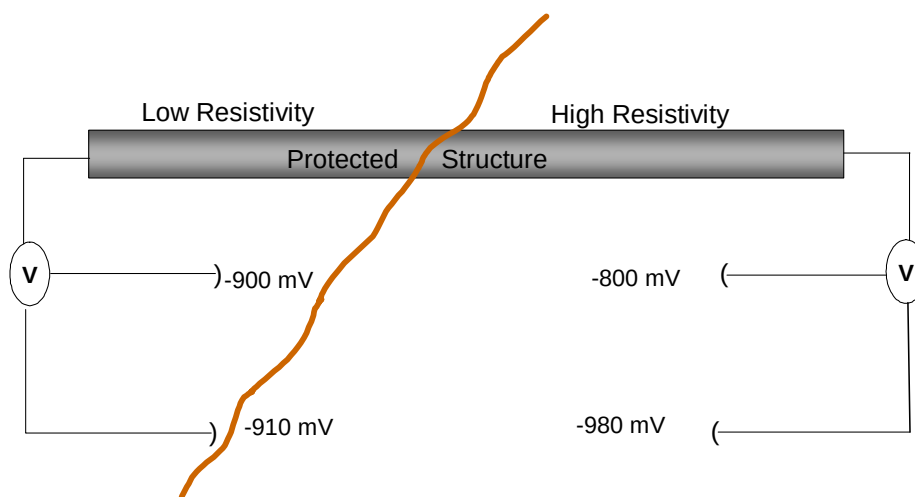


Figure 1.17 IR Drop at Remote Earth

## Interrupt Current

The most effective method of eliminating IR-drop errors is by making the current zero at the “instant off” potential measurement, thereby making the IR product equal to zero. Typically, zero IR drop is achieved by temporarily interrupting the flow of current and instantly reading the structure potential. This potential must be read quickly since the structure will begin to depolarize with time. However, there may be significant spiking of the potential due to inductive and capacitance effects associated with the interruption of the cathodic protection current. The “instant-off” potential should be measured after this spiking has decayed but before significant depolarization of the structure has occurred as shown in Figure 1.18.

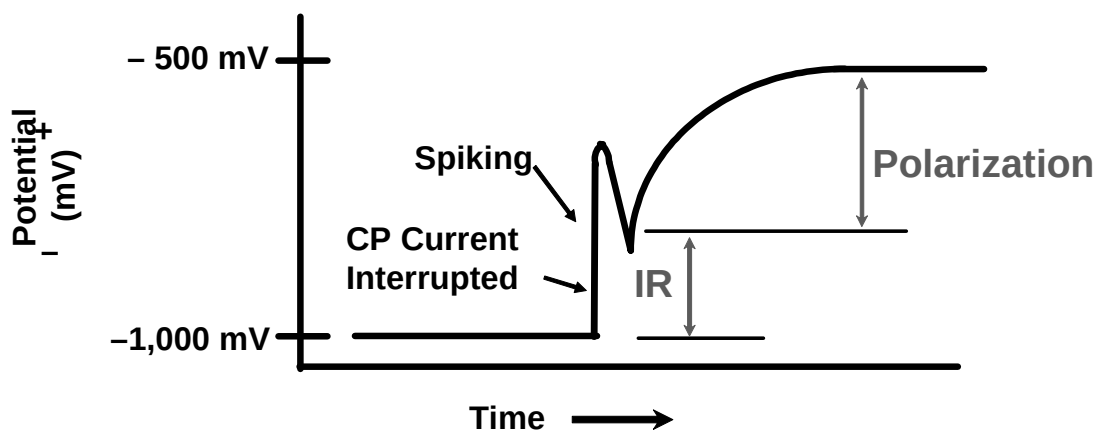


**Figure 1.18 Elimination of IR Drop by Current Interruption**

This technique has the added advantage that the IR drop in the circuit's metallic path is also eliminated. On structures having multiple current sources influencing the potential reading it may be difficult to interrupt all the sources or to interrupt them simultaneously. Since IR drop at any given location is the sum of the effects of current applied at all sources, the total IR drop can be calculated by summing the individual effects.

$$IR_x = I_1R_{x,1} + I_2R_{x,2} + I_3R_{x,3} + \dots + I_nR_{x,n} \quad \text{Eq. 1.5}$$

where:

$IR_x$  = total IR drop at location "x", V

$I_n$  = current at source "n", A.

$R_{x,n}$  = potential shift at "x" per A. at "n"

## Stepwise Current Reduction

Where multiple current sources are present and cannot practically be interrupted synchronously, the stepwise method of current reduction can be used. As shown in Figure 1.19 both the structure-to-electrolyte potential and surface voltage gradient are measured.

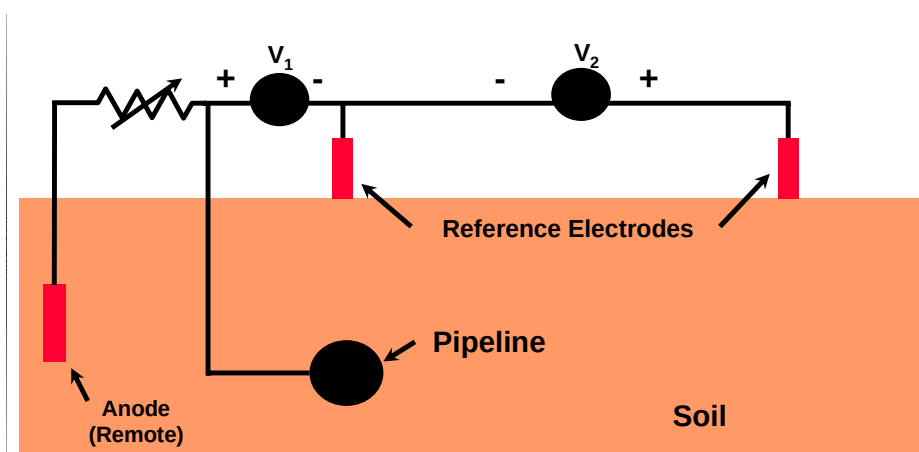


**Figure 1.19 Stepwise Current Technique for Correction of IR Drop**  
**Correction**

After initial potentials  $V_1$  and  $V_2$  are measured with all currents applied, the current is reduced and the potentials are measured again. The change in structure potential as a result of the current reduction is plotted on the vertical axis (see Figure 1.20), and the new surface gradient is plotted on the horizontal axis. Extension of these values creates a point,  $P_1$ . By continuing to decrease the current to  $I_2$ ,  $I_3$ , etc., a series of points  $P_2$ ,  $P_3$ , etc. is established by new values of  $\Delta V_2$ ,  $\Delta V_3$ , etc. Finally, extrapolation of these values to zero current results in the intersection of the current on the y-axis at a value equal to the total IR-drop error contained in the original potential reading,  $V_1$ , which can then be corrected accordingly. This must be done for each current source that has an influence at the location of interest.

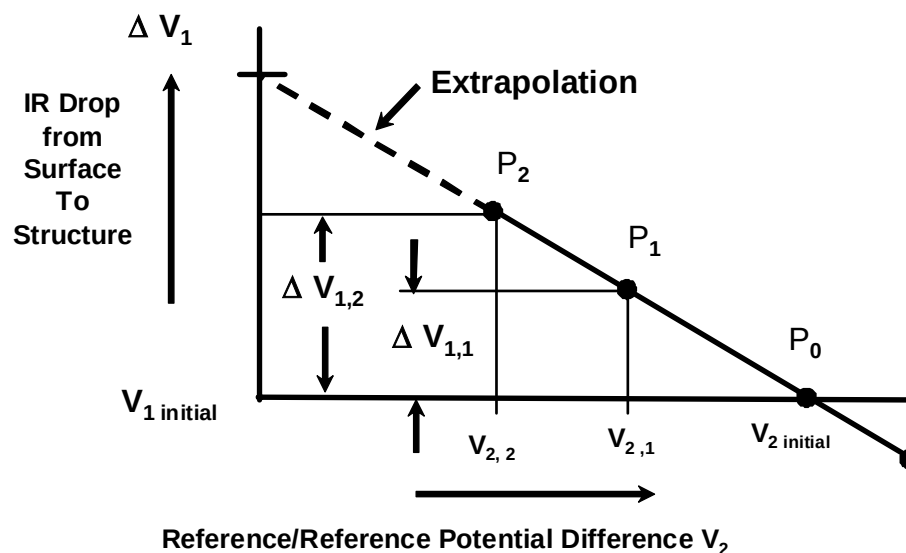


**Figure 1.20 Extrapolation of Stepwise Current Reduction for IR Drop Determination and Correction**

This technique will not identify metal IR drop errors.

### ***Use of Coupons and Probes***

Coupons are sometimes used to minimize IR-drop errors. Coupons are of the same metal as the structure being protected, are in the same electrolyte as the structure being protected, and are connected to the structure being protected. In this method, the current to the coupon is small and IR drop is minimized. Placing the coupon so that a reference electrode can be placed very near the coupon minimizes IR drops even further. In some cases, coupons are buried with long-life reference electrodes next to them. The proximity of the reference electrode to the metal sample in the coupon allows for potential measurements with minimal IR drop.

Probes are resistance elements constructed from the same material as the structure. Like coupons they are connected to the protected structure. If corrosion occurs on the probe, the electrical resistance will increase. Measurement of resistance over time will indicate whether corrosion is or is not being controlled by the cathodic protection system.

Even though the basic technique is not new, the use of coupons and probes to minimize IR-drop errors has received more notice recently. However, the technique relies on many assumptions that may or may not be appropriate in many cases. Perhaps the most critical assumption is that the metal in the probe will respond to cathodic protection in an identical manner to the metal in the structure.

A number of special cathodic protection monitoring test stations are available. Most are constructed with a steel coupon which is connected through the test station wiring to the pipe that is cathodically protected. The test station is positioned so that the coupon rests near the pipeline in soil typical of the backfill around the pipe. A reference electrode is placed in the test station riser or in the soil near the coupon to permit measurement. The coupon is momentarily disconnected from the pipe and its potential is read. This allows an essentially IR drop free reading of the coupon potential to the reference cell and therefore the equivalent instant-off potential of the pipe surface since they should have both been at the same potential before the reading is made.

Some of these test stations are available with resistance type corrosion probes located in the foot of the test station. The element is connected to the pipeline and is under the same level of cathodic protection as the pipe. If corrosion is occurring, the resistance probe will reflect the condition by showing higher resistance over time. Figure 1.21 illustrates one type of special test station that includes the features described.

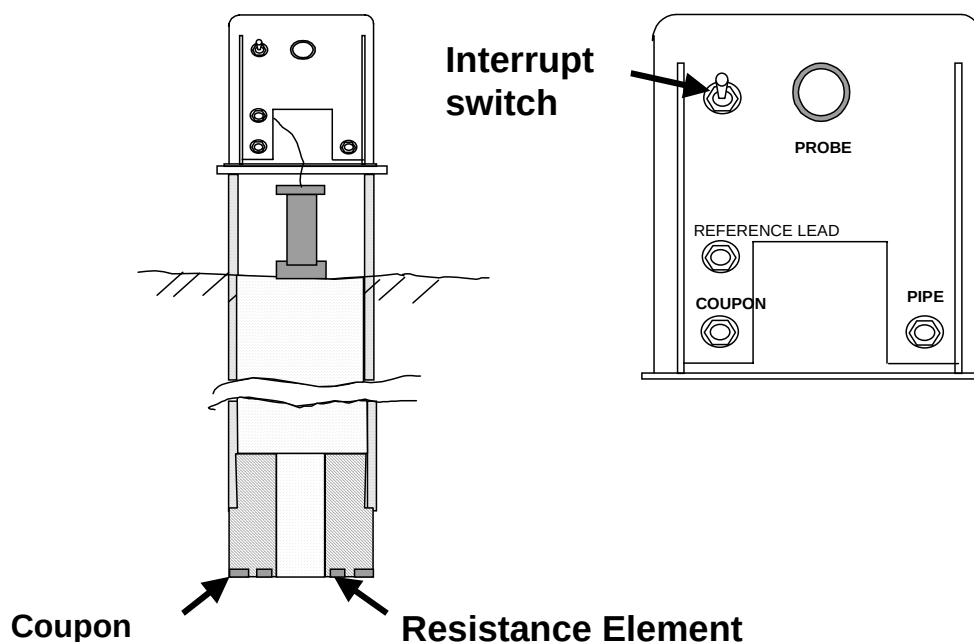


**Figure 1.21 Special Test Station For Monitoring Cathodic Protection**  
The advantages and limitations of the various techniques for IR-drop correction are summarized in Table 1.9.



**Table 1.9 Summary of IR Drop Correction Techniques**

| <b>Technique</b>           | <b>Advantages</b>                                | <b>Limitations</b>                                                                    |
|----------------------------|--------------------------------------------------|---------------------------------------------------------------------------------------|
| Remote Earth               | Accounts for maximum error.                      | Requires constant current density and resistivity.                                    |
| Reference Near Structure   | Accuracy.                                        | May require excavation.                                                               |
| Current Interruption       | Accuracy.                                        | Difficulties in interrupting multiple current sources.<br>Spiking.<br>Depolarization. |
| Stepwise Current Reduction | Applicable where multiple current sources exist. | Time-consuming and not valid for multiple pipelines.                                  |
| Coupons and Probes         | Potential for accuracy.                          | Assumes metal response to cathodic protection                                         |

# CHAPTER 2

## Factors Influencing Cathodic Protection Design

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### Introduction

This chapter deals with the many factors that affect the design of cathodic protection systems. Before a cathodic protection design can begin, consideration must be given to all possible environmental and structural parameters that will influence the design.

### Environmental

#### ***Moisture***

Without moisture the usual electrochemical reactions of corrosion and cathodic protection cannot occur. For example, solidly frozen water prevents ion migration and ice becomes very high in resistivity. Likewise, although uncommon, a totally dry soil will not transfer charge.

Moisture may not only contain soluble chemical compounds that provide ions for charge transfer, it may also contain dissolved oxygen that influences polarization, and other gasses such as carbon dioxide and sulfur dioxide that lower pH.

#### ***Soil Texture***

Soil texture (particle size) is important in that it influences how readily liquids and gasses can permeate the soil. Differences in soil texture can create differential aeration cells that can be very corrosive. Those areas that are deficient in dissolved oxygen become anodes with respect to aerated locations. Dense clay and silt promote anaerobic conditions suitable for development of certain microbiological forms that produce aggressive corrosion.

## pH

The current required for cathodic protection generally is greater in acids compared to that required in basic and neutral environments. Two phenomena account for this increase. These are: (1) a shift in the positive direction of the structure's open-circuit cathode potential, and (2) a flattening of the cathodic polarization curve for the structure, as indicated in Figure 2.1. Flattening the slope of the polarization curve means that more current is required to change the surface polarized potential by a given amount.

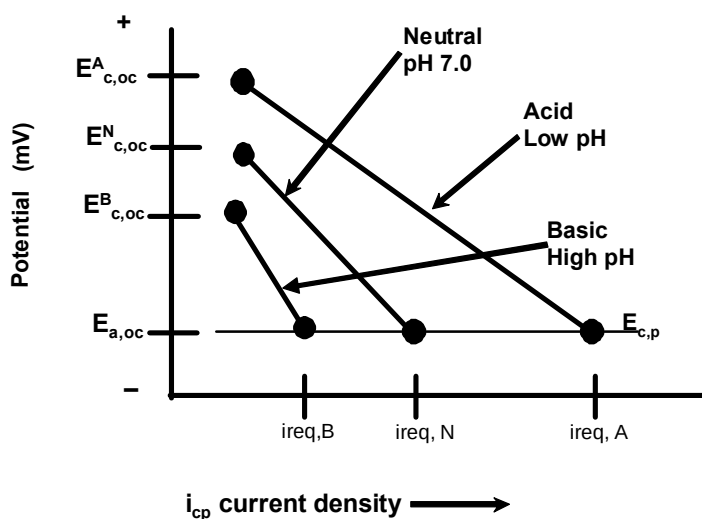
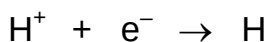


**Figure 2.1 Effect of Environment pH on Current Density Required for Protection**

The structure's cathodic polarization slope is flattened with increasing acidity because of the increased concentration of reducible hydrogen ions ( $H^+$ ) according to the reaction:



$$pH = \log \frac{1}{[H^+]} \quad \text{Eq. 2.1}$$

The higher the hydrogen ion concentration,  $[H^+]$ , the lower the pH.

**Table 2.1 Hydrogen And Hydroxyl Ion Concentrations As A Function Of pH**

| pH | H <sup>+</sup>    | OH <sup>-</sup>   |
|----|-------------------|-------------------|
| 0  | 10 <sup>0</sup>   | 10 <sup>-14</sup> |
| 2  | 10 <sup>-2</sup>  | 10 <sup>-12</sup> |
| 4  | 10 <sup>-4</sup>  | 10 <sup>-10</sup> |
| 6  | 10 <sup>-6</sup>  | 10 <sup>-8</sup>  |
| 8  | 10 <sup>-8</sup>  | 10 <sup>-6</sup>  |
| 10 | 10 <sup>-10</sup> | 10 <sup>-4</sup>  |
| 12 | 10 <sup>-12</sup> | 10 <sup>-2</sup>  |
| 14 | 10 <sup>-14</sup> | 10 <sup>0</sup>   |

The pH of an electrolyte (soil or water) is rarely a neutral 7. This results from the presence of various ionic species in the electrolyte as a result of the hydrolysis of salts (e.g. sodium carbonate, ammonium sulfate, and others). Depending on the nature of the salt, the pH can shift in either the acidic or basic direction. For example, ammonium sulfate (an acid salt) used as a fertilizer tends to decrease the pH of the soil. Concrete, which has a pH of approximately 13, has an inhibiting effect on corrosion of steel and reduces current requirements.

## Temperature

Increased temperature has a depolarizing effect because of the increased rate of diffusion of reducible species to the cathodic sites, a decrease in concentration polarization. Accordingly, the rate of the reduction reaction is increased, thus decreasing the level of polarization and increasing the cathodic protection current requirement, as illustrated in Figure 2.2.

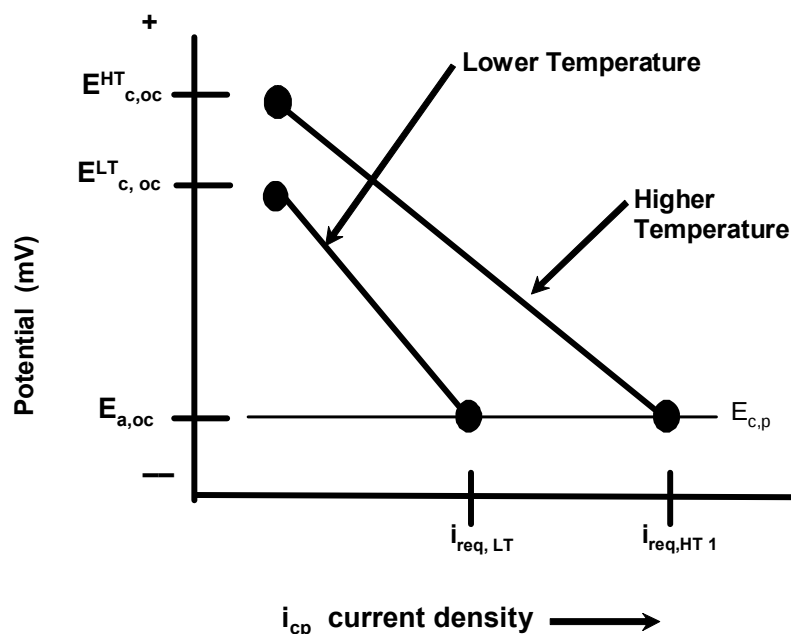
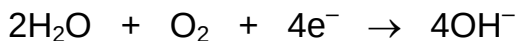


**Figure 2.2 Effect of Temperature on Current Required for Cathodic Protection**

Also, increased temperature will increase ionization. As ionization increases, the electrolyte's conductivity increases, which increases corrosion current and the amount of cathodic protection current required for adequate protection. Also, activation polarization decreases because the electrochemical reactions speed up.

## Oxygen Content

Oxygen or other oxidizers increase the current requirements as a result of flattening the cathodic polarization slope. Oxygen, for instance, participates in the cathodic reduction reaction:



thereby reducing polarization. This effect is illustrated in Figure 2.3.

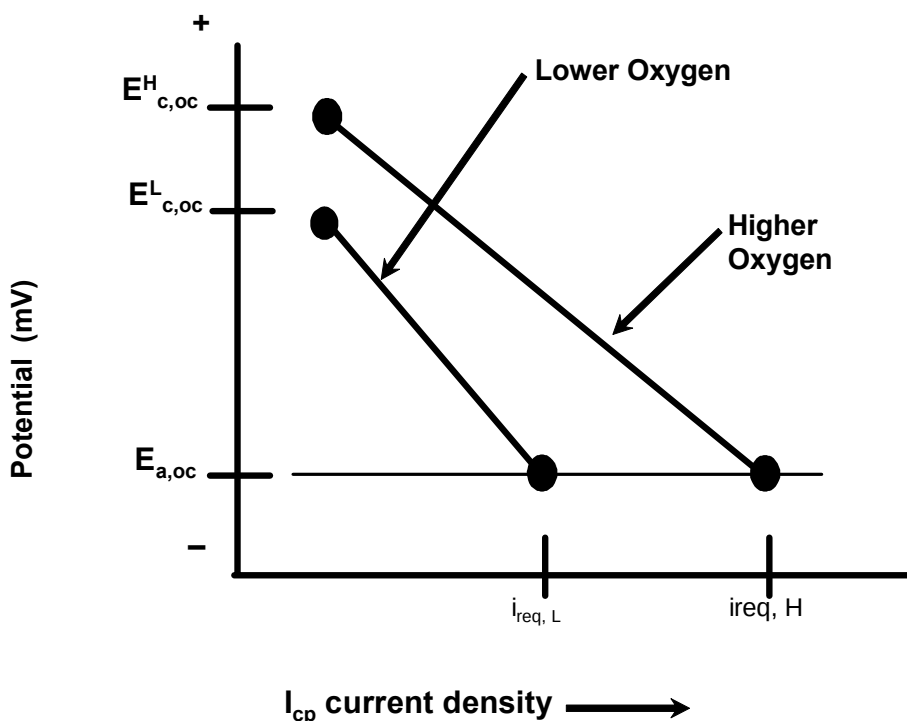


**Figure 2.3 Effect of Oxygen on Current Required for Cathodic Protection**

Accordingly, structures in well-aerated soils, such as sand and gravel, require more cathodic protection current than structures surrounded by relatively deaerated soils, such as clay. The solubility of oxygen is greater in cold water than in hot. Therefore, cold-water environments with contact to air have higher current requirements than warmer waters.

## Movement

An increase in the relative movement between the electrolyte and the structure causes an increase in current requirement. This is due primarily to the increased availability of reducible species at the structure surface and the resulting increase in the rate of the reduction reaction. This effect, illustrated in Figure 2.4, is exhibited on such structures as ship propellers, docks and offshore structures exposed to seawater flow or tides, and internal surfaces of condenser water boxes.

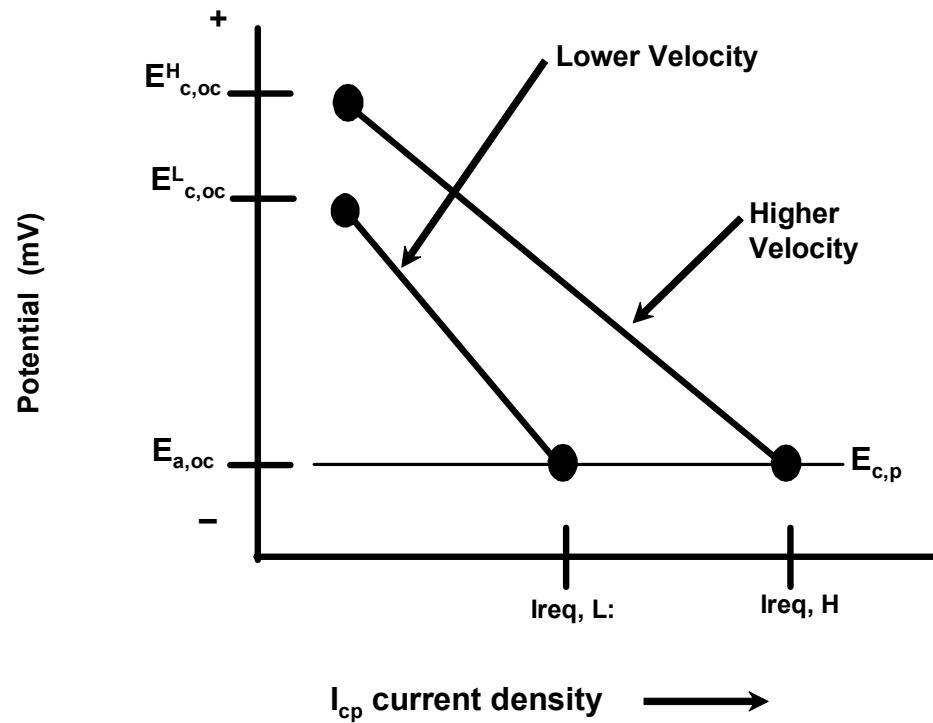


**Figure 2.4 Effect of Relative Movement on Current Required for Cathodic Protection**

The current requirements, however, are not necessarily a linear function of the fluid velocity. If the fluid flow is laminar, as opposed to turbulent, then the requirements are lower, as illustrated in Figure 2.5.

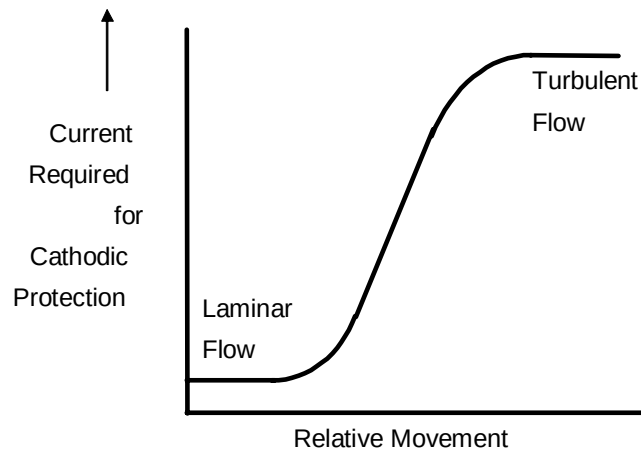


**Figure 2.5 Effect of Laminar and Turbulent Flow on Current Required for Cathodic Protection**

For instance, a ship under way requires more cathodic protection current than a ship at rest; similarly, the stern of a ship requires more current than the bow.

### ***Microbiological Activity***

Microbiological activity can increase the corrosion rate of a metal in several ways, including corrosion by the bacteria by-products, the formation of oxygen concentration cells and depolarization. In the case of sulfate-reducing bacteria, two theories include depolarization by the removal of a hydrogen reaction product and the production of iron sulfide and reactions involving phosphorus. Depolarization involves the removal of hydrogen from the cathode, which increases the anodic reaction. The formation of iron sulfide removes iron ions, which also depolarize the anode.



The reactions given in Table 2.1<sup>1</sup> show this:

**Table 2.2 Equations of reactions associated with SRB**

|                       |                                                                                |                  |
|-----------------------|--------------------------------------------------------------------------------|------------------|
| Ionization of water   | $8\text{H}_2\text{O} \rightarrow 8\text{OH}^- + 8\text{H}^+$                   |                  |
| Corrosion of iron     | $4\text{Fe} \rightarrow 4\text{Fe}^{++} + 8\text{e}^-$                         | (Anode)          |
| Formation of hydrogen | $8\text{H}^+ + 8\text{e}^- \rightarrow 8\text{H}$ Adsorbed                     | (Cathode)        |
| Removal of hydrogen   | $\text{SO}_4^{--} + 8\text{H} \rightarrow \text{S}^{--} + 4\text{H}_2\text{O}$ | (Depolarization) |
| Secondary reactions   | $\text{Fe}^{++} + \text{S}^{--} \rightarrow \text{FeS}\downarrow$              | (Anode)          |
|                       | $3\text{Fe}^{++} + 6(\text{OH})^- \rightarrow 3\text{Fe}(\text{OH})_2$         | (Anode)          |

Because of the depolarizing influence of the bacteria normal cathodic protection criteria do not apply. Research has indicated that where bacteria are present, steel should be polarized to a potential of at least –950 mV CSE.

## Structure

Structures themselves have a significant influence on cathodic protection. Some of the more important considerations are:

- materials of construction
- method of fabrication
- the geometry of the structure and its' neighbors
- protective coating that may be present
- electrical isolation from other structures or within the structure
- electrical grounding requirements

## Materials of Construction

### Electrochemical Position

Bi-metal connections are an obvious source of energy differences. These differences introduce the potential for galvanic corrosion. The electrical potential among the various materials of construction must be equalized through the application of cathodic protection. The least active components must be polarized to at least the potential of the most active component. Use of steel fasteners to join large copper sheets would be highly undesirable, as this would require that the entire copper surface be polarized to a potential equal to that of the small steel fasteners. Potential dif-

<sup>1</sup> W.P. Iverson, "Mechanism of Anaerobic Corrosion of Steel by Sulfate Reducing Bacteria", *Materials Performance*, March 1984, pp. 28-30

ferences and in some cases, relative positions of metal activity can vary with the environment.

Some alloys (stainless steels are an example) can exhibit potentials that are either active or passive depending on the chemistry and other parameters of the environment. In general, stainless steels depend on the presence of oxygen to maintain passivity.

A tabulation of common metals and alloys in seawater in order of their galvanic activity from cathodic to anodic is given in Table 2.2.

**Table 2.3 Galvanic series of metals and alloys in sea-water at 25 °C<sup>2</sup>**

| <b>Metal or Alloy</b>                   | <b>Potential (V) (Ag-AgCl ref.)</b> |
|-----------------------------------------|-------------------------------------|
| Magnesium Anode (high purity)           | −1.65                               |
| Mg-6Al-3Zn standard anode (proprietary) | −1.50                               |
| Aluminum anode (proprietary)            | −1.10                               |
| Zinc (Mil-A-18001G) anode               | −1.03                               |
| Aluminum alloys                         | −0.90 to −0.65                      |
| 2% Ni cast iron                         | −0.68                               |
| Cast iron                               | −0.61                               |
| Carbon Steel                            | −0.61                               |
| High-strength low-alloy steel           | −0.60                               |
| 430 stainless steel (active)            | −0.57                               |
| 304 stainless steel (active)            | −0.53                               |
| 410 stainless se                        | −0.52                               |
| Ni resist type I                        | −0.47                               |
| Bronze                                  | −0.40                               |
| Yellow brass                            | −0.36                               |
| Copper                                  | −0.36                               |
| Admiralty brass                         | −0.36 (24.6°C)                      |
| Red brass                               | −0.33                               |
| Gunmetal                                | −0.31                               |
| Admiralty brass                         | −0.30 (11.9°C)                      |
| Aluminum brass                          | −0.29                               |
| 90-10 cupronickel (1.4 Fe)              | −0.29 (17°C)                        |
| 90-10 cupronickel (0.82 Fe)             | −0.28                               |
| 70-30 cupronickel (.45 Fe)              | −0.25                               |
| 70-30 cupronickel (.51 Fe)              | −0.24 (17°C)                        |
| 90-10 cupronickel (1.4 Fe)              | −0.24 (6°C)                         |
| 90-10 cupronickel (1.5 Fe)              | −0.22 (24°C)                        |
| 70-30 cupronickel (.51 Fe)              | −0.22 (6°C)                         |
| 430 stainless steel (passive)           | −0.22                               |
| 70-30 cupronickel (.51 Fe)              | −0.20 (26.7°C)                      |
| Nickel                                  | −0.20                               |
| 316 stainless steel (active)            | −0.18                               |
| Inconel                                 | −0.17                               |
| 410 stainless steel (passive)           | −0.15                               |
| Silver                                  | −0.13                               |
| Titanium (passive)                      | −0.0                                |
| 304 stainless steel (passive)           | −0.08                               |
| Hastelloy C                             | −0.08                               |
| Monel                                   | −0.08                               |
| 316 stainless steel (passive)           | −0.06                               |
| Graphite                                | +0.25                               |
| Platinum                                | +0.26                               |

<sup>2</sup> Cathodic Protection of Reinforcement Steel in Concrete. KGC Berkeley, S. Pathmanaban, Butterworths & London (1990). pg. 5.

## ***Susceptibility to Hydrogen Damage***

Atomic hydrogen generated at the surface either by cathodic protection or corrosion reactions can react with certain metals to form metal hydrides or can diffuse into the metal. This atomic hydrogen can cause damage to the metal in several ways. These include blistering, formation of brittle particles, embrittlement, or the facilitation of stress corrosion cracking. The embrittlement of the metal can cause cracks to form, which can grow and cause the structure to fail. Examples of metals that can be adversely affected by hydrogen diffusion include:

- carbon steel above 200 ksi (1380 MPa) ultimate tensile strength
- low alloy steel (e.g., 4130, 4340, D6AC) above 200 ksi (1380 MPa)
- martensitic stainless steel
- precipitation hardening stainless steel (certain heat treatment conditions)
- some 2000 series Aluminum alloys
- some 7000 series Aluminum alloys (except T73 heat treatment)
- some cast Aluminum alloys
- some Copper alloys under certain hardness conditions
- magnesium alloys
- titanium (formation of titanium hydride particles)

Figure 2.6 illustrates the effect of hydrogen on the ductility of steel. These tests were conducted on high tensile strength suspension bridge wire in water with a pH of 6.5. The test samples were notched to provide a stress concentrator. The graph plots the percent reduction in area and the normalized notch fracture stress against potential. The normalized fracture stress is the fracture stress in air/fracture stress under the conditions of the test. Initial tests in air, in air after the samples were baked to remove any residual hydrogen in the metal, immersed under freely corroding conditions ( $E_{\text{CORR}}$ ), and immersed with the potential controlled below  $E_{\text{CORR}}$  indicate the strength and ductility of the steel when hydrogen is not present. Severe reductions in ductility appear at potentials more active than the hydrogen evolution potential.

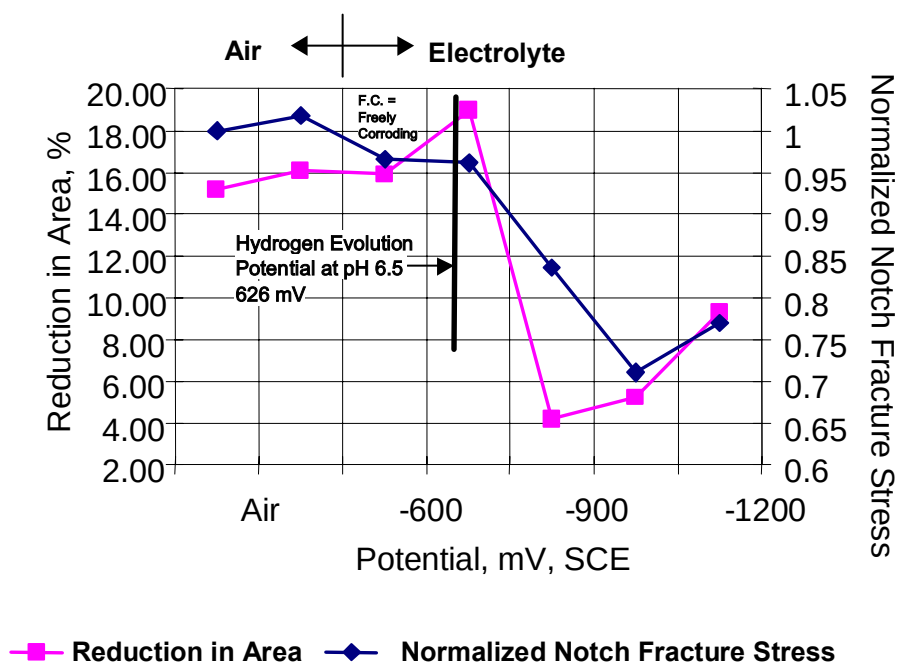


**Figure 2.6 Percent reduction in area and the normalized notch fracture stress vs. potential**

In addition, some conditions of internal stress and cold work can make a normally resistant metal, such as low strength carbon steel, to be susceptible to hydrogen damage. For a more detailed discussion, see the *Metals Handbook, Vol. 13 Corrosion*, 9<sup>th</sup> Edition, ASM International, Materials Park, OH, 1987.

The prevention of hydrogen embrittlement depends on keeping the potential below the hydrogen evolution potential, which depends on the pH. The general formula for the potential of the reaction  $H_2 \rightarrow 2H^+ + 2e^-$  is given by Pourbaix<sup>3</sup>:

$$E_0 = -0.0591 \text{ pH} \quad \text{Eq. 2.2}$$

Where  $E_0$  = Hydrogen evolution potential (hydrogen scale) in volts.

Clearly, the higher the pH, the more negative the potential needed to generate hydrogen. For example, in a soil or water with a neutral pH 7,  $E_0 = -0.414$  volt (SHE) or  $-0.730$  volt (CSE). In a pH 12 environment, such as in sound concrete, hydrogen is generated at  $E_0 = -0.709$  volt (SHE) or  $-1.025$  volt (CSE).

<sup>3</sup> M. Pourbaix, *Atlas of Electrochemical Equilibria in Aqueous Solutions*, NACE, Houston, TX, 1974

For aluminum, the polarized potential must be kept more positive than –1200 mV (CSE) to avoid alkali corrosion (see Amphoteric Metals below); however, for susceptible alloys, the limiting potential might be more positive. For titanium, the limiting potential is –700 mV (silver-silver chloride) to prevent hydriding. Overprotection levels are discussed in some cathodic protection criteria documents and might differ from these potentials somewhat. For prestressed concrete, polarized potentials more negative than –1,000 mV (CSE) should be avoided.

Care must be taken in designing and operating cathodic protection systems where materials susceptible to hydrogen embrittlement or hydriding are used to limit the structure-to-electrolyte potential below the hydrogen evolution potential.

### ***Amphoteric Metals***

Some metals (notably aluminum and lead) are subject to corrosion in both alkaline and acidic environments, which can affect the effectiveness of cathodic protection. Overprotection of amphoteric metals will cause an increase in pH at the metal/electrolyte interface. At a high pH, the protective oxides formed on these metals dissolve and the metal can react directly with water, producing rapid corrosion. Zinc is corroded by alkaline conditions where the pH greater than 12.5. Aluminum is not corroded under all alkaline conditions. The corrosion rate of 1100 aluminum alloy in sodium hydroxide and sodium carbonate increases rapidly above a pH of 9. Potentials that produce a high pH should be avoided when amphoteric metals are present. NACE Recommended Practice RP0169-96 recommends that the potential of aluminum not exceed -1200 mV (CSE) under cathodic protection.

Figure 2.7 shows the effect of pH on the corrosion of zinc.

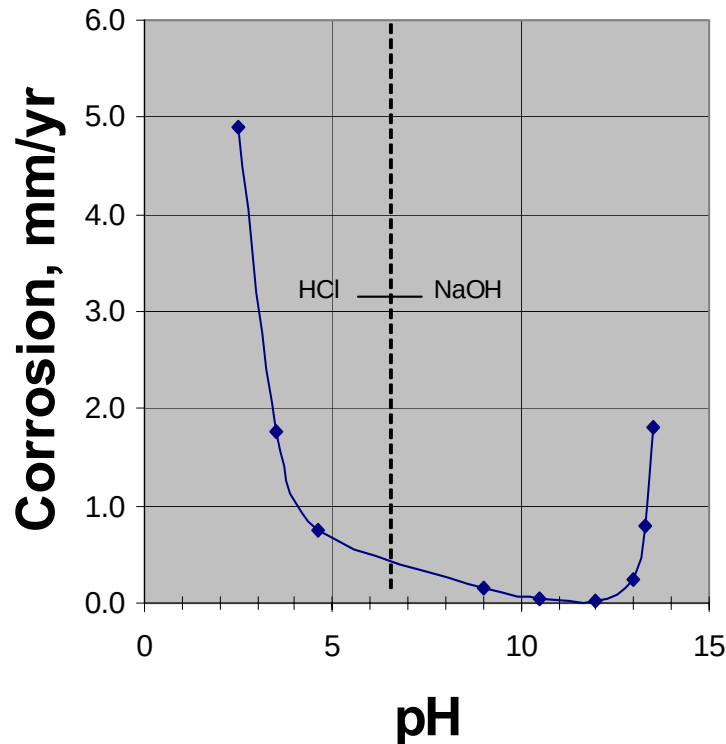


**Figure 2.7 Effect of pH on the Corrosion of Zinc<sup>4</sup>**

## Summary of Materials Effect on CP Design

Materials of construction play an essential role in the design of cathodic protection. The particular cautions noted have a direct impact on whether or not cathodic protection can be successfully or safely applied to a particular structure or component.

## Combined Material and Environment Effect

### Stress Corrosion Cracking

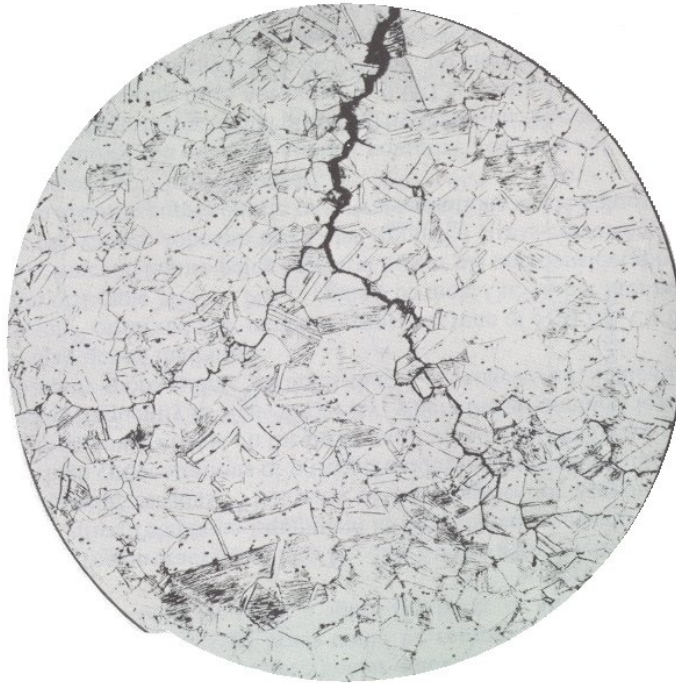
Stress corrosion cracking (SCC) is the cracking of a metal under a tensile stress (either externally or applied or an internal residual stress) in the presence of a corrosive environment. The corrosive environment that causes SCC is usually specific. Examples of some common metals susceptible to SCC are listed in Table 2.3.

<sup>4</sup>Zinc: *Its Corrosion Resistance*, C.J. Slunder and W.K. Boyd, International Lead Zinc Research Organization, Inc., New York, NY.

**Table 2.4 Metals susceptible to SCC**

|                                           |                                                  |
|-------------------------------------------|--------------------------------------------------|
| Carbon steels                             | Aqueous carbonates, nitrates, aqueous hydroxides |
| Copper                                    | Amines, ammonia, nitrates and nitrites, steam    |
| Aluminum                                  | Chlorides                                        |
| 200 and 300 series stainless steels       | Chlorides, hydroxides, sulfides with chlorides   |
| 400 series stainless steels (martensitic) | Hydroxides, nitrates, sulfides with chlorides    |
| Titanium                                  | Chlorinated solvents                             |

The crack initiates at a defect on the surface of the metal, such as a corrosion pit, inclusion in the metal, or other stress raiser. Figure 2.8 shows typical branched stress corrosion cracking.

**Figure 2.8 Stress Corrosion Cracking of Brass**

Cathodic protection generally reduces or eliminates stress corrosion cracking in many environments because it stops the corrosion process; however, carbon steel is susceptible to SCC in hydroxides and carbonates. Two different types of stress corrosion of pipelines in soils have been identified. At pH values between 6.5 and 7.5, transgranular SCC has been identified as being caused by hydrogen formation. At pH values between 8 and 10.5, intergranular SCC can occur. At the higher pH values, hydrogen generation stops or slows down and the steel begins to form a passive film,



but rupture of the passive film followed by corrosion of the exposed steel causes the crack to grow. Stress corrosion cracking is associated with the following conditions:

- carbonates and bicarbonates at the metal interface that are formed from the reaction of carbon dioxide in the soil with hydroxide that is formed from the cathodic protection reaction. This is a localized condition at the metal-to-electrolyte interface and is not associated with the chemistry of the electrolyte.
- a potential range at the metal surface between  $-525$  mV and  $-725$  mV (CSE). The potential range is not fixed and decreases (becomes slightly more negative) and narrows as the pH increases.
- holidays and disbonded coating on the pipe
- pipe surface temperatures between  $22^{\circ}\text{C}$  and  $90^{\circ}\text{C}$  ( $72^{\circ}\text{F}$  and  $195^{\circ}\text{F}$ )
- a stress level greater than 60 percent of the specified minimum yield strength. Cyclic loading also increases the chances of SCC
- the metallurgical structure and surface finish can also influence the occurrence of SCC
- the presence of mill scale on the pipe surface increases chances for SCC.

The effective use of cathodic protection will reduce the occurrence of corrosion, particularly pitting corrosion that can act as initiation sites for SCC. NACE standard RP0169 cautions that should not exceed against using potentials less negative than  $-850$  mV CSE when pipeline pressures and conditions are conducive to SCC.

## ***Fabrication Methods***

### ***Mechanical***

Mechanical methods of joining components on a structure may affect its susceptibility to corrosion and the application of cathodic protection. Mechanical connections in themselves are not necessarily good electrical conductors. Often, thin layers of corrosion products (oxides) form electrical insulators between joined components. Crevices produced by a mechanical method of joining may introduce environments that are corrosive. The zone within a crevice generally is low in dissolved oxygen and becomes the anode of a differential aeration cell. The effect of crevices in corrosion is often overcome by cathodically polarizing the surface outside the crevice to a potential sufficiently negative to prevent aggressive crevice attack. Mechanical methods are not in general desirable on a structure to which cathodic protection will be applied.



## ***Fusion Welded***

Welding assures electronic continuity from one portion of a structure to another. Complete fusion welds as opposed to fillet welds are more corrosion resistant and more suited to long term effectiveness of cathodic protection.

## ***Summary of Fabrication Effect on CP Design***

The design engineer must have full knowledge of the fabrication methods employed in the construction of a structure for which he is designing cathodic protection. Often additional electrical continuity bonding is required for some forms of construction.

## ***Electrical Continuity and Lineal Resistance***

### ***Methods of Joining***

As indicated under Fabrication Methods, mechanical joining may produce electrically discontinuous connection of one component to the next. Threaded pipe and piping units joined by bolting or mechanical couplings often develop significant amounts of linear resistance in a pipeline. Mechanical joints may even act as electrical isolation joints.

When considering cathodic protection for steel reinforcing in reinforced concrete structures it is essential that electrical continuity be established among the various metal components. If some of the reinforcing steel is not electrically connected, it will not receive protective current and may be subject to corrosive interference.

### ***Resistivity***

Resistivity is the property of a material that defines its resistance to the flow of electrical charge. The resistivity of a material can be determined by measuring the resistance across a known length of the material with a known cross section area.

$$\rho = \frac{RA}{L} \quad \text{Eq. 2.3}$$

where:

$\rho$  = resistivity

R = resistance across measured length of sample

A = cross section area of sample

L = length of sample

The lineal resistance of a structure is directly proportional to the resistivity of the material. From the above equation:

$$R = \frac{\rho L}{A} \quad \text{Eq. 2.4}$$

The higher the resistivity, the greater the resistance per unit length. Resistivity is more important when the cross-sectional area is small or the current carrying conductor is long

### ***Metal Thickness***

Cross-sectional area of metal in a component has an important influence on the lineal resistance. In this case, the resistance is inversely proportional to the cross sectional area of metal in the conductor. A thin wall pipe will exhibit a higher electrical resistance per unit length than will a thicker wall pipe of the same material.

## ***Summary of Electrical Continuity Effect on CP Design***

If cathodic protection is to be applied to a long metallic structure, particularly in a highly conductive (low resistivity environment), its electrical continuity is a major factor. As current accumulates on a long metallic structure, the current produces a voltage drop along the structure. This voltage drop increases as the current flow increases. The effect is termed attenuation.

Attenuation is a major factor in the design of cathodic protection systems for long pipelines or systems with lengthy parallel anode configurations. The latter occurs where current must be supplied to distance anodes through long connecting wires.

## Geometry

When a structure includes many component parts such as a field of foundation piles, one part of the structure can shield another part from receiving adequate protection current.

The presence of other structures in close proximity to or crossing the structure that is to be protected must be considered in cathodic protection design. Stray current from the cathodic protection system may have an adverse effect on surrounding structures. This effect may be associated with the location of the cathodic protection anode or it may be associated with protective coating faults on the structure. Such faults will cause local areas of current exchange with nearby structures.

## Voltage Gradients from Current Sources and Sinks

The rise in earth potential, at any point,  $x$ , caused by current entering (or leaving) the earth through a vertical electrode starting at the earth's surface is given by the following equation<sup>5</sup>:

$$V_r = \frac{\rho I}{2\pi L} \cdot \ln \left[ \frac{L + (L^2 + X_r^2)^{0.5}}{X_r} \right] \quad \text{Eq. 2.5}$$

where:

- $I$  = current delivered (by the anode) to the earth (A)
- $\rho$  = average resistivity of the earth (ohm-m)
- $L$  = length of rod below grade (meters)
- $X_r$  = distance (meters) from the center of the anode to the point  $x$
- $V_r$  = the voltage rise at  $x$  (volt) with respect to remote earth

<sup>5</sup> Corrosion Handbook, H.H. Uhlig, Editor, 1948, p. 941, John Wiley & Sons, Inc., New York

Figure 2-9 is a plot of voltage rise per ampere of current around a single vertical rod driven 2 meters into the soil.

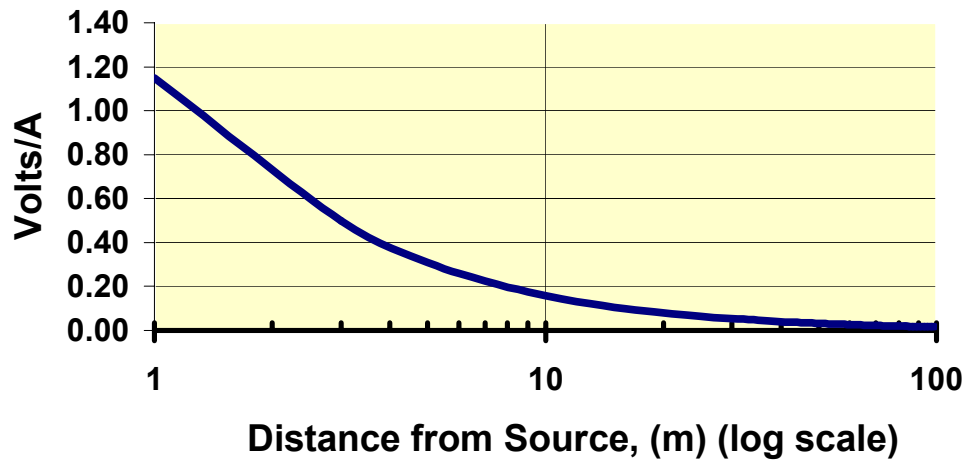


**Figure 2.9 Voltage rise (volts/amp) around 2 meter rod driven into 10 ohm-m soil.**

If  $X_r$  is greater than about 10 times  $L$  then the equation reduces to:

$$V_r = \frac{0.16I\rho}{X_r} \quad \text{Eq. 2.6}$$

From this simplified formula, it is evident that the voltage rise ( $V_r$ ) is inversely proportional to the distance  $X_r$  from the current source (anode) or sink, (exposed metal on a cathodic surface).

The ratio of voltage rise at a point ( $X_r$ ) distant from a vertical anode to the voltage rise of the anode measured to remote earth can be estimated using the ratio of the voltage rise equation at ( $I$ ) amperes:

$$V_r = \frac{\rho I}{2\pi L} \cdot \ln \left[ \frac{L + (L^2 + X_r^2)^{0.5}}{X_r} \right] \quad \text{Eq. 2.7}$$

to ( $I$ ) amperes times Dwight's equation for a vertical rod:

$$V = IR = \frac{\rho I}{2\pi L} \left[ \ln \left( \frac{8L}{d} \right) - 1 \right]$$

Carrying out the division yields:

$$\frac{V_r}{IR} = \frac{\ln \left[ \frac{L + (L^2 + X_r^2)^{0.5}}{X_r} \right]}{\ln \left[ \frac{8L}{d} \right] - 1}$$

where:

- $V_r$  = voltage rise per ampere at distance  $X_r$  meters from the anode (volts)
- $IR$  = voltage between the anode and remote earth at a current of 1 ampere
- $X_r$  = distance from anode
- $L$  = length of anode below the surface (meters)
- $d$  = diameter of the anode (meters)

Note that the formula is independent of resistivity and current. The formula permits estimates to be made of the relative "remoteness" of an anode with respect to structures in the area.

Figure 2-10 is a plot showing voltage gradient in soil as percent of electrode voltage to remote earth. Also shown is the percentage of electrode voltage gradient, which falls within the distance from the electrode to that point.

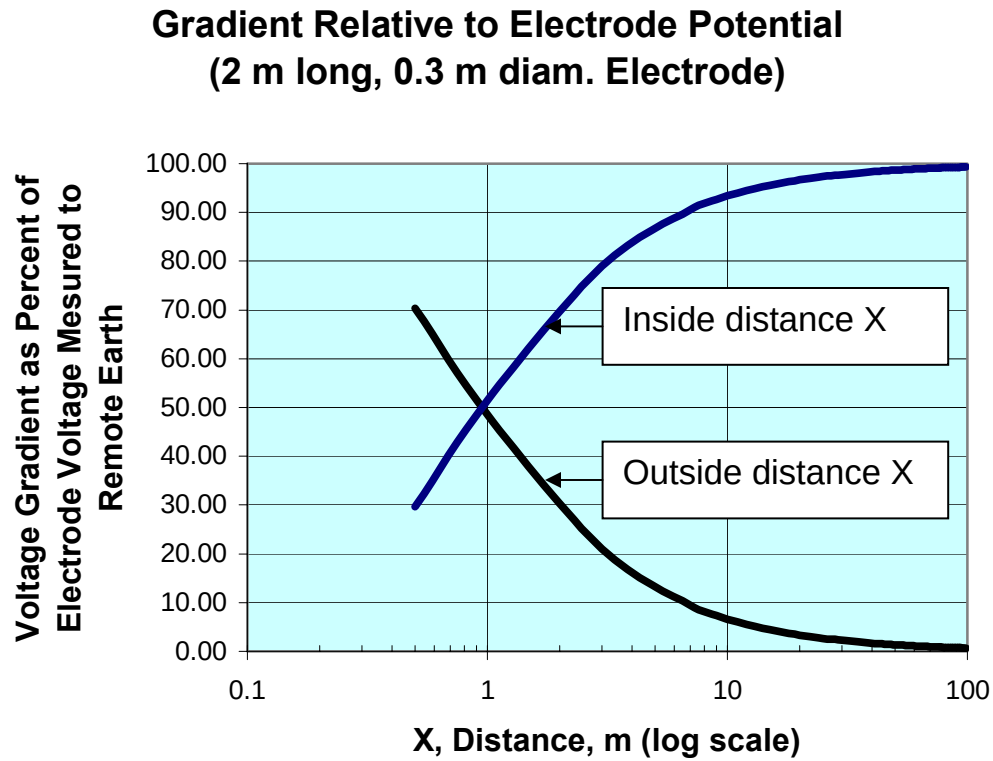


**Figure 2.10** *Voltage gradient as percent of electrode potential to remote earth*

# Estimating Current Required

## ***Need***

Design of a cathodic protection system requires some estimate of current needed to provide protection of structures. Doing the groundwork is one of the most important parts in the design process. Many costly mistakes can be avoided with some prudent preliminary work. This is especially true for unusual or complex systems.

## ***Current Requirements***

Estimating current required for cathodic protection before a structure is built involves making a number of assumptions.

The procedure is as follows:

- obtain general information about the environment.
- if the current requirement for the material in that environment is documented, use that figure.
- if the environment or operating conditions is unusual or in question, run laboratory scale tests using a known surface area of the material under the environmental conditions to be encountered.
- estimate the total area of the metal that will contact the environment. If protective coatings are to be used in conjunction with cathodic protection, consider how much of the structure will not be protected by the coating.
- calculate the total current required for cathodic protection using the following formula:

$$I_t = A_s i \quad \text{Eq. 2.8}$$

where:

- $I_t$  = total current required
- $A_s$  = Exposed metal surface
- $i$  = Current density required

Table 2.4 is a guide for estimating the magnitude of current density needed for cathodic protection in a variety of environments.



**Table 2.5 Typical values of current requirements for steel free from adverse galvanic influences in various environments**

| ENVIRONMENT                                                       | Required Current Density<br>$\text{mA/m}^2 \div 10.76 = \text{mA/ft}^2$ |
|-------------------------------------------------------------------|-------------------------------------------------------------------------|
| <b>BARE STEEL:</b>                                                |                                                                         |
| Sterile, neutral soil                                             | 4.2 - 16.1                                                              |
| Well-aerated neutral soil                                         | 21.5 - 32.3                                                             |
| Dry, well-aerated soil                                            | 5.4 - 16.1                                                              |
| Wet soil, moderate/severe conditions                              | 26.9 - 64.6                                                             |
| Highly acid soil                                                  | 53.8 - 161.4                                                            |
| Soil supporting active sulphate-reducing bacteria                 | 451.9                                                                   |
| Heated in soil (e.g. hot-water discharge line)                    | 53.8 - 269.0                                                            |
| Dry concrete                                                      | 5.4 - 16.1                                                              |
| Moist concrete                                                    | 53.8 - 269.0                                                            |
| Stationary fresh water                                            | 53.8                                                                    |
| Moving fresh water                                                | 53.8 - 64.6                                                             |
| Fresh water highly turbulent and containing dissolved oxygen      | 53.8 - 161.4                                                            |
| Hot water                                                         | 53.8 - 161.4                                                            |
| Polluted estuarine water                                          | 538.0 - 1614.0                                                          |
| Sea-water                                                         | 53.8 - 269.0                                                            |
| Chemicals, acid or alkaline solution in process tanks             | 53.8 - 269.0                                                            |
| Heat-exchanger water boxes with non-ferrous tube plates and tubes | 1345.0 overall                                                          |
| <b>WELL-COATED STEELS:</b>                                        |                                                                         |
| Soils                                                             | 0.01 - 0.2                                                              |

## Field Testing

When a structure is in place in its final configuration, it is generally possible to perform current requirement tests. Such tests have the advantage of producing data on the actual structure and do not involve assumptions as to effectiveness of the protective coating and other factors. Structures which have been designed for the application of cathodic protection (electrically isolated and coated pipelines are an example) can be tested in their entirety. Structures involving interconnections with metal elements outside the desired protection area are more difficult to test.

Current requirement testing generally involves installation of either a permanent or test anode system. The purpose is to introduce current into the earth at the site where the permanent groundbed (anode) will be located.

For large structures, a representative sample section can be chosen for the initial test phase. A suitable power supply (batteries, test rectifier, or motor generator system) is then connected between the structure and test grounded as illustrated in Figure 2.11. Test current is applied between the grounded and the structure and the effects on the structure are measured.

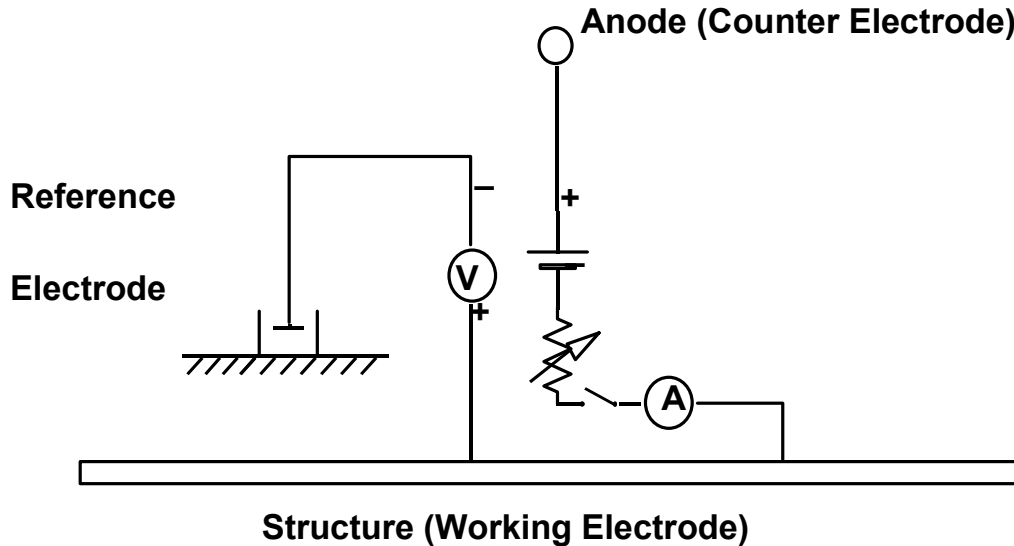
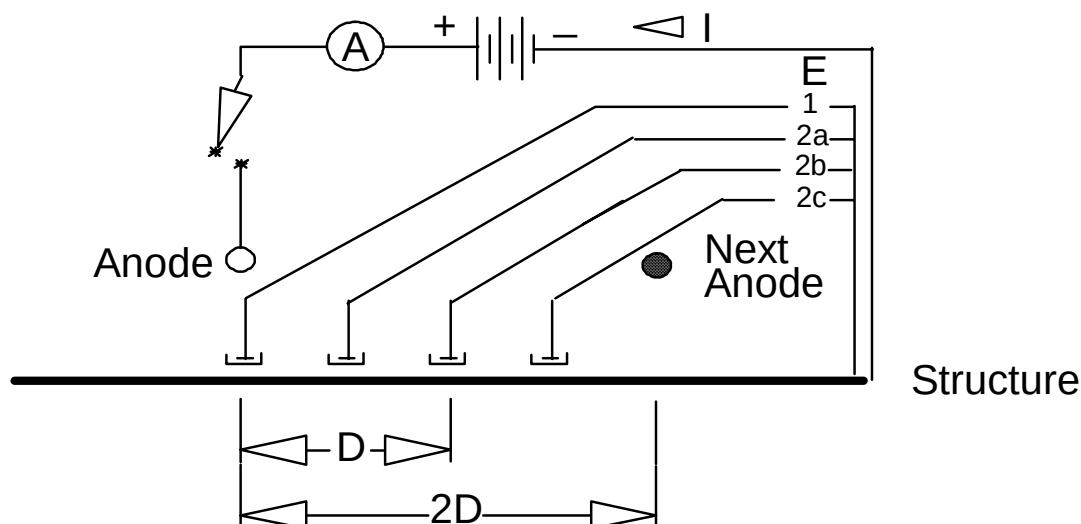


**Figure 2.11. Current Requirement Test Circuit**

Among the tests that can be performed are:

- electrochemical testing for polarization shift.
- network analysis to determine current distribution on pipe and cable systems.
- tests to locate electrical grounds on otherwise isolated structures.
- optimum permanent placement of the anode bed location.
- possible interference effects on other structures.

If only a portion of a long structure (pipe or cable) is being tested for the affect of applied current, a pilot test is often possible. One approach to determining the spacing for anodes along such a structure is illustrated in Figure 2.12.



Adjust distance "D" so  $\Delta E_2 / \Delta I = 0.5 \Delta E_1 / \Delta I$

Place next anode 2D units from first anode

**Figure 2.12 Current Requirement Test for a Distributed Anode System**

A test anode is placed at an acceptable distance perpendicular to the structure to be protected. The distance may be dictated by physical constraints (e.g. inside utility right of way) or by the presence of other structures. A reference electrode is then placed over the structure at a point opposite to the test anode.

The change in structure to soil potential per ampere of test current (ground voltage coupling,  $R_{1,I}$ ) is measured:

$$R_{1,I} = \Delta V_1 / \Delta I = (V_{1on} - V_{1off}) / (I_{on} - I_{off}) \quad \text{Eq. 2.9}$$

where:

$R_{1,I}$  = change in structure to soil potential at location 1 per ampere of current

$\Delta V_1$  = voltage change at location 1

$\Delta I$  = change in test current

The reference electrode is then moved along the structure until the change in voltage ( $\Delta V_2$ ) produced by current ( $I$ ) is equal to  $0.5 \times R_{1,I}$ . The second anode is then positioned at a distance  $2D$  from the first anode. Succeeding anodes are then placed along the structure on a spacing

equal to 2D. A fairly accurate estimate of current required to protect such a structure can be obtained by installing three to five test anodes in this fashion. Cathodic polarization tests are then run to determine the amount of current required to properly meet protection criteria opposite the central anode of the group. Current for the entire structure and the number of anodes required can then be calculated.

### Example 2.1

The concentric neutral of an underground electric cable is corroding. Cathodic protection is to be applied to 914 meters (3000 feet) of this cable using a string of anodes placed along the curb line. The corrosion technician uses the method illustrated in Figure 2.12 to determine anode spacing. The test suggests that anodes on 9.1 meter (30-foot) centers will meet the requirements:

$$\Delta V_2/\Delta I = 0.5 \Delta V_1/\Delta I \text{ at } D = 4.6 \text{ m (15 ft.)}$$

The technician then sets up a test anode array consisting of 5 ground rods driven into the soil on 9.1 meter (30-foot) centers. All 5 rods are then tested with a ground megger to determine the resistance of each rod to the cable neutral. All the rods are found to have a rod to neutral resistance within about 15% of each other. This test assures that about equal amounts of current will be discharged from each of the rods when they are grouped together as a test anode.

The rods are then connected together to form a distributed test anode along 45.7 meters (150 feet) of the cable. Using a circuit similar to the one in Figure 2.11, the technician performs an E log i test. The beginning of the Tafel slope occurs at a current of 150 mA. What are the total requirements in terms of current and number of anodes to protect the 914 meters (3000 feet) of cable neutral?

The anodes are to be on 9.1 m (30 ft.) centers, therefore, the number of anodes required is:  $914/9.1 + 1 = 101$  anodes

The average current output from each anode in the test at the required total output of 150 mA was:  $150 \text{ mA}/5 = 30 \text{ mA}$

The total current required to protect the 914 m (3000 ft). of cable is:  $30 \text{ mA} \times 101 = 3030 \text{ mA} = 3 \text{ A}$

## Coatings

Dielectric protective coatings often perform the greatest percentage of corrosion control on structures exposed to corrosive environments. If a coating has excellent dielectric properties and will not significantly degrade under the alkaline conditions produced by cathodic protection, the coating will be compatible with cathodic protection. High dielectric organic coating types will greatly reduce the total current requirements from a cathodic protection system. The reason is that the coating effectively separates most of the metal surface from direct contact with the environment. This leaves only small damaged areas (holidays) for the cathodic protection system to protect.

Generally, coatings with poor dielectric properties will require significantly greater cathodic protection current output to achieve corrosion control. On long structures in very conductive environments (e.g. seawater), the dielectric properties of the coating have a significant impact on attenuation. The poorer the dielectric properties, the greater the attenuation.

The importance of protective coatings in the design of cathodic protection systems cannot be overemphasized. For this reason, it is important to have a sound background in the different types and properties of coatings used in conjunction with cathodic protection.

### **General**

Dielectric type protective coatings that are properly selected and applied have a dramatically beneficial effect on current distribution and reduce the total current requirements. This is achieved by almost complete separation of the metal of the structure's surface from the environment. The principal effect of the coating involves its high electrical resistivity, which increases the structure leakage resistance,  $R_L$ , thereby minimizing current attenuation.

The structure's leakage resistance ( $R_{L,S}$ ) as shown in Figure 2.13, is the sum of the coating's leakage resistance ( $R_{L,C}$ ) and the leakage resistance to remote earth ( $R_{L,E}$ ).

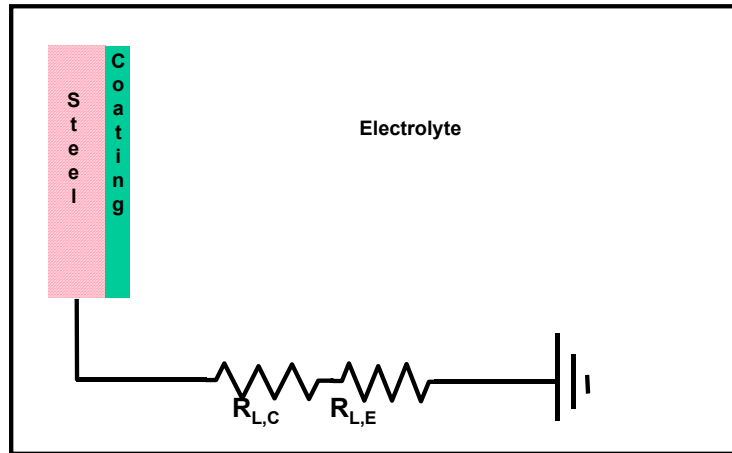


**Figure 2.13 Leakage Resistance Coated Structure to Remote Earth**

The coating's leakage resistance is a function of its electrical resistivity, thickness, and surface area exposed to the electrolyte. Therefore,

$$R_{LC} = \frac{\rho_c t}{A_s} \quad \text{Eq. 2.10}$$

where:

- $R_{LC}$  = resistance of coating in ohm
- $\rho_c$  = coating electrical resistivity in ohm-cm
- $t$  = coating thickness in cm
- $A_s$  = coated surface area in  $\text{cm}^2$ .

Typical resistivities for today's pipeline coatings are on the order of  $10^{10}$  to  $10^{12}$  ohm-cm, and coating thickness is on the order of 0.03 cm (12 mils). Older "high build" coatings were much thicker. Some mastics were as thick as 2 cm. Accordingly, the resistance  $R_{LC}$  for one square meter of a very thin coating would be as follows:

$$R_{LC} = \frac{(10^{10} \text{ ohm-cm}) \times (0.03 \text{ cm})}{10^4 \text{ cm}^2}$$

$R_{LC}$  = 30,000 ohm for 1 square meter of surface.

The value of the leakage resistance,  $R_{L,E}$ , from outside the coating to remote earth can be approximated by assuming the surface is a disc with an area of one square meter. In this case, the resistance,  $R_{L,E}$ , is given by the following expression:

$$R_{L,E} = \frac{\rho_s}{2d} \quad \text{Eq. 2.11}$$

where:

$\rho_s$  = electrolyte resistivity in ohm-cm  
 $d$  = diameter of disc, cm

For a disc with a surface area of  $1 \times 10^4 \text{ cm}^2$  (i.e.,  $1 \text{ m}^2$ ), the diameter would be:

$$d = 2\sqrt{\frac{A_s}{\pi}} = 2\sqrt{\frac{10^4}{\pi}} = 113 \text{ cm}$$

Therefore, for a soil resistivity of 1,000 ohm-cm

$$R_{L,E} = \frac{1,000 \text{ ohm-cm}}{2 \times 113 \text{ cm}} = 4.42 \text{ ohm for 1 square meter of surface.}$$

This example shows that the coating resistance  $R_{L,C}$  is the dominant component of the total leakage resistance of the structure.

The leakage resistance of most coatings can be expected to decrease in service because coatings deteriorate with time. For this reason, it is important to measure the structure's coating resistance periodically. By assuming that most of the voltage drop occurs across the coating rather than in the electrolyte (this is generally true for most well-coated structures), the leakage resistance of all, or a portion of the structure can be determined by the following expression:

$$R_{L,C} = \frac{\Delta V_{avg}}{\Delta I_{C,P}}$$

where:

$\Delta V_{avg}$  = the average potential change on the structure with the current on and instantaneously off

$\Delta I_{c,p}$  = the change in cathodic protection current on all or a portion of the structure.

The specific leakage resistance,  $r'_{L,C}$ , for the coating is then related to the average leakage resistance,  $R_{L,C}$ , by the equation:

$$r'_{L,C} = R_{L,C} A_s$$

and where  $A_s$  is the surface area of the portion of the structure under test. The specific leakage resistance, therefore, is typically expressed in units of ohm-ft<sup>2</sup> or ohm-m<sup>2</sup>.

Figure 2.14 illustrates the field test for determining effective coating resistance.

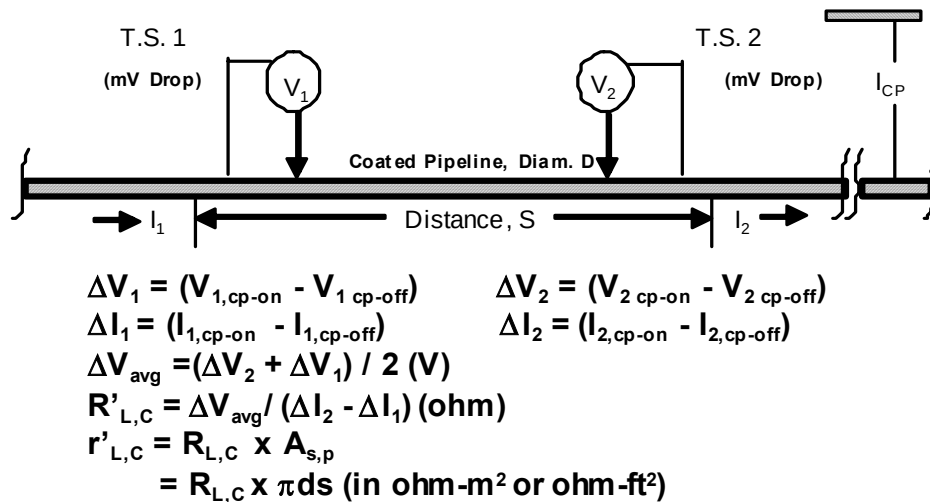


**Figure 2.14 Coating resistance test**

Coating quality can be rated on the basis of specific coating resistance or conductance, as shown in Table 2.5.



**Table 2.6 Typical Pipe to Earth Leakage Conductance for Dielectric Protective Coatings in 1000 Ohm Cm Soil**

| Long Pipelines with Few Fittings                    | AVERAGE SPECIFIC COATING CONDUCTANCE     |                                          |
|-----------------------------------------------------|------------------------------------------|------------------------------------------|
|                                                     | g' or 1/r'<br>Siemens/ft <sup>2</sup>    | g' or 1/r'<br>Siemens/m <sup>2</sup>     |
| <b>Quality of Work</b>                              |                                          |                                          |
| Excellent                                           | $<1 \times 10^{-5}$                      | $<1 \times 10^{-4}$                      |
| Good                                                | $1 \times 10^{-5}$ to $5 \times 10^{-5}$ | $1 \times 10^{-4}$ to $5 \times 10^{-4}$ |
| Fair                                                | $5 \times 10^{-5}$ to $1 \times 10^{-4}$ | $5 \times 10^{-4}$ to $1 \times 10^{-3}$ |
| Poor                                                | $>1 \times 10^{-4}$                      | $>1 \times 10^{-3}$                      |
| Bare pipe<br>(2" to 12")<br>(5 cm to 30 cm)         | $4 \times 10^{-3}$ to $2 \times 10^{-2}$ | $4 \times 10^{-2}$ to $2 \times 10^{-1}$ |
|                                                     |                                          |                                          |
| <b>Gas or Water Distribution with Many Fittings</b> |                                          |                                          |
| <b>Quality of work</b>                              |                                          |                                          |
| Excellent                                           | $<5 \times 10^{-5}$                      | $<5 \times 10^{-4}$                      |
| Good                                                | $5 \times 10^{-5}$ to $1 \times 10^{-4}$ | $5 \times 10^{-4}$ to $1 \times 10^{-3}$ |
| Fair                                                | $1 \times 10^{-4}$ to $5 \times 10^{-4}$ | $1 \times 10^{-3}$ to $5 \times 10^{-3}$ |
| Poor                                                | $>5 \times 10^{-4}$                      | $>5 \times 10^{-3}$                      |
| Bare pipe<br>(2" to 12")<br>(5 cm to 30 cm)         | $4 \times 10^{-3}$ to $2 \times 10^{-2}$ | $4 \times 10^{-2}$ to $2 \times 10^{-1}$ |

Electrical leakage through a coating on a long structure such as a pipeline has an important impact on the distribution of current from a cathodic protection source.

Although a good-quality coating will significantly diminish attenuation and enhance current distribution, the current density is only uniform through the coating. At breaks in the coating called *holidays*, the current density can be extremely variable. For instance, in Figure 2.15, the current density at Holiday A will be much greater than at Holiday B when the anode is in

close proximity to the holidays. Moreover, the current density at a holiday is also a function of the holiday size and shape. Consider that for a circular disk shaped holiday the resistance to remote earth is approximated by:

$$R_{L,E} = \frac{\rho_s}{4r} \quad \text{Where } r = \text{radius of the circular holiday.}$$

The area of the holiday is given by:

$$A_{\text{hol}} = \pi r^2$$

The current density for the holiday is:

$$i = \frac{\Delta V_{\text{ave}}}{R_{L,E} A_{\text{hol}}} = \frac{\Delta V_{\text{ave}} 4r}{\rho_s \pi r^2} = \frac{4\Delta V_{\text{ave}}}{\rho_s \pi r}$$

The current density at circular holidays, therefore, is inversely proportional to the radius of the holiday for any given driving voltage and soil resistivity. Current densities at small holidays can be significantly higher than large ones.

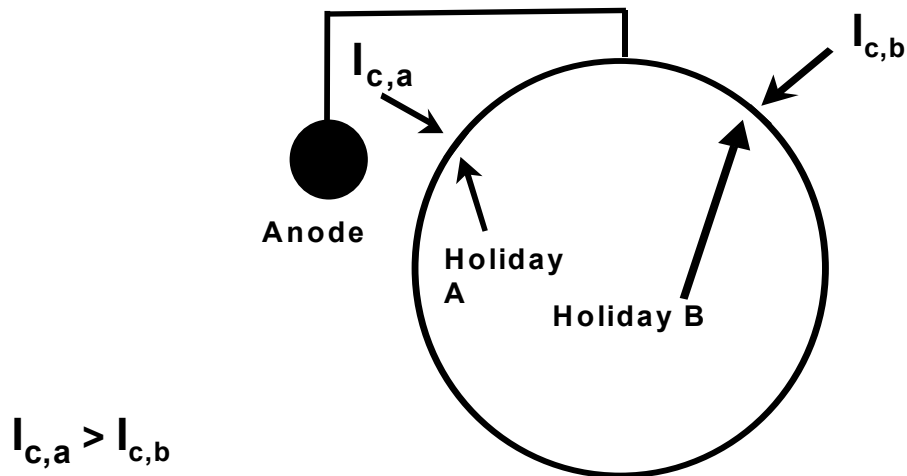


**Figure 2.15 Current Densities at Holidays at Different Distances from the Anode**

## ***Types of Coatings***

Coatings can be classified in a variety of ways. One way is to classify coatings as organic or inorganic.

### ***Organic Coatings***

Most coatings are organic, i.e. they are formulated of carbon compounds. These are the materials that give long-term corrosion protection to industrial, marine, chemical, and petroleum structures.

Organic coatings contain carbon-to-carbon bonding as well as carbon-to-other element bonds. They are generally made from living, or once living, things, such as vegetable oil, animal fats and waxes, petroleum, coal, etc. Alkyds, epoxies, oil, and tars are examples of organic coatings.

### ***Inorganic Coatings (Non-carbon-Containing)***

Inorganic coatings do not contain carbon-to-carbon bonding. They are generally made up of salts of sodium, lithium, potassium, and silica. Inorganic coatings have very specific properties and are primarily used for specialized areas. Examples include phosphating coatings, metallics, silicates, cement, and glass.

Mortar coatings depend on the high pH ( $13\pm$ ) of the cement to produce and maintain a passive film on the surface of steel structures. Active metal coatings such as zinc (galvanize) and aluminum depend, in part, on their sacrificial properties to protect the steel substrate.

For those interested in further discussion of protective coatings and their relation to cathodic protection, please refer to Appendix H "Protective Coatings Supplement".

# Use of Electrical Isolation

## ***Galvanic Couples***

A structure that is electronically connected through metal attachments to other structures is susceptible to galvanic couples. An excellent example is steel gas or water piping connected to copper grounding mats. The steel components become anodes (corroding elements) of the galvanic couple with the copper. Cathodic protection of such couples requires that the noble components (copper) be polarized to a potential at least as electronegative as the steel components.

## ***Current Distribution***

Interconnection of a structure to which cathodic protection is to be applied with other structures significantly impacts current distribution. A grounded structure or element often requires many orders of magnitude, greater current, for cathodic protection than an identical structure that is electrically isolated from other structures or grounding systems.

## ***Summary of Isolation Effect on CP Design***

Whether or not a structure (which is to be cathodically protected) must be grounded or must be interconnected with other grounded structures has a significant bearing on the cathodic protection design. Cathodic protection systems must overcome the galvanic couples introduced by such grounding. To do this, the CP system must provide sufficient current to significantly polarize the grounding elements.

## Grounding

For safety reasons, some structures must meet certain codes on grounding. This may require that the cathodic protection system be designed so that the grounding requirements are not circumvented. Special care must be taken to meet the applicable codes.

## Required Life

### ***Existing Structures***

Not all structures are required to last indefinitely. Generally, a useful service life is assigned by the owner or engineer. When corrosion is affecting



an existing structure the need for extension of the life may become apparent. For existing structures undergoing active corrosion it is necessary to establish, through survey, an estimate of the condition. For containment vessels such as pipelines and storage tanks, such an evaluation may be in the form of a statistical pit depth analysis or leak history. For structural members, a loss of section may be the critical factor. Cathodic protection cannot restore a structure. If a condition analysis indicates that the structure is corroded to a point beyond safety considerations, it should be replaced rather than cathodically protected. If the evaluation assessment indicates reasonable conditions and a projected additional life of 10 years for example, and it is desired to extend the life to 20 years, complete cathodic protection would be required for only 10 additional years.

## ***New Structures***

Two options are sometimes possible to increase the life of a new structure. Increase the thickness of metal to compensate for active corrosion, or use thinner metal sections and install cathodic protection to provide the necessary service life. The economic life of many structures cannot be projected beyond about 30 years. Therefore, many cathodic protection systems are designed to last for such a period. A decision can be made at a future date, on whether or not to re-establish cathodic protection. Often on new structures, most of the corrosion control is achieved through application of an effective protective coating system. This reduces the current requirements for cathodic protection significantly.

If cathodic protection is to be an integral part of the design of the structure, electrical isolation of the structure may provide a major improvement in overall cathodic protection effectiveness and service life.

## **Construction Inspection**

Construction inspection should provide for proper adherence to specifications. This particularly applies to structure fabrication (welding, bonding, and joining) and to the application of corrosion mitigation coatings. Quality inspection can have a great bearing on the efficiency as well as adequacy of a cathodic protection system. Poor construction inspection invariably results in problems for or with a cathodic protection system.

## **Effect of Stray Current on CP Design**

The presence of stray currents, both AC and DC, must be taken into consideration in the design of cathodic protection systems. Auto rectification from AC stray current flowing between a structure and a rectifier-powered groundbed may render control of the cathodic protection unacceptable.

Cathodic protection systems may have to take into account stray current discharge areas on a structure. Placement of cathodic protection components (particularly anodes) may be influenced by the presence of stray direct currents.

## Subsurface Geology

### ***Effect on CP Current Distribution***

Mention has been made of the effect of rock ledges on the flow of current in the earth. Layers of rock and non-conductive material may severely limit the distribution of cathodic protection currents, particularly on large structures, such as the bottoms of steel tanks in a petroleum tank farm. Subsurface geology surveys may also provide information on highly conductive strata of soils several hundred feet below the surface. Such soil strata may be useful in the design of "deep anode" cathodic protection systems. In such cases, the anode introduces current into the highly conductive strata well below the surface. This improves distribution of cathodic protection currents to remote portions of the structure. It also limits voltage gradients produced by current flow from the anode to a deep location well away from other structures. Such gradients can produce stray current interference on other structures that cross them.

## Backfill (Structure)

### ***Effect on CP***

The type of backfill employed around a structure may have some influence on the effectiveness of cathodic protection. A pipe or other structure installed in a well-drained coarse gravel may be subject to atmospheric type corrosion which cathodic protection cannot control. In such cases there is no continuous electrolytic path between the cathodic protection system and the corroding metal surface. In other situations, installation of poor quality backfill (large rocks and similar refuse) may severely damage protective coatings applied to the structure. This may significantly increase the amount of cathodic protection current required to control corrosion.

# Surrounding Structures

## ***Effect on CP Design***

The presence of other structures in close proximity to or crossing the structure, which is to be protected, must be considered in cathodic protection design. Stray current from the cathodic protection system may have an adverse effect on surrounding structures. This effect may be associated with the location of the cathodic protection anode or it may be associated with protective coating faults on the structure. Such faults will cause local areas of current exchange with nearby structures.

# Accessibility

## ***Effect on CP Design***

The accessibility of a structure for application of cathodic protection is a critical issue. If the structure cannot be readily accessed for electrical connection (e.g. steel pilings under a building), cathodic protection may be difficult, if not impossible to realize. It is important during structure design that accessibility problems be addressed. Similarly, if a pipeline is constructed in an inaccessible location using electrically noncontinuous joining materials, it may be virtually impossible to design a cost effective cathodic protection system once that structure has been built.

# AC Power Availability

## ***Effect on CP Design***

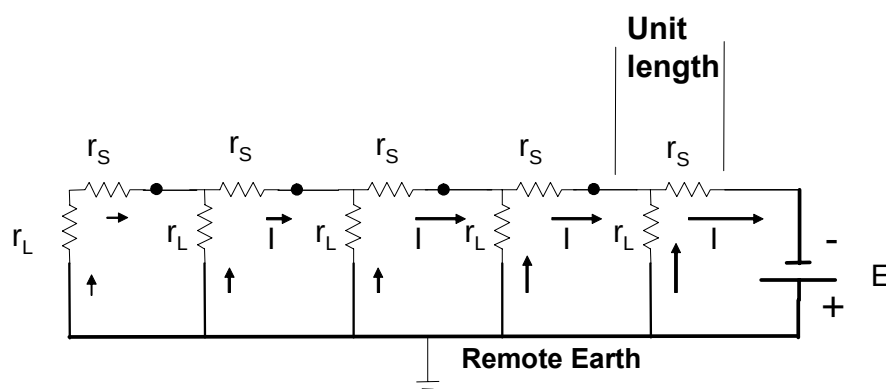
The presence or absence of available commercial power is a factor in the type of cathodic protection system that may be considered for a structure. If AC power is not available, selection of a power source is limited to sacrificial anodes, solar converters, wind generators, or fossil fuel power generation. Along pipelines and similar structures it is necessary to consider the availability of electric power for cathodic protection systems at road crossings and inhabited areas.

# Attenuation

## General

Cathodic protection on a structure requires that electric charge be transferred from the soil to exposed metal surfaces of the pipe in sufficient density to overcome the corrosion mechanisms present at the pipe-soil interface. The cathodic protection system must provide sufficient electric potential between the structure and soil to maintain the required level of charge transfer at all locations where bare metal surfaces of the pipe come in contact with the earth. Various corrosion mechanisms associated with the specific conditions along a structure dictate the actual current required.

On an electrically long structure, such as a pipeline, attenuation is the term applied to the decrease in pipe to soil electric potential shift produced by a cathodic protection system as the distance from the source of current, generally a rectifier, increases. On a pipeline, the incremental loss in pipe to soil potential shift is caused an increasing current path resistance and hence diminishing current density. Figure 2.16 is an electrical circuit that illustrates how attenuation occurs. The voltage drop is greatest near the current source where the highest current flow is present on the pipe. The lower the attenuation, the greater the possible separation of cathodic protection power sources along a pipeline.



$r_s$  = unit lineal resistance of structure (ohms)

$r_L$  = unit leakage resistance (ohms)

$g = 1/r_L$  = unit leakage conductance (S)

**Figure 2.16 Attenuation circuit diagram**



Six mathematical equations defining attenuation are given in the following section. Those equations are helpful in estimating the effect of attenuation when designing cathodic protection for a long pipeline. The key constants employed in the equations are "r", the unit resistance along the pipeline, and "g", the unit conductance between the pipe and soil. The unit lineal resistance is controlled by the amount of metal in the wall of the pipe. The thicker the wall the better the electrical conductivity and therefore, the lower the electrical resistance per unit of length. In attenuation, the lower the unit resistance of the structure, the less the attenuation. The unit conductance between the pipe and soil is dependent on the effectiveness of any dielectric coating applied to the pipe and the electric conductance of the soil. Conductance is the reciprocal of resistance. In attenuation, the lower the pipe-to-soil unit conductance, the lower the attenuation. Therefore, good coating quality and high soil resistivity reduce attenuation.

Consider now how the problem of attenuation can be addressed when considering current distribution from a single source to a long structure such as a pipeline.

## ***Calculations***

Figure 2.18 provides the basic formulas for calculating attenuation effects. The general equations (1–6) have been derived for direct current from the more general equations governing attenuation on long power transmission lines in the electric power industry. Excluded are factors that relate to alternating current. The equations assume that there is a zero resistance bus at remote earth and therefore, the potential, E, is the potential difference between the structure and remote earth. The equations also assume constant coating leakage conductance and uniform soil resistivity throughout any given section. Larger than average coating faults or attachments to the structure that provide a current leakage path can have a significant effect. The important variables are as follows.

The propagation or attenuation constant,  $\alpha$ , that is determined by the electrical resistance per unit length of the structure and the electrical leakage conductance per unit length between the structure and remote earth. It is defined by:

$$\alpha = (rg)^{0.5}$$

where r is the resistance in ohms per unit length of the structure, and g is the leakage conductance, in Siemens per unit length. Since conductance is the reciprocal of resistance, the equation can be written as follows.

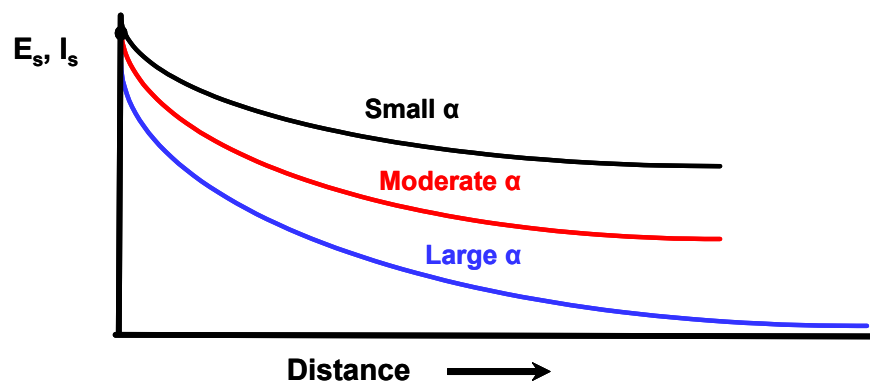
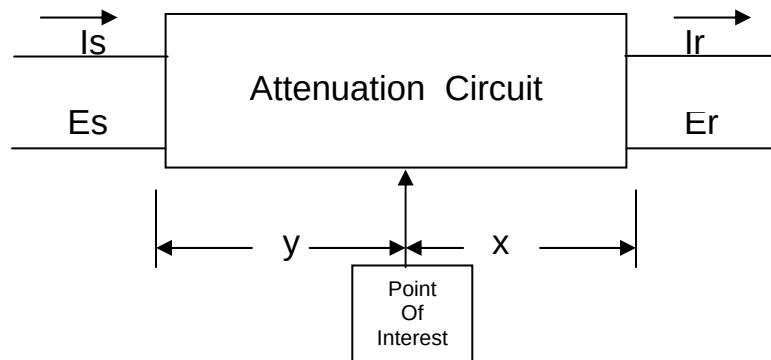


**Figure 2.17 Attenuation Characteristic versus Attenuation Constant**

### DC Attenuation Formulas



$\alpha = \sqrt{rg}$  propagation or attenuation constant

$R_G = \sqrt{\frac{r}{g}}$  characteristic resistance (ohms)

$r =$  unit lineal resistance, ohms/unit length

$g =$  unit conductance to earth S/unit length

$x =$  number of unit lengths from receiving end

$y =$  number of unit lengths from sending end

| General Equations                                                           | Where:                                          |
|-----------------------------------------------------------------------------|-------------------------------------------------|
| 1. $E = E_r \cosh(\alpha x) + R_G I_r \sinh(\alpha x)$                      | $E_r$ = receiving end potential                 |
| 2. $I = I_r \cosh(\alpha x) + \left(\frac{E_r}{R_G}\right) \sinh(\alpha x)$ | $I_r$ = receiving end current                   |
| 3. $E = E_s \cosh(\alpha y) - R_G I_s \sinh(\alpha y)$                      | $E_s$ = sending end potential                   |
| 4. $I = I_s \cosh(\alpha y) - \left(\frac{E_s}{R_G}\right) \sinh(\alpha y)$ | $I_s$ = sending end current                     |
| 5. $R_{so} = R_G \coth(\alpha x)$                                           | $R_{so}$ = Resistance looking into open line    |
| 6. $R_G = \sqrt{R_{so} R_{ss}}$                                             | $R_{ss}$ = Resistance looking into shorted line |

**Figure 2.18 DC Attenuation Formulas**

$$\alpha = \sqrt{\frac{r_s}{r_L}}$$

where  $r_s$  is the unit linear resistance of the structure (ohm/unit length) and  $r_L$  is the unit resistance of the structure to remote earth (ohm/unit length). The value of unit linear resistance for the structure is calculated from the cross sectional area of the metal in the structure section, the length of the section and the resistivity of the metal.

$$r = \frac{\rho L}{A}$$

or for a pipeline, 
$$r = \frac{\rho L}{\frac{\pi}{4}(OD^2 - ID^2)}$$

where

OD = outside diameter of pipe

ID = inside diameter of pipe

## Example 2.2

As an example, consider a 60.96cm (24 in.) diameter steel pipe with 1.27 cm (0.5 in.) wall. Assume the resistivity of the steel is 13.4  $\mu\text{ohm-cm}$  (5.29  $\mu\text{ohm-in.}$ ). The cross section area, A, of the pipe wall will be 238.15  $\text{cm}^2$  (36.91  $\text{in}^2$ ). If we choose a unit length, L, of 16.09 km (10.0 miles), the lineal resistance of a unit length of pipe will be:

$$r = \frac{13.4 \times 10^{-6} \text{ ohm-cm} \times 16.09 \times 10^5 \text{ cm}}{238.15 \text{ cm}^2} = 0.0905 \text{ ohm/unit}$$

The value of leakage conductance, g, depends on the type of coating, the resistivity of the soil and the number and size of coating faults. Unlike the pipe resistance, which can be accurately determined, the leakage conductance can only be estimated based on experience or by actual test on the completed structure. Table 2.6 lists some typical values of specific leakage conductance,  $g'$ , in 1000 ohm-cm soil. If we expect an excellent quality coating with no major faults (holidays), we might assume a specific leakage conductance of  $4.3 \times 10^{-5} \text{ S/m}^2$  in 1000 ohm-cm soil. This is equal to an average specific pipe-to remote-earth resistance of 23255 ohms- $\text{m}^2$  (250,348 ohm- $\text{ft}^2$ ). The surface area on a unit length of our pipeline is:

$$A_s = \pi dL = \pi \times 0.6096 \text{ m} \times 16090 \text{ m} = 30,814 \text{ m}^2 / \text{unit}$$

The unit leakage conductance in 1000 ohm-cm soil is:

$$g_{1000} = g' \times A_s$$

$$g = 4.3 \times 10^{-5} \text{ s / m}^2 \times 30,814 \text{ m}^2 = 1.325 \text{ S / unit}$$

$$\begin{aligned} g_{1000} &= \text{unit leakage in 1000 ohm-cm soil} \\ g' &= \text{specific leakage conductance s/m}^2 \\ A_s &= \text{surface area of coated structure} \end{aligned}$$

**Table 2.7 Typical Specific Pipe to Earth Leakage Conductance for Dielectric Protective Coatings in 1000 Ohm Cm Soil**

| Long Pipelines with Few Fittings             | AVERAGE SPECIFIC COATING CONDUCTANCE, g' |                                          |
|----------------------------------------------|------------------------------------------|------------------------------------------|
|                                              | Siemens/ft <sup>2</sup>                  | Siemens/m <sup>2</sup>                   |
| Quality of Work                              |                                          |                                          |
| Excellent                                    | $<1 \times 10^{-5}$                      | $<1 \times 10^{-4}$                      |
| Good                                         | $1 \times 10^{-5}$ to $5 \times 10^{-5}$ | $1 \times 10^{-4}$ to $5 \times 10^{-4}$ |
| Fair                                         | $5 \times 10^{-5}$ to $1 \times 10^{-4}$ | $5 \times 10^{-4}$ to $1 \times 10^{-3}$ |
| Poor                                         | $>1 \times 10^{-4}$                      | $>1 \times 10^{-3}$                      |
| Bare pipe<br>(2" to 12")<br>(5 cm to 30 cm)  | $4 \times 10^{-3}$ to $2 \times 10^{-2}$ | $4 \times 10^{-2}$ to $2 \times 10^{-1}$ |
|                                              |                                          |                                          |
| Gas or Water Distribution with Many Fittings |                                          |                                          |
| Quality of work                              |                                          |                                          |
| Excellent                                    | $<5 \times 10^{-5}$                      | $<5 \times 10^{-4}$                      |
| Good                                         | $5 \times 10^{-5}$ to $1 \times 10^{-4}$ | $5 \times 10^{-4}$ to $1 \times 10^{-3}$ |
| Fair                                         | $1 \times 10^{-4}$ to $5 \times 10^{-4}$ | $1 \times 10^{-3}$ to $5 \times 10^{-3}$ |
| Poor                                         | $>5 \times 10^{-4}$                      | $>5 \times 10^{-3}$                      |
| Bare pipe<br>(2" to 12")<br>(5 cm to 30 cm)  | $4 \times 10^{-3}$ to $2 \times 10^{-2}$ | $4 \times 10^{-2}$ to $2 \times 10^{-1}$ |

If the average soil resistivity is 5,000 ohm-cm instead of 1000 ohm-cm, the leakage conductance will be proportionally less.

$$g = \frac{1.325 \text{ S} \times 1000 \text{ ohm} - \text{cm}}{5,000 \text{ ohm} - \text{cm}} = 0.265 \text{ S/unit}$$

In 5,000 ohm-cm soil the attenuation propagation constant will be:

$$\alpha = \sqrt{rg} = \sqrt{0.0905 \text{ ohm} \cdot 0.265 \text{ S}} = 0.1549$$

and the characteristic resistance of the pipeline is:

$$R_G = \sqrt{\frac{r}{g}} = \sqrt{\frac{0.0905 \text{ ohm}}{0.265 \text{ S}}} = 0.584 \text{ ohm}$$

Once the propagation constant and characteristic resistances are calculated, the designer can use the general equations from Figure 2.17 to calculate current distribution and pipe-to-soil potential shift for any current source draining to or from the pipeline.

Assume that the pipeline with the above constants is ten units long and electrically isolated at both ends. The design engineer wishes to know what the effect will be from a cathodic protection source applied at one end of the line.

From Figure 2.18, equation 5, the resistance is calculated between the pipeline and remote earth looking into the source end  $x$  units from the receiving end.

$$R_{SO} = R_G \coth(\alpha x) = 0.584 \text{ ohm} \coth(0.1549 \cdot 10) = 0.639 \text{ ohm}$$

By Ohm's law, 1.0A, returned at the source end will shift the pipe to remote earth potential by:

$$E_s = 1 \text{ A} \cdot 0.639 \text{ ohm} = 0.639 \text{ V}$$

Figure 2.18, Equation 3 is now used to calculate the voltage shift at the receiving end,  $y = 10$  units from the source.

$$E = E_s \cosh(\alpha y) - R_G I_s \sinh(\alpha y)$$

$$E = (0.639 \text{ volt} \times 2.460) - (0.584 \text{ ohm} \times 1.00 \text{ amp} \times 2.247) = 0.260 \text{ V}$$

The potential shift at the receiving end is only about 41% of that at the source end.

By using the equations available in Figure 2.18 it is possible to calculate the percentage of source current flowing at any point on the pipeline as well as differential current received along the line.

## Electrically Long

As indicated in previous paragraphs, long pipelines and groundbed header cables can be modeled as DC electrical transmission lines. The magnitude of the input variables, current and voltage, decreases or attenuates with increasing distance from the input end of the line as determined by the attenuation constant. If the line is physically long enough or the attenuation constant is large enough, the input variables will approach zero at some distance. If a transmission system is such that the input variables approach zero, the line is referred to as being "electrically long".

An electrically long transmission line is defined as a transmission line where the input variables cannot be detected at the receiving end of the line. Another way of defining electrically long is a transmission line with an input resistance equal to its characteristic resistance. In other words, as the length of a given transmission line increases, the input resistance decreases until it reaches its characteristic resistance. Once the characteristic resistance is reached, additional line length has no effect on the input resistance. At this length, the input variables cannot be detected at the receiving end of the line. This can be seen from a plot of the input resistance ( $R_{SO}$ ) versus length for the previous transmission line example. See Figure 2.19.



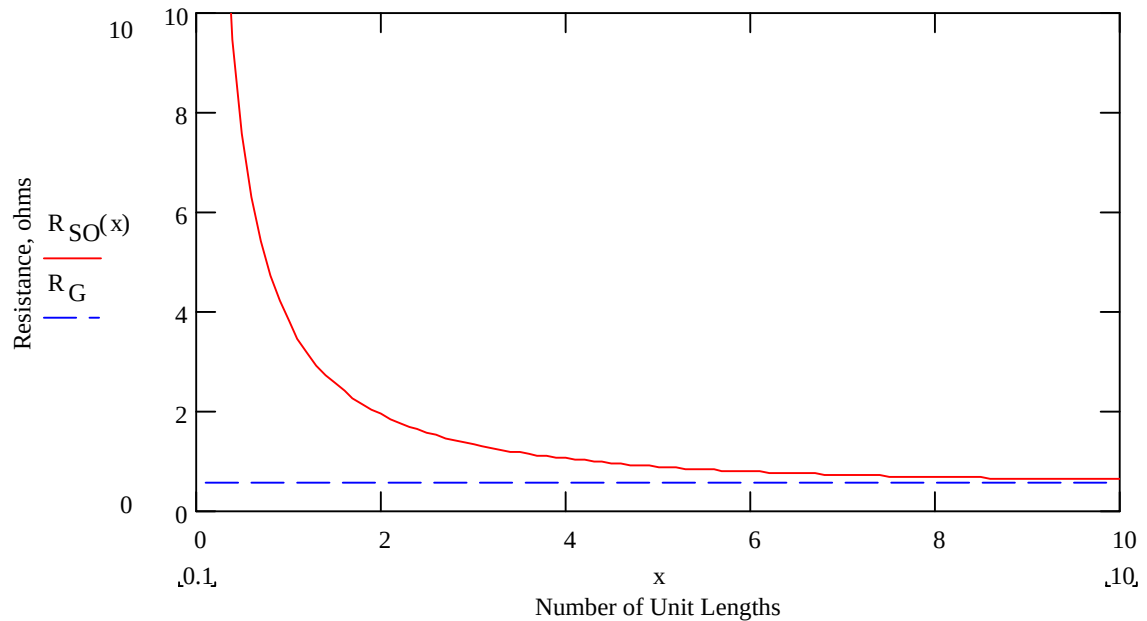


**Figure 2.19 An Electrically Long Structure**

As a practical example of the effect of a transmission system becoming electrically long, consider a very long header cable supplying distributed anodes. As the length of the header cable reaches electrically long, adding additional anodes on the end of the header cable will have no effect on the resistance-to-earth of the ground bed. Also, the current discharged by the rectifier will attenuate with distance along the header cable to the point that the last anodes will not discharge current.

# Galvanic Anode Systems

## Concept

### *Electrochemical Power Source*

All galvanic anode systems rely on the electrochemical energy difference between the anode material and the material of the structure for production of current. The electrical driving force (potential) available varies depending upon the materials involved. For any given structure material, the more active the anode metal position in the electromotive force series, the greater the voltage available to drive the cathodic protection current.

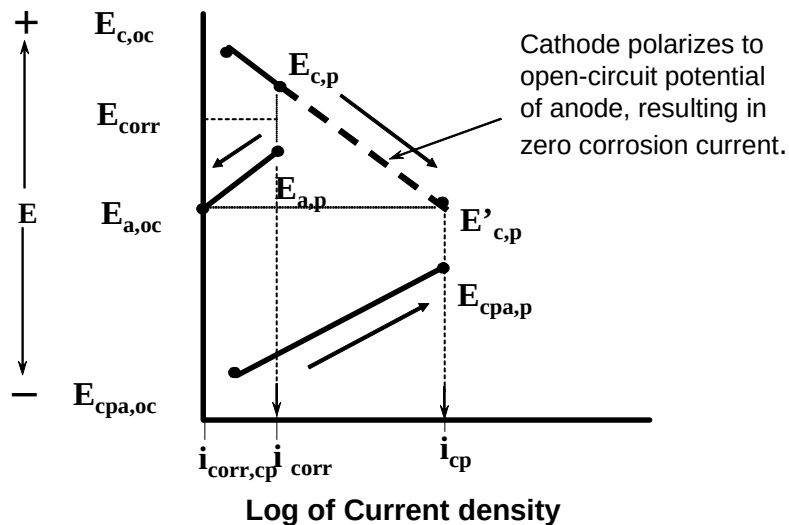


**Figure 3.1 Polarization of a corroding metal employing a sacrificial anode**

The action is illustrated by the Evans diagram in Figure 3.1. Figure 3.2 is the equivalent circuit for a galvanic anode system.

The circuit includes the following components:

- anode
- metallic connection,  $R_M$  (metal circuit).
- structure (cathode).
- electrolyte path,  $R_E = R_a + R_s$
- anode to structure potential difference,  $E = |E_{cpa,p} - E_{c,p}|$
- cathodic protection current

where:

- $R_M$  = metallic circuit resistance
- $R_a$  = anode resistance to remote earth.
- $R_s$  = structure resistance to remote earth.
- $E_{cpa,p}$  = polarized cathodic protection anode potential
- $E_{c,p}$  = polarized structure (cathode) potential.
- $I_{cp}$  = cathodic protection current.

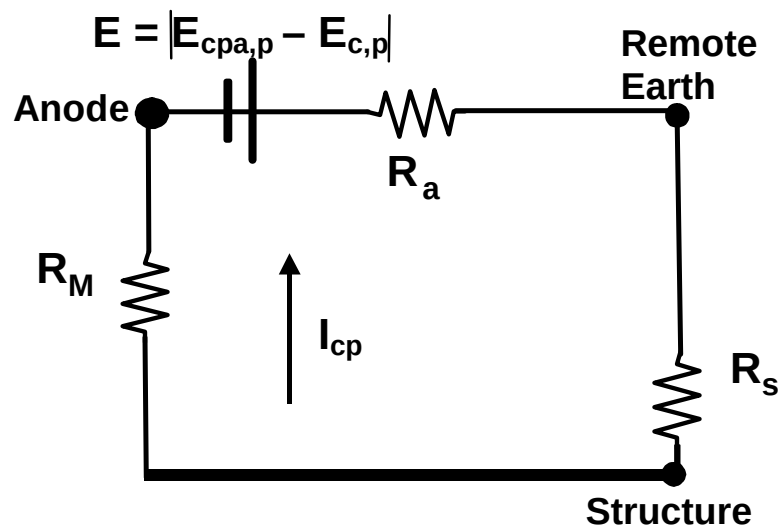


**Figure 3.2 Galvanic Anode System Schematic**

The metallic circuit resistance ( $R_M$ ) is controlled by:

- the size of the wire joining the anode to the structure.
- any electrical resistance inserted into the connection to deliberately control current.
- the electrical resistance of the attachment of the wire to the anode material.
- the resistance of the attachment of the wire to the structure.

The electrolyte circuit resistance ( $R_e$ ) includes:

- the anode to electrolyte (soil) resistance.
- the resistance of the structure to electrolyte.

Factors that influence the internal resistance include:

- the physical dimensions of the anode.
- the resistivity of the electrolyte (soil).
- the physical dimensions of the structure.
- the presence or absence of a dielectric protective coating on the structure.

The battery symbol (E) in the diagram represents the electrochemical potential between the anode material and the structure material. The potential consists of the difference between the open circuit half-cell potentials of the materials involved, less any anodic and cathodic polarization which occurs at the respective surfaces.

## ***Advantages***

Galvanic anode systems have a number of practical advantages:

- low susceptibility to damage by outside influences.
- low maintenance costs throughout the design life.
- do not require an outside source of energy such as commercial power.
- fewer system components.
- are well suited to the protection of electrically isolated or segmented structures (such as mechanically joined pipe sections) in which each component is provided with its own galvanic anode.
- low potential operation seldom produces significant corrosive interference (stray current) on other structures.

## ***Limitations***

Galvanic anodes have a number of limitations that may limit their use in some applications. Limitations include:

- electrical potential available is limited
- subject to seasonal variations affecting operation
- in acid environments, the acid directly attacks the anode materials and the life and efficiency are extremely low
- maximum service life is dependent on the quantity of anode material
- chemistry of the electrolyte (soil) and temperature may have an undesirable effect on the anode half-cell potential.

# Magnesium Anode Properties

## ***Alloys***

Magnesium anodes are available in two general alloys: high potential (–1.75 volts referenced to the copper/copper sulfate electrode) and standard (–1.55 volts referenced to the copper/copper sulfate electrode). Presence of impurities, particularly iron and other heavy metals, can significantly influence the consumption rate (efficiency) of the alloy. At best, the magnesium alloys exhibit an efficiency of approximately 50%. What this means is that about half of the metal of the alloy is consumed in self-corrosion during its life. Table 3.1 lists the alloy specifications for anodes falling into the category of high potential and standard alloys.

**Table 3.1 - Magnesium Anode Alloy Specifications**

**Cr = 8 kg/A-yr\*   Ca = 1100 A-hr/kg\*   \*@50% efficiency**  
**Or Ca = 0.125 A-yr/kg**

| Element | High Potential                      | Standard Potential –1550mV/CSE |            |            |
|---------|-------------------------------------|--------------------------------|------------|------------|
|         | –1750mV/CSE                         | Grade A                        | Grade B    | Grade C    |
| Al      | 0.010% Max                          | 5.3 - 6.7%                     | 5.3 - 6.7% | 5.0 - 7.0% |
| Mn      | 0.50 - 1.30%                        | 0.15% Min                      | 0.15% Min  | 0.15% Min  |
| Zn      | .....                               | 2.5 - 3.5%                     | 2.5 - 3.5% | 2.0 - 4.0% |
| Si      | .....                               | 0.10% Max                      | 0.3% Max   | 0.3% Max   |
| Cu      | 0.02% Max                           | 0.02% Max                      | 0.05% Max  | 0.1% Max   |
| Ni      | 0.001% Max                          | 0.002% Max                     | 0.003% Max | 0.003% Max |
| Fe      | 0.003% Max                          | 0.003% Max                     | 0.003% Max | 0.003% Max |
| Other   | 0.05% each or<br>0.03% Max<br>Total | 0.30% Max                      | 0.30% Max  | 0.30% Max  |

Magnesium anodes are produced in a wide variety of physical shapes ranging from ribbon to blocks. They are available packaged with special backfill which assures maximum possible efficiency and reliability in underground use. Magnesium provides the highest available driving potential of all common sacrificial anode materials. It is, therefore, most useful in applications where the electrolyte resistivity is moderately high. This includes fresh water and most soils. Magnesium also has low toxicity and has been used for many years in the internal cathodic protection of potable water storage tanks. In highly conductive environments (seawater) the low efficiency of magnesium limits its economic value as a galvanic anode material. Magnesium can be used in combination with less active anode materials (aluminum) to aid in rapid polarization of structures in seawater.

## ***EMF***

The corrosion potential of magnesium anodes will range from about –1.55 volt CSE (standard alloy) to –1.75 volt CSE (high potential alloy). In practice, these potentials will drift slightly in a positive direction as current flow causes polarization. In most applications this anode polarization is small compared with other variables. Its effect is accounted for in design work by an overall safety factor.

The operating voltage of a magnesium anode is the difference between the anode corrosion potential and the polarized half-cell potential of the structure to which the anode is connected.

### Example 3.1

If the polarized potential of a buried steel tank is to be  $-0.85$  volt CSE, what would be the operating voltage between a standard alloy magnesium anode and the tank? Neglect any anode polarization.

The difference in half-cell potentials is:

$$E = -1.55 - (-0.85) = -0.70 \text{ volt}$$

The resistance between the anode and the tank is 10 ohms. Tests have determined that 40 milliamperes of current will polarize the tank to  $-0.850$  volt CSE. How much resistance must be inserted into the wire between the anode and the tank to avoid greater polarization of the tank?

By Ohm's Law:

$$E = IR = I (R_{cp} + R_M)$$

$$\frac{E}{I} = R_{cp} + R_M$$

$$I$$

$$R_M = \frac{E}{I} - R_{cp}$$

where:

$R_M$  = resistance to be inserted (ohms).

$R_{cp}$  = the measured resistance between the anode and the tank (10 ohms).

$E$  = potential between the anode to the polarized steel tank as defined above (0.70 volts)

$I$  = current required to maintain polarization of the tank (0.04 A)

$$R_M = (0.70\text{volt}/0.040\text{amp}) - 10\text{ohm}$$

$$R_M = 7.5 \text{ ohm}$$



## ***Ampere Hour Capacities***

The consumption rate of any galvanic anode is determined from Faraday's Law and an efficiency rating.

Faraday's Law:

$$W = MIt/nF$$

where:

- W = weight loss (grams)
- M = atomic weight of the anode material (grams)
- t = time (sec.)
- I = average current flow (A) over time t
- n = number of electrons transferred per atom of anode metal
- F = the Faraday constant (96,500 coulombs)

For magnesium:

- M = 24.32 grams
- I = 1A
- n = 2
- t = 1 year ( $3.156 \times 10^7$  sec)
- W = 3976 grams/(8.767 lbs)

Therefore, the theoretical consumption rate

$$C_r = \frac{3976\text{gm}}{\text{A} - \text{yr}} \times \frac{\text{kg}}{1000\text{gm}} = \frac{3.98\text{kg}}{\text{A} - \text{yr}}$$

There are 8,766 hours in a year. The ampere-hour capacity per pound of anode metal can be calculated from the formula:

$$\text{Theoretical Capacity (C}_a\text{)} = \frac{8766\text{hr}}{\text{yr}} \times \frac{\text{A} \cdot \text{yr}}{3.98\text{kg}} = \frac{2203\text{A} \cdot \text{hr}}{\text{kg}}$$

For magnesium:

Efficiency = 50%

Practical Capacity = 1102 A-h/kg (499.9 A-h/lb.)

Practical Consumption Rate = 3.98kg/A-Yr x 2 = 7.96kg/A-yr

## ***General Usage***

Magnesium anodes are commonly used in fresh water and soil applications where there is a modest current required. Anodes may be used in a distributed fashion along a pipeline or around a more complex structure or group of structures. They may also be joined together and installed as an anode bed. Extruded ribbons may be laid in pipe trenches, wrapped around structures or formed to fit inside vessels.

## **Zinc Anode Properties**

### ***Alloys***

Zinc alloys have been developed for two general applications, one for use in fresh waters and soils, and the other for seawater and brackish water. Some available zinc alloy compositions are listed in Table 3.2.

**Table 3.2- Zinc Anode Alloy Specifications**

**\*Cr = 11.9 kg/A-yr      \*Ca = 738 A-hr/kg      \*@90% efficiency**

| $E_{\text{corr}} = -1100\text{mV/CSE}$ | Hi-AMP™                                     | Mil. Spec.    | ASTM B-418-73 |                    | HI-PURE™    |
|----------------------------------------|---------------------------------------------|---------------|---------------|--------------------|-------------|
| Element                                | Zinc                                        | A-18001-H     | Type I        | Type II            | Zinc        |
| <b>Al</b>                              | 0.1 - 0.4%                                  | 0.10 - 0.50%  | 0.10 - 0.50%  | 0.005% Max         | .....       |
| <b>Cd</b>                              | 0.025 - 0.06%                               | 0.025 - 0.15% | 0.03 - 0.10%  | 0.003% Max         | 0.003% Max  |
| <b>Fe</b>                              | 0.005% Max                                  | 0.005% Max    | 0.005% Max    | 0.0014% Max        | 0.0014% Max |
| <b>Pb</b>                              | 0.006% Max                                  | 0.006% Max    | 0.003% Max    | 0.003% Max         | 0.003% Max  |
| <b>Cu</b>                              | .....                                       | 0.005% Max    | .....         | .....              | .....       |
| <b>Si</b>                              | .....                                       | 0.125% Max    | .....         | .....              | .....       |
| <b>Zn</b>                              | Remainder                                   | Remainder     | Remainder     | Remainder          | Remainder   |
| <b>Application</b>                     | Seawater & brackish water<br>(Temp. <60 °C) |               |               | Soil & fresh water |             |

As with other galvanic materials, zinc can be fabricated in a wide variety of physical shapes and with different methods of mounting. The zinc alloy anodes have a nominal corrosion potential of  $-1.10$  volt versus the saturated copper/copper sulfate reference electrode. Its efficiency as a sacrificial material is relatively high, ranging from 90 to 95 percent. Certain conditions of temperature and environmental chemistry can cause the potential of zinc to become significantly more noble than the normal potential. Chemistry and temperature of concern include water containing bicarbonates, carbonates or nitrates at temperatures of  $60^{\circ}\text{C}$  ( $140^{\circ}\text{F}$ ) or more.

Zinc with a gypsum and bentonite backfill is used in soils having relatively low resistivity ( $< 2000 \text{ ohm-cm}$ ) where high efficiency may make it more cost effective than magnesium. Zinc is also commonly used as a galvanic anode for marine applications, particularly as a galvanic anode on steel

ship hulls. Zinc ribbon is also used to mitigate induced AC on coated pipelines.

## ***EMF***

In seawater and in soil with special backfill, the open circuit half-cell potential of zinc anodes is quite stable at  $-1.10$  volt vs. CSE. Zinc anodes are sometimes used as a reference electrode in potential controlled cathodic protection systems.

As with other galvanic anodes, the operating potential is the difference between the zinc half-cell potential and the polarized structure half-cell potential.

### **Example 3.2**

What would be the operating voltage between a zinc anode and the buried steel tank of Example 3.1?

$$E = -1.10 - (-0.85) = -0.25 \text{ volts}$$

Would the zinc anode be able to supply the 40 milliamperes necessary to polarize the tank to  $-0.85$  volts vs. CSE?

$$I = 0.25/10 = 0.025 \text{ A (25 mA)}$$

The answer is no.

#### **Ampere Hour Capacities**

The efficiency of zinc anodes ranges from 90 to 95%. The theoretical consumption rate for zinc is (from Faraday's Law) 10.7 kg/A-yr (23.57lbs/A-yr). At 90% efficiency, the capacity of a zinc anode is:

$$\text{Capacity (C}_a\text{)} = 738 \text{ A-hr/kg (335 A-hr/lb)}$$

## General Usage

The modest operating potential of zinc limits its application to designs that involve either low current requirements or low resistivity environments. The greatest usage (aside from galvanizing) is probably in seawater service. Anode configurations are similar to those described for magnesium.

## Aluminum Anode Properties

### Alloys

Galvanic anodes fabricated with aluminum alloys are primarily used in seawater environments. Each atom of aluminum produces three electrons vs two for magnesium and zinc. Three common alloys are listed in Table 3.3.

**Table 3.3 Aluminum Anode Alloy Specifications for Seawater use**  
**Cr = 3.10 kg/A-yr    Ca = 2833 A-hr/kg    @95% efficiency**

|            | -1100mV <sub>CSE</sub> |                   | -1150mV <sub>CSE</sub>                   |
|------------|------------------------|-------------------|------------------------------------------|
| Element    | Alloy I                | Alloy II          | Alloy III                                |
| <b>Zn</b>  | 0.35 – 0.50%           | 3.5 – 5.0%        | 3.0%                                     |
| <b>Si</b>  | 0.10% Max              | .....             | 0.1%                                     |
| <b>Hg</b>  | 0.035 -<br>0.048%      | 0.035 -<br>0.048% | .....                                    |
| <b>In</b>  | .....                  | .....             | 0.015%                                   |
| <b>Al</b>  | Remainder              | Remainder         | Remainder                                |
| <b>Use</b> | Seawater               | Saline mud        | Seawater<br>Brackish water<br>Saline mud |

Most of the physical shapes and construction of aluminum anodes are keyed to marine applications. Forms include:

- Bracelets for attachment to offshore pipelines.
- Configurations with steel straps for attachment to ship hulls.
- Anodes cast with large hooks and eyes for suspension from piers and wharves.
- Forms with cast-in standoff supports for use on offshore structures.

Other alloys and shapes are available for fresh water use.

## **EMF**

The potential of aluminum alloys for galvanic anode service is between – 1.10 and –1.15 volt vs. CSE. This is very similar to zinc and the operating potential is also similar.

## **Ampere Hour Capacities**

The efficiency of aluminum anodes is between 85% (Al-Zn-In alloy) and 95% (Al-Zn-Hg alloys). The theoretical consumption rate for aluminum is:

Consumption =

$$(26.97 \text{ gm} \times 3.15576 \times 10^7 \frac{\text{sec}}{\text{yr}} \times 1 \text{ A}) / (3 \times 96,500 \frac{\text{coulombs}}{\text{gmequivalent}})$$

Consumption = 2.94 kg/A-yr (6.476 lb/A/yr)

At 95% efficiency:

Capacity = (8766/2940) x 0.95

Capacity = 2833 A-hr/kg (1286 A-h/lb)

At 85% efficiency:

Capacity = 2534 A-hr/kg (1150 A-h/lb)

## **General Usage**

The primary use of aluminum alloy galvanic anodes is in seawater and brackish water environments. Offshore platforms and pipelines are examples of structures where aluminum galvanic anodes have wide usage.

# Anode Attachments

## ***Electrical Connection***

In most cases, metals used for galvanic anodes cannot be directly attached by bolting or welding to the structure. Some intermediate form of metal connection is required. For smaller anodes used in underground cathodic protection of pipelines and storage tanks, the means of attachment is generally a copper wire. This wire must be suitably connected to the anode core and sealed against the environment to prevent corrosion at the attachment. The wires are then connected either through test stations or directly to the structure. The attachment to the structure is frequently made by brazing or welding techniques rather than by strictly mechanical methods (clamps). Larger anodes that will be directly connected to major structures (particularly marine structures) often include a cast-in core that extends beyond the anode. The cores are generally made of steel and can be welded, or otherwise attached to the structure where protection is required.

## ***Mechanical Forces***

The mechanical forces that may act upon the anode are an important consideration in the method of attachment to a structure. In marine environments, particularly when the anode must be attached to a structure such as a wharf or offshore rig, the mechanical forces may be very high. Wave action, floating debris, tidal currents and abrasion must be considered in the design of anode attachments for this type of service. Since the anode core material (e.g. steel) is more noble than the anode metal, it is not of critical importance that the connection be electrically protected from contact with the environment. Cathodic protection is achieved on the connecting device in the same manner as on the structure proper. However, it is good practice to use coated wire or coated brackets when installing anodes on structures. This limits local wastage of the anode due to proximity effects where the core or wire enters the anode.

Abrasion in flowing seawater can reduce the theoretical life of galvanic anodes. The amount of the reduction depends on the conditions present.

# Sacrificial Anode Backfills

Sacrificial anodes for burial in soil are generally pre-packaged with a prepared backfill. The backfill material is chemically compatible with the anode metal ion, retains soil moisture necessary for proper operation, and provides effective electrolytic contact between the anode and the soil.



Backfill for magnesium anodes generally contains:

- ground Hydrated Gypsum 75%
- powdered Bentonite 20%
- anhydrous Sodium Sulfate 5%

Backfill for zinc anodes generally contains:

- ground Hydrated Gypsum 50%
- powdered Bentonite 50%

## Special Applications

Galvanic anode material can be used for cathodic protection of steel reinforcing in atmospherically exposed concrete structures. Aluminum and zinc alloys are the most common materials used for this service as they can be deposited on concrete surfaces using flame or arc spray techniques.

# Impressed Current Systems

## Concept

### *External Power Source*

Impressed current systems rely on the presence of an external source of energy to provide the direct current. Since the voltage of such a source can be readily adjusted. The corrosion potential for the material used for the anode is not a factor. External power sources include rectified AC power, motor generators, thermoelectric generators, wind generators and solar generators.

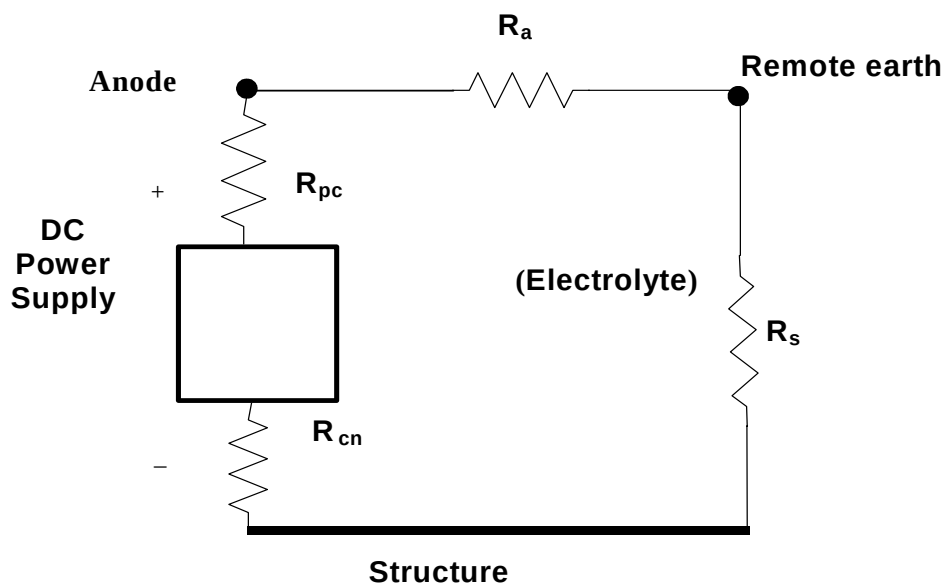


**Figure 3.3** *Impressed Current System Schematic*

### *Equivalent Circuit*

Figure 3.3 shows the equivalent circuit of an impressed current cathodic protection system. The circuit consists of an anode, the power source, the structure and the environment. The external circuit resistance ( $R_{pc} + R_{cn}$ ) includes all those electronic resistive components between the anode and the structure including the electrical resistance of the power source. The internal resistance between the anode and the structure ( $R_a + R_s$ ) includes the anode-to-electrolyte resistance, resistance of the electrolyte and the structure-to-electrolyte resistance. The primary source of may be any D.C.

source as noted above. In some instances, external filters are provided to smooth the pulsations from rectified AC and thus provide a filtered DC.

## ***Advantages***

The advantages of impressed current systems include:

- the electrical potential available through the power supply can be fully adjustable from very low values to quite high values.
- the power is limited only by the source.
- a wide variety of materials are available for impressed current anodes.
- many impressed current anode materials have very low consumption rates and can provide high output with limited size.
- electronic methods of control and monitoring are possible.

## ***Limitations***

Some of the limitations of impressed current systems include:

- impressed current systems require an outside source of energy.
- regular maintenance is essential.
- anode lead wires may corrode.
- can cause interference current on other structures.
- electro-osmosis can drive moisture from soil around anode.
- Gas blockage can occur at anode surface.

If AC power is not available, other power sources can be used. Batteries (which can be recharged or replaced regularly), wind driven generators, solar or thermal energy generators used in conjunction with storage batteries are alternatives.

Impressed current systems operate at potentials considerably in excess of that where the wiring material is stable when exposed to an electrolyte. These high potentials require that all connecting wires and attachments to the anode system be completely insulated from the environment and sealed against moisture penetration. A failure in the insulation on the positive cables will ultimately result in failure of the conductor by corrosion.

## ***Safety***

Safety must always be considered when designing an impressed current system. The “step” and “touch” potentials should be analyzed to ensure a

safe working environment. All applicable electrical codes should be followed.

# Anodes General

## ***Anode Reactions***

There are a number of anode materials that are used for underground applications of cathodic protection. Graphite, silicon-chromium-iron, platinized titanium/niobium and mixed metal oxide are some of the materials from which corrosion engineers can choose when designing groundbeds. Each material has unique characteristics that influence performance in a given environment. These performance characteristics vary from one environment to the next and must be examined for every application. Since the reactions that occur on the surface of the anode largely influence the performance of the material, our discussion will begin with a brief review of the primary anode reactions.

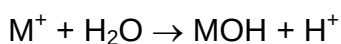
There are many oxidation reactions that may occur on the surface of an anode. The anode material and the environment largely determine the reaction that dominates. The three primary reactions at the surface of the anode are:

- metal oxidation
- oxygen evolution
- chlorine evolution

For sacrificial anode materials, the primary anodic reaction is normally the oxidation of the metal:



In neutral soils, the metal ion is unstable and will react with water to form a hydroxide or hydrated oxide and hydrogen ions.

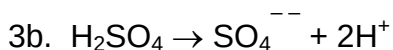
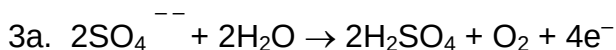


These reactions also apply to impressed current anodes to the extent the anode is consumed.

For impressed current anodes in applications where the soil/water has extremely low chloride concentrations, the primary anodic reaction will be oxygen evolution.

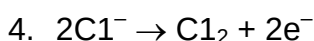
1.  $2H_2O \rightarrow O_2 + 4H^{+} + 4e^{-}$
2.  $4OH^{-} \rightarrow 2H_2O + O_2 + 4e^{-}$

A similar reaction takes places when sulfate ions are present in the electrolyte.



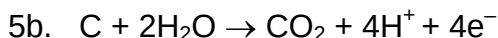
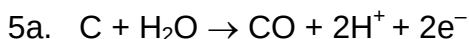
Once again, oxygen is liberated and hydrogen ions are formed.

The evolution of chlorine is a reaction that takes place on the surface of an impressed current anode in the presence of chloride ions.



The chlorine gas will then meet with water to form hypochlorous and hydrochloric acid. Hypochlorous acid does not dissociate and form hydrogen ions to the same extent as many acids. The evolution of chlorine therefore lowers the pH of the anode surface to less than the evolution of oxygen.

Where coke is used as backfill material for impressed current anodes, anodic reactions will occur at the surface of the coke particles:



Anodic consumption of the coke particles contributes to lowering the pH of the anode environment.

All of the major anodic reactions decrease the pH of the solution in the vicinity of the anode.

The standard redox potential is +0.40 volts SHE for hydroxyl ions and +1.36 volts SHE for chloride ions. From a thermodynamic point of view, if an anode were polarized in an electrolyte containing both ions, oxygen would be generated first and then chlorine. This is not necessarily true in practice. On graphite, for example, the overvoltage for oxygen evolution is much higher than that for chlorine evolution. When anodically polarized, a graphite anode will first generate chlorine.

## ***Mass Transport***

Properties of mass transport through the electrolyte are other extremely important factors in underground applications. Chlorine evolution will occur in seawater in preference to oxygen evolution because the reactants (chloride ions) can move to the surface of the anode more readily and the reaction product (chlorine gas) can move away more readily than is the case with the oxygen evolution reaction. Underground, this is often not the case, depending upon water flow, migration of ions and diffusion. Chloride depletion and restriction of chloride migration will cause the oxygen evolution reaction to dominate. This behavior has been confirmed through direct observation. In actual practice, anodic environments, with a pH as low as 1.0 have been reached after several days of operation. Anode materials used for cathodic protection in underground environments must therefore be resistant to acid attack.

## ***Graphite***

The satisfactory performance of graphite anodes installed underground with carbonaceous backfill is well established. Graphite exhibits excellent performance characteristics where chlorine evolution is the predominant anodic reaction. Under these conditions, the consumption rate is quite low and usually falls in the range of 0.1 to 0.3 kg/A-yr. Where oxygen evolution takes place on the surface of a graphite anode, the carbon will be oxidized to form carbon dioxide. Severe conditions of low pH and high sulfate concentration can increase the consumption rate to levels approaching less than 1 kg/ampere-year.

Graphite is a relatively soft material and is not recommended for use in fast flowing water where corrosion will occur. It should be avoided where the anode is subjected to cavitation or impingement attack. At temperatures above approximately 50°C (122°F), the consumption rate increases rapidly. Graphite is also brittle and must be handled carefully during installation to avoid breakage.

Graphite is a highly porous material. Gases produced in the internal pores as a result of anodic reactions will result in mechanical and chemical deterioration of the material. At times, this produces softening and swelling of the anode. By treating the anode with oil, wax or resin, the penetration of the electrolyte is reduced and the mechanical strength is increased. Where oxygen evolution is the primary reaction at the anode surface, treatment will reduce the graphite deterioration by approximately 20%.

Graphite has a propensity to neck and pencil, particularly in underground environments with moving groundwater. This can be compensated for by making the electrical connection at the center of the anode rather than at

the end. Center connections dramatically improve the utilization factor for graphite anodes. Installed in carbonaceous backfills and operated at current densities of from 5 to 10 amps/m<sup>2</sup>, graphite is often an economic choice for underground applications.

Table 3.4 lists advantages and disadvantages of graphite anodes.

**Table 3.4 Graphite**  
**Cr = 1 kg/A-yr**

| ADVANTAGES                | DISADVANTAGES                          |
|---------------------------|----------------------------------------|
| Performs well in coke     | Oxygen evolution increases consumption |
| Best under dry conditions | Soft-erodes in flowing water           |
| Economical                | Brittle-breaks easily                  |
| Proven                    | Porous-treatment recommended           |
| Readily available         | End effects-center connections advised |
|                           | Size-large                             |

## Silicon-Chromium-Iron

Silicon iron consists of a very hard matrix of silico-ferrite in which the major part of the carbon is in the form of graphite flakes at the grain boundaries. The presence of graphite between the grains produces an inherent weakness in the alloy. Alloying with chromium eliminates the graphite and thus strengthens the alloy.

The performance of silicon-chromium-iron electrodes as anodes for cathodic protection is highly dependent upon the formation of a thin layer of hydrated, silicon dioxide on the surface of the anode. This film is partially protective of the anode. The protective properties are not fully developed until the alloy contains at least 14.5% silicon. Oxidation of the alloy is necessary to form this protective film.

Uncontaminated, silicon dioxide is dielectric with a resistivity of approximately 10<sup>14</sup> ohm-cm. Although the mechanism is not clear, silicon dioxide is highly conductive when formed by oxidation on the surface of an anode. It is known that the oxidation of silicon to form silicon dioxide requires the inward diffusion of hydroxyl ions and water molecules. The oxidation reac-

tion will produce hydrogen ions that will further enhance the conductivity of the film. The limited diffusion of water to the anode surface in underground applications under acid conditions will therefore interfere with forming a highly conductive silicon dioxide film. This may explain why the resistance-to-earth of silicon-chromium-iron anodes is sometimes observed to climb dramatically in underground applications of cathodic protection.

Silicon-chromium-iron is highly resistant to corrosion in acid solutions and is therefore a good anode choice for these environments. The silicon dioxide film is however, soluble in alkaline solutions that will increase the anode consumption rate and limit performance. It is apparent that when soils contain high concentrations of sulfate ions, the reaction that occurs at the anode surface either interferes with the formation of the silicon dioxide film or damages the protective properties. The performance of the anode is limited accordingly.

Silicon-chromium-iron anodes are brittle in comparison to graphite but the hardness of the alloy makes the anode less susceptible to damage from abrasion or erosion. Installed underground with carbonaceous backfill, the anode performs very similar to graphite. When installed without backfill and where oxygen evolution is the predominant anodic reaction, the silicon-chromium-iron anodes perform better than graphite. As was the case with graphite, placing the electrical connection in the center of the anode greatly improves the utilization factor.

Table 3.5 lists the advantages and disadvantages of silicon-chromium-iron anodes.



**Table 3.5- Silicon - Chromium - Iron**  
**Cr = 0.5 to 1.0 kg/A-yr**

| ADVANTAGES                        | DISADVANTAGES                         |
|-----------------------------------|---------------------------------------|
| Performs well in coke             | Poor performance in sulfates          |
| Best under wet conditions         | Poor performance under dry conditions |
| Can be installed without backfill | Brittle-breaks easily                 |
| Acid resistant                    | Size-large and heavy                  |
| Proven                            | Expensive                             |

## Platinized Titanium and Niobium

The two most common platinized anodes in use in the cathodic protection industry incorporate titanium and niobium substrates. The anodes were developed primarily for use in seawater and other chloride environments since both substrates form protective, dielectric oxide layers when made anodic even in the presence of chlorides. Niobium is more expensive than titanium but has higher electrical conductivity and forms a protective oxide with a higher breakdown voltage. The performance of these anodes in seawater at high current densities is well established. Where the predominant anodic reaction is the evolution of chlorine, the consumption rate of platinum will be  $2.4 \times 10^{-6}$  to  $1.2 \times 10^{-5}$  kg/amp-year ( $5.3 \times 10^{-6}$  to  $2.6 \times 10^{-5}$  pounds /amp-year).

Platinized anodes are only economical when operated at high current densities as is possible in seawater because of the rapid migration of chlorides to the anode and products away from the anode. Where the predominant anodic reaction is the evolution of oxygen, higher driving voltages are needed due to overpotential and IR drop. In terms of both the cost of the anode and the power required, it is therefore not usually economical for underground applications.

In analyzing the performance of platinized titanium and niobium anodes in underground applications the limitations of the material in other environments should be examined. From condenser water box and ship hull experience, it is known that anodically formed manganese dioxide on the surface of the anode will adversely affect performance by favoring oxygen evolution over chlorine evolution. The anodic dissolution rate of platinum is approximately ten times greater when oxygen evolution is the predominant reaction. Silting of platinized anodes will shorten the anode life to 10% of

that observed in seawater due to acid attack on both the platinum and titanium or niobium substrates. Other factors that adversely affect the anode performance include the formation of scale, biofouling, the presence of certain organic materials, low frequency AC ripple and even short periods of current reversal.

When installed underground, the platinized anodes must be designed to function by providing electrical contact to the backfill and not as a surface for anodic reactions. This means that the pressure on the backfill must be sufficiently high and that the current density should be limited to 150 amps/m<sup>2</sup> to 300 amps/m<sup>2</sup>. Direct contact with soil must be avoided. Some anode failures have occurred in backfill due to corrosion of the titanium and niobium substrates. These are believed to have resulted from locally high acidity. It should be noted that niobium is even more susceptible to acid attack than titanium.

When platinized materials are used in deep anode installations, high rates of dissolution may be observed due to local heating, and the evolution of oxygen, which increases the acidity. Dilute brines are usually encountered in deep anode installations. Typically, the chloride ion concentrations will be approximately 15% that of seawater, which results in a much higher rate of platinum consumption. Critical factors affecting the anode performance may include the presence of water-bearing strata, the proximity to coastal areas and the permeability of the formation. In general, the higher the chloride concentration and the greater the rate of diffusion, the more chlorine evolution will predominate and hence, the better the anode will perform.

Table 3.6 lists the advantages and disadvantages of platinized niobium/titanium anodes.

**Table 3.6 Platinized Niobium/Titanium**

| ADVANTAGES                            | DISADVANTAGES                        |
|---------------------------------------|--------------------------------------|
| Performs well with chlorine evolution | Performs poorly with O <sub>2</sub>  |
| Proven in seawater                    | Not recommended underground          |
| Size-variable and light weight        | Breakdown voltage cannot be exceeded |
|                                       | Attacked by low frequency ripple     |
|                                       | Wear rate increases for deep anodes  |

## Mixed Metal Oxide

Mixed metal oxide anodes (also referred to as DSA for dimensionally stable anode) consist of electrocatalytic-activated coatings on a titanium substrate. The metal oxide coating is highly conductive and demonstrates an extremely low weight loss (less than 1 milligram per ampere year) when operated as a cathodic protection anode. Unlike all other anodes discussed, the metal coating is fully oxidized in a controlled environment prior to field installation. These electrodes therefore have the distinct advantage of not depending upon the formation of a protective film when energized anodically in a soil environment.

The anodes were brought to the United States from Europe in 1969 when they were extensively used in chlor-alkali and metal-winning operations. In 1971, mixed metal oxide anodes were used for cathodic protection in seawater and buried in seabed muds. These first applications continue to operate without detectable wearing of the mixed metal oxide coating. In the early 1980's, the anode was employed underground for cathodic protection of tanks and piping.

Mixed metal oxide anodes are extremely resistant to acid attack even at a pH of less than one. As discussed earlier, this is an extremely important characteristic, particularly for underground applications of cathodic protection.

Even at current densities over 100 amps/m<sup>2</sup>, the mixed metal oxide has a minimum overvoltage (0.004 volts/decade current) to chlorine evolution. In

other words, the prevailing anodic reaction is always chlorine evolution, even at high current densities. Any secondary reaction bringing about oxygen evolution and increased acidity has no effect on the metal oxide coating since it is acid resistant.

Table 3.7 lists the advantages and disadvantages of mixed metal oxide anodes.

**Table 3.7 Mixed Metal Oxide**

| ADVANTAGES                     | DISADVANTAGES                      |
|--------------------------------|------------------------------------|
| Fully oxidized surface         | Lack of long term performance data |
| Low consumption rate           | Only applied over titanium         |
| Resistant to acid attack       | Low breakdown voltage              |
| High current density rating    |                                    |
| Size-variable and light weight |                                    |
| Economical on cost per A-yr.   |                                    |

## Conductive Polymers

There are several types of conductive polymer materials available for impressed current systems. The Federal Highway Administration developed a catalytic-setting liquid compound that can be poured into slots in concrete surfaces or sprayed on the surface of reinforced concrete beams and pilings. Other conductive polymer anodes consist of the polymer extruded over a copper conductor. This type of anode can be handled like any other cable and embedded in a concrete surface or buried in soil.

Conductive polymer anodes have a relatively low limit on current discharge, about  $1.3 \text{ A/m}^2$  ( $0.12 \text{ A/ft}^2$ ) in soil with coke backfill and about  $0.25 \text{ A/m}^2$  ( $0.023 \text{ A/ft}^2$ ) in water.

**Table 3.8 Conductive Polymer**

| ADVANTAGES                                 | DISADVANTAGES                                                                  |
|--------------------------------------------|--------------------------------------------------------------------------------|
| Easy installation                          | Relatively low surface current density limit                                   |
| Good where a distributed anode is required | Limited to temperatures below about $66^\circ\text{C}$ ( $150^\circ\text{F}$ ) |
| Size-variable and light weight             | Susceptible to lightning                                                       |
| Economical                                 |                                                                                |

## Carbon Backfill (Coke)

### ***Metallurgical***

There are two primary categories of carbon backfill (coke) available: metallurgical coke and petroleum coke. Metallurgical coke is produced by heating coal in the temperature range of  $510^\circ\text{C}$  ( $950^\circ\text{F}$ ) to  $815^\circ\text{C}$  ( $1500^\circ\text{F}$ ) without air contact. This process results in the separation of various gases and liquids from the coal leaving a solid, carbonaceous product coke. Within the coking ovens, large variations in temperature occur throughout the coal beds. Although metallurgical coke is usually less expensive than calcined petroleum coke, lack of temperature control coupled with the non-uniformity of the naturally-produced coal results in a coke product with highly variable characteristics.

## Petroleum

Calcined Petroleum coke is produced as a residue from the distillation of petroleum oil. Petroleum cokers are carefully controlled to produce a uniform product. Depending upon the specific coking process employed, petroleum coke can be produced with various sizes, shapes, and other characteristics. Petroleum coke has very high resistivity in the “as-produced” or “green” form, which is not acceptable as a carbon backfill. To improve the electrical characteristics of the coke, it must be heat-treated (calcined). Depending upon the specific type of calciner employed, the coke is exposed to temperatures as low as 510°C(950°F) or as high as 1204°C (2200°F). Higher temperature results in more conductive, uniform cokes.

Carbon backfills are placed around impressed current anodes to:

- decrease anode current density thereby limiting the lowering of the pH
- lower the anode resistance-to-earth by effectively increasing the anode size
- decrease anode polarization, gas blockage, and drying caused by electro-osmosis by increasing the anodic reaction surface area
- increase the anode life by shifting the anodic (corrosion) reaction to the backfill surface.

To accomplish the above objectives effectively, the carbon backfill must be electronically conductive. In fact, when the possible current discharge paths from the anode surface are considered, it becomes obvious that two parallel current discharge paths exist. Current will flow through both the electronic path of the carbon backfill and the electrolytic (ionic) path of the water contained within the backfill. As the electronic discharge path becomes more and more conductive through the selection of low resistivity carbon and denser compaction, the tendency to discharge current electrolytically from the anode surface becomes less and less. The result is a shift in the oxidation reaction from the anode/backfill surface to the carbon backfill/soil surface.

Considering the purposes of the carbon backfill, there are several important factors to consider in the selection of a specific carbon backfill: resistivity, specific gravity, carbon content, and particle sizing and shape.

The necessity for a low resistivity carbon backfill has been previously introduced. The important resistivity for this application is the in situ bulk resistivity. In other words, the specific resistivity of the carbon particles as well as the particle-to-particle contact resistance is important. The specific resistivity of the carbon particles is a function of the contaminants in the carbon (ash, volatiles, etc.) together with the degree of heat treatment to which the carbon has been subjected. Heat treatment of the carbon parti-

cles results in the loss of volatiles, increased particle density, activation of the particle surface, and increased graphitization.

The effects of heat treatment depend upon the time-temperature relationship. As the particles give up volatiles and become semi-graphitized, the specific resistivity of the particles decreases.

Also, the surface activation results in lower particle-to-particle contact resistance. Finally, the particle-to-particle contact resistance may be further improved by surface treatments and compaction.

Since the carbon backfill is placed around an anode in the earth, the in situ condition usually involves the presence of water. In fact, the carbon backfill often is completely submerged in water, especially in deep anode systems. Since the contact resistance of the carbon particles is pressure sensitive, the greater the weight of the particles underwater, the lower the in situ bulk resistivity will be. Therefore, the in situ resistivity depends upon the specific gravity of the carbon particles. In addition to selecting materials with higher specific gravity, consideration should be given to possible air entrapment on the particle surface due to cracks or irregularities in the surface. Surfactants may be utilized to reduce the particle surface tension resulting in the release of trapped surface air and increased effective weight underwater.

The shape and sizing of the carbon particles is also important for maximum performance. Spherical particles will settle compactly without the requirement of mechanical tamping as required for irregularly shaped particles. Also, any gas generated can permeate through carbon backfills composed of spherical particles much easier than through backfills composed of flat, irregular shaped particles. This will minimize the tendency for any gas blockage problems. Particle sizing should be selected based upon consideration of the anode diameter. The average backfill particle size should be small compared to the anode diameter to ensure maximum anode contact area. However, very small carbon particles (less than 75 microns or 200 Tyler mesh) are not desirable since they have much higher ash content, higher resistivity, and are dusty.

Finally, the carbon content is an important factor since the carbon is sacrificed in the anodic reaction necessary to produce the cathodic protection current. In other words, the greater the carbon weight per unit of volume, the greater the ampere-year capacity. The carbon content can be quoted either as carbon percentage by weight or fixed carbon percentage. Fixed carbon percentage is, by definition, one hundred percent minus the percentages of ash, moisture, and volatiles.

In addition to proper backfill selection, the procedure used to place the backfill around the anode is important to maximize anode performance

and life. Clean carbon backfill should be placed uniformly around the anode without voids. For surface-type anodes, proper backfill placement usually requires only reasonable care to avoid contamination of backfill with soil and tamping if non-spherical backfill particles are utilized. However, in a deep anode system, proper backfill placement becomes much more critical. Tamping is impossible, and the hole is often filled with drilling mud to maintain stability. In this case, pumping a backfill-water slurry from the bottom of the hole upward, carefully displacing the drilling fluids from the top of the hole, will result in a cleaner, more compact backfill column. Although pouring the backfill into the top of the hole may be acceptable for completely dry holes or holes containing only very clean water, this procedure should be avoided for most deep anode systems.

Prepackaged anodes should be vibrated to maximize coke content within the container.

## DC Power Supplies

Details relating to the operation and maintenance of various power supplies are covered in detail in Level 1 and Level 2 courses. Your instructor will review some of these details in the slide presentation of this chapter. Detailed diagrams and principles of operation are not included in this course manual. The student should consult manufacturer's literature for specific information on the various power supplies available.

### ***Conventional Rectifiers***

Single-phase and three-phase rectifiers are the most common source of power for impressed current cathodic protection systems. The rectifying elements used in conventional rectifiers may be silicon diodes or selenium stacks.

Conventional rectifiers are available in a wide range of output voltage and current ratings. Rectifiers can be ordered for all common AC supply lines.

### ***Constant Current and Constant Potential Rectifiers***

Many cathodic protection designs require a constant current level under conditions of variable circuit resistance. Other situations require that the current output from the rectifier automatically adjusts to maintain a constant structure-to-reference potential. Rectifiers are available with automatic control circuits to met these requirements. Constant-current and constant-potential rectifiers can be obtained with ratings similar to conventional rectifiers.



## ***Solar***

Some solar cell units are available for cathodic protection use. Generally, these devices require an accompanying storage battery to permit continued operation during periods of no sunlight. The relatively high cost of this type of device and modest power availability limit their use to remote regions where commercial power is not readily available, and where sacrificial anodes cannot provide the desired operating characteristics.

## ***Wind Generators***

Cathodic protection power can be obtained using wind-driven generators. Such systems generally require storage batteries and control circuits similar to solar powered systems. In the absence of AC power, wind generators may be a viable alternative energy source.

## ***Thermoelectric***

Thermoelectric generators have been employed where readily available fuel makes their selection desirable. They are not a common type of power supply for general cathodic protection use.

In thermoelectric generators, heat is applied to one side of a junction of dissimilar electric conductors while the other side of the junction is kept cool, generally with heat-rejecting fins. The difference in temperature across the junction generates electricity. Heat for thermoelectric generators may be derived from catalytic “burning” of a hydrocarbon fuel (e.g. methane, propane, etc.) mixed with air. The “burning” is oxidation that takes place on a catalytic screen at temperatures below the flash point of the fuel. Open flame is not involved in these units. Any factor (e.g. wind, rain, snow, etc.) that improves cooling on the heat rejection side of the junction improves performance.

The low voltage produced by thermoelectric junctions can be increased by DC-to-DC converters. Nominal output voltages of 12 volts and 24 volts are standard. Additional circuitry can be furnished to provide voltage and current regulation.

## **Lightning Protection**

In many locations, cathodic protection systems are vulnerable to lightning strikes and/or secondary effects, which result from lightning. The cathodic protection design should provide suitable lightning protection for the power supply. On rectifiers, this may require lightning arrestors in both the input and output circuits.

# Electrical Cable and Connections

## Requirements

All electrical connections used in impressed current cathodic protection systems (except the active anode surfaces) must be completely sealed with dielectric insulating materials. Further, the connections must not have significant electrical resistance to avoid overheating.

The passage of current ( $I$ , amperes) through a resistance ( $R$ , ohms) over time ( $t$ , hours) produces heat energy according to the equation:

$$E = I^2 R t \text{ watt hours}$$

where:

$E$  = Energy (watt-hrs)

$I$  = current (A)

$R$  = circuit resistance (ohms)

$t$  = time (hrs.)

Some impressed cathodic protection systems operate at high current (50 A–500A) and heat buildup may be appreciable if there is any unexpected resistance in electrical connections. Wire sizing is also an important consideration. All wiring and connections should meet applicable electrical codes.

Wire and cable are often critical elements in a corrosion control system. The almost exclusive use of copper as the conducting component of wire and cables for corrosion control work stems from the frequent requirement that the wire be welded or brazed to a steel or iron structure. Use of aluminum, a common conductor in the electric power industry, for this kind of attachment is unacceptable. Aluminum is an active metal in the galvanic series and will rapidly fail in the presence of moisture when coupled with less active metals.

In corrosion control work, the type of insulation used is of critical importance. The insulation must be able to resist the conditions present in the environment over long periods of time. Even the smallest electrical leakage of direct current from an exposed conductor in an electrolyte can cause the conductor to corrode, which is a critical point in an impressed current cathodic protection anode circuit. Wire manufacturers can supply a variety of insulations to meet the application requirements.

Depending on the situation, wires and cables may be run in raceways, metal or plastic conduits, or be exposed directly to soil or other electrolytes. The thickness of insulation required will be different depending upon the physical stress to which the insulation will be subjected.



The designer must consider the following when specifying wire and cable:

- the current carrying requirements (ampacity)
- the allowable voltage drop in the cable
- the type and chemical properties of the environment to which the wire will be exposed
- whether or not splices will be allowed and if so, the method of splicing
- operating temperature
- need for physical protection (conduit)
- prevailing electrical codes.

## ***Methods of Connection***

Most of the common methods used to provide electrical connections and power distribution also apply to cathodic protection systems. In general, a metallurgical bond (exothermic weld, solder or braze) is preferred over a mechanical connection, where a connection is made to a structure. Wire-to-wire connections may be made by either metallurgical or compression methods considered suitable for power distribution. The connection made within anodes such as graphite, high-silicon iron, and other anode forms, is usually a pressure fitting, a threaded fitting or a cast lead connection. These connections must be completely sealed with a suitable potting compound to prevent intrusion of electrolyte to the connection. All wires and splices leading to and from the anode part of the system must be completely insulated and free of any pinholes or other current leakage points.

The wiring from the negative terminals of the power supply is connected to the structure in a variety of ways. Where steel structures are involved, the most common form of attachment is the thermite weld process (discussed below) or brazing. It is often desirable to first attach the copper wires to a steel coupon and then fillet weld the coupon to the structure. Wires connected to the negative terminal of the power supply are not adversely affected by electrolytic corrosion, as are the positive feed cables to the anodes.

## ***Exothermic Welding***

When finely powdered aluminum is mixed with copper oxide and ignited, an intensely hot chemical reaction takes place. The products are molten copper and aluminum oxide. Advantage is taken of this reaction in exothermic welding of copper wire attachments to steel structures.

Several manufactures market equipment that is designed to attach copper wires ranging in size from No. 14 AWG to 2000 MCM to other wires, or to steel and cast iron pipe and other surfaces. Since there are many combi-



nations of wire sizes and pipe diameters, the equipment used must be specifically manufactured for the proper combination in order to produce a satisfactory weld. Also, there are different thermite formulations for attaching copper wires to steel and to cast iron. There are other uses of the process besides the attachment of copper wires to steel and iron structures. Each use employs its own combination of thermite formulation and equipment. It is essential that the user employ the proper combination of thermite powder and equipment to suit the specific application.

Because of the high temperature produced in the reaction, great care must be taken to assure safe use. The process should never be used in areas where combustibles are present and there is a danger of fire or explosion. The process can readily burn through metal sheets or pipe walls that are too thin for the size of thermite charge employed.

Exothermic welding can adversely affect the physical properties of steel. Before using this method of wire attachment, determine whether the process is acceptable for the specific structure involved.

When specifying or using the thermite brazing process for corrosion control applications, the following should be considered:

- size of wire required
- type of surface to which wire will be brazed (curved or flat)
- location of attachment (horizontal or vertical)
- materials involved
- thickness of metal adequate for thermite charge size
- safe environment for use
- the metal surface is properly prepared according to the manufacturers instructions
- graphite mold, accessories and charges are the proper size for the specific application
- attachment style (e.g. copper sleeves tabs, and/or crows foot)
- possible adverse effect on the physical properties of the structure involved.

### Design Factors

#### Available Data

The first step in cathodic protection design is assembly of data. One approach to organizing data is to prepare a Data Summary and Checklist. An example of such a form is included at the end of this chapter. An item by item review of the form will indicate the relevance of the data to cathodic protection design.

#### *Summarizing the Data*

An organized summary of data is a good starting point for design work. The summary should include information on:

- history
- structure design life
- surface areas to be protected
- materials of construction
- fabrication
- protective coatings
- electrical isolation
- properties of the environment (electrical and chemical)
- operating concerns
- relevant literature
- possible modes of protection.

## ***Estimating Current Requirements***

Current requirements can be estimated using field and/or laboratory test data.

## ***Electrical continuity***

Electrical continuity must be maintained within the elements of a structure that is to be protected.

## ***Electrical Isolation***

Wherever possible, the structure to be protected by cathodic protection should be electrically isolated from other structures.

## ***Stray Currents***

The effects of stray current must be considered at the design stage.

## ***Structure Life Expectancy***

Expected useful life of the structure as well as the service life of cathodic protection components should be considered as they relate to overall economics of protection.

## ***Monitoring & Maintenance***

Monitoring and maintenance of cathodic protection systems is essential for successful corrosion control.

## ***Distribution of CP Current***

How current is distributed from an anode system and along the surfaces of a protected structure must be examined.

## ***Power Source***

Selection of a suitable power source depends on availability, amount of current required, and environment.

## ***Safety***

All applicable electrical and safety codes must be complied within a cathodic protection design.

### ***Interference with Other Structures***

Cathodic protection may cause undesirable side effects on other structures.

### ***Consequences of CP By-products***

Where anodes and cathodes contact process materials (potable water, food products, etc.), there may be undesirable side effects.

### ***Economics***

Economic considerations include:

- installation costs
- power usage
- component replacement and maintenance.

# Calculations

## Current Requirements

### *From Estimated Exposed Surface Area*

Current requirements based on expected exposed surface are always subject to error. There are many factors that affect the results.

Consider the following factors:

- total surface area in contact with soil or other electrolyte
- dielectric properties of any protective coating
- factors which may damage a protective coating during installation
- expected protective coating life under service conditions
- expected percentage coverage by protective coating
- past experience with coating applicators and construction contractors
- current density required for cathodic protection of the metal(s) in the environment.

In the end, the expected current requirement depends on calculating the area of exposed metal in contact with the electrolyte and multiplying it by the “best estimate” of current density for the conditions present.

There is an alternate approach for coated electrically isolated structures (pipes, underground storage tanks, etc.) where there is data available on existing cathodic protection systems.

The approach requires reliable local data on:

- expected leakage conductance (Siemens/unit area) in 1000 ohm cm. soil for a class of coating (epoxy, polyethylene tape, etc.) and type of service (transmission pipeline, gas distribution, fuel tank)
- soil resistivity in the service area
- structure-to-electrolyte potential shift required to produce polarization needed to meet cathodic protection criteria. This is the immediate change in potential of an isolated structure measured to a point at “remote earth” when cathodic protection is applied. The value is not a criteria for protection. However, under a given set of operating and exposure conditions, a potential shift will provide a good estimate of current needed to meet accepted criteria.

The approach is best understood by using an example.



## Example 4.1

A gas utility is planning to install 3049 meters (10,000 feet) of 5.1 cm (2 inches) coated steel distribution mains in a new development. The average soil resistivity in the area is 5,000ohm cm. The corrosion engineer wishes to estimate the approximate current required to cathodically protect the pipes.

Experience in the utility has developed the following data on cathodic protection current requirements:

- Average specific leakage conductance  $g'$  for distribution type service is  $2.14 \times 10^{-3} \text{ S/m}^2$  in 1000 ohm-cm soil.
- Average potential shift ( $\Delta V$ ) measured to “remote earth” to achieve protection is  $-0.250$  volt.

## Calculations

Total surface area of the proposed pipe:

$$A_s = \pi d L = (5.1\text{cm} \times 3.1416/100\text{cm/m}) \times 3049\text{m} = 488 \text{ m}^2$$

Estimated leakage conductance of new pipe in 1000 ohm-cm soil:

$$G = g' A = 2.14 \times 10^{-3} \text{ S/m}^2 \times 488\text{m}^2 = 1.04 \text{ Siemens}$$

Since resistance =  $1 / \text{conductance}$ :

$$\text{Resistance to remote earth} = 1/1.04 \text{ S} = 0.96 \text{ ohm}$$

Estimated resistance to remote earth in 5000 ohm-cm soil: (Resistance is directly proportional to resistivity)

$$0.96 \text{ ohms} \times 5 = 4.8 \text{ ohms}$$

Estimated current to shift pipe potential to remote earth  $-0.250$  volt.  
From Ohm's Law ( $I = E/R$ ):

$$I = 0.250 \text{ volts} / 4.8 \text{ ohms} = 0.052 \text{ A.}$$

Table 4.1 lists ranges of coating conductance for piping in various classes of service in 1000 ohm-cm soil.

## ***From Field Tests***

Field testing provides the most reliable way to estimate current requirements on an existing structure. If the structure is electrically isolated and provided with a dielectric protective coating (buried pipes and underground storage tanks), it should be possible to determine current requirements directly. A temporary anode (groundbed) is constructed and a portable power source (battery, generator or rectifier) is connected between the structure and the anode. If possible, the test anode should be located at or near a site suitable for the permanent installation.

### **Example 4.2**

An airport fuel distribution piping system is to be placed under cathodic protection. The piping is coated, and includes about 1524 meters (5000 feet) of 20.3 cm (8 inch) and smaller pipe. It extends from a tank farm in one corner of the airport to fuel hydrants at the terminal complex. All connections to other structures including fuel tanks, pumps and grounded structures have been electrically isolated. Fueling hydrants are not isolated from the pipe and have a driven ground rod attached to them. Because most of the pipe is under a concrete apron, the only practical location for the cathodic protection anode is at the supply end, near the tank farm. Soil resistivity averages 4000 ohm-cm.

How might the corrosion engineer determine the current required to protect this fueling system?

**Table 4.1 Typical Specific Pipe to Earth Leakage Conductance for Dielectric Protective Coatings in 1000 Ohm Cm Soil**

| Long Pipelines with Few Fittings             | AVERAGE SPECIFIC COATING CONDUCTANCE     |                                          |
|----------------------------------------------|------------------------------------------|------------------------------------------|
|                                              | g'<br>Siemens/ft <sup>2</sup>            | g'<br>Siemens/m <sup>2</sup>             |
| Quality of Work                              |                                          |                                          |
| Excellent                                    | $<1 \times 10^{-5}$                      | $<1 \times 10^{-4}$                      |
| Good                                         | $1 \times 10^{-5}$ to $5 \times 10^{-5}$ | $1 \times 10^{-4}$ to $5 \times 10^{-4}$ |
| Fair                                         | $5 \times 10^{-5}$ to $1 \times 10^{-4}$ | $5 \times 10^{-4}$ to $1 \times 10^{-3}$ |
| Poor                                         | $>1 \times 10^{-4}$                      | $>1 \times 10^{-3}$                      |
| Bare pipe (2" to 12")<br>(5 cm to 30 cm)     | $4 \times 10^{-3}$ to $2 \times 10^{-2}$ | $4 \times 10^{-2}$ to $2 \times 10^{-1}$ |
|                                              |                                          |                                          |
| Gas or Water Distribution with Many Fittings | AVERAGE SPECIFIC COATING CONDUCTANCE     |                                          |
|                                              | g'<br>Siemens/ft <sup>2</sup>            | g'<br>Siemens/m <sup>2</sup>             |
| Quality of work                              |                                          |                                          |
| Excellent                                    | $<5 \times 10^{-5}$                      | $<5 \times 10^{-4}$                      |
| Good                                         | $5 \times 10^{-5}$ to $1 \times 10^{-4}$ | $5 \times 10^{-4}$ to $1 \times 10^{-3}$ |
| Fair                                         | $1 \times 10^{-4}$ to $5 \times 10^{-4}$ | $1 \times 10^{-3}$ to $5 \times 10^{-3}$ |
| Poor                                         | $>5 \times 10^{-4}$                      | $>5 \times 10^{-3}$                      |
| Bare pipe (2" to 12")<br>(5 cm to 30 cm)     | $4 \times 10^{-3}$ to $2 \times 10^{-2}$ | $4 \times 10^{-2}$ to $2 \times 10^{-1}$ |

Step 1. Verify electrical isolation and electrical continuity of the piping.

- Identify points where electrical contact can be made to the piping (fueling hydrants, line valves, above grade manifolds etc.). Prepare a sketch of the system. See Figure 4.1.

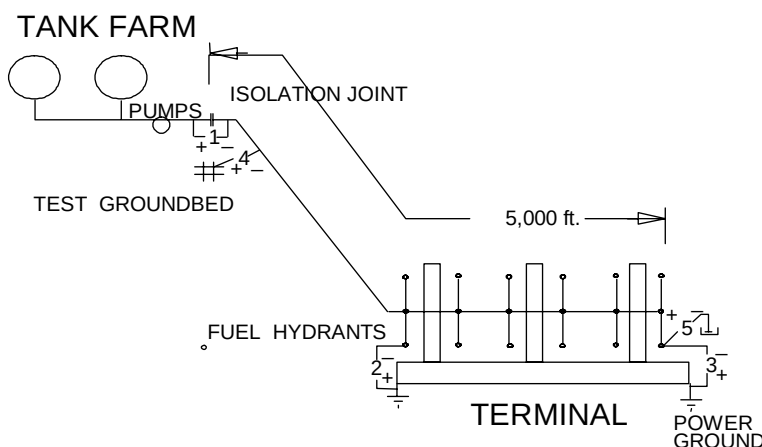


**Figure 4.1 Tank Farm Layout**

- Measure piping-to-earth resistance. In this case, since the tank farm has grounded pumps and by comparison to the piping system a very low resistance to remote earth, the electrical resistance across the dielectric isolation joint at the tank farm would approximate the pipe to remote earth resistance. Using two attachments on each side of the isolation joint (Terminal 1 of Figure 4.1), the resistance  $R_{1,1}$  was measured at 0.80 ohm. The total surface area of the piping is approximately 1000 m<sup>2</sup> (10,500 square feet). The resistance, 0.80 ohms, is equal to a conductance of 1.25 Siemens. The average specific conductance per unit area of coating (in 4000 ohm-cm soil) is:

$$g' = 1.25 \text{ S} / 1000 \text{ m}^2 = 1.25 \times 10^{-3} \text{ S/m}^2 \text{ (} 1.2 \times 10^{-4} \text{ S/ft}^2 \text{)}$$

or:

$$g' = 1.25 \times 10^{-3} \text{ S/m}^2 \times 4 = 5 \times 10^{-3} \text{ S/m}^2 \text{ in } 1000 \text{ ohm cm soil}$$

From Table 4.1, this equates to fair quality coating on distribution type piping with many fittings. Considering that the fuel hydrants have ground rods attached, there is nothing to suggest an electrical contact to a major grounded structure.

- Confirm isolation and continuity of the piping. Apply current at terminal 1 (Figure 4.1) and measure voltage change between piping and electrical power grounds in the terminal area. Electrical coupling values

are 0.75 volt/A and 0.70 volt/A for  $R_{2,1}$  and  $R_{3,1}$  respectively. See Appendix J— *DC Network Analysis* for an explanation of electrical couplings.

If the piping were short-circuited to a grounded structure, the pipe-to-earth resistance would normally be considerably less than 0.1 ohm. If the pipe contained an unknown isolation joint between the tank farm and the terminal,  $R_{2,1}$  and  $R_{3,1}$  would be greatly less than  $R_{1,1}$ .

## Step 2. Determine current required to protect piping

- Drive steel rods into the ground at the tank farm to form a test groundbed (Terminal 4, Figure 4.1).
- If a potential shift of  $-0.300$  volt between the pipe and earth is commonly required to polarize coated steel pipes in the region, and the electrical coupling value is 0.70 volt/A, then the estimated current needed to protect the piping at terminal 3 would be (from Ohm's Law):

$$I = 0.300 \text{ volt} / 0.7 \text{ volt/A} = 0.429 \text{ A}$$

- Measure the pipe-to-soil potential at the fuel hydrant using a copper/copper sulfate reference electrode placed next to the hydrant. If possible, locate the reference cell in the hydrant pit in contact with native soil.
- Apply 0.450 ampere test current at the groundbed and monitor the potential to the reference at Terminal 5. Interrupt the current flow and measure the instant-off potential ( $E_p$ ) periodically until the change in polarized potential with time approaches zero (i.e.,  $\Delta E_p / \Delta t \rightarrow 0$ ). Then calculate the design current as follows:

$$I_{cp} = \frac{100 \text{ mV} \cdot I_{\text{test}}}{\Delta E_p}$$

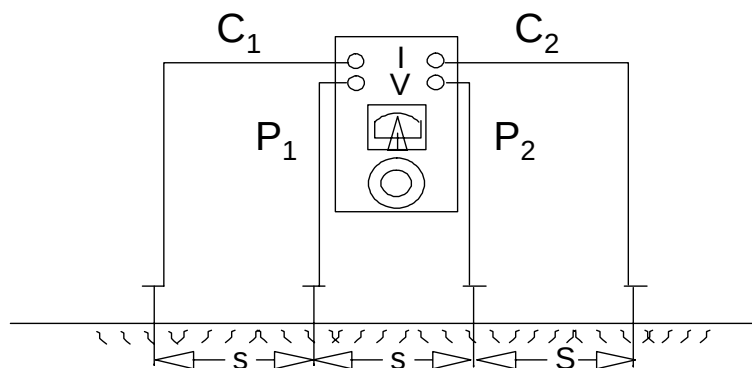
On extensive structures that are not isolated, it may be necessary to conduct a series of local tests and extrapolate the results to the gross structure.

## Anode Resistance-to-Earth

### General

The calculation of the electrical resistance of anode systems to remote earth is generally performed using mathematical formulas developed by H. B. Dwight<sup>1</sup>. These and other formulas will be used in illustrative examples later in this chapter. Manufacturers of anodes often provide tables or graphs specific to the size and shape of their anodes. In any case, the average resistivity of the soil (or other electrolyte) will be needed to make the calculation. The resistivity value used must be representative of the volume resistivity affecting the anode. A common way to obtain the resistivity is to use the Wenner four-pin method (ASTM G57-78).

Four equally spaced metal pins are driven into the soil in a straight line. The current source of the instrument is attached to the outer pins and the voltage measurement terminals are connected to the two inner pins. The arrangement is shown in Figure 4.2.



$$\text{Resistivity} = 2\pi sR$$

Where:

s is in cm.

R is resistance in ohms

**Figure 4.2 Wenner four pin resistivity measurement**

The resistance (Ohms) is read directly from the instrument. The resistivity of the soil is calculated by the expression:

<sup>1</sup> H. B. Dwight, "Calculation of Resistance to Ground", *Elec. Eng.*, **55**, 1319-1328 December 1936.

$$\rho = 2\pi sR$$

where:

$\rho$  = resistivity (ohm-cm)  
 $s$  = spacing between pins (cm)  
 $R$  = resistance measured (ohms)

If the spacing (  $s$  ) is measured in feet, the expression becomes

$$\rho = 191.5 sR$$

Instruments for measuring soil resistivity by this technique are widely available. Pin spacing should be selected such that the measurement reflects the mean volume resistivity for the extent of the anode bed. The pin spacing must be about the same as the lineal dimension of the groundbed. This is particularly important where the resistivity varies greatly with depth. For deep anodes (discussed below), resistivity must be estimated either from samples obtained by well drillers in the area or by the Barnes Layer analysis technique. Consider the example, given in English units, shown in Figure 4.3.

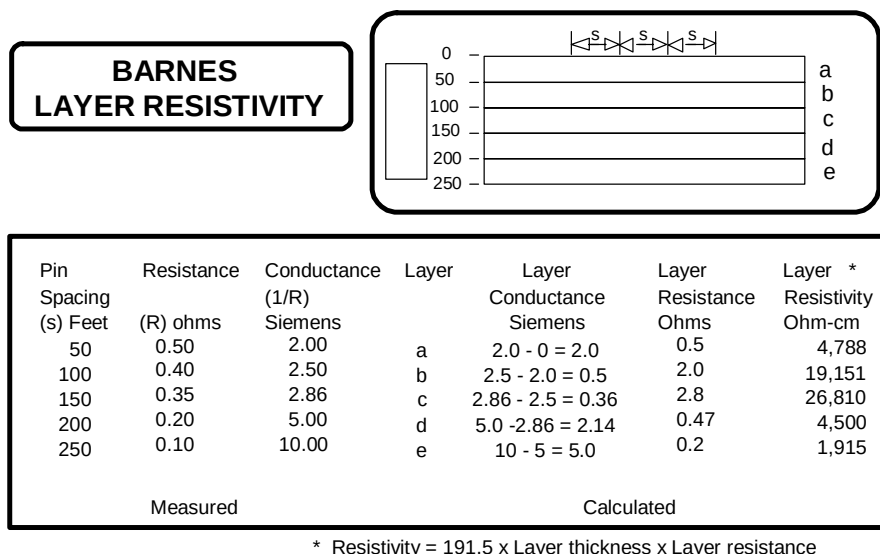


**Figure 4.3 Barnes layer resistivity profile**

Represented is a profile of soil layers each 50 feet (15.2 meters) deep and having different average resistivities. Surface measurements of total resistance ( $R_T$ ) using the Wenner four-pin method at pin spacings of 50, 100, 150, 200 and 250 feet (15.2, 30.4, 45.6, 60.8 and 76 meters) yield the resistance values shown. The first reading is the resistance “seen” by

the instrument as the average for a soil layer 50 feet deep. The second reading is the resistance measured in the first layer paralleled by the resistance “seen” in the next layer from 50 feet to 100 feet. Increasing the pin spacing another 50 feet adds a third layer in parallel with the first two. The procedure can be continued as long as the instrument has the sensitivity to resolve the small differences in measured total resistance. The equation that allows us to calculate resistances in parallel is:

$$1/R_T = 1/R_1 + 1/R_2 + 1/R_3 + \dots 1/R_n$$

or in the form of conductance

$$G_T = G_1 + G_2 + G_3 + \dots G_n \text{ Siemens}$$

To calculate the average resistance of any layer (n), subtract the conductance ( $1/R_T$ ) measured at the pin spacing representing all the soil on top of the layer of interest from the conductance that contains the layer of interest. In the example shown in Figure 4.3, the resistance of the layer between 200 feet and 250 feet can be calculated as follows:

$$G_e = G_{T250} - G_{T200}$$

or

$$1/R_e = 1/R_{T250} - 1/R_{T200}$$

$$1/R_e = 1/0.1 - 1/0.2 = 5 \text{ Siemens}$$

$$R_e = 0.2 \text{ ohm}$$

Since the layer between 200 feet and 250 feet is 50 feet thick, the resistivity of the layer can be calculated from the formula:

$$\rho = 191.5 \text{ sR}$$

$$\rho = 191.5 \times 50 \times 0.2 = 1,915 \text{ ohm-cm}$$



Care needs to be exercised with respect to test methods, instrumentation and subsurface geology when measuring resistivities to depths greater than approximately 15 meters (50 feet).

## Conventional Groundbed

Most conventional groundbeds consist of either a straight horizontal bed similar to a length of pipe or a row of short vertical anodes in a straight line. The resistance of a horizontal bed can be approximated using Dwight's formula for a horizontal rod (or pipe) in earth.

$$R = \frac{\rho}{2\pi L} \left( \ln \left( \frac{4L}{d} \right) + \ln \left( \frac{L}{h} \right) - 2 + \frac{2h}{L} \right)$$

where:

$\rho$  = average soil resistivity ohm-m

$L$  = length of groundbed (meters)

$d$  = diameter of groundbed (m)

$h$  = depth to center of groundbed (m)

If resistivity is given in ohm-cm rather than ohm-m, the equation is often written as follows:

$$R = \frac{\rho}{2\pi L} \left( \ln \left( \frac{4L}{d} \right) + \ln \left( \frac{L}{h} \right) - 2 + \frac{2h}{L} \right)$$

or:

$$R = \frac{0.005\rho}{\pi L} \left( \ln \left( \frac{4L}{d} \right) + \ln \left( \frac{L}{h} \right) - 2 + \frac{2h}{L} \right)$$

If any of the factors are not in the correct units, then conversion factors must be included where appropriate. For example, if diameter,  $d$ , is in cm and,  $L$  and  $h$ , are in m and  $\rho$  is in ohm-cm, then:

$$R = \frac{0.005\rho}{2\pi L} \left( \ln \left( \frac{400L}{d} \right) + \ln \left( \frac{L}{h} \right) - 2 + \frac{2h}{L} \right)$$

Take care to check units when using any formula. Many of the examples presented in this course use specific equations that include conversion factors rather than general forms of equations.

## Example 4.3

Estimate the resistance of a horizontal groundbed 30.5 cm (12 inches) in diameter by 15.2 meters (50 feet) long in soil averaging 4,000 ohm-cm in resistivity. Assume the depth of the groundbed to be 1.2 meters (4 feet).

From Dwight's equation for a horizontal rod ( general equation):

$$R = \frac{\rho}{2\pi L} \left( \ln\left(\frac{4L}{d}\right) + \ln\left(\frac{L}{h}\right) - 2 + \frac{2h}{L} \right)$$

$$R = \frac{4000 \text{ ohm-cm}}{100 \frac{\text{cm}}{\text{m}}} \left( \ln\left(\frac{4(15.2\text{m})}{30.5\text{cm}}\right) + \ln\left(\frac{15.2\text{m}}{1.2\text{m}}\right) - 2 + \frac{2(1.2\text{m})}{15.2\text{m}} \right)$$

$$R = 0.419 \text{ ohm} (\ln(199) + \ln(12.7) - 2 + 0.158)$$

$$R = 0.419 \text{ ohm} (5.99)$$

$$R = 2.51 \text{ ohm}$$

If the groundbed consists of a group of short vertical anodes in a row, the Sunde equation provides a good approximation of the resistance to remote earth.

$$R_N = \frac{\rho}{2\pi N L} \left( \ln\left(\frac{8L}{d}\right) - 1 + \frac{2L}{s} \ln(0.656N) \right)$$

where:

- $R_N$  = groundbed resistance (ohm)
- $\rho$  = average soil resistivity (ohm-m)
- $N$  = number of anodes in parallel
- $L$  = length of an anode (m)
- $d$  = anode diameter (m)
- $s$  = spacing of anodes in groundbed (m)

### Example 4.4

Estimate the resistance of a groundbed 15.2 meters (50 feet) long in 4,000 ohm-cm soil when it consists of 6 each, 0.305 m (12 inch) diameter vertical anodes on 3.05 meter (10 ft.) centers. The anodes are 1.52 meters (5 feet) long and have a nominal 0.46 meter (18 inches) of cover. (Note that the Sunde equation does not consider the depth of the anode below grade.)

Using the general form of the Sunde equation and making corrections for units:

$$R_N = \frac{\rho}{2\pi NL} \left( \ln \left( \frac{8L}{d} \right) - 1 + \frac{2L}{s} \ln(0.656N) \right)$$

$$R_N = \frac{\frac{4000 \text{ohm-cm}}{100 \text{cm}}}{\frac{2\pi 6(1.52 \text{m})}{\text{m}}} \left( \ln \left( \frac{8 \cdot 1.52 \text{m}}{0.305 \text{m}} \right) - 1 + \frac{2 \cdot 1.52 \text{m}}{3.05 \text{m}} \ln(0.656 \cdot 6) \right)$$

$$R_N = 0.698 \text{ohm} (\ln(39.9) - 1 + .997 \ln(3.94))$$

$$R_N = 0.698 \text{ohm} (4.05)$$

$$R_N = 2.83 \text{ohm}$$

### Vertical Anode

Dwight's equation for a single vertical rod or pipe to remote earth is:

$$R_v = \frac{\rho}{2\pi L} \left( \ln \left( \frac{8L}{d} \right) - 1 \right)$$

where:

- $\rho$  = resistivity (ohm-cm)
- $L$  = length of anode (cm)
- $d$  = diameter of anode (cm)

Note: This equation assumes that  $L \gg d$

In this equation, the length of the rod extends down from grade a length,  $L$ , in meters. In practice,  $L$ , represents the length of active anode in a deep anode system. The top of the active anode section may be some distance below the surface. For practical estimation of anode-to-remote earth resistance, ignoring the effect of the layer between the top of the active anode and grade does not appear to produce significant error.

### Example 4.5

Assume the Barnes layer resistivities shown in Figure 4.3. Estimate the resistance of a deep anode 20.3 cm (8 inches) in diameter to remote earth if the active section will be located between 45.7 and 76.2 meters (150 and 250 feet) below grade.

Solution:

Calculate the average soil resistivity in the zone where the active anode element will be located (layers d and e):

$$\text{Conductance of d + e: } (G) = 5.0S + 2.14S = 7.14S$$

$$\begin{aligned} \text{Resistance of layers: } R &= (1/7.14S) = 0.14 \text{ ohm} \\ \rho &= 2\pi s R \end{aligned}$$

$$\rho = 2 \times 3.14 \times 3048 \text{ cm} \times 0.14 \text{ ohm} = 2,680 \text{ ohm-cm}$$

Note that 3048 cm (100 ft.) in the above equation is the total thickness of layers d and e.

Using Dwight's equation for a vertical rod:

$$\begin{aligned} R &= \frac{\rho}{2\pi L} \left( \ln \left( \frac{8L}{d} \right) - 1 \right) \\ R &= \frac{\frac{2680 \text{ ohm-cm}}{100 \text{ cm}}}{\frac{\text{m}}{2\pi(30.48 \text{ m})}} \left( \ln \left( \frac{8 \cdot 30.48 \text{ m}}{.203 \text{ m}} \right) - 1 \right) \\ R &= 0.140 \text{ ohm}(6.09) = 0.852 \text{ ohm} \end{aligned}$$

where:

$$\begin{aligned} \rho &= \text{average soil resistivity (26.8 ohm-m)} \\ L &= \text{active length of anode (30.48 meters)} \\ d &= \text{anode diameter (.203 meters)} \end{aligned}$$

### Distributed Anodes



Distributed anodes are frequently located close to the structure they are designed to protect. This proximity tends to reduce the effective resistance between the anode and the structure. An estimate of anode-to-remote earth resistance using the Sunde equation is, therefore, conservative.

In distributed anode systems, the lineal resistance of the feeder cable may be a significant factor. Voltage and current attenuation along the anode feeders must be considered. Attenuation calculations require an estimate of the average conductance to earth of a unit length of the distributed anode system. The calculations also require the value of lineal resistance for the anode feeder (bus) wire. Unless individual anodes in the distributed anode system are widely spaced, there will be a paralleling effect. The electric field produced by current flow from an anode affects the field and therefore the current output of all other anodes in the vicinity. This mutual effect increases the effective resistance of each anode above that of the resistance for a single anode in a given soil resistivity. See Table 4.2 for an example for 5,000 ohm-cm soil.

#### *Sunde Equation*

$$R_N = \frac{\rho}{2\pi NL} \left( \ln \left( \frac{8L}{d} \right) - 1 + \frac{2L}{s} \ln(0.656N) \right)$$

where:

$R_N$  = groundbed resistance (ohm) for N anodes

$\rho$  = average soil resistivity (50 ohm-m)

N = number of anodes in parallel (20)

L = length of an anode (1.52 m)

d = anode diameter (0.305 m)

s = spacing of anodes in groundbed (m)

[See table]

**Table 4.2 Paralleling Effect**

| <b>s(meters)</b> | <b>R<sub>n</sub> (ohms)</b> | <b>Avg. R/anode (ohms)</b> |
|------------------|-----------------------------|----------------------------|
| 0.5              | 4.800                       | 96.0                       |
| 1.0              | 2.751                       | 55.0                       |
| 1.5              | 2.069                       | 41.4                       |
| 2.0              | 1.727                       | 34.5                       |
| 2.5              | 1.522                       | 30.4                       |
| 3.0              | 1.386                       | 27.7                       |
| 3.5              | 1.288                       | 25.8                       |
| 4.0              | 1.215                       | 24.3                       |
| 4.5              | 1.158                       | 23.2                       |
| 5.0              | 1.113                       | 22.3                       |
| 5.5              | 1.075                       | 21.5                       |
| 6.0              | 1.044                       | 20.9                       |

For spacing greater than 6 meters (20 feet), the paralleling effect is often neglected.

The average conductance,  $G$ , for a typical 1.52 meter (5 ft) x 0.305 meter (1 ft) anode with 6 or more meters of separation in 5,000 ohm-cm soil is:

$$G = 1/R_a = 1/20.9 \text{ ohms} = 0.048 \text{ Siemens}$$

Assuming the unit length of an anode system is a single anode plus the length of header cable between anodes, the unit conductance of the anode system,  $g$ , is the average conductance of one anode,  $G$ , calculated above. If a No. 4 AWG copper wire (0.82 ohm/1000 m) is used, and the anodes have a 15 meter (49.2 ft) separation, the unit resistance of the wire is:

$$r = (0.82 \text{ ohms}/1000 \text{ m}) \times (15 \text{ m}/\text{unit}) = 0.0123 \text{ ohm}/\text{unit}$$

where the unit length is 15 meters.

The resistance between the input end of a long distributed anode bus to remote earth is given by the equation:

$$R = R_G \coth(\alpha x)$$

where:

$R_G$  =  $(r/g)^{0.5}$  (characteristic resistance)

$\alpha$  =  $(rg)^{0.5}$  (attenuation constant)

$x$  = unit distance (number of units) from the open end

$\coth$  = is the hyperbolic cotangent



## Example 4.6

Calculate the resistance at the feed end of a 1,000 meter (3,280 ft.) long distributed anode bus to remote earth. The bus is AWG No. 4 copper wire (0.82 ohm/1000 m), the anodes have 15 meter (50 ft.) separation, the individual anodes are 1.52 meters (5 ft) long and 0.3 meters (1 ft.) in diameter. The average soil resistivity is 5,000 ohm-cm.

Solution:

Consider each anode and the 15 m (50 ft.) of bus wire as a unit. The total number of units in the system is:

$$x = (1,000/15) = 66$$

From Table 4.2 and the calculations shown for 6 m as a reasonable approximation:

$$g = 0.048 \text{ Siemens/unit}$$

$$r = 0.0123 \text{ ohm/unit}$$

therefore:

$$R_G = \left(\frac{r}{g}\right)^{0.5} = \left(\frac{0.0123 \text{ ohm}}{0.048 \text{ S}}\right)^{0.5} = 0.506 \text{ ohm}$$

$$\alpha = (rg)^{0.5} = (0.0123 \text{ ohm} \times 0.048 \text{ S})^{0.5} = 0.024$$

$$R_{so} = R_G \coth(\alpha x) = 0.506 \text{ ohm} \coth(0.024 \times 66)$$

$$R_{so} = (0.506 \text{ ohm})(1.088) = 0.551 \text{ ohm}.$$

If attenuation were not considered, what would the resistance of the 66 anodes be when measured to remote earth?

$$R_s = \frac{1}{66g} = \frac{1}{66 \times 0.048 \text{ S}} = 0.316 \text{ ohm}$$

## Cathode Resistance-to-Earth

### *From estimated coating characteristics*

Calculation of cathode-to-earth resistance is essentially what was done when calculating the current needed to lower the potential to earth a specified amount. To review:

- calculate the total surface area of the structure
- from experience with construction practice and average coating characteristics calculate the total leakage conductance for the structure
- take the reciprocal of the total conductance ( $1/G$ ) to obtain the structure to remote earth resistance

### *From Field Tests*

As with long distributed anode systems, attenuation may be involved in determining the structure-to-earth resistance. Measuring the resistance between an electrically isolated structure and any well grounded structure will give the approximate resistance of the cathode to remote earth. Example 4-2 used this technique. Another approach is to apply a test current between the structure and either a test groundbed or the permanent groundbed and measure the structure-to-earth coupling ( $\Delta V/\Delta A$ ) at several locations on the structure. The reference electrode used to obtain the earth potential shift must be far enough from the structure such that any further separation will not result in any further change in value of the coupling. Unless there is significant attenuation involved, the average of the several coupling values will be the resistance of the structure (cathode) to remote earth.

## Total DC Circuit Resistance

### *Anode-to-Structure Resistance*

The anode-to-structure resistance is the sum of the resistance of the anode and the structure to remote earth. In the case of a non-coated or poorly coated structure and closely arranged anodes the anode to structure resistance will be lower than the sum of the resistances to remote earth. This is frequently the case when anodes are used to protect components in process equipment or for "hot spot" protection on buried piping systems.

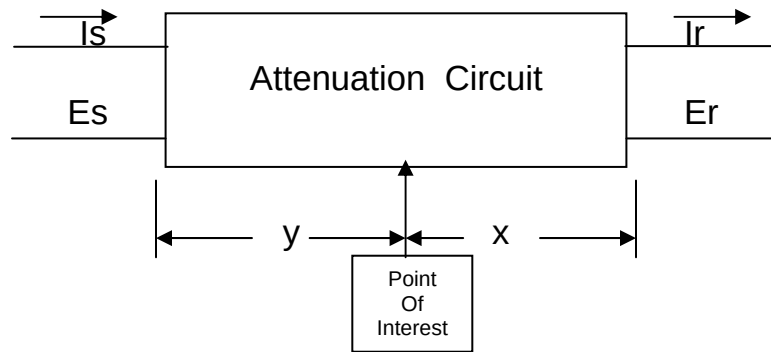
### ***Other Sources of Resistance***

Electrical connections, wire and internal resistance in power systems all may include some resistance. Such resistances are in series with the anode-to-earth and structure-to-earth resistances.

### ***Current Attenuation***

The formulas apply only where the environment has a relatively uniform resistivity.

## DC Attenuation Formulas



$\alpha = \sqrt{rg}$  propagation or attenuation constant

$R_G = \sqrt{\frac{r}{g}}$  characteristic resistance (ohms)

$r =$  unit lineal resistance, ohms/unit length

$g =$  unit conductance to earth S/unit length

$x =$  number of unit lengths from receiving end

$y =$  number of unit lengths from sending end

| General Equations                                                           | Where:                                          |
|-----------------------------------------------------------------------------|-------------------------------------------------|
| 1. $E = E_r \cosh(\alpha x) + R_G I_r \sinh(\alpha x)$                      | $E_r$ = receiving end potential                 |
| 2. $I = I_r \cosh(\alpha x) + \left(\frac{E_r}{R_G}\right) \sinh(\alpha x)$ | $I_r$ = receiving end current                   |
| 3. $E = E_s \cosh(\alpha y) - R_G I_s \sinh(\alpha y)$                      | $E_s$ = sending end potential                   |
| 4. $I = I_s \cosh(\alpha y) - \left(\frac{E_s}{R_G}\right) \sinh(\alpha y)$ | $I_s$ = sending end current                     |
| 5. $R_{so} = R_G \coth(\alpha x)$                                           | $R_{so}$ = Resistance looking into open line    |
| 6. $R_G = \sqrt{R_{so} R_{ss}}$                                             | $R_{ss}$ = Resistance looking into shorted line |

**Figure 4.4 Attenuation formulas**

## Anode System Attenuation

Example 4.6 shows the effect of attenuation on the input resistance of a long distributed anode. The mathematical equation for the voltage shift at any point “y” between an open-ended anode bus and remote earth is:

$$E = E_s \cosh(\alpha y) - (I_s R_G) \sinh(\alpha y)$$

where:

- $E_s$  = the voltage shift at the input end of the anode bus
- $I_s$  = the current input to the anode bus
- $\alpha$  = the attenuation constant
- $R_G$  = the characteristic resistance
- $y$  = the number of unit lengths from the input end of the anode bus

### Example 4.7

In Example 4.6, what is the approximate current output of an anode located 1,000 meters from the rectifier if the voltage between the structure and the anode bus at the rectifier is 15 volts when the rectifier is ON and 3.0 volts when it is OFF? Assume that there is negligible resistance between the structure and remote earth and negligible attenuation on the structure.

Solution:

The change in voltage at the source ( $E_s$ ) is:

$$E_{0on} - E_{0off} = 15 - 3 = 12 \text{ volts}$$

From example 4.6:

$$\begin{aligned} R_G &= 0.506 \text{ ohms} \\ \alpha &= 0.024 \\ R_{so} &= 0.551 \text{ ohms} \end{aligned}$$

There are:

$$1,000 / 15 = 66 \text{ unit lengths (s) to the point of interest (i.e. } y = 66)$$

$$E = E_s \cosh(\alpha y) - (I_s R_G) \sinh(\alpha y)$$

$$I_s = E_0 / R_{so} = 12 \text{ volts} / 0.551 \text{ ohms} = 21.8 \text{ A}$$

$$E = 12 \text{ volts} \cosh(1.584) - (21.8 \text{ A} \times 0.506 \text{ ohm}) \sinh(1.584)$$

$$E = (12 \text{ volts} \times 2.54) - (11.03 \text{ volts} \times 2.33) = 4.78 \text{ volts}$$

Since the average conductance of a single anode from example 4-6 is 0.048 Siemens, the current from an anode near the 1,000 m location will be:

$$I = E_g$$

$$I = 4.78 \text{ volts} \times 0.048 \text{ S} = 0.229 \text{ A}$$

How does this compare with the average current output from anodes near the feed end of the bus?

$$I = 12.0 \text{ volt} \times 0.048 \text{ S} = 0.576 \text{ A}$$

## ***Structure Attenuation***

The attenuation of current on a long structure is similar to that for the long anode run described in Examples 4.6 and 4.7. If the structure is very long or has high average leakage conductance to remote earth, the resistance looking each direction from a cathodic protection power source will be approximately equal to the  $R_G$  (the characteristic resistance). For shorter structures and structures with low leakage conductance, the resistance in each direction from the power source will be given by the formula for an open ended line that was used in Example 4.6. The concept is illustrated in the following example.

### Example 4.8

Consider a 20.3 cm (8 inch) welded steel pipeline (lineal resistance = 0.0287 ohm/1000 m) which has a measured specific coating leakage conductance,  $g'$ , that averages  $7.5 \times 10^{-5}$  Siemens/m<sup>2</sup>. The pipeline is 32,200 meters long with isolation joints at each end. The soil averages 10,000 ohm-cm resistivity throughout the region. What is the cathode (structure) resistance to remote earth from the center of the line in each direction as "seen" by a power source located there? What will the relationship between the current density received by the pipe at each end (16,100 meters from the power source) to that received near the power source at the middle of the pipeline?

#### Solution:

Consider a unit length to be 1,000 meters.

Given:

$r = 0.0287$  ohms/ unit  
 pipe diameter ( $d$ ) = 20.3 cm (0.203 m)  
 $g'$  - specific leakage conductance =  $7.5 \times 10^{-5}$  S/m<sup>2</sup> in 10,000ohm-cm soil

$$g = \pi d L g'$$

$$g = \pi(0.203\text{m})(1000\text{m})(7.5 \times 10^{-5} \text{ S/m}^2) = 0.0478 \text{ S/unit}$$

$$\alpha = (rg)^{0.5} = 0.037$$

$$R_G = (r/g)^{0.5} = 0.775 \text{ ohms}$$

From equation #5 (Figure 4.4)

$$R_{so} = R_G \coth(\alpha x)$$

$$x = 16,100/1000 = 16.1 \text{ unit lengths}$$

$$R_{so} = 0.775\text{ohms} \coth(0.037 \times 16.1) = 1.45 \text{ ohms}$$

Then resistance of structure-to-remote earth is  
 $1.45/2 \text{ ohms} = 0.73 \text{ ohms}$ .



From equation #3 (Figure 4.4):

$$E = E_s \cosh(\alpha y) - R_G I_s \sinh(\alpha y)$$

Assume a 1.0 volt shift in pipe-to-remote earth potential at the power source.

$$\begin{aligned} I_s &= E_s / R_{s0} &&= 1.0V / 1.45\Omega = 0.69A \\ \alpha y &= 0.037 \times 16.1 &&= 0.596 \\ E &= 1.0V \cosh(0.596) - (0.775\Omega \times 0.69A) \sinh(0.596) \\ E &= 1.183V - 0.338V &&= 0.845 \text{ volt} \\ E/E_s &= 0.845 \end{aligned}$$

Since current density received on the pipe surface from earth is proportional to the voltage shift measured to earth:

$$i_r = 0.845 i_s$$

Note that all of the current attenuation calculations are valid at time zero, in the absence of any electrochemical polarization. The pipe-to-remote earth potential shifts calculated in the attenuation equations are the sum of IR drops between the pipe at the point of interest and remote earth, caused by the flow of the source current.

## System Life

### *Sacrificial Anodes*

All components of a cathodic protection system have a finite service life. Rectifier components, wire insulation, and anodes all deteriorate with time. Sacrificial anodes are consumed in the process of production of current. Ampere-hour capacity (with the efficiency factor for the specific anode material) allows us to determine what weight of anode metal is required to provide a given number of ampere hours of current.

In estimating the system life for a galvanic anode cathodic anode system consider:

- annual mean temperature of the environment and the effect of temperature on the anode potential, current requirements and circuit resistance
- anode circuit resistance
- structure circuit resistance and its behavior with time
- total operating voltage including polarization of the cathode and the anode.

### Example 4.9

A field test indicates 0.375A is required to protect a coated section of pipe. At this current, the pipe is polarized to  $-0.900$  volt vs. a copper/copper sulfate reference electrode. The pipe has a resistance of  $0.8$  ohm measured to remote earth. Experience suggests that the resistance will slowly decrease during the next several years and level off at about half the present value ( $0.4$  ohm). Assuming that the same pipe to remote earth potential shift will maintain protection, how many  $7.7$  kg ( $17$  lb.) high potential magnesium anodes would be needed to protect the pipe section? How long would the expected useful service life be?

#### Solution:

The potential shift at present is:

$$E = 0.375\text{A} \times 0.80 \text{ ohm} = 0.30 \text{ volt}$$

The long term current required to maintain a potential shift of  $0.30$  volt is:

$$I = 0.30 \text{ volt} / 0.40 \text{ ohm} = 0.75 \text{ A}$$

The anode suppliers' literature says that in  $5,000$  ohm-cm soil a high potential magnesium anode will output  $0.040$  A ( $40$  mA) to a structure polarized to  $-0.85$  volt CSE. The data infers that the structure has negligible resistance to earth and therefore no IR drop. The resistance to remote earth of a single high potential ( $-1.75$  volt CSE) magnesium anode can be calculated:

$$R_a = (1.75\text{V} - 0.85\text{V})/0.040\text{A} = 22.5 \text{ ohms}$$

Assuming that the pipe section will continue to be polarized to  $-0.900$  volt CSE, the available driving voltage for the galvanic anode system will be:

$$E_{\text{net}} = -1.75\text{V} - (-0.900\text{V}) = -0.850 \text{ volt}$$

The total circuit resistance that will permit  $0.75\text{A}$  of current at a driving voltage of  $0.85$  volt is:

$$R_t = 0.85\text{V}/0.75\text{A} = 1.133 \text{ ohms}$$

Since the pipe-to-earth resistance is estimated to become  $0.40$  ohm, the resistance of the sacrificial anode group must be:



$$R_{a,g} = 1.133\Omega - 0.4\Omega = 0.73 \text{ ohm}$$

Assume that the anodes can be spaced far enough apart to avoid the paralleling effect, the number of anodes required to give the needed groundbed resistance is:

$$\begin{aligned} N &= R_a/R_{a,g} \\ N &= 22.5\Omega / 0.73\Omega = 30.8 \text{ (31) anodes} \end{aligned}$$

The total weight of magnesium in the anode system will be:

$$31 \text{ anodes} \times 7.7\text{kg /anode} = 239 \text{ kg}$$

The annual total ampere hours output will be:

$$365 \text{ d/yr} \times 24 \text{ hr/d} \times 0.75 \text{ A} = 6,570 \text{ Ampere-hrs/yr}$$

The ampere hour capacity of the anode system (assuming 1100 A-hrs./kg) is:

$$239\text{kg} \times 1100\text{A-hrs/kg} = 262,900 \text{ A-hrs.}$$

The anode service is estimated at:

$$262,900\text{A-hrs}/6,570\text{A-hrs/yr} = 40 \text{ yrs.}$$

Note: The ampere-hrs./kg capacity for magnesium anodes is dependent on current density and the specific backfill employed during installation. The actual service life can vary. Also, utilization factor (the percentage of useable anode) was not included in the above calculations.

## Coated Steel/Rectifier/Conventional Groundbeds

### Description

It is proposed to construct a water transmission main from an existing filtration plant to a new storage facility. There will be a number of interconnections with existing transmission and distribution piping. The main will consist of 7,646 meters (25,080 ft.) of 92 cm (36 in.) diameter pipe between the filter plant and an interconnection with an existing transmission main. An additional 6,402 meters (21,000 ft.) of 128 cm (42 in.) pipe will continue to the new water storage facility and other interconnections with the distribution system. Pipe will have a nominal wall thickness of 1.27 cm (0.500 in.). Plans require many drain attachments (blow offs), air valves and flow control valves.

The route of the main is through rural and suburban communities. There are to be many crossings with gas and water distribution pipes and with several major cathodically protected oil and gas pipelines. There is also a DC powered rapid transit rail system in the area. There are not to be any direct crossings with that transit system.

Construction is to be of coal-tar epoxy coated steel with mechanically coupled joints. Pipe joints are nominal 12.2 meters (40 ft.) long. The water utility requires a minimum service life of 40 years from this main but expected extended life well beyond that time frame.

As the utility's corrosion engineer, you are asked to review this construction and make recommendations for corrosion control.

## Approach

1. Review pipeline design plans and specifications.
2. Perform pre-construction route survey of soil resistivity, power sources, foreign structure locations, stray current activity and general topography. Review available records on corrosion of underground utilities in the area.
3. Prepare conceptual design for corrosion control.
4. Establish locations for electrical isolation joints, corrosion control test stations and prepare construction specifications for corrosion control items associated with construction of the water transmission main.
5. Perform field tests on completed water transmission line.
6. Activate protection system.

## Pre-Construction Parameters

| Pipe Design Factors                     |                                                          |
|-----------------------------------------|----------------------------------------------------------|
| Material                                | Carbon steel                                             |
| Coating                                 | Coal-tar and felt wrap                                   |
| Joining                                 | Mechanical couplings                                     |
| Attachments                             | Limited number                                           |
| Fittings many valves, blow offs and air | Release valves                                           |
| Dimensions                              | 7,650 m of 92 cm diam. 1.27 cm wall pipe (12.2 m/joint)  |
|                                         | 6,450 m of 128 cm diam. 1.27 cm wall pipe (12.2 m/joint) |
| Surface area                            | 48,048 m <sup>2</sup>                                    |

| <b>Environmental (from pre-construction survey)</b> |                                                                                                                         |
|-----------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|
| Resistivity                                         | 2,000 to 50,000 ohm-cm (5,000 ohm-cm avg.)                                                                              |
| Moisture                                            | Year round                                                                                                              |
| Temperature (-18° C to 32° C)                       | Temperate                                                                                                               |
| Stray currents                                      | Present on existing utilities                                                                                           |
| Corrosion histories                                 | penetrations of 9.5 mm (0.375 in.) and 12.7 mm (0.500 in.) steel pipe walls in pipes with ages between 20 and 30 years. |

A Data Summary and Checklist is included at the end of this design. The following conclusions can be drawn from this information:

1. Soil-related corrosion sufficient to cause pipe wall penetrations in 20 to 30 years on unprotected pipe should be expected. Cathodic protection is required if the long service life that is required from this pipeline is to be realized.
2. Stray current from active mass transit systems in the area will undoubtedly affect the proposed water main. The actual magnitude of the effect cannot be determined prior to construction.
3. Limited number of interconnections with other piping makes electrical isolation of the transmission pipe a practical option.
4. Even with a high quality protective coating, the large number of fittings (valves, air valves, mechanical couplings and blow offs) will produce significant pipe to soil leakage conductance. In 5,000 ohm-cm average soil resistivity, the effective specific coating conductance (Table 5.1- Good coating) would not be expected to be lower than about:

$$g' = 5.0 \times 10^{-4} / 5 = 1.0 \times 10^{-4} \text{ Siemens/m}^2 \text{ (} 9.3 \times 10^{-6} \text{ Siemens/ft}^2 \text{)}$$

For the total transmission main of 48,048 m<sup>2</sup> surface area, the lowest expected conductance to earth will be:

$$G = g'A_s = 1.0 \times 10^{-4} \text{ S/m}^2 \times 48,048 \text{ m}^2 = 4.8 \text{ Siemens}$$

$$R = 1/G = 1 / 4.8 \text{ S} = 0.21 \text{ ohms resistance to earth}$$

A poor job could result in an average conductance to earth of:



$$g' = 5.0 \times 10^{-3} / 5 = 1.0 \times 10^{-3} \text{ Siemens/m}^2 \text{ (} 9.3 \times 10^{-5} \text{ Siemens/ft}^2 \text{)}$$

$$G = g'A_s = 1.0 \times 10^{-3} \text{ S/m}^2 \times 48,048 \text{ m}^2 = 48 \text{ Siemens}$$

$$R = 1/G = 1 / 48 \text{ S} = 0.021 \text{ ohms resistance to earth for the total line}$$

**Table 5.1 Typical Specific Leakage Conductance for Dielectric Protective Coatings in 1000 ohm-cm Soil**

| Long Pipelines with Few Fittings             | AVERAGE SPECIFIC COATING CONDUCTANCE<br>$g'$ |                                          |
|----------------------------------------------|----------------------------------------------|------------------------------------------|
|                                              | Siemens/ft <sup>2</sup>                      | Siemens/m <sup>2</sup>                   |
| Quality of Work                              |                                              |                                          |
| Excellent                                    | $<1 \times 10^{-5}$                          | $<1 \times 10^{-4}$                      |
| Good                                         | $1 \times 10^{-5}$ to $5 \times 10^{-5}$     | $1 \times 10^{-4}$ to $5 \times 10^{-4}$ |
| Fair                                         | $5 \times 10^{-5}$ to $1 \times 10^{-4}$     | $5 \times 10^{-4}$ to $1 \times 10^{-3}$ |
| Poor                                         | $>1 \times 10^{-4}$                          | $>1 \times 10^{-3}$                      |
| Bare pipe<br>(2" to 12")<br>(5 cm to 30 cm)  | $4 \times 10^{-3}$ to $2 \times 10^{-2}$     | $4 \times 10^{-2}$ to $2 \times 10^{-1}$ |
|                                              |                                              |                                          |
| Gas or Water Distribution with Many Fittings |                                              |                                          |
| Quality of work                              |                                              |                                          |
| Excellent                                    | $<5 \times 10^{-5}$                          | $<5 \times 10^{-4}$                      |
| Good                                         | $5 \times 10^{-5}$ to $1 \times 10^{-4}$     | $5 \times 10^{-4}$ to $1 \times 10^{-3}$ |
| Fair                                         | $1 \times 10^{-4}$ to $5 \times 10^{-4}$     | $1 \times 10^{-3}$ to $5 \times 10^{-3}$ |
| Poor                                         | $>5 \times 10^{-4}$                          | $>5 \times 10^{-3}$                      |
| Bare pipe<br>(2" to 12")<br>(5 cm to 30 cm)  | $4 \times 10^{-3}$ to $2 \times 10^{-2}$     | $4 \times 10^{-2}$ to $2 \times 10^{-1}$ |

5. Mechanical couplings cannot be relied upon for electrical conduction across pipe joints. Bond wires will be required across each coupling if cathodic protection is to be applied to the transmission main.
6. There is no compelling reason to design power sources for cathodic protection prior to construction. There are several important unknowns (stray current, magnitude and pattern, coating quality



and proximity of other structures to the water line) that could be critical to the design.

Corrosion control measures which, in addition to the protective coating, are required for the pipe construction phase are:

1. Installation of isolation joints at the ends of the transmission main and at all interconnections and taps from the main. A test station should be installed at each isolation joint.
2. Electrical bonding straps across all mechanical couplings in the main. For reliability, two No. 2 AWG copper wire bonds per joint are the minimum that should be installed. The lineal resistance of the steel (assuming  $2.06 \times 10^{-5}$  ohm-cm resistivity for steel) pipe per joint (unit length) is:

92 cm diameter 1.27 cm wall pipe

$$R_p = \frac{\rho \cdot L}{A}$$

$$R_p = \frac{\rho \cdot L}{\frac{\pi}{4} (OD^2 - ID^2)}$$

where  $R_p$  = longitudinal resistance of pipe  
 $\rho$  = pipeline steel resistivity  
 $L$  = length of pipeline on per unit basis  
 $A$  = cross sectional area of pipeline steel  
 $OD$  = outside diameter of pipe  
 $ID$  = inside diameter of pipe

$$R_p = \frac{2.06 \times 10^{-5} \text{ ohm-cm} \cdot 1220 \text{ cm}}{\frac{\pi}{4} ((92 \text{ cm})^2 - (89.46 \text{ cm})^2)} = 0.00007 \text{ ohms/unit} = 7 \times 10^{-5} \text{ ohms/unit}$$

128 cm diameter 1.27 cm wall pipe

$$R_p = \frac{2.06 \times 10^{-5} \text{ ohm} \cdot \text{cm} \cdot 1220 \text{ cm}}{\frac{\pi}{4} ((128 \text{ cm})^2 - (125.46 \text{ cm})^2)} = 0.00005 \text{ ohms/unit} = 5 \times 10^{-5} \text{ ohms/unit}$$

Two No. 2 AWG copper wire bond wires 46 cm long will have a resistance of:

$$R_B = \frac{R_w \cdot L_w}{N_w}$$

where  $R_B$  = total bond resistance  
 $R_w$  = resistance of bond wire per unit length  
 $L_w$  = total length of bond  
 $N_w$  = number of bond wires in parallel

$$R_B = \frac{7.9 \times 10^{-6} \frac{\text{ohms}}{\text{cm}} \cdot 46 \text{ cm}}{2} = 0.00018 \text{ ohms/bond} = 1.8 \times 10^{-4} \text{ ohms/bond}$$

In addition to the pipe and bond strap resistances, there is also a resistance that is caused by current closing into the bond weld point in the pipe wall. It is called fringing resistance. The following formula will approximate the fringing resistance:

$$R_f = 2 \cdot OD \cdot R_L \cdot \ln \left( \frac{OD}{N \cdot d_b} \right)$$

where:

$R_f$  = fringing resistance (ohms)  
 $OD$  = O.D. of pipe (cm)  
 $R_L$  = lineal resistance of pipe (ohm/cm)  
 $N$  = number of bonds per joint  
 $d_b$  = diameter of the bond weld buttons (cm)

For most standard weight steel pipe the fringing resistance is from 1.0 to 3.0 x 10<sup>-5</sup> ohms per joint and can be neglected. In this particular example, the fringing resistance is negligible.

From these calculations, the majority of the lineal resistance of the main will be associated with the bonds.

3. Current measuring test stations should be installed about every 1,800 to 2,000 meters along the main. Test stations are important to corrosion control analysis especially where stray currents may be encountered.
4. Maintain a minimum of 30 cm separation at crossing underground structures (pipes, cables, etc.). Include a dielectric pad in between (and not in contact with) the water main and the other structure. This will increase the electrical distance between the structures and reduce corrosive interference effects.

## Post-Construction Parameters

Figure 5.1 is a schematic drawing of the water transmission main. The numbered locations represent IR drop (current measuring) test stations (four wire) which are spaced about 1800 to 2000 meters apart.

## COATED STEEL WATER TRANSMISSION MAIN

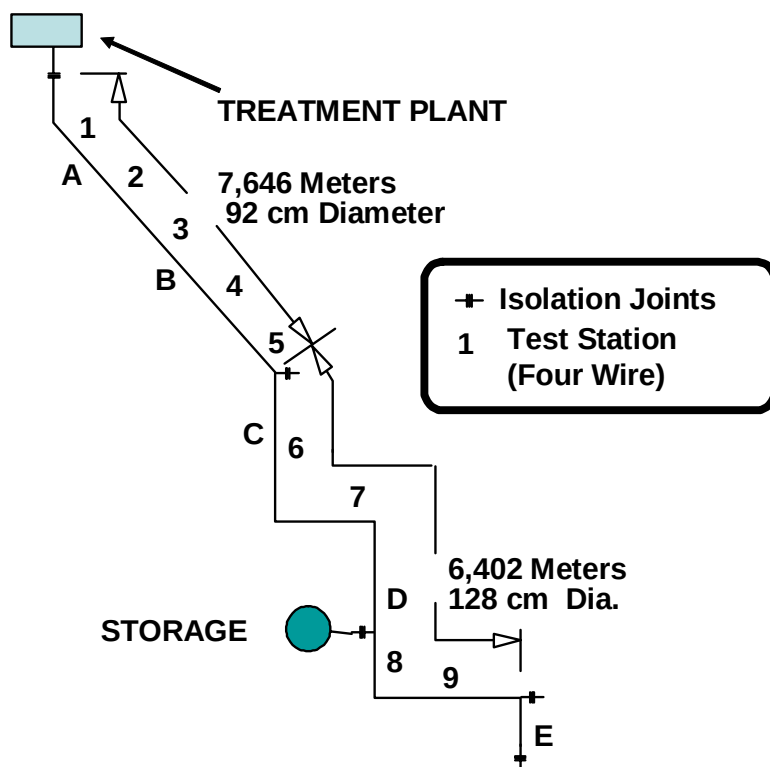


**Figure 5.1 Coated Water Transmission Main Schematic**

The first tests are to verify electrical continuity and isolation of the main. At location "E" (Figure 5.1) there is a welded steel gas main which does not have a protective coating and can be considered a well grounded structure. The resistance between the water main and the gas main is 0.180 ohm. Of this resistance 0.168 ohm is resistance between the water main and remote earth and 0.012 is the resistance of the gas main to remote earth. The measurement is made by impressing a measured current between the electrically isolated water main and the gas main. The immediate shift in pipe-to-soil potential divided by the impressed current is a close approximation of the relative resistances of the two structures to remote earth. The reference electrode used to measure the pipe-to-soil potential shift should be located as far away from both structures as possible. Ideally the reference should be far enough away such that adding any further distance results in no change in measured values. At the time the tests are made the potential between the water main and the gas main is observed to vary between +0.5 volt and -0.5 volt. A correlation of this potential with the potential of the water main to a

reference half-cell near location "E" show that essentially all of the activity is present in the water main pipe-to-soil potential.

Table 5.2 lists the percentage of the test current applied between the water main and the gas main at the IR drop test stations along the water main.

**Table 5.2 Test Current Profile**

| Location T.S. No. | Distance km From E | Percent Test Current on Line |
|-------------------|--------------------|------------------------------|
| 9                 | 0.4                | 93.0                         |
| 7                 | 2.35               | 80.0                         |
| 6                 | 4.18               | 64.3                         |
| 5                 | 6.40               | 41.3                         |
| 4                 | 7.90               | 30.4                         |
| 2                 | 9.70               | 13.0                         |
| 1                 | 12.6               | 8.6                          |

The pipe-to-soil (remote earth) shift at the Treatment Plant is 0.060 V/A.

These data suggest appreciable attenuation along the water main. To estimate the characteristic resistance ( $R_G$ ) of the system, we use the equations presented in Chapter 2. The formulas are reproduced here as Figure 5.2. Equation 6 of Figure 5.2 provides a method to estimate  $R_G$ .

$$R_G = (R_{SO} R_{SS})^{0.5}$$

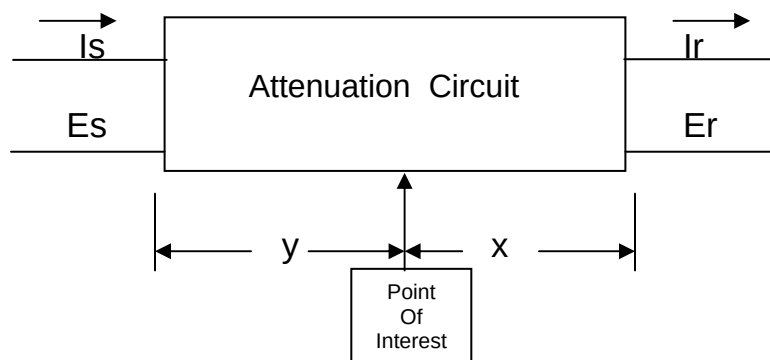
$R_{SO}$  is the resistance to remote earth measured at location "E" with the pipe isolated at the Treatment Plant. The value measured was 0.168 ohm. By short circuiting the isolation joint at the plant and repeating the measurement at "E" we can obtain  $R_{SS}$ . This test produces a value for  $R_{SS}$  of 0.147 ohm.

From equation 6 (Figure 5.2):

$$R_G = (0.168\text{ohm} \times 0.147\text{ohm})^{0.5}$$

$$R_G = 0.157 \text{ ohm}$$

## DC Attenuation Formulas



$\alpha = \sqrt{rg}$  propagation or attenuation constant

$R_G = \sqrt{\frac{r}{g}}$  characteristic resistance (ohms)

$r =$  unit lineal resistance, ohms/unit length

$g =$  unit conductance to earth S/unit length

$x =$  number of unit lengths from receiving end

$y =$  number of unit lengths from sending end

| General Equations                                                           | Where:                                          |
|-----------------------------------------------------------------------------|-------------------------------------------------|
| 1. $E = E_r \cosh(\alpha x) + R_G I_r \sinh(\alpha x)$                      | $E_r$ = receiving end potential                 |
| 2. $I = I_r \cosh(\alpha x) + \left(\frac{E_r}{R_G}\right) \sinh(\alpha x)$ | $I_r$ = receiving end current                   |
| 3. $E = E_s \cosh(\alpha y) - R_G I_s \sinh(\alpha y)$                      | $E_s$ = sending end potential                   |
| 4. $I = I_s \cosh(\alpha y) - \left(\frac{E_s}{R_G}\right) \sinh(\alpha y)$ | $I_s$ = sending end current                     |
| 5. $R_{so} = R_G \coth(\alpha x)$                                           | $R_{so}$ = Resistance looking into open line    |
| 6. $R_G = \sqrt{R_{so} R_{ss}}$                                             | $R_{ss}$ = Resistance looking into shorted line |

**Figure 5.2 DC Attenuation Formulas**

Since:

$$R_G = (r/g)^{0.5} \quad \text{then,}$$

$$R_G^2 = r/g$$

If we know  $R_G$  and can estimate  $r$ , we can calculate  $g$ . If we assume a unit length of pipeline to be 1 km, then the number of joints per unit length is:

$$N_j = \frac{L_u}{L_j} = \frac{1000 \frac{\text{m}}{\text{unit}}}{12.2 \frac{\text{m}}{\text{jt}}} = 81.96 \text{ jts/unit} = 82 \text{ jts/unit}$$

where  $N_j$  = number of joints per unit length  
 $L_u$  = unit length  
 $L_j$  = length of a single joint

The average resistance of a unit length of pipe is about:

$$r = N_j(R_B + R_p) = 82(0.00018 \text{ ohms} + 0.00006 \text{ ohms}) = 0.0197 \text{ ohms/unit}$$

where 0.00006 ohms/joint is the average resistance of the two pipe sizes.

Therefore, the per unit coating conductance for the pipe is:

$$g = r/R_G^2$$

$$g = 0.0197 \text{ ohms} / 0.025 \text{ ohms}^2 = 0.78 \text{ Siemens/unit}$$

For the entire 14.1 km of pipeline the conductance is 11 Siemens (0.78 S x 14.1). Since there are 48,048 m<sup>2</sup> of surface area on the pipeline, the average specific coating conductance is equivalent to  $2.3 \times 10^{-4}$  S/m<sup>2</sup> in 5,000 ohm-cm soil resistivity. This is equivalent to  $1.15 \times 10^{-3}$  S/m<sup>2</sup> in 1,000 ohm-cm soil. Referring to Table 5.1, Typical Specific Pipe to Earth Leakage Conductance for Dielectric Protective Coatings in 1000 ohm-cm Soil, coating quality must be considered fair.

The attenuation constant is:

$$\alpha = (rg)^{0.5}$$

$$\alpha = (0.0197 \text{ ohms} \times 0.78 \text{ S})^{0.5} = 0.124$$

If we apply equation 4 from Figure 5.2 to the test station locations of Table 5.2 we get the values listed in Table 5.3. For convenience in making the calculations use 100 A for the source current ( $I_s$ ). Source voltage will be 16.8 volts ( $I_s R_{so}$ ).

**Table 5.3 Theoretical Current Profile**

| Location T.S. No. | Distance km From E | Percent Test Current on Line |
|-------------------|--------------------|------------------------------|
| 9                 | 0.4                | 94.8                         |
| 7                 | 2.35               | 72.5                         |
| 6                 | 4.18               | 55.7                         |
| 5                 | 6.40               | 39.0                         |
| 4                 | 7.90               | 29.5                         |
| 2                 | 9.70               | 19.4                         |
| 1                 | 12.6               | 6.0                          |

Figure 5.3 is a graph showing the actual and theoretical current profiles on the transmission main. The correlation is good, and indicates freedom from any unexpected electrical grounds to other structures.

Analysis of stray current activity over the route of the pipe confirms that the most active area is near location "E". Corrosive potential shifts (pipe moving positive with respect to soil) of 0.500 volts occur regularly in this area during peak stray current periods. It will be necessary to apply cathodic protection current capable of reversing this condition. Experience in the area has shown that a pipe-to-soil (remote earth) potential shift of 0.300 volt is normally adequate to polarize steel pipe exposed to the soils in the area. The cathodic protection design must at least meet this criterion, on average, over the entire line as well as account for the stray current problem.



## ATTENUATION ON WATER TRANSMISSION LINE

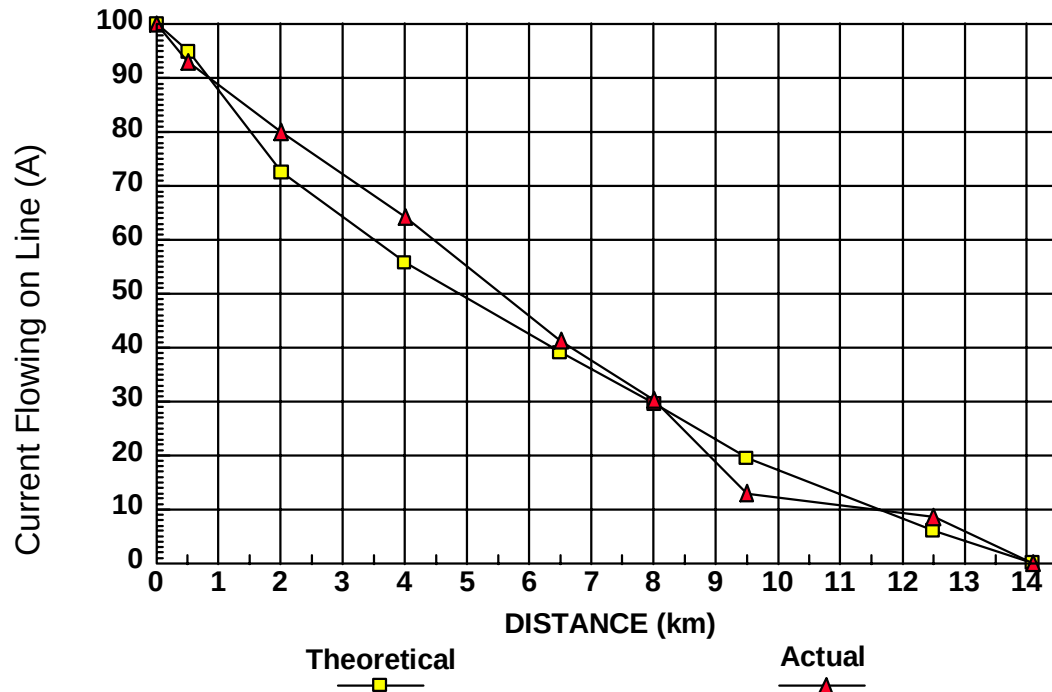


**Figure 5.3 Current Attenuation Profile**

Given the attenuation properties of the main, consideration must be given to multiple current sources for cathodic protection. The current attenuation profile (Figure 5.3) indicates that about half of the current supplied to the main from one end is received from earth over the first 5 km (one-third of the length of the main). Three sources of cathodic protection current located  $1/6$ ,  $3/6$  and  $5/6$  of the distance from either end of the main would be expected to provide the most uniform current distribution to the main.

Possible sites for impressed current groundbeds are indicated in Figure 5.1 by letters "A" through "C". These locations have a source of commercial power and are located away from other underground structures. Sites at "D" and "E" are possible, but involve other utilities. The distances from the end of the main at location "E" are given in Table 5.4.

**Table 5.4 Possible Groundbed Locations**

| Location Fig. 5-1a | Distance km From E |
|--------------------|--------------------|
| A                  | 12.0               |
| B                  | 8.5                |
| C                  | 5.0                |
| D                  | 2.0                |
| E                  | 0.0                |

Let us examine the possibility of a single rectifier and groundbed at location "C". "C" is located 9.1 km from the treatment plant and 5 km from "E". We must move the pipe-to-soil (remote earth) potential at least 0.5 volts negative at point "E" to cancel the stray current effects. It is also desirable to provide an additional 0.3 volt to ensure polarization of the main at this location.

Using equation 1, (from Figure 5.2):

$$E = E_r \cosh(\alpha x) + R_G I_r \sinh(\alpha x)$$

Let  $E_r = 0.800$  volt be the required pipe-to-remote earth potential shift.

$$\begin{aligned} x &= 5 \text{ km} \\ \alpha &= 0.124 \\ R_G &= 0.157 \, \Omega \\ I_r &= 0 \text{ (isolation joint)} \\ E &= \text{Pipe-to-remote earth potential required at "C"} \\ E &= 0.8 \text{ V} \cosh(0.124 \times 5) + 0 = 0.959 \text{ V} \end{aligned}$$

The resistance of the pipe to remote earth at "C" looking toward the open end "E" is given by equation 5 (from Figure 5.2).

$$R_{so} = R_G \coth(\alpha x)$$

$$R = 0.157 \, \Omega \coth(0.124 \times 5) = 0.285 \, \Omega$$

The current drawn from the direction of "E" will be:

$$I = 0.959 \text{ V} / 0.285 \, \Omega = 3.365 \text{ A}$$

The resistance looking toward the treatment plant is:

$$R = 0.157 \, \Omega \coth(0.124 \times 9.1) = 0.194 \, \Omega$$

The current drawn from the direction of the filter plant is:

$$I = 0.959 \text{ V} / 0.194 \, \Omega = 4.94 \text{ A}$$

$$\text{Total current} = 3.365 \text{ A} + 4.94 \text{ A} = 8.305 \text{ A}$$

This solution produces a pipe-to-soil potential shift at "C" that is over three times that required for polarization of the pipe.

## Alternative 2

Consider an alternative solution. Use a potential-controlled rectifier at location "E" to cancel stray current effects as needed and provide 0.300 volts potential shift during periods of no stray current activity. Explore the effect of three additional rectifiers at locations "A", "B" and "C".

The calculated resistances looking each direction from the proposed rectifier locations are summarized in Table 5.5.

**Table 5.5 Resistance and Current Flow from Possible Groundbed Locations**

| SOURCE LOCATION | TOWARD TREATMENT PLANT     |                      | TOWARD "E"                 |                      |
|-----------------|----------------------------|----------------------|----------------------------|----------------------|
|                 | Resistance $R_{so}$ (ohms) | Current $I_s$ (Amps) | Resistance $R_{so}$ (ohms) | Current $I_s$ (Amps) |
| A               | 0.616                      | 0.244                | 0.174                      | 0.862                |
| B               | 0.261                      | 0.575                | 0.200                      | 0.750                |
| C               | 0.194                      | 0.773                | 0.285                      | 0.526                |
| E               | 0.167                      | var.                 | inf.                       | var.                 |

Assume that one-half of the required pipe-to-soil potential shift ( $E_s = 0.150$  volt) at rectifier locations "A", "B" and "C" will be produced by the rectifier at that location. Assume that the combined effects of the other rectifiers will provide the remainder of the 0.300 volts.

Using the current values from Table 5.5 for  $I_s$ , and:

$y$  = distance from a source to any point of interest along the main

$R_G = 0.157 \Omega$

$\alpha = 0.124$

$E_s = 0.15 \text{ V}$

it is possible to develop a pipe to soil potential shift profile for the main with three constant current sources operating. This is done using Equation 3 from Figure 5.2. Once the effect of the three sources (A, B and C) are calculated for location "E" the requirements and effect of a potential controlled rectifier at "E" can be determined.

Table 5.6 summarizes the calculations.

**Table 5.6 Pipe-to-Soil Voltage Shifts Produced by Current Sources**

| Source      | Current (A)          |                 | Pipe to Soil Locations |                    |         |                    |         |                    |         |                    |         |                    |
|-------------|----------------------|-----------------|------------------------|--------------------|---------|--------------------|---------|--------------------|---------|--------------------|---------|--------------------|
|             | $I_s$<br>North South |                 | Treatment Plant        |                    | A       |                    | B       |                    | C       |                    | E       |                    |
|             |                      |                 | y<br>km                | $\Delta E$<br>volt | y<br>km | $\Delta E$<br>volt | y<br>km | $\Delta E$<br>volt | y<br>km | $\Delta E$<br>volt | y<br>km | $\Delta E$<br>volt |
| A           | 0.244                | 0.862           | 2.1                    | 0.145              | 0       | 0.150              | 3.5     | 0.104              | 7.0     | 0.103              | 12      | 0.065              |
| B           | 0.575                | 0.750           | 5.6                    | 0.120              | 3.5     | 0.124              | 0       | 0.150              | 3.5     | 0.112              | 8.5     | 0.093              |
| C           | 0.773                | 0.526           | 9.1                    | 0.088              | 7       | 0.091              | 3.5     | 0.110              | 0       | 0.150              | 5       | 0.125              |
| Totals      | 1.592                | 2.138           |                        | 0.353              |         | 0.365              |         | 0.364              |         | 0.365              |         | 0.283              |
| E<br>(Var.) | 0.101<br>2.980       | (base)<br>(max) | 14.1                   | 0.006<br>0.177     | 12      | 0.006<br>0.180     | 8.5     | 0.007<br>0.215     | 5       | 0.010<br>0.290     | 0       | 0.017<br>0.500     |

Equation:  $E = E_s \cosh(\alpha y) - R_G I_s \sinh(\alpha y)$

Constants:

$$\alpha = 0.124$$

$$R_G = 0.157 \, \Omega$$

$$E_s = 0.150 \, V$$

The potential shifts caused by the individual power sources are additive for any given location. For example, at the treatment plant source "A" produces a pipe-to-remote earth voltage shift of 0.145 volts. Sources "B" and "C" produce shifts of 0.120 and 0.088 volts respectively. The sum of these pipe-to-soil shifts is 0.353 volt. The variable current source, "E", produces an additional shift of between 0.006 and 0.177 volts depending on the current output at the time.

The total estimated current to achieve a minimum  $-0.300$  volts pipe-to-soil shift along the transmission main ranges from 3.8 to 6.7 amperes compared with a constant output from a single source system output of 8.3 A. The lower total current will be less stressful to the protective coating and prove less likely to produce interference effects.

## Groundbed Calculations

Conventional grade level groundbeds are proposed for this main. Sub-soil conditions are not suited for deep anodes. Figure 5.4 shows a typical

groundbed design. Graphite is a good choice for the primary anode material. The modest current requirements are well below the limit for this material, the cost is competitive and the relatively dry groundbed locations make graphite a good choice. Surface soil resistivities at all proposed rectifier locations are between 5,000 and 7,000 ohm-cm. However, resistivity measurements obtained by the Wenner four-pin method at a pin spacing of 30 meters (the length of the proposed groundbeds) indicate an average volume resistivity of 12,000 ohm-cm. Experience has shown that low conductivity sub-soils (rock) has a very significant effect on the resistance to remote earth of a groundbed of large dimension. This would include a length such as 30 meters. Pin spacing comparable to the span of the groundbed gives resistivity values that take the deeper layer resistivity into account. Using Dwight's formula for the resistance of a horizontal "rod" in earth, calculate the expected groundbed resistances. Assume 12,000 ohm-cm soil resistivity.

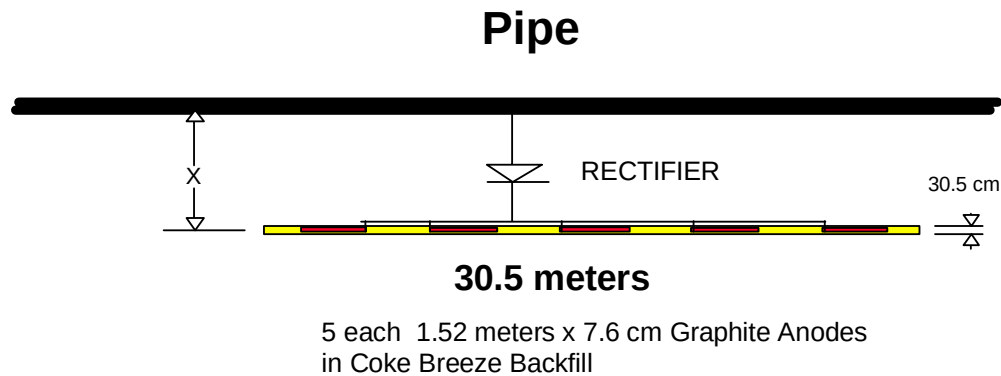


**Figure 5.4 Typical Groundbed**

$$R = \frac{0.005\rho}{\pi L} \left( \ln\left(\frac{4L}{d}\right) + \ln\left(\frac{L}{h}\right) - 2 + \frac{2h}{L} \right)$$

where:<sup>1</sup>

$$\begin{aligned} \rho &= 12,000 \text{ ohm-cm (resistivity)} \\ L &= 30.5 \text{ m (length of groundbed)} \\ d &= .305 \text{ m (diameter of groundbed)} \\ h &= 1 \text{ m (depth of groundbed center)} \end{aligned}$$

$$R = 0.629 [\ln(400) + \ln(30.5) - 2 + 0.07]$$

$$R = 4.7 \text{ ohms}$$

It is desirable to provide as much separation between the pipe and anode as possible. This is to minimize the effect of anode voltage gradient on the pipe. An approximation of the voltage rise in the earth caused by the flow of current from the anode is given by the formula <sup>1</sup>:

$$E_r = \frac{0.005I\rho}{\pi L} \left( \ln\left( \frac{L + (L^2 + r^2)^{0.5}}{r} \right) \right)$$

where:

$$\begin{aligned} E_r &= \text{voltage rise at } r \text{ meters from the anode} \\ \rho &= \text{resistivity (12,000 ohm-cm)} \\ I &= \text{anode current (1.2 A)} \\ L &= \text{length of anode (30 meters)} \\ r &= \text{radial distance from the anode (30 meters)} \end{aligned}$$

Practical considerations at locations "A", "B" and "C" will require that distance "X" (Figure 5.4) cannot be much greater than about 30 meters. The approximate pipe-to-soil voltage rise caused by an average anode current of 1.2 A at the groundbed locations will be:

$$E_r = \frac{0.005 \cdot 1.2 \cdot 12,000}{\pi \cdot 30} (\ln(2.41)) = 0.672 \text{ volts}$$

The total voltage rise of the groundbed-to-remote earth is obtained by multiplying the average current output by the groundbed resistance to remote earth.

$$E_T = IR = 1.2 \text{ A} \times 4.7 \text{ } \Omega = 5.64 \text{ volts}$$

The percentage rise at r, 30 m, is :

$$\begin{aligned} \text{\%rise} &= (0.672\text{V}/5.64\text{V}) 100\% = 12\% \\ &(\text{i.e., this point is outside of 88\% of the total rise}). \end{aligned}$$

The designer must realize that the increase in pipe-to-soil potential caused by the voltage gradient of the anode will increase the accumulation of current on the structure at coating defects subject to the greater potentials. If there is appreciable exposed metal-to-soil contact in the areas of increased pipe-to-soil potential, the actual distribution of current along the structure can be different from that predicted by attenuation formulas which do not account for these departures from "remote earth" behavior. In the real world of cathodic protection, there is no true "remote earth".

The pipe-to-earth resistance and circuit wiring resistance are small compared to the groundbed resistance and can be neglected. Although the present current requirements are less than 2.0 amperes for rectifier sites "A", "B" and "C" and 3.0 amperes for site "E", it is wise to provide rectifier capacity which will permit adjustment for future deterioration of the electrical properties of the system. Also, there may be interference problems on other utilities that will require mitigation bonds. Such bonds will lower the efficiency of the cathodic protection system and require more current. Select rectifiers with at least 4-ampere capacity. The minimum voltage rating should be:

$$E = 4 \text{ A} \times 4.7 \text{ } \Omega = 18.8 \text{ volts}$$

Since graphite anodes have a potential of about 2 volts positive to steel, an additional 1 to 2 volts of rectifier capacity is in order. Suitable rectifiers would have 4 ampere, 20 volt ratings. The rectifier for location "E" should be an automatic potential-controlled type.

Upon completion of construction of the groundbeds and rectifiers, the system must be tested for effectiveness. The rectifiers are activated at the design current outputs. The effect of each rectifier is measured at the most critical points that were determined during the initial survey of the transmission main. Pipe-to-soil potentials are monitored at each location to determine if the pipe is polarizing. Since there are stray currents from mass transit operations on the pipe, pipe-to-soil potentials must be



evaluated during periods of minimum activity or by extrapolating stray current activity to zero. (Dynamic stray current analysis is beyond the scope of this course.) Polarization can be determined by measuring the potential of the pipe to a reference with all rectifiers operating then subtract the IR effect from each source from the reading. The IR-free potential is then compared with the potential obtained prior to activation of the cathodic protection systems.

If an acceptable potential has been reached, the system is operating effectively. Adjustment in current output from any or all of the rectifiers can be made to fine tune the system.

Cooperative interference tests must be held with representatives of the other utilities and pipelines in the area. If mitigation bonds are required, the effect on the cathodic protection must be tested and adjustments made.

**DATA SUMMARY AND CHECKLIST**

**Title of Project**                      Project Water Transmission Main

**General Description**            7.65 km (25,100 ft.) of 92 cm (36 inc.) diameter and 6.45 km (21,100 ft.) of 128 cm (42 in.) diameter coated steel pipe.

| History                                 | Yes      | No |
|-----------------------------------------|----------|----|
| Proposed structure (not yet built)      | X        |    |
| Pre-construction survey performed       | X        |    |
| Existing structure                      | NA       |    |
| Evaluation (condition) survey performed | NA       |    |
| Structure Design Life (Life Extension)  | 40+ yrs. |    |

**Surfaces to be Protected**

| DESCRIPTION                                     | TOTAL SURFACE AREA (sq. m) |
|-------------------------------------------------|----------------------------|
| External                                        | 43,500                     |
| Internal                                        | NA                         |
| Total length<br>(if single, long<br>pipe/cable) | 14,100 m                   |

## Material(s) of Construction

| Metal (alloy)   | Alkali Sensitive |    | Hydrogen Sensitive |    | Velocity Sensitive |    | Area |
|-----------------|------------------|----|--------------------|----|--------------------|----|------|
|                 | yes              | no | yes                | no | yes                | no |      |
| 1. Carbon Steel |                  | X  |                    | X  |                    | X  | NA   |
| 2.              |                  |    |                    |    |                    |    |      |
| 3.              |                  |    |                    |    |                    |    |      |
| 4.              |                  |    |                    |    |                    |    |      |

## Method(s) of Fabrication

Fusion weld ☐ Mechanical X Gaskets X

## Protective Coating(s)

| Generic Type | Thickness | CP Tolerance |    | Estimated % Coverage |
|--------------|-----------|--------------|----|----------------------|
|              |           | yes          | no |                      |
| 1. Coal tar  | 5 mm      | X            |    | 95 %                 |
| 2.           | mm        |              |    | %                    |
| 3.           | mm        |              |    | %                    |

## Electrical Isolation and Grounding

|                                                   | YES | NO |
|---------------------------------------------------|-----|----|
| Structure isolated                                | X   |    |
| Structure can be isolated                         | X   |    |
| If isolated, requires electrical surge protection |     | X  |

**Environment**

|                         |                 |
|-------------------------|-----------------|
| Description             | rural, suburban |
| Resistivity<br>(ohm cm) | 5,000           |
| Velocity<br>(cm/sec)    | NA              |
| Temperature<br>(°C)     | 20              |

|                                    | YES | NO |
|------------------------------------|-----|----|
| Commercial<br>Power Available      | X   |    |
| Other Structure<br>Involved        | X   |    |
| Presence of<br>Stray Currents      | X   |    |
| Fire and/or<br>Explosion<br>Hazard |     | X  |

## Possible Concerns with Cathodic Protection

|                                     | YES | NO |
|-------------------------------------|-----|----|
| Electrical attenuation on structure | X   |    |
| Electrical attenuation on anode     |     | X  |
| Hydrogen embrittlement on structure |     | X  |
| Hydride formation on structure      |     | X  |
| Effect of CP on process chemistry   |     | X  |
| Stray current interference          | X   |    |
| Safety considerations               |     | X  |

### Additional Information:

Utilities histories show penetration of 9.5 mm (0.375 in.) and 12.7 mm (0.500 in.) steel pipe walls in pipes with ages between 20 and 30 years.

# Bare Steel/Rectifier/Distributed Anodes

## Description

A number of external corrosion leaks have occurred on a 76 cm diameter riveted steel water transmission main. The leaks are clustered in a local area that is continually wet and has a soil resistivity of 3,000 ohm-cm. Examination of the pipe in this area reveals local pitting resulting from anaerobic sulfate-reducing bacterial activity. There are no other underground structures in the area. There is AC power available at a road crossing in the area of the problem.

A soil survey of the immediate area indicates that the wet clay soil associated with the corrosion activity is limited to about 430 meters of pipe. The problem is to design cathodic protection for this "hot spot" section of pipe.

## Analysis

The pipe is bare steel and is of riveted construction. There should be no problem of electrical continuity on the structure. It is not practical to install isolation joints in the main, therefore, a closely arranged distributed anode system is indicated.

There are about 1,030 m<sup>2</sup> of exposed steel surface in the corrosive section. Research suggests that a current density of 1 to 3 x 10<sup>-6</sup> A/cm<sup>2</sup> is needed to protect steel in SRB conditions<sup>2</sup>. The expected current requirements for the section of pipe are:

$$I = iA_s = 3 \times 10^{-6} \text{ A/cm}^2 \times 1,030 \text{ m}^2 \times 10,000 \text{ cm}^2/\text{m}^2 = 31 \text{ A}$$

Using Dwight's formula, a continuous ribbon-type anode would have a resistance to remote earth of:

---

<sup>2</sup> S. C. Dexter, Editor, Biologically Induced Corrosion, NACE-8, p 345, 1986

$$R = \frac{0.005\rho}{\pi L} \left( \ln\left(\frac{4L}{d}\right) + \ln\left(\frac{L}{h}\right) - 2 + \frac{2h}{L} \right)$$

where:

$\rho = 3,000$  ohm-cm (resistivity)

$L = 430$  m (length of groundbed)

$d = .025$  m (diameter of groundbed)

$h = 1$  m (depth of groundbed)

$$R = 0.011 [\ln(68,800) + \ln(430) - 2 + 0.0] \text{ ohms}$$

$$R = 0.167 \text{ ohms}$$

The maximum driving potential from high potential magnesium to unpolarized steel is about 1.2 volts. The maximum current attainable from a single sacrificial ribbon anode would be about:

$$I = 1.20V/0.167\Omega = 7.2 \text{ A}$$

This is only about 20% of the likely current requirements. A sacrificial anode system is not likely to protect this section of pipeline.

Consider a distributed impressed current anode system. If 10 meter spacing of the anodes is selected (adequate current distribution for 3 meter pipe to anode separation allowed by pipeline right-of-way) there will be 44 anodes required. Assuming a maximum current requirement of 40 A, each anode would be required to deliver about 1 A. A number of anode materials could be used. We select 6.7 cm O.D. x 106.7 cm long high-silicon tubular anodes. The surface area is 2,246 cm<sup>2</sup>. The average density of current discharge will be 0.445 mA/cm<sup>2</sup>, well within the capacity of this material. The weight of an anode is 14 kg. Under the worst conditions the consumption rate should not exceed 0.3 kg/yr/A. At 50% utilization this would yield a life of 23 years. For best performance in soil, the anodes will be installed in coke breeze with outer dimensions of 0.3 m diameter by 1.5 m length.

## DISTRIBUTED ANODE 430 METERS OF 76 cm DIAMETER STEEL PIPE

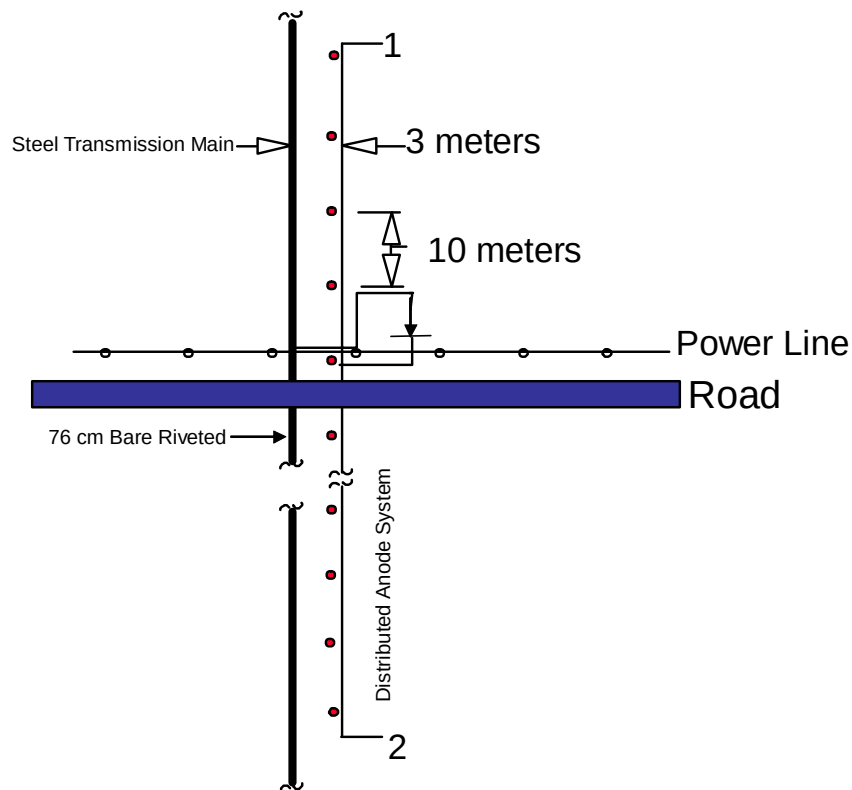


**Figure 5.5 Distributed Anode System**

The Sunde equation provides an estimate of the resistance of a distributed anode system for a conceptual design shown in Figure 5.5.

$$R_N = \frac{0.005\rho}{\pi NL} \left( \ln\left(\frac{8L}{d}\right) - 1 + \frac{2L}{s} (\ln(0.656N)) \right)$$



where:

$$\begin{aligned}\rho &= 3,000 \text{ ohm-cm} \\ N &= 44 \text{ (number of anodes on 10 m centers in groundbed)} \\ L &= 1.5 \text{ m (length of individual anode)} \\ d &= 0.3 \text{ m (diameter of anode and backfill)} \\ s &= 10 \text{ m (spacing between anodes)}\end{aligned}$$

$$R_N = 0.268 \text{ ohm}$$

The resistance of No. 4 AWG copper wire is  $8.2 \times 10^{-4}$  ohm/m or  $8.2 \times 10^{-3}$  ohm for each 10 meters between anodes (r). The average conductance of an anode to remote earth is:

$$g = 1/(44 \times 0.268) = 0.084 \text{ Siemens}$$

The attenuation constant for the anode is:

$$\alpha = (rg)^{0.5} = (6.9 \times 10^{-4})^{0.5} = 0.026$$

The characteristic resistance is:

$$R_G = (r/g)^{0.5} = 0.312 \text{ ohm}$$

The longer anode run from the rectifier to location 2 (Figure 5.5) will be 300 meters (30 unit lengths). The resistance to remote earth of this run will be:

$$R = R_G \coth(\alpha x) = 0.312 \Omega \coth(0.78) = 0.478 \Omega$$

For each volt between the anode and remote earth (the bare pipe) the sending current will be:

$$I_s = 1.0V/0.478 \Omega = 2.09 \text{ A}$$

The potential driving the end anode of the run will be:

$$E = E_s \cosh(\alpha y) - R_G I_s \sinh(\alpha y)$$

$$E = 1.0 \text{ V} \cosh(0.78) - 0.312 \Omega \times 2.09 \text{ A} \sinh(0.78)$$

$$E = 1.32 \text{ V} - 0.562 \text{ V} = 0.760 \text{ volts}$$

A voltage drop of 25% in the anode run is about the greatest acceptable attenuation. This means that 75% as much current is supplied by the end anodes on the bus as is supplied by anodes at the power supply end. Put another way, the anodes near the source must be driven 33% harder than

the end anodes in order to achieve adequate current at the end of the coverage area. Since anode life is a function of current density, having anodes in a system with greater than about 33% variation in life expectancy can result in future maintenance problems. No. 4 AWG copper wire is a suitable bus wire.

Provide test stations on the pipe at the ends of the anode runs. It is also convenient to have a test station at the remote ends of the anode buss wires. These test stations must be protected from electrical leakage to avoid electrolytic corrosion.

### ***Post-construction Tests***

Upon completion of anode construction and prior to selecting a rectifier conduct an E-Log  $i$  current requirement test. This type of test is very reliable on bare structures under the conditions present in this case. Select a suitable rectifier unit based on the test results. Since the pipe is bare, there will be no coating deterioration over time. The maximum current required will be the initial current. As polarization is achieved, future current requirements will likely decrease.

A Data Summary and Checklist for this job follows.

## DATA SUMMARY AND CHECKLIST

**Title of Project** "Hot Spot" Protection  
**General Description** 430 meter section of a 76 cm diameter steel water transmission main

| History                                 | Yes     | No |
|-----------------------------------------|---------|----|
| Proposed structure (not yet built)      |         | X  |
| Pre-construction survey performed       |         | X  |
| Existing structure                      | X       |    |
| Evaluation (condition) survey performed | X       |    |
| Structure Design Life (Life Extension)  | 20 yrs. |    |

### Surfaces to be Protected

| DESCRIPTION                               | TOTAL SURFACE AREA (sq. m) |
|-------------------------------------------|----------------------------|
| External                                  | 1,030                      |
| Internal                                  | NA                         |
| Total length (if single, long pipe/cable) | 430 m                      |

### Material(s) of Construction

| Metal (alloy)   | Alkali Sensitive |    | Hydrogen Sensitive |    | Velocity Sensitive |    | Area   |
|-----------------|------------------|----|--------------------|----|--------------------|----|--------|
|                 | yes              | no | yes                | no | yes                | no | sq. cm |
| 1. Carbon Steel |                  | X  |                    | X  |                    | X  | NA     |
| 2.              |                  |    |                    |    |                    |    |        |
| 3.              |                  |    |                    |    |                    |    |        |
| 4.              |                  |    |                    |    |                    |    |        |

### Method(s) of Fabrication

Fusion weld ☐ Mechanical ☒ Gaskets ☐



## Protective Coating(s)

| Generic Type | Thickness | CP Tolerance |    | Estimated % Coverage |
|--------------|-----------|--------------|----|----------------------|
|              |           | yes          | no |                      |
| 1. None      | mm        |              |    | %                    |
| 2.           | mm        |              |    | %                    |
| 3.           | mm        |              |    | %                    |

## Electrical Isolation and Grounding

|                                                   | YES | NO |
|---------------------------------------------------|-----|----|
| Structure isolated                                |     | X  |
| Structure can be isolated                         |     | X  |
| If isolated, requires electrical surge protection |     | NA |

## Environment

|                      |          |
|----------------------|----------|
| Description          | suburban |
| Resistivity (ohm cm) | 3,000    |
| Velocity (cm/sec)    | NA       |
| Temperature (°C)     | Amb      |

|                              | YES | NO |
|------------------------------|-----|----|
| Commercial Power Available   | X   |    |
| Other Structures Involved    |     | X  |
| Presence of Stray Currents   |     | X  |
| Fire and/or Explosion Hazard | X   |    |

### Possible Concerns with Cathodic Protection

|                                     | YES | NO |
|-------------------------------------|-----|----|
| Electrical attenuation on structure |     | X  |
| Electrical attenuation on anode     | X   |    |
| Hydrogen embrittlement on structure |     | X  |
| Hydride formation on structure      |     | X  |
| Effect of CP on process chemistry   |     | X  |
| Stray current interference          |     | X  |
| Safety considerations               |     | X  |

# Coated Steel/Rectifier/Deep Anodes

## Description

A 121 km long gas pipeline is to be constructed between a major gas transmission company main line and a municipal gas company gate station. The pipe will be 40.65 cm diameter, 7.95 mm wall welded steel. Isolation joints are to be installed at both ends of the pipeline. A high quality extruded polyethylene coating will be applied to the pipe. The route of the pipeline is cross-country. The design life of the pipeline is 40 years. There are many road crossings, most with electric power distribution lines. Power for impressed current cathodic protection will not be a problem. Figure 5.6 is a schematic drawing of the layout.

DEEP ANODES  
120.7 km, 40.6 cm COATED GAS TRANSMISSION PIPELINE

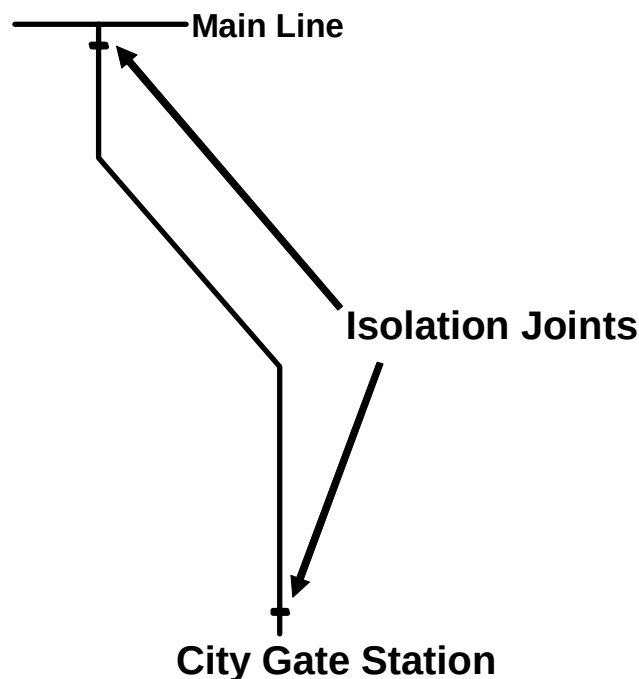


**Figure 5.6 Coated Gas Transmission Pipeline**

A pre-construction survey of the proposed route of the pipeline indicates a mean soil resistivity of 4,000 ohm-cm. Mean resistivity is the statistical

mean of all the soil resistivity measurements made along the proposed route of the pipeline at the average depth of the pipeline. It is the average resistivity that the pipe metal will encounter at small coating faults. Design a cathodic protection system that can be installed concurrently with the pipeline.

## Analysis

A Data Summary and Checklist is prepared (see end of design). It is expected that the absence of fittings and attachments to the pipe will result in a very good quality of electrical isolation. The length of the pipeline (120.7 km) requires that attenuation be considered in the cathodic protection design. The first step in the design analysis will be to estimate attenuation using attenuation formulas. All pipe-to-soil potential shifts will have a negative sign (the pipe will be shifted more negative with respect to remote earth).

1. Calculate the lineal resistance of 1 km of pipe (unit length):

$$r = \frac{\rho \cdot L}{\frac{\pi}{4} (OD^2 - ID^2)}$$

Resistivity of steel =  $2.06 \times 10^{-5}$  ohm-cm

$$r = \frac{2.06 \times 10^{-5} \text{ ohm-cm} \cdot 100,000 \text{ cm}}{\frac{\pi}{4} ((40.65 \text{ cm})^2 - (39.06 \text{ cm})^2)} = 0.0207 \text{ ohms/unit}$$

2. Assume good quality protective coating with a specific leakage conductance of  $1 \times 10^{-4}$  Siemen/m<sup>2</sup> in 1,000 ohm-cm soil. Conductivity in 4,000 ohm-cm soil per unit (km) of pipeline:

$$g = g'As / 4$$

$$g = 1 \times 10^{-4} \text{ S/m}^2 (3.14 \times 0.406 \text{ m} \times 1000 \text{ m}) / 4 = 0.032 \text{ S/unit}$$

3. Calculate the attenuation constant:

$$\alpha = (rg)^{0.5}$$

$$\alpha = (0.0207 \Omega \times 0.032 \text{ S})^{0.5} = 0.0257$$

4. Calculate the characteristic resistance:

$$R_G = (r/g)^{0.5}$$

$$R_G = (0.0207 \, \Omega / 0.032 \, S)^{0.5} = 0.804 \, \text{ohm}$$

5. Calculate attenuation from a single groundbed at the center of the pipeline.

Resistance looking each way from the center:

$$R_{s0} = R_G \coth(\alpha x) \quad \text{where } x = 60.5 \text{ units}$$

$$R_{s0} = 0.804 \, \Omega \coth(0.0257 \times 60.5) = 0.879 \, \text{ohm}$$

Current in each direction from the center to produce a 1.0 volt shift in potential at the source:

$$I_s = E_s / R_{s0} = 1.0V / 0.878 \, \Omega = 1.14 \, A$$

(Total source current = 2.28 A)

Voltage shift at each end of pipeline for a 1.0 volt shift at the source:

$$E = E_s \cosh(\alpha y) - R_G I_s \sinh(\alpha y)$$

$$\alpha y = 0.0257 \times 60.5 = 1.55$$

$$E = 1.0 \, V \cosh(1.55) - 0.804 \, \Omega \times 1.14 \, A \sinh(1.55) = 0.400V$$

A single power source at or near the center of the pipeline could protect the entire line under these assumed conditions without greatly over protecting the central area. If the quality of the coating is less than expected, the attenuation could be considerably higher. As the pipeline ages, the pipe-to-soil conductance will increase and a single cathodic protection power source would be taxed to reach the ends of the pipeline.

6. Examine a two source system with sources at 30 km and 90 km stations on the pipeline.

Calculate the resistance and current distribution from each source.

Looking toward the isolated ends 30 km from the sources:

$$R_{s0} = R_G \coth(\alpha x)$$



where:

$$\begin{aligned}\alpha &= 0.0257 \\ x &= 30 \text{ units} \\ R_G &= 0.804 \, \Omega\end{aligned}$$

$$R_{s0} = 0.804 \, \Omega \coth(0.771) = 1.242 \text{ ohm}$$

$$I_s = E_s / R_{s0}$$

$$I_s = 1.0 \text{ V} / 1.242 \, \Omega = 0.805 \text{ A}$$

For  $x = 90$  units

$$R_{s0} = 0.804 \, \Omega \coth(2.313) = 0.820 \text{ ohm}$$

$$I_s = 1.0 \text{ V} / 0.820 \, \Omega = 1.220 \text{ A}$$

Each source will shift the potential of its end of the line by the amount:

$$E = E_s \cosh(\alpha y) - R_G I_s \sinh(\alpha y)$$

where:

$$\begin{aligned}y &= 30 \text{ units} \\ \alpha &= 0.0257 \\ R_G &= 0.804 \, \Omega \\ I_s &= 0.805 \text{ A} \\ E_s &= 1.0 \text{ V}\end{aligned}$$

$$E = 1.0 \text{ V} \cosh(0.771) - (0.804 \, \Omega \times 0.805 \text{ A}) \sinh(0.771)$$

$$E = 0.762 \text{ volt}$$

Each source will shift the potential of the opposite end of the line by the amount:

$$E = E_s \cosh(\alpha y) - R_G I_s \sinh(\alpha y)$$

where:

$$\begin{aligned}y &= 90 \text{ units} \\ \alpha &= 0.0257 \\ R_G &= 0.804 \, \Omega \\ I_s &= 1.220 \text{ A} \\ E_s &= 1.0 \text{ V}\end{aligned}$$

$$E = 1.0 \text{ V} \cosh(2.313) - (0.804 \, \Omega \times 1.220 \text{ A}) \sinh(2.313)$$

$$E = 0.195 \text{ volts}$$

The total potential shift at the ends will be:

$$E = 0.762 \text{ V} + 0.195 \text{ V} = 0.957 \text{ volts}$$

At each power source the potential shift will be 1.0 volt from the local source plus the following shift from the other source:

$$E = E_s \cosh(\alpha y) - R_G I_s \sinh(y)$$

where:

$$\begin{aligned} y &= 60 \text{ units} \\ \alpha &= 0.0257 \\ R_G &= 0.804 \Omega \\ I_s &= 1.220 \text{ A} \\ E_s &= 1.0 \text{ V} \end{aligned}$$

$$E = 1.0 \text{ V} \cosh(1.542) - (0.804 \Omega \times 1.220 \text{ A}) \sinh(1.542)$$

$$E = 0.257 \text{ volts}$$

This yields a total shift at each source of:

$$E = 1.000 \text{ V} + 0.257 \text{ V} = 1.257 \text{ volts}$$

The potential shift at the center of the pipeline from each source will be:

$$E = E_s \cosh(\alpha y) - R_G I_s \sinh(\alpha y)$$

where:

$$\begin{aligned} y &= 30 \text{ units} \\ \alpha &= 0.0257 \\ R_G &= 0.804 \Omega \\ I_s &= 1.220 \text{ A} \\ E_s &= 1.0 \text{ V} \end{aligned}$$

$$E = 1.0 \text{ V} \cosh(0.771) - (0.804 \Omega \times 1.22 \text{ A}) \sinh(0.771)$$

$$E = 0.479 \text{ volts}$$

The total shift will be:

$$E = 0.479 \text{ V} + 0.479 \text{ V} = 0.958 \text{ volts}$$

The ratio of the highest potential shift of the pipeline versus the lowest potential shift in the case of one power supply is :

$$\text{Potential Shift Ratio (1 source)} = 1/0.4 = 2.5$$

In the case of two power supplies, the ratio is :

$$\text{Potential Shift Ratio (2 sources)} = 1.257/0.957 = 1.31$$

All potential shifts are negative with respect to remote earth.

The distribution is considerably better than for a single source.

## Deep Anode Installation

There is no room in the right-of-way for conventional groundbeds. Barnes Layer resistivity tests indicate a general underlying strata of 1,000 ohm-cm resistivity between 50 and 80 meters deep at both the 30 km and 90 km locations. This suggests that deep anodes would be good candidates for the cathodic protection system on this pipeline.

The design shown in Figure 5.7 is suitable as would be one of the available proprietary replaceable anode systems. During the design of deep anodes, it is necessary to consider all environmental regulations concerning surface and aquifer sealing. The dimension "x" would be 50 meters (the depth down to the 1,000 ohm-cm strata). The estimated current required (about 1.0 ampere from each groundbed) is low. To provide for lower than expected coating quality and future coating degradation, design each groundbed to have a capacity of 4.0 A. For this project the impressed current primary anode material is not critical. In this case, for greatest reliability, provide four (4) separate primary anodes in each groundbed with the anodes on 3 meter centers. Each anode should be conservatively rated to provide half of the total current for the entire groundbed (2 A) during the design life. A design life for a deep anode system of greater than about 20 years is not realistic. For these groundbeds each primary anode should be selected to provide 20 years of operation at an average current of 2 A. The current density should be within the rated value for the material chosen.

## DEEP ANODE INSTALLATION (Typical)

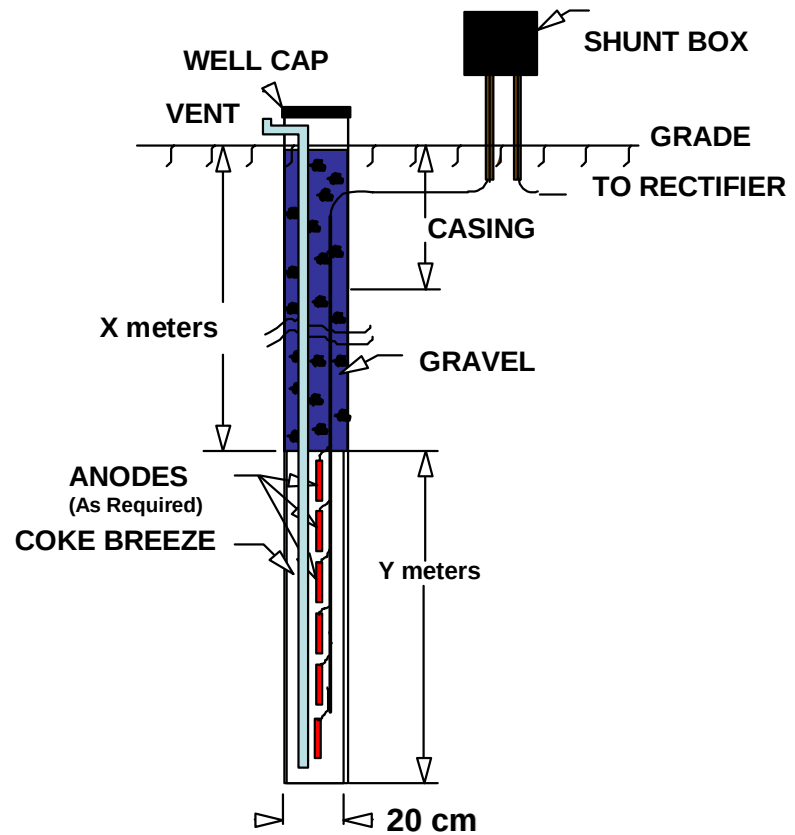


**Figure 5.7 Deep Anode**

The dimension "y" will be:

$$y = 4 \times 3 = 12 \text{ meters}$$

Using Dwight's formula for a single vertical rod (pipe) in earth:

$$R = \frac{0.005\rho}{\pi L} \left( \ln \left( \frac{8L}{d} \right) - 1 \right) \text{ with top of Anode at earth's surface.}$$

where:

$$\begin{aligned} \rho &= 1000 \text{ ohm-cm} \\ L &= 12 \text{ meters} \\ d &= 0.2\text{m} \end{aligned}$$

$$R = (0.133 \Omega)(5.174) = 0.69 \text{ ohms}$$

The Dwight equation above is based on an anode extending down from the surface of the ground. There is another equation for use when the entire electrode (groundbed) is infinitely deep. The equation is:

$$R = \frac{0.005\rho}{\pi L} \left( \ln \left( \frac{4L}{d} \right) - 1 \right) \text{ with top of Anode infinitely deep.}$$

Using this equation for our calculation yields:

$$R = (0.133 \, \Omega)(4.481) = 0.596 \, \text{ohm}$$

The probable resistance for a deep anode lies somewhere between these limits.

Assuming the results from the first (standard) equation, the rectifier voltage required is:

$$E = IR = 4 \, \text{A} \times 0.69 \, \Omega = 2.75 \, \text{volts}$$

Considering the back voltage of the pipe to anode of about 2.0 volts, select rectifiers to provide 0 to 4 A at 5 to 6 volts, continuously variable over the range.

On long pipelines such as this, provide the following additional corrosion control and monitoring features:

- Lightning protection for isolation joints and rectifiers.
- Test stations at all crossings with other pipelines or cable systems.
- Current measuring (IR drop) test stations at all or most road crossings.
- A regular program for monitoring the effectiveness of cathodic protection.

**CAUTION:** *Should the pipeline share a right-of-way with overhead high tension power transmission lines, a study needs to be performed to determine the safety requirements for both pipeline construction and operation. This study will indicate the extent to which safety precautions (e.g. grounding, personnel protection) are required during construction. In addition, it may be necessary to design permanent devices to provide for induced AC mitigation, fault protection and personnel safety.*

**DATA SUMMARY AND CHECKLIST**

**Title of Project**                      Deep Anode C.P.  
**General Description**            120.7 km 40.6 cm diameter coated gas  
                                                  transmission pipeline

| History                                 | Yes     | No |
|-----------------------------------------|---------|----|
| Proposed structure (not yet built)      | X       |    |
| Pre-construction survey performed       | X       |    |
| Existing structure                      |         | NA |
| Evaluation (condition) survey performed |         | NA |
| Structure Design Life (Life Extension)  | 40 yrs. |    |

**Surfaces to be Protected**

| DESCRIPTION                                  | TOTAL SURFACE AREA<br>(sq. m) |
|----------------------------------------------|-------------------------------|
| External                                     | 151,680                       |
| Internal                                     | NA                            |
| Total length (if single,<br>long pipe/cable) | 120,700 m                     |

## Material(s) of Construction

| Metal<br>(alloy)      | Alkali<br>Sensitive |    | Hydrogen<br>Sensitive |    | Velocity<br>Sensitive |    | Area   |
|-----------------------|---------------------|----|-----------------------|----|-----------------------|----|--------|
|                       | yes                 | no | yes                   | no | yes                   | no |        |
| Designation           |                     |    |                       |    |                       |    | sq. cm |
| 1.<br>Carbon<br>Steel |                     | X  |                       | X  |                       | X  | NA     |
| 2.                    |                     |    |                       |    |                       |    |        |
| 3.                    |                     |    |                       |    |                       |    |        |
| 4.                    |                     |    |                       |    |                       |    |        |

## Method(s) of Fabrication

Fusion weld ☒ Mechanical ☒ Gaskets ☐

## Protective Coating(s)

| Generic Type    | Thickness | CP Tolerance |    | Estimated %<br>Coverage |
|-----------------|-----------|--------------|----|-------------------------|
|                 |           | yes          | no |                         |
| 1. Polyethylene | 1.2 mm    | X            |    | 99 %                    |
| 2.              | mm        |              |    | %                       |
| 3.              | mm        |              |    | %                       |

## Electrical Isolation and Grounding

|                                                         | YES | NO |
|---------------------------------------------------------|-----|----|
| Structure isolated                                      | X   |    |
| Structure can be isolated                               | X   |    |
| If isolated, requires<br>electrical surge<br>protection | X   |    |



## Environment

| Description          | rural |
|----------------------|-------|
| Resistivity (ohm cm) | 4,000 |
| Velocity (cm/sec)    | NA    |
| Temperature (°C)     | Amb   |

|                              | YES | NO |
|------------------------------|-----|----|
| Commercial Power Available   | X   |    |
| Other Structures Involved    | X   |    |
| Presence of Stray Currents   |     | X  |
| Fire and/or Explosion Hazard | X   |    |

## Possible Concerns with Cathodic Protection

|                                     | YES | NO |
|-------------------------------------|-----|----|
| Electrical attenuation on structure | X   |    |
| Electrical attenuation on anode     |     | X  |
| Hydrogen embrittlement on structure |     | X  |
| Hydride formation on structure      |     | X  |
| Effect of CP on process chemistry   |     | X  |
| Stray current interference          | X   |    |
| Safety considerations               | X   |    |

# Coated Steel/Magnesium/Distributed Anodes

## Description

A mobile home park has experienced increasing leak occurrence on bare steel gas services. It has been determined that the cause of the leaks is corrosion. The entire gas system consists of 670 meters of 6 cm diameter mains and 81 – 2.7 cm diameter services ranging in length from 3 m to 9 m. The relatively thin wall services have all been replaced with epoxy coated steel pipe of the same size as the original services. The services are tied directly to the old bare steel mains but are isolated at the home. An isolation joint has been installed at the master meter for the park. The layout of the mobile home park is shown in Figure 5.8. Prepare a design for cathodic protection of the gas system in the mobile home park that is projected to extend the useful life of the piping by about 20 years.

### DISTRIBUTED MAGNESIUM ANODE SYSTEM SMALL BARE AND COATED GAS DISTRIBUTION PIPING

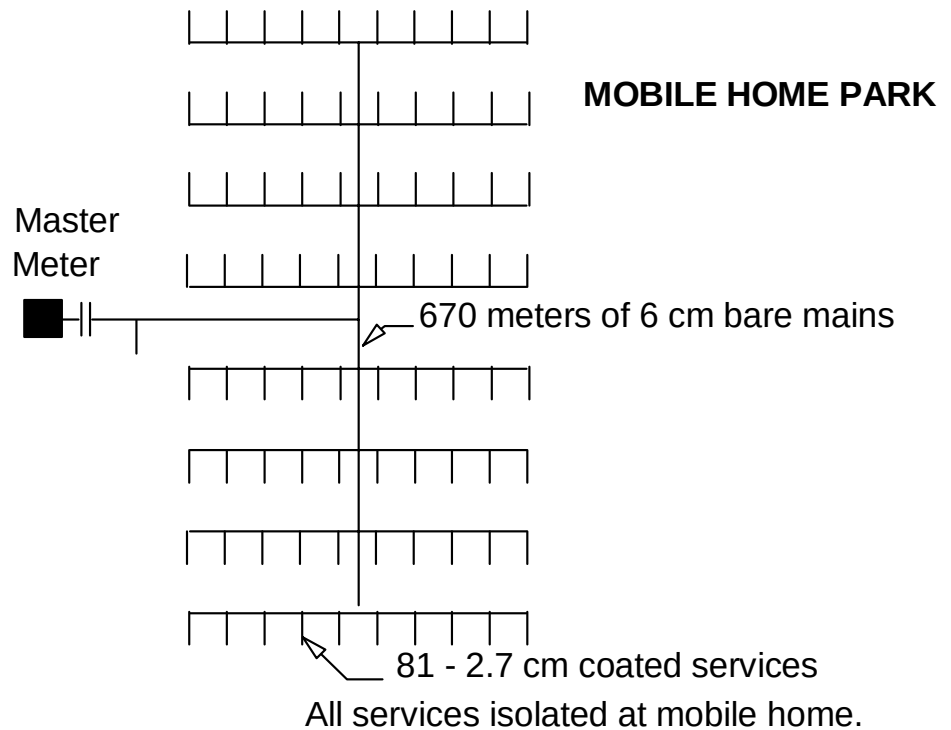


**Figure 5.8 Distributed Galvanic Anode System**

#### Work Plan

1. Obtain data on soil resistivity and chemistry
2. Excavate and examine pipe to determine type of corrosion.
3. Test effectiveness of isolation.
4. Conduct a pipe-to-soil survey of the gas system.
5. Perform a current requirement test.
6. Prepare details for a suitable design.

## Survey Results

1. Soil resistivity ranges from 1,000 to 3,400 ohm-cm. Generally, one area (which includes about 6 percent of the pipe) averages about 3,400 ohm-cm and the remaining sections of the park (94 percent of the pipe) have soils that average 1,400 ohm-cm resistivity. There are no detectable chlorides or sulfides in the chemistry of the soil. The pH is a slightly acidic 5.7.
2. Excavation of the bare gas main in an area of the 1,500 ohm-cm resistivity soil reveals general loss of metal with an irregular surface profile. The appearance is typical of general galvanic corrosion.
3. A contact locator survey detects one omitted service isolation coupling. The service is subsequently isolated and the gas system rechecked for other contacts or short circuits. None are found.
4. A general survey of pipe-to-soil potentials is made with data taken at all service insulators. The measurements range from –600 mV to –740 mV vs. a saturated copper/copper sulfate reference electrode.
5. As a test for current requirements estimate the contact area of steel with soil

$$A_s = \pi dL$$

where:

$$\begin{aligned} d &= \text{pipe diameter} = 0.06 \text{ m.} \\ L &= \text{length of main} = 670 \text{ m} \\ A_s &= 3.1416 \times 0.06 \text{ m} \times 670 \text{ m} = 126 \text{ m}^2. \end{aligned}$$

Assume that  $2.15 \mu\text{A}/\text{cm}^2$  will protect the isolated steel pipe against galvanic corrosion. The total current required would be:

$$I = iA_s$$

where:

$$A = 126 \text{ m}^2 \times 10,000 \text{ cm}^2 / \text{m}^2 = 1.26 \times 10^6 \text{ cm}^2$$

$$I = 2.15 \times 10^{-6} \text{ A}/\text{cm}^2 \times 1.26 \times 10^6 \text{ cm}^2 = 2.71 \text{ A}$$

The pipe records are only accurate to about 10% so estimate the required current at approximately 3.0 amperes.

Using an isolated steel drain culvert as a test anode and a 12 volt automobile battery (the only current source readily available), measure the pipe-to-soil potential shift for whatever current flows. The current is 5.1 A and the average pipe-to-soil potential shift at the mobile home end of several coated services is -505 mV or:

$$R \text{ (coupling factor)} = \Delta V / \Delta I = -505\text{mV}/5.1\text{A} = -99 \text{ mV/A}$$

The pipe-to-soil potential shift produced by the estimated current required of 3.0 A (based on  $2.15 \mu\text{a}/\text{cm}^2$ ) is:

$$\Delta V = R\Delta I = -99 \text{ mV / A} \times 3.0 \text{ A} = -297 \text{ mV}$$

As a check, the value is in good agreement with the -300 mV p/s potential shift to "remote earth" (6 meters from the bare main). Such a potential shift is often sufficient to produce electrochemical polarization that meets several of the recognized criteria for cathodic protection.

6. Prepare a Data Summary and Checklist for the project (See end of problem).

### ***Design Calculations for this Example***

The extensive bare pipe configuration requires a deep anode (about 100 to 150 meters deep), a remote conventional groundbed or a distributed anode system to achieve reasonable current distribution. A deep anode for this particular project is estimated to cost about \$25,000 (1999). A conventional groundbed is impractical because property limits are not great enough (100 to 200 meters) to provide adequate separation of the groundbed from the piping. The logical first choice for a cathodic protection design is a distributed anode system.

Relatively low soil resistivity (1,400 to 3,400 ohm-cm) should provide a suitable environment for galvanic anodes. High potential magnesium has a potential of about -1.75 volt measured against a saturated copper/copper sulfate reference half-cell. The average potential of the gas system was measured at -0.670 volt CSE. The net initial driving potential for activation of cathodic protection is:

$$E = -1.750 \text{ V} - (-0.670 \text{ V}) = -1.080 \text{ volts}$$

A 14.5 kg (32 lb.) high potential anode is approximately 0.5 m long by 13 cm diameter. Using Dwight's formula for resistance of a vertical rod in 1,400 ohm-cm soil:

$$R = \frac{0.005\rho}{\pi L} \left( \ln \left( \frac{8L}{d} \right) - 1 \right)$$

where:

$$\begin{aligned} \rho &= 1,400 \text{ ohm-cm} \\ L &= 0.5 \text{ meter} \\ d &= .13 \text{ meter} \end{aligned}$$

$$R = (4.456) \times (2.43) = 10.8 \text{ ohm/anode}$$

The maximum current output from a single anode is:

$$I = 1.08 \text{ V} / 10.8 \Omega = 0.100 \text{ A}$$

For anodes in the area of 3,400 ohm-cm soil:

$$R = 10.8 \, \Omega \times (3400/1400) = 26.2 \, \text{ohms}$$

$$I = 1.08 \, \text{V} / 26.2 \, \Omega = 0.041 \, \text{A}$$

Six percent of the pipe is in the 3,400 ohm-cm soil. The current needed is assumed to be 6.0% of the total estimated current for the park:

$$I_{(3400)} = 0.06 \times 3.0 \, \text{A} = 0.180 \, \text{A}$$

The remainder of the current (2.82 A) will be required in the 1,400 ohm-cm soil.

Assume the individual anodes in the distributed system will be sufficiently separated (about 6 meters) to not electrically interfere with each other. The number of anodes required in the 3,400 ohm soil area of the park will be:

$$N = I_T / I_a$$

where:

$$\begin{array}{ll} I_T & = \text{total current (0.180 A) in 3,400 ohm-cm soil} \\ I_a & = \text{single anode output (0.041 A)} \end{array}$$

$$N = 0.180 \, \text{A} / 0.041 \, \text{A} = 4.3 = 5 \, \text{anodes}$$

In the 1,400 ohm-cm soil:

$$N = 2.82 \, \text{A} / 0.100 \, \text{A} = 28.2 = 29 \, \text{anodes}$$

The anodes should be evenly spaced along the bare pipe within the respective zones of soil resistivity. The anodes should be offset from the pipe by about 1 meter and the top of the anode should be at about pipe depth. At an estimated installed cost of about \$280 per anode (1999), the entire protection system will cost \$9,520. This is less than half the cost of a deep anode in this case.

The estimated anode life can be calculated. Assume that the steel pipe will polarize to at least a potential of  $-0.850$  volt CSE. This will result in a net driving potential for the anodes of:

$$E = -1.75 \, \text{V} - (-0.850 \, \text{V}) = -0.90 \, \text{volt}$$

In the 1,400 ohm-cm area, the current per anode will eventually be:

$$I = 0.90 \text{ V} / 10.8 \Omega = 0.083 \text{ A}$$

At 50% efficiency, the ampere-hour capacity of magnesium is 1100 A-hr/kg. Divide 1100 by 8766 (the number of hours in a year) to obtain 0.125 A-yr/kg. The estimated years of life for an average anode in the 1,400 ohm-cm area is:

$$t = \frac{f_u C_a W}{I}$$

where:

- t = life of anode (years)
- $f_u$  = utilization factor (85%)
- $C_a$  = 0.125 A-yr/kg capacity @ 50% efficiency
- W = 14.5 kg (weight of an anode)
- I = 0.083 A (average current output over life of the anode)

$$t = 18.6 \text{ years}$$

This estimated service life is about 7% below the required design life. The next larger standard anode size has a weight of 21.8 kg (48 lb.). The estimated service life for the larger anodes is:

$$t = (0.85 \times (0.125 \text{ A-yr/kg}) \times 21.8 \text{ kg}) / 0.083 \text{ A} = 27.9 \text{ years}$$

In the 3,400 ohm-cm soil the 14.5 kg anodes will have a life of:

$$I = 0.90 \text{ V} / 26.2 \Omega = 0.034 \text{ A}$$

$$t = (0.85 \times (0.125 \text{ A-yr/kg}) \times 14.5 \text{ kg}) / 0.034 \text{ A} = 45.3 \text{ years}$$



**DATA SUMMARY AND CHECKLIST**

**Title of Project**      Bare/Isolated/Distributed Galvanic Anode

**General Description**    670 meters of 6 cm diameter gas distribution piping with 81 coated 2.7 cm diameter

| History                                 | Yes     | No |
|-----------------------------------------|---------|----|
| Proposed structure (not yet built)      |         | X  |
| Pre-construction survey performed       |         | X  |
| Existing structure                      | X       |    |
| Evaluation (condition) survey performed | X       |    |
| Structure Design Life (Life Extension)  | 20 yrs. |    |

**Surfaces to be Protected**

| DESCRIPTION                               | TOTAL SURFACE AREA (sq. m) |
|-------------------------------------------|----------------------------|
| External                                  | 126                        |
| Internal                                  | NA                         |
| Total length (if single, long pipe/cable) | 670 m                      |

**Material(s) of Construction**

| Metal (alloy)      | Alkali Sensitive |    | Hydrogen Sensitive |    | Velocity Sensitive |    | Area   |
|--------------------|------------------|----|--------------------|----|--------------------|----|--------|
| Designation        | yes              | no | yes                | no | yes                | no | sq. cm |
| 1.<br>Carbon Steel |                  | X  |                    | X  |                    | X  | NA     |
| 2.                 |                  |    |                    |    |                    |    |        |
| 3.                 |                  |    |                    |    |                    |    |        |
| 4.                 |                  |    |                    |    |                    |    |        |

**Method(s) of Fabrication**Fusion weld X      Mechanical X      Gaskets ☐**Protective Coating(s)**

| Generic Type | Thickness | CP Tolerance |    | Estimated % Coverage |
|--------------|-----------|--------------|----|----------------------|
|              |           | yes          | no |                      |
| 1. None      | mm        |              |    | %                    |
| 2.           | mm        |              |    | %                    |
| 3.           | mm        |              |    | %                    |

**Electrical Isolation and Grounding**

|                                                   | YES | NO |
|---------------------------------------------------|-----|----|
| Structure isolated                                | X   |    |
| Structure can be isolated                         | X   |    |
| If isolated, requires electrical surge protection |     | X  |

**Environment**

|                      |               |
|----------------------|---------------|
| Description          | suburban      |
| Resistivity (ohm cm) | 1,400 & 3,400 |
| Velocity (cm/sec)    | NA            |
| Temperature (°C)     | Amb           |

|                              | YES | NO |
|------------------------------|-----|----|
| Commercial Power Available   | X   |    |
| Other Structures Involved    |     | X  |
| Presence of Stray Currents   |     | X  |
| Fire and/or Explosion Hazard |     | X  |

### Possible Concerns with Cathodic Protection

|                                     | YES | NO |
|-------------------------------------|-----|----|
| Electrical attenuation on structure |     | X  |
| Electrical attenuation on anode     |     | X  |
| Hydrogen embrittlement on structure |     | X  |
| Hydride formation on structure      |     | X  |
| Effect of CP on process chemistry   |     | X  |
| Stray current interference          |     | X  |
| Safety considerations               |     | X  |

Additional Information: Service pipes range from 3 to 9 meters long. All have been replaced with coated steel and are isolated at the home end only. History in the area suggests  $2.15 \mu\text{A}/\text{cm}^2$  of bare steel is required to electrochemically polarize buried pipe in this soil to potentials meeting the requirements of the Natural Gas Pipeline Safety Act (40CFR, Part 192). Field tests indicate the above current density will produce a p/s potential shift of about  $-300 \text{ mV}$  with soil reference 6 m from the pipe.

# Ductile Iron/Magnesium/Distributed Anodes

## Description

Several blocks of city water distribution pipes are to be replaced with ductile iron pipe. The pipe will be 20 cm diameter 5.5 meter long and have bell and spigot rubber gasket joints. Soil in the area has an average resistivity of 1,000 ohm-cm and is generally wet. It is acceptable to electrically isolate water services from the main by inclusion of a short length of plastic pipe in the service line and to bond pipe joints for electrical continuity.

Design a cathodic protection system that will last 30 years using sacrificial galvanic anodes.

The student should prepare a Data Summary and Checklist for this problem. A blank form can be found at the end of this problem.

## Calculations

The approximate surface area of each pipe joint is:

$$A_s = \pi dL$$

where:

$$\begin{array}{ll} A_s & = \text{area (m}^2\text{)} \\ d & = \text{diameter (m)} \\ L & = \text{length (m)} \end{array}$$

$$A_s = 3.5 \text{ m}^2/\text{joint}$$

Estimate the current required to protect the total metal surface of a pipe length using  $2.15 \mu\text{A/cm}^2$ :

$$I = iA_s$$

where:

$I$  = current required (A)  
 $i_{cp}$  = current density required (A/cm<sup>2</sup>)  
 $A_s$  = surface area per joint (cm<sup>2</sup>)

$$I = 2.15 \times 10^{-6} \text{ A/cm}^2 \times 3.5 \times 10^4 \text{ cm}^2 = 0.075 \text{ A/joint}$$

The minimum life for the anode system is to be 30 years. At 50% efficiency magnesium anodes have a capacity of 1100 A-hr/kg (0.125 A-yr/kg). The weight of magnesium required to provide a 30 year life is given by the formula:

$$W = It/f_u C_a$$

where:

$W$  = weight of metal (kg)  
 $I$  = average current output over life (amp)  
 $t$  = life (yr)  
 $f_u$  = utilization factor (85%)  
 $C_a$  = ampere capacity of the metal (A-yr/kg)

The average current ( $I$ ) must be estimated from Dwight's formula for the resistance of a vertical electrode and the expected polarized potential of the pipe.

$$R = \frac{0.005\rho}{\pi L} \left( \ln \left( \frac{8L}{d} \right) - 1 \right)$$

where:

$\rho$  = 1,000 ohm-cm  
 $L$  = anode length (assume 0.5 m)  
 $d$  = anode diameter (assume .13 m)

$$R = (3.183 \Omega)(2.43) = 7.73 \text{ ohm/anode}$$

Assume an initial pipe-to-soil potential of  $-540$  mV CSE. Standard magnesium (H-1 alloy) has a potential of  $-1550$  mV CSE. The net driving potential is:

$$E = -1550 \text{ mV} - (-540) \text{ mV} = -1010 \text{ mV} (-1.01 \text{ V})$$

$$I = 1.01 \text{ V} / 7.73 \Omega = 0.131 \text{ A/anode}$$

The current density on a joint of pipe would be:

$$i = 0.131 \text{ A} / 3.5 \text{ m}^2 = 0.037 \text{ A/m}^2 = 3.7 \mu\text{A/cm}^2$$

The pipe would be expected to polarize strongly at this current density. Assume an operating polarized potential of the pipe equal to  $-1000$  millivolt CSE. The operating driving potential of a standard magnesium anode will then be:

$$E = -1550 \text{ mV} - (-1000 \text{ mV}) = -550 \text{ mV} (0.55 \text{ volts})$$

The steady state current per anode will be:

$$I = 0.55 \text{ V} / 7.73 \Omega = 0.071 \text{ A}$$

Substituting this current value in the weight formula:

$$W = (0.071 \text{ A} \times 30 \text{ yr}) / (0.125 \text{ A-yr/kg} \times 0.85) = 20 \text{ kg}$$

The nearest commercial anode to this weight is  $21.5$  kg. These anodes have the same diameter as that assumed in the calculation of resistance ( $13$  cm) but are  $0.8$  m long. The increased length of anode will decrease the anode resistance to  $7.1$  ohms. This will not significantly affect the results.

The design for protection of the ductile iron pipe should include one  $21.5$  kg standard magnesium anode attached to each joint of pipe. Test stations to permit monitoring current output and potential should be included at several points along the main replacement.

## DATA SUMMARY AND CHECKLIST

### Title of Project

### General Description

| History                                 | Yes | No |
|-----------------------------------------|-----|----|
| Proposed structure (not yet built)      |     |    |
| Pre-construction survey performed       |     |    |
| Existing structure                      |     |    |
| Evaluation (condition) survey performed |     |    |
| Structure Design Life (Life Extension)  |     |    |

### Surfaces to be Protected

| DESCRIPTION                                  | TOTAL SURFACE AREA<br>(sq. m) |
|----------------------------------------------|-------------------------------|
| External                                     |                               |
| Internal                                     |                               |
| Total length (if single,<br>long pipe/cable) | m                             |

### Material(s) of Construction

| Metal (alloy)   | Alkali Sensitive |    | Hydrogen Sensitive |    | Velocity Sensitive |    | Area   |
|-----------------|------------------|----|--------------------|----|--------------------|----|--------|
| Designation     | yes              | no | yes                | no | yes                | no | sq. cm |
| 1. Carbon Steel |                  |    |                    |    |                    |    |        |
| 2.              |                  |    |                    |    |                    |    |        |
| 3.              |                  |    |                    |    |                    |    |        |
| 4.              |                  |    |                    |    |                    |    |        |

**Method(s) of Fabrication**Fusion weld ☐ Mechanical ☐ Gaskets ☐**Protective Coating(s)**

| Generic Type | Thickness | CP Tolerance |    | Estimated % Coverage |
|--------------|-----------|--------------|----|----------------------|
|              |           | yes          | no |                      |
| 1.           | mm        |              |    | %                    |
| 2.           | mm        |              |    | %                    |
| 3.           | mm        |              |    | %                    |

**Electrical Isolation and Grounding**

|                                                   | YES | NO |
|---------------------------------------------------|-----|----|
| Structure isolated                                |     |    |
| Structure can be isolated                         |     |    |
| If isolated, requires electrical surge protection |     |    |

**Environment**

| Description          |  |
|----------------------|--|
| Resistivity (ohm cm) |  |
| Velocity (cm/sec)    |  |
| Temperature (°C)     |  |

|                              | YES | NO |
|------------------------------|-----|----|
| Commercial Power Available   |     |    |
| Other Structures Involved    |     |    |
| Presence of Stray Currents   |     |    |
| Fire and/or Explosion Hazard |     |    |



**Possible Concerns with Cathodic Protection**

|                                     | YES | NO |
|-------------------------------------|-----|----|
| Electrical attenuation on structure |     |    |
| Electrical attenuation on anode     |     |    |
| Hydrogen embrittlement on structure |     |    |
| Hydride formation on structure      |     |    |
| Effect of CP on process chemistry   |     |    |
| Stray current interference          |     |    |
| Safety considerations               |     |    |

# Coated Steel/Rectifier/Conventional Groundbeds

## Description

A housing subdivision is under construction. Included with other utilities is a welded steel gas distribution system. The gas piping is 15.2 cm diameter pipe coated with a fusion bonded epoxy. The total length of gas mains is 3,700 meters. Services are plastic. The interconnections to existing gas supply lines have isolation joints. There is a small stream and park area between two sections of the subdivision. The general layout is shown in Figure 5.9.

## Distribution Piping

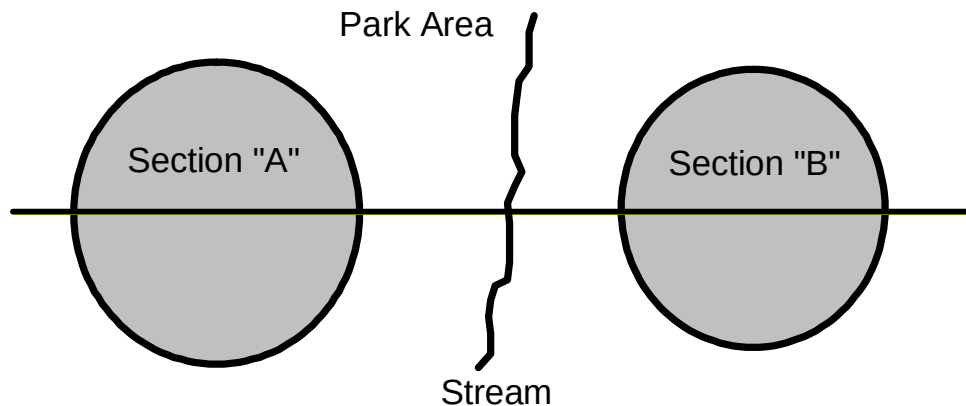


**Figure 5.9 Subdivision**

Following the general practice of the gas utility, test stations are installed at all main isolation joints and at several distributed locations throughout the subdivision.

Design a suitable cathodic protection system for the gas distribution piping.

## Analysis

The first step is to obtain data on the environment and the electrical parameters of the gas system. In this case the data indicate the piping is isolated from accidental grounds and attachments. The soil is natural and free from waste and rubble. It is variable in resistivity with a mean value of 5,000 ohm-cm. A Data Summary and Checklist is prepared.

The configuration of the subdivision lends itself to cathodic protection. The presence of an open area with a natural stream in the heart of the piping network is a natural for a groundbed location. The stream provides an easy solution for in place testing of cathodic protection before actual construction. A roll of aluminum foil is laid along the stream perpendicular to the gas main. A known test current is applied between the main and the foil and electrical couplings (p/s voltage shift per ampere of test current) are obtained at various locations throughout the subdivision.

The average coupling value is 0.180 volt/ampere. This is a low value for this quantity of coated pipe. A search for one or more contacts or grounds to other structures is made. No contacts or single source of poor coating is found. E Log i testing is a sound method of determining current requirements when there appears to be many coating faults (low pipe-to-soil resistance) and low oxygen concentration at the pipe surface. An estimate is made of the expected range of current requirement using a pipe-to-soil potential shift of -0.300 volts.

$$I = \Delta V / R$$

where:

|            |                                  |
|------------|----------------------------------|
| I          | expected current requirement (A) |
| $\Delta V$ | 0.300 volt p/s shift             |
| R          | volt/ampere coupling value (ohm) |

$$I = 0.300 \text{ V} / 0.18 \text{ V/A} = 1.67 \text{ A}$$

To conduct an acceptable E Log i test requires a source of current that can deliver about four times the current actually needed for protection. In this case the current capacity of the test power supply must be about 7.0 amperes. If the resistance of our foil groundbed is 3 ohms, the power source must have a rated voltage of:

$$E = 7.0 \text{ A} \times 3 \Omega = 21 \text{ volts}$$

To obtain the best E Log i data requires a continuously variable output from the power source.

The results of the E Log i test indicate "Tafel" behavior at current above 1.2 A. To allow for future deterioration of the electrical properties of the piping system design the permanent groundbed to deliver about 2.5 A. Since the area where the anode will be placed is park land, anode voltage must be kept at a safe level. We choose 12 volts as the upper limit.

On this basis the final groundbed resistance to earth must be:

$$R = E/I$$

where:

- R = the desired resistance (ohm)
- E = maximum allowed potential less anode/pipe galvanic back voltage (10 volt)
- I = desired maximum current (2.5 A)

$$R = 10 \text{ V} / 2.5 \text{ A} = 4 \text{ ohms}$$

Prepackaged mixed metal oxide anodes are light and easy to install with light equipment. Typical anodes of this type have the dimension 7.62 cm diameter by 1.5 meter long. Using Dwight's formula for a vertical rod:

$$R = \frac{0.005\rho}{\pi L} \left( \ln \left( \frac{8L}{d} \right) - 1 \right)$$

where:

- $\rho$  = 5,000 ohm-cm
- L = anode length (1.5 m)
- d = anode diameter (.076 m)

$$R = (5.3 \Omega)(4.059) = 21.5 \text{ ohm/anode}$$

To achieve a 4 ohm groundbed (with anodes widely spaced) would require:

$$N = R_a / R_T$$

where:

- N = number of anodes in parallel
- $R_a$  = resistance of a single anode (21.5 ohm)
- $R_T$  = total groundbed resistance (4.0 ohm)

$$N = 5.4 = 6 \text{ anodes}$$

For an anode separation of 3 meters use the Sunde equation:

$$R = \frac{0.005\rho}{\pi NL} \left( \ln \left( \frac{8L}{d} \right) - 1 + \frac{2L}{s} \ln(0.656N) \right)$$

where:

- $R_N$  = groundbed resistance (ohm)
- $\rho$  = 5,000 ohm-cm average soil resistivity
- N = number of anodes in parallel
- L = length of an anode (1.5 m)
- d = anode diameter (0.0762 m)
- s = spacing of anodes in groundbed (3 m)

$$R_N = (0.884 \Omega) [\ln(157) - 1 + 1 \times \ln(3.936)]$$

$$R_N = (0.884 \Omega) (4.06 + 1.370) = 4.8 \text{ ohms}$$

This resistance is 20% higher than desired. Therefore, the number of anodes will be increased from 6 to 7 to achieve the desired results.

## DATA SUMMARY AND CHECKLIST

**Title of Project** Coated Steel/Rectifier/Conventional Groundbed

**General Description** 3,700 meters of 15.2 cm diameter coated and isolated gas distribution mains

| History                                 | Yes     | No |
|-----------------------------------------|---------|----|
| Proposed structure (not yet built)      |         | X  |
| Pre-construction survey performed       | X       |    |
| Existing structure                      |         | X  |
| Evaluation (condition) survey performed | NA      |    |
| Structure Design Life (Life Extension)  | 30 yrs. |    |

### Surfaces to be Protected

| DESCRIPTION                               | TOTAL SURFACE AREA (sq. m) |
|-------------------------------------------|----------------------------|
| External                                  | 1,767                      |
| Internal                                  | NA                         |
| Total length (if single, long pipe/cable) | 3,700 m                    |

### Material(s) of Construction

| Metal (alloy)   | Alkali Sensitive |    | Hydrogen Sensitive |    | Velocity Sensitive |    | Area   |
|-----------------|------------------|----|--------------------|----|--------------------|----|--------|
|                 | yes              | no | yes                | no | yes                | no |        |
| Designation     |                  |    |                    |    |                    |    | sq. cm |
| 1. Carbon Steel |                  | X  |                    | X  |                    | X  | NA     |
| 2.              |                  |    |                    |    |                    |    |        |
| 3.              |                  |    |                    |    |                    |    |        |
| 4.              |                  |    |                    |    |                    |    |        |

**Method(s) of Fabrication**Fusion weld ☒ Mechanical ☐ Gaskets ☐**Protective Coating(s)**

| Generic Type           | Thickness | CP Tolerance |    | Estimated % Coverage |
|------------------------|-----------|--------------|----|----------------------|
|                        |           | yes          | no |                      |
| 1. Fusion bonded epoxy | 1.0 mm    | X            |    | ?%                   |
| 2.                     | mm        |              |    | %                    |
| 3.                     | mm        |              |    | %                    |

**Electrical Isolation and Grounding**

|                                                   | YES | NO |
|---------------------------------------------------|-----|----|
| Structure isolated                                | X   |    |
| Structure can be isolated                         | X   |    |
| If isolated, requires electrical surge protection |     | X  |

**Environment**

| Description          | suburban |
|----------------------|----------|
| Resistivity (ohm cm) | 5,000    |
| Velocity (cm/sec)    | NA       |
| Temperature (°C)     | Amb      |

|                              | YES | NO |
|------------------------------|-----|----|
| Commercial Power Available   | X   |    |
| Other Structures Involved    | X   |    |
| Presence of Stray Currents   |     | X  |
| Fire and/or Explosion Hazard |     | X  |

### Possible Concerns with Cathodic Protection

|                                     | YES | NO |
|-------------------------------------|-----|----|
| Electrical attenuation on structure |     | X  |
| Electrical attenuation on anode     |     | X  |
| Hydrogen embrittlement on structure |     | X  |
| Hydride formation on structure      |     | X  |
| Effect of CP on process chemistry   |     | X  |
| Stray current interference          | X   |    |
| Safety considerations               | X   |    |



## Examples Summary

1. An example of a cathodic protection design that includes the following features:
  - coated, isolated steel with many coating faults
  - mechanical couplings
  - significant current attenuation
  - dynamic stray currents
  - multiple conventional groundbeds
2. An example of "hot spot" protection for a steel transmission water main. The design includes the following features:
  - no protective coating
  - no isolated structure
  - distributed impressed current anode system
  - calculation of attenuation in the anode bus
3. An example of a long, well coated, transmission pipeline with deep anodes. The design features:
  - high quality coating
  - long line attenuation
  - deep anode design
  - caution note concerning induced high voltage
4. An example of bare steel, electrically isolated, gas distribution pipe with distributed galvanic anodes. The design features:
  - estimating current requirements on bare metal exposed to soil followed by field tests
  - determination of number of sacrificial anodes required in different soil resistivities
  - estimating anode life
5. An example of protection for an electrically discontinuous ductile iron water distribution main in low resistivity, wet soil using galvanic anodes.
6. An example of coated, isolated gas distribution mains and services with a conventional impressed current groundbed. The example illustrates use of in place testing to aid in design of cathodic protection of new construction.

## Underground Storage Tanks Design Examples

### ***New Coated UST/Magnesium/Distributed***

#### ***Description***

Three new 123,000-liter (35,000-gal.) storage tanks are to be installed in a small underground tank farm as shown in Figure 6.1. The dimensions of the tanks are 3.66 meters (12 ft) in diameter by 12.2 meters (40 ft) in length. There will be approximately 90 meters (295 ft) of 7.3 cm (2.875 in) OD piping connected directly to the tanks. This piping will be isolated at interconnections to other structures. Design a sacrificial anode cathodic protection system that will provide a minimum 20 years service life for the storage facility. Assume the protective coating on the tanks will be 90% effective (10% bare) and that the coating on the connecting steel pipe will be 95% effective (5% bare). Soil resistivity in the area is 4,000 ohm-cm.

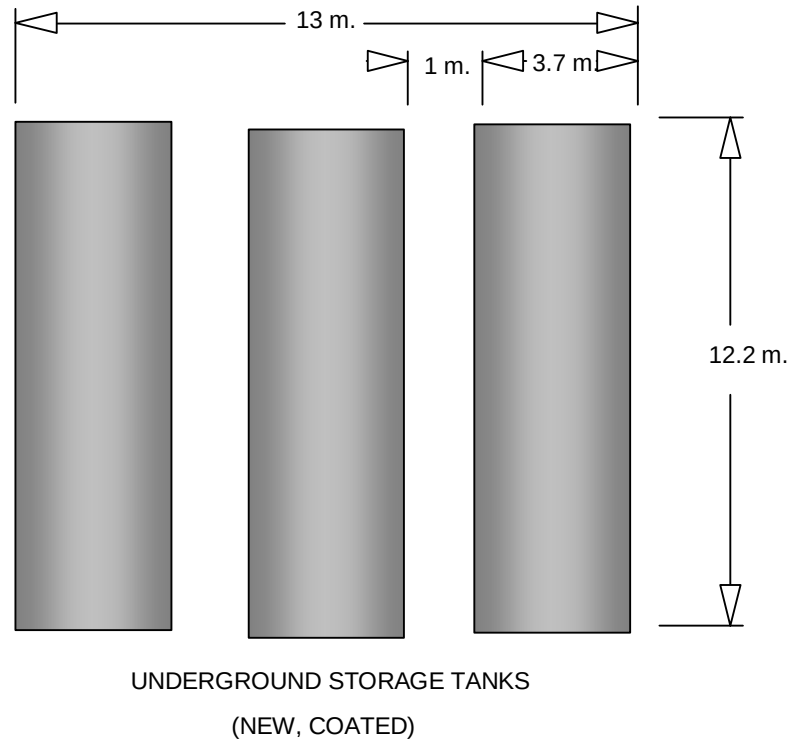


**Figure 6.1 Tank Arrangement**

### Procedure

The first step in the design of the cathodic protection is to calculate the surface area of each tank and the connecting piping.

The surface area of each tank will be:

$$A_s = 2\pi r^2 + \pi dL$$

where:

- $A_s$  = area (sq.meters)
- $r$  = tank radius (1.83m)
- $d$  = tank diameter (3.66m)
- $L$  = tank length (12.2m)

$$A_s = 161.3 \text{ m}^2 (1,735 \text{ sq. ft})$$

For three tanks the total surface area will be 483.9 square meters.

The surface of the connecting piping is:

$$A_s = \pi dL$$



where:

d = pipe diameter (0.073m)

L = pipe length (90m)

$$A_s = 20.6\text{m}^2 \text{ (222 sq.ft)}$$

The exposed metal on the tanks and pipes can be calculated as follows:

Tanks:

$$A_s = 0.10 \times 483.9 \text{ m}^2 = 48.4\text{m}^2 \text{ (521 sq.ft)}$$

Piping:

$$A_s = 0.05 \times 20.6 \text{ m}^2 = 1\text{m}^2 \text{ (10.8 sq. ft)}$$

The total expected bare surface yielded by this calculation is therefore 49.4 square meters (532 sq. ft) or 494,000 square centimeters.

Assume that the current requirements in the soils present at the tank farm will be 2.15 micro-amps per square centimeter (2 mA/ft<sup>2</sup>). The total current required for the 494,000 square centimeters of exposed steel is:

$$I = 2.15 \times 10^{-6} \text{ A/cm}^2 \times 4.94 \times 10^5 \text{ cm}^2 = 1.06 \text{ A.}$$

Next calculate the amount of magnesium required to provide 20 years of continuous output at 1.06A.

Magnesium has a capacity of 0.125 A-yr/kg at 50% efficiency

$$W = (t \ I)/C_a$$

where:

W = weight of magnesium required (kg)

T = time (20 yrs)

I = current (1.06A)

C<sub>a</sub> = capacity (0.125 A-yr/kg)

$$W = (20 \text{ yr} \times 1.06 \text{ A}) / (0.125 \text{ A-yr/kg}) = 169.6\text{kg} \text{ (373 lbs.)}$$

**Note:** The capacity (c) includes the electrochemical "self corrosion" efficiency factor. When an anode is consumed, it is never possible to utilize all of the anode material theoretically available. The physical size and/or the mechanical integrity will decrease to the point where the anode

fails to function. Commonly, an 85% utilization factor is also applied. This means that once 85% of the anode has been consumed, it can no longer be relied upon to function effectively as an anode. Therefore, its adjusted weight requirement is:

$$W = 169.6 \text{ Kg}/0.85 = 199.5 = 200 \text{ Kg}$$

Consider 14.5 kilogram (32 lb.) magnesium anodes. Determine the number of these anodes that would be required to supply the necessary 200 kilograms.

$$N = 200 \text{ kg}/14.5 \text{ kg} = 13.8$$

Fourteen anodes will be required.

Next calculate the approximate resistance of a single anode in 4,000 ohm-centimeter soil. Neglect proximity effects and the resistance of the tanks to earth. The following calculations will give an estimate of the actual resistance<sup>1</sup>.

Using Dwight's equation:

$$R = \frac{0.005\rho}{\pi L} \left( \ln \left( \frac{8L}{d} \right) - 1 \right)$$

where:

|        |                              |
|--------|------------------------------|
| R      | = anode resistance (ohms)    |
| $\rho$ | = resistivity (4,000 ohm-cm) |
| L      | = anode length (0.5m)        |
| d      | = anode diameter (.13m)      |

$$R = (12.7 \Omega)(2.43) = 30.9 \text{ ohms}$$

Ignoring the dimensions and resistivity of the special backfill and the tank to remote earth resistance, the approximate resistance of a single anode would be 31 ohms. If we assume high potential magnesium, which operates at a potential of -1.75 volts vs. copper/copper sulfate and the tank, polarized at -850 mV (-0.85 volt), the net driving potential would be

<sup>1</sup> The actual resistance of the circuit consists of the series resistances of the tanks to soil, the wire between the tanks and the anodes and the anode to soil resistance. There are also mutual charge (proximity) effects among the various components which influence the effective resistances. The formulas used are based on resistance to remote earth. Since the tanks and anodes are not at remote earth with respect to each other, the calculations are an approximation only.

–0.9 volt. The current output from a single anode (neglecting proximity effects) is given by the equation:

$$I = 0.9 \text{ V} / 31 \Omega = 0.03 \text{ A./anode.}$$

The 0.03 amperes per anode multiplied by the minimum number of anodes required to provide the weight necessary (14) yields a total current:

$$I = 14 \times 0.03 \text{ A} = 0.42 \text{ A.}$$

This current amounts to less than one-half that required for protection of the tanks at the proposed current density of 2.15 microamperes per square centimeter.

#### Alternative

Consider 9 kilogram anodes. These anodes have a length equal 1.5 meters and a diameter of 5 centimeters. Again using Dwight's equation with the new values for L and d:

$$R = (4.24 \Omega)(4.48) = 19 \text{ ohms/anode.}$$

The current output per anode is:

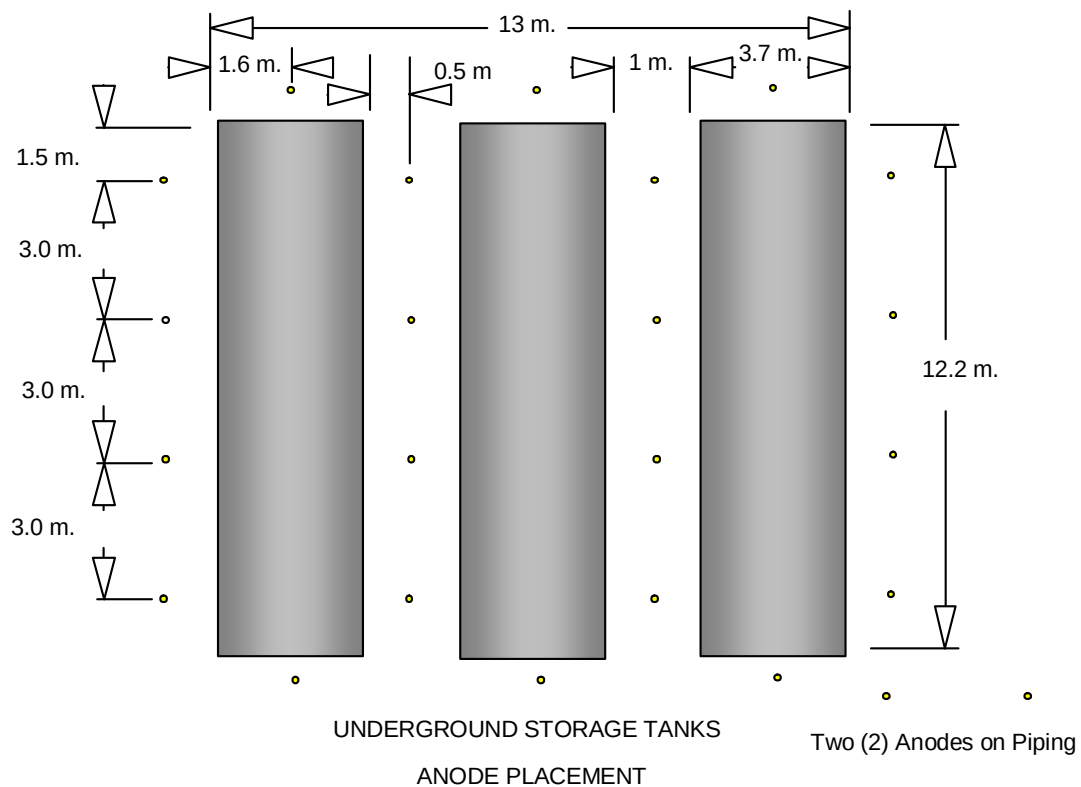
$$I = 0.9 \text{ V} / 19 \Omega = 0.047 \text{ A./anode.}$$

The number of anodes necessary to produce the 1.06 amperes would be:

$$N = 1.06 \text{ A} / 0.047 \text{ A} = 22.6.$$

To the nearest whole number, 23 anodes. the total weight of magnesium contained in 23 – 9kg. anodes is 207 kilograms. This is more than the minimum weight of 200 kilograms required to yield a 20 year life. Therefore, the anodes should last more than the required 20 years.

For symmetry, use 24 anodes instead of 23. These anodes can be arranged as shown in Figure 6.2, 22 anodes around the tanks and 2 on the connecting piping.



### Figure 6.2 Anode Configuration

It is good practice to install permanent reference electrodes of some type at a point below the tank bottom, as well as one or two near the surface. These can be to check performance of the cathodic protection system, with time, and may also be used to accurately determine the current required for cathodic protection once the tanks are installed. It is also good practice to connect the anode groups together through a current measuring shunt and to provide for insertion of a control resistance which can limit the flow of current should excessive current output unnecessary for protection be produced in the actual installation.

## ***Existing UST/Rectifier/Distributed***

### ***Description***

Consider existing tanks of the same dimension and configuration as that in the preceding problem. Further consider that these tanks do not have an overall effective protective coating, but are electrically isolated from other structures.

Design a rectifier powered distributed anode system that will provide cathodic protection to these underground storage tanks.

### ***Procedures***

The first step is to check the electrical isolation of the existing tanks. This can be done by measuring the tank resistance to remote earth or to a well-grounded structure. AC contact detectors may also prove helpful.

Assume that 2 microamperes per square centimeter of tank surface will be required to cathodically protect the tanks. Using the total surface area of the tanks calculated in the preceding problem, the total current required will be given by the following equation:

$$I_T = A_s i$$

where:

|       |                                                                                                             |
|-------|-------------------------------------------------------------------------------------------------------------|
| $I_T$ | = total current (A.)                                                                                        |
| $A_s$ | = total tank surface area ( $4.84 \times 10^6 \text{ cm}^2$ ) ( $5,210 \text{ ft}^2$ )                      |
| $i$   | = current density required for protection ( $2.0 \times 10^{-6} \text{ A/cm}^2$ ) ( $1.9 \text{ mA/ft}^2$ ) |

$$I_T = 9.7 \text{ A}$$

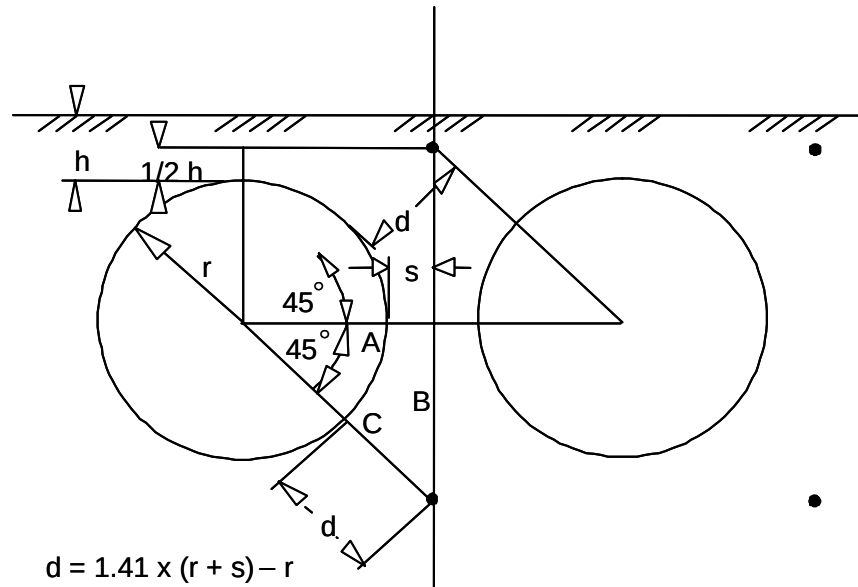
The current required is therefore 9.7 amperes.



The next step is to confirm that there are no other underground structures in the immediate vicinity of the tanks that might be adversely affected by the installation of distributed anodes around the tanks. We assume no such structures are detected.

For this problem we select mixed metal oxide rod-type anodes, 0.64 cm (0.25 in) in diameter by 122 cm (4 ft) long. Assembled in a 7.6 cm (3 in) diameter by 152 cm (5 ft) long metal canister filled with coke breeze, these anodes are in a form suited for insertion into small-cored holes in the vicinity of underground storage tanks where spacing is limited.

The next step is to determine the configuration that will provide the best distribution of current to all of the surfaces of the buried tanks. Figure 6.3 shows the geometry involved for two typical tanks in this group of three. In this case, the separation between tanks and the cover over the tanks is approximately equal. In this configuration, the geometry lends itself to installation of surface anodes (anodes approximately half the depth between the top of the tank and the grade level) running horizontally parallel to the long dimension of the tanks and midway between each of the tank rows. A similar anode arrangement is used for the outside tanks in the group. To cover the lower quadrants of the tanks, vertical anodes must be installed with the centers of the anodes located sufficiently below the tanks to project a good distribution of current up to the bottom surfaces. The equation indicating the distance between the lower quadrant surface of the tank at an angle  $45^\circ$  below the spring line and anode midpoint is given in Figure 6.3.



• Best Locations for Anode Centers

**Figure 6.3 Anode Geometry**

The calculations are as follows:

$$\begin{aligned}\cos 45^\circ &= (r + s)/(r + d) \\ d &= (r + s)/\cos 45^\circ - r \\ d &= \sqrt{2} (r + s) - r \\ d &= 1.41 (r + s) - r\end{aligned}$$

where:

$$\begin{aligned}d &= \text{distance between tank surface } 45^\circ \text{ below spring line (m)} \\ r &= \text{radius of the tank (1.83m)} \\ s &= 0.5 \times \text{space between tanks (0.5m)} \\ d &= 1.46\text{m}\end{aligned}$$

Experience indicates that the current from each anode will adequately cover the surface of a tank subtending an angle of about  $120^\circ$  from the center of the anode. The length of tank surface covered is calculated by the equation:

$$L = 2 d \tan 60^\circ$$

where:



L = length of tank wall covered (m)  
d = distance of center of anode from tank surface (1.46m)

$$L = 2 \times 1.46 \text{ m} \times 1.73 = 5.05 \text{ m}$$

The length covered (L) is also the distance between anodes. The logic of this relationship rests in the geometry. The distance from the anode to the point  $1/2$  L along the tank surface is twice the distance between the tank and the anode at the point where the anode is located. It will be shown in a later problem that the voltage rise in the earth produced by current flowing from a long thin anode is approximately inversely proportional to the distance from the anode. If two anodes are L meters apart, each anode will create a voltage rise at the mid point between the anodes equal to about  $1/2$  the voltage rise directly opposite each anode. The additive effect on voltage rise in the earth at the point between anodes tends to even out the current distributed to the tank surface. The true current distribution is complex, however, practical results make this relationship very useful in the design of cathodic protection systems.

Since the tanks are 12.2 meters long, the number of anodes required to distribute current to one of the lower quadrants is:

$$N = 12.2 \text{ m} / 5.05 \text{ m} = 2.42 = 3 \text{ anodes}$$

An additional anode is required to distribute current to each end of each of the tanks.

Current distribution to the top quadrants of the tanks can best be achieved by installing horizontal anodes parallel to the tanks. Four anodes are chosen here to provide as uniform current distribution as possible to the top of the tanks. Experience shows that shallow cover inhibits current from reaching the top centerline of the tanks, especially in the absence of a quality protective coating.

For the best geometry established as shown in Figure 6.4, the anodes are then installed. Great care must be taken to avoid striking the tanks during drilling and to avoid electrical contact of the anodes with the tanks or piping. Backfilling the canister with coke breeze will assure good contact with the soil. Header cables are brought together in groups through a distribution box, preferably with individual shunts to measure current flow to each of the anodes. Ground connections from each of the three tanks are also brought to a common junction box to be connected to the negative terminal of the future rectifier.

## UNDERGROUND STORAGE TANKS ANODE PLACEMENT

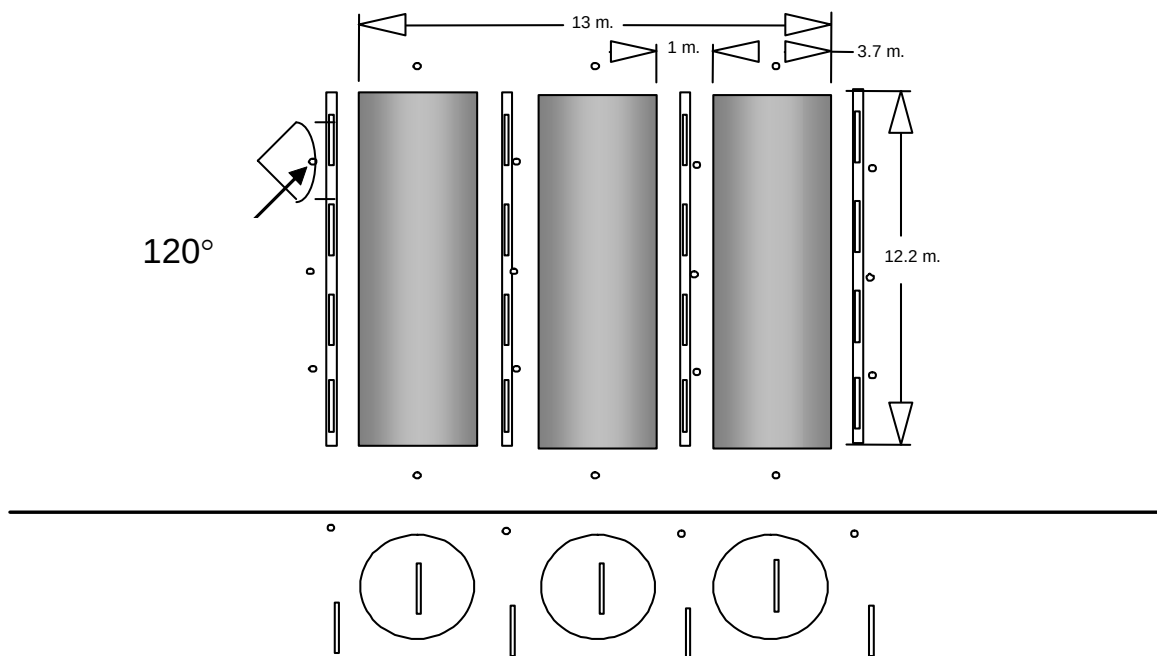


**Figure 6.4 Final Anode Configuration**

With installed tanks of this type, it is preferred to run current requirement tests to confirm the actual magnitude of current necessary to achieve cathodic protection. Since it is estimated that approximately 10 amperes of current will be required, a power supply at least capable of producing two to three times this magnitude of current, should be employed. Depending on the actual resistance of the anodes, this may require a sizeable portable generator or welding machine. Test rectifiers are frequently employed in conducting polarization tests in this kind of installation.

As with the previous example, it is desirable to install one or more reference electrodes at a depth at least capable of observing the underside of the tank bottoms. Such a reference electrode should be located at an intermediate point between two of the deep anodes installed between each of the parallel tanks. Once current requirement tests have been determined (using E-Log-I or net polarization criteria) a suitable rectifier can be purchased and installed.

With mixed metal oxide anodes of the size chosen the maximum current per anode is 1.8 amperes/anode. Since there are 34 anodes in this installation, each capable of producing 1.8 amperes, the anodes should readily provide a minimum 20-year life before replacement is required.

# Aboveground Storage Tank Bottom Design Examples

## ***New Construction/Rectifier/Under Tank***

### ***Description***

A new fuel tank, 36.6 meters (120 ft) in diameter, is to be constructed. The tank will include a nonmetallic, dielectric membrane as secondary containment. It will be installed approximately 1 meter beneath the tank. A ring wall will be installed around the tank perimeter, and the fill within the ring wall will be washed sand. Wet washed sand typically has a resistivity of 10,000 ohm-cm or more. It is anticipated that rain run-off will eventually contaminate the sand within the containment area, and may result in corrosion of the underside of the tank bottom.

Design a cathodic protection system that will provide the necessary corrosion control for the underside of the tank bottom. The anode system should have a design life of 40 years.

### ***Procedure***

The secondary containment acts as a dielectric shield of the tank bottom. This prevents effective use of anodes installed below the membrane for protection of the tank bottom. The anode system must be located in the fill area between the tank bottom and the membrane.

Assume the current necessary to provide cathodic protection in washed sand will be 1 microampere per square centimeter. The total current required for the 36.6 meter diameter tank can be calculated:

$$I_T = A_s i$$

where:

$I_T$  = total current required (A)

$A_s$  = area of the tank bottom ( $1.05 \times 10^7 \text{ cm}^2$ )

$i$  = current density required ( $1.0 \times 10^{-6} \text{ A/cm}^2$ )

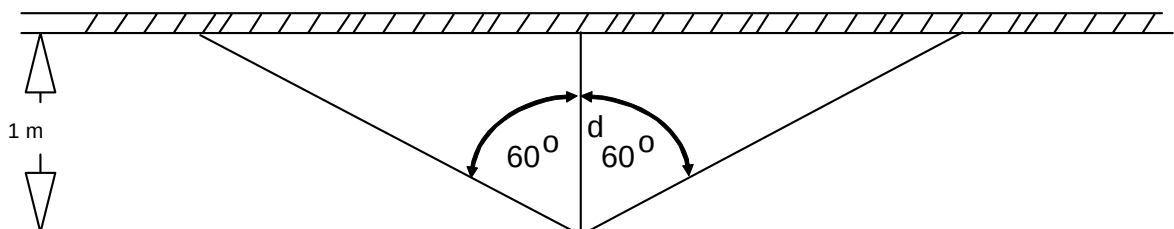
$$I_T = 10.5 \text{ A}$$

The total current is approximately 10.5 amperes.



Because there will be limited separation between the tank and the anode (maximum 1 meter) multiple ribbon type anodes will be required in order to provide distribution of current on the tank bottoms. A  $120^\circ$  angle between the ribbon and the tank bottom defines the likely coverage zone. Figure 6.5 illustrates this.

### EXPECTED ANODE THROW



$$L = 2d \tan 60^\circ$$

**Figure 6.5 Anode Coverage**

The coverage is given by the following equation:

$$L = 2 d \tan 60^\circ$$

where:

- L = width of coverage from ribbon anode (m)
- d = distance between ribbon anode and tank bottom (1.0m)

$$L = 2 \times 1.0 \text{ m} \times 1.73 = 3.46 \text{ m}$$

Therefore, the maximum space between ribbon anodes placed immediately above the membrane that can effectively cover the tank bottom, will be 3.46 meters. For design considerations, select three meters as the maximum separation between ribbon anodes.

The next step is to calculate the minimum total length of anode system required with three-meter separation.

$$N = d/s$$

where:

- N = number of ribbon anodes in parallel  
 d = tank diameter (36.6m)  
 s = ribbon separation (3.0m)

$$N = 36.6 \text{ m} / 3 \text{ m} = 12.2$$

There must be 13 ribbons on 3-meter centers.

For the minimum configuration, the following equation (a manipulation of the Pythagorean Theorem) defines the length of each ribbon moving from the center of the tank to one side.

$$y = (r^2 - x^2)^{0.5}$$

where:

- x = distance from tank center (m).  
 y = 1/2 the length of ribbon x meters from the center ribbon  
 r = radius of the tank (18.3m)

Table 6.1 summarizes the calculation of the total length of anode ribbon required for the minimum configuration.

**Table 6.1 Lengths of Anode Ribbons**

| x(m)         | y(m)        |
|--------------|-------------|
| 0            | 18.3        |
| 3            | 18.1        |
| 6            | 17.3        |
| 9            | 15.9        |
| 12           | 13.8        |
| 15           | 10.5        |
| 18           | 3.3         |
| <b>TOTAL</b> | <b>97.2</b> |

The center ribbon is common to two quadrants. The minimum total length of ribbon anode required to provide adequate coverage of the tank bottom is:

$$L = 4 \times (97.2 \text{ m} - 18.3 \text{ m}) + 2 \times 18.3 \text{ m} = 352 \text{ m}$$

### ***Selection of Anode Material***

It is conceivable that sacrificial type anodes would function in this type cathodic protection system. It is also possible to consider mixed metal oxide rectifier driven anodes.

First consider sacrificial anodes. The following is data for high potential magnesium ribbon type anode:

|                   |                                                |
|-------------------|------------------------------------------------|
| Alloy             | Magnesium (high potential)                     |
| Capacity          | 1,100 ampere hours per kilogram (500 A hr/lb.) |
| Consumption rate  | 8.0 kilograms (17.6 lbs.) per ampere year      |
| Ribbon dimensions | 0.94 cm (0.37 in) by 1.9 cm (0.75 in)          |
| Weight            | 0.36 kg per meter (0.24 lb./ft)                |

Calculate the weight of magnesium required to deliver 10.5 amperes of current for 40 years.

$$W = tIC_r$$

where:

|                |                                    |
|----------------|------------------------------------|
| W              | = weight of metal (kg.)            |
| t              | = time (40 yrs.)                   |
| I              | = current required (10.5A.)        |
| C <sub>r</sub> | = consumption rate -<br>(8kg/A-yr) |

$$W = 40 \text{ yr} \times 10.5 \text{ A} \times 8.0 \text{ kg/A-yr} = 3,360 \text{ kg (7,390 lbs.)}$$

The length of ribbon required would be given by the equation:

$$L = W_T / w$$

where:

|                |                                           |
|----------------|-------------------------------------------|
| L              | = length of ribbon required (m)           |
| W <sub>T</sub> | = total weight (3,360 kg.)                |
| w              | = weight/meter of anode ribbon (0.36kg/m) |

$$L = 3,360 \text{ kg} / 0.36 \text{ kg/m} = 9,333 \text{ m (30,600 ft)}$$

At \$3.75 per meter (1999), the anode material cost would be \$35,000.





Consider zinc ribbon. Following is the data for zinc:

|                  |                                          |
|------------------|------------------------------------------|
| Alloy            | - zinc                                   |
| Capacity         | - 738 ampere hours per kg (335 A-hr/lb.) |
| Consumption rate | - 11.9 kg/A-yr) (26 lb./A-yr)            |
| Ribbon dimension | - 2.5 cm (1 in)x3.2 cm (1.25 in)         |
| Weight per meter | - 3.57 kgs/m (2.4 lbs./ft)               |

The total weight of zinc required to deliver 10.5 amperes for 40 life is:

$$W = tIC_r$$

where:

|                |                                                 |
|----------------|-------------------------------------------------|
| W              | = weight of metal (kg.)                         |
| t              | = time (40 yrs.)                                |
| I              | = current required (10.5A.)                     |
| C <sub>r</sub> | = consumption rate (11.9kg/A-yr) (26 lbs./A-yr) |

$$W = 40 \text{ yr} \times 10.5 \text{ A} \times 11.9 \text{ kg/A-yr} = 4,998 \text{ kg.}$$

The length of ribbon required would be given by the equation:

$$L = W_T/w$$

where:

|                |                                           |
|----------------|-------------------------------------------|
| L              | = length of ribbon required (m)           |
| W <sub>T</sub> | = total weight (4,998 kg.)                |
| w              | = weight/meter of anode ribbon (3.57kg/m) |

$$L = 4,998 \text{ kg} / 3.57 \text{ kg/m} = 1,400\text{m} (4,592 \text{ ft})$$

At \$28.00 per meter (1999), the anode material cost would be \$39,200.

Consider mixed metal oxide coated titanium ribbon anode. Properties of this material are:

|           |                                          |
|-----------|------------------------------------------|
| Capacity  | 0.016 A/m (5 mA./ft) for 40 - 50 yr life |
| Dimension | 0.64 cm x 0.064 cm (0.25in x 0.025in)    |

Total length of ribbon required to deliver 10.5 amperes of current given by the following equation:

$$L = I/C_a$$

where:

L = length of ribbon required (m)

I = Total current (10.5A.)

C<sub>a</sub> = capacity (0.016A./m)

$$L = 10.5 \text{ A} / 0.016 \text{ A/m} = 656.3\text{m} (2,153 \text{ ft}).$$

Since the length necessary is about 1.9 times that required by a minimum current distribution configuration, a decrease in the ribbon spacing from 3m to a smaller value is required. By trial and error, 1.6m yields about the necessary spacing for a 656 m long anode.

**Table 6.2 Lengths of Anode Ribbons**

| x(m)         | y(m)         |
|--------------|--------------|
| 0            | 18.3         |
| 1.6          | 18.2         |
| 3.2          | 18.0         |
| 4.8          | 17.7         |
| 6.4          | 17.1         |
| 8.0          | 16.5         |
| 9.6          | 15.6         |
| 11.2         | 14.5         |
| 12.8         | 13.1         |
| 14.4         | 11.3         |
| 16.0         | 8.9          |
| 17.6         | 5.0          |
| <b>TOTAL</b> | <b>174.2</b> |

This yields a total ribbon length of:

$$L = 4 \times (174.2 \text{ m} - 18.3 \text{ m}) + 2 \times 18.3 \text{ m} = 660.2 \text{ m} (2,165 \text{ ft})$$

With a mixed metal oxide ribbon, it is necessary to also install cross connecting bus bars to achieve electrical continuity without excessive attenuation. The ribbon considered for this design has a cross sectional

area of about  $0.04 \text{ cm}^2$ . ASM "Metals Handbook"<sup>2</sup> lists the resistivity of commercially pure titanium as  $4.2 \times 10^{-7}$  to  $5.2 \times 10^{-7}$  ohm-cm. Alloys may differ.

Using  $42 \times 10^{-6}$  ohm-cm, the resistance per meter of ribbon is:

$$R = \rho L / A_x$$

where:

- $\rho$  = resistivity of titanium ( $42 \times 10^{-6}$  ohm-cm)
- $L$  = length of anode ribbon (100cm per meter)
- $A$  = cross sectional area of titanium ribbon ( $0.04 \text{ cm}^2$ )
- $R$  = lineal resistance of ribbon (ohm)

$$R = 42 \times 10^{-6} \text{ ohm-cm} \times 100 \text{ cm} / 0.04 \text{ cm}^2 = 0.105 \text{ ohm per m}$$

An estimate can be made of the anode resistance to the tank bottom. Unfortunately, the presence of the dielectric membrane, the paralleling configuration of the anode ribbons, and the proximity of the anode grid to the tank bottom complicate the estimate.

Assume the average length of an anode ribbon to be:

$$L_{\text{avg}} = 660 \text{ m} / 23 = 28.7 \text{ meters}$$

Using Dwight's modified formula:

$$R = \frac{0.005 \rho}{\pi L} \left( \ln \left( \frac{4L}{d} \right) + \ln \left( \frac{L}{h} \right) - 2 + \frac{2h}{L} \right)$$

where:

- $R$  = resistance of one average ribbon anode (ohms)
- $\rho$  = resistivity (assume 10,000 ohm-cm)
- $L$  = average length of ribbon (28.7m)
- $d$  = diameter of ribbon (approximately  $1.4/\pi = 0.0045\text{m}$ )
- $h$  = depth of ribbon (1m)

$$R = 0.555 \Omega (10.15 + 3.36 - 2 + 0.07) = 6.42 \text{ ohms/ribbon}$$

<sup>2</sup> ASM Vol. 2, 10<sup>th</sup> Ed., "Metals Handbook, 1990, p620

One average ribbon would have a resistance of 6.42 ohms, or:

$$R_T = 6.42 \, \Omega/\text{ribbon} / 23 \text{ ribbons} = 0.28 \, \text{ohm}$$

for the 23 ribbons in parallel (neglecting mutual interference effects).

It is also possible to estimate the resistance using the cross section configuration of a ribbon "looking" at a 160 centimeter (1.6 meters) wide strip of tank bottom.

Figure 6.6 illustrates the approach.

Consider a strip of the bottom plate of the tank 1.6m wide with one of the ribbon anodes at the apex of a triangular prism of 10,000 ohm-cm sand. Current flows from the ribbon (0.0064m wide) through increasing areas of the sand. Resistance is proportional to resistivity and the length of the path and is inversely proportional to the cross sectional area. Using calculus, we can develop a formula for the resistance of a single anode strip. If we assume that  $w \ll D$ , then the resistance can be estimated by the following formula:

$$R = \frac{\rho}{2L \tan \theta} \ln \left( \frac{2D \tan \theta}{w} \right)$$

where:

- R = resistance of anode L cm in length, ohms
- $\rho$  = resistivity (10,000 ohm-cm)
- $\theta$  =  $\frac{1}{2}$  angle formed by ribbon and the bottom strip (38.7°)
- L = average anode length, cm
- w = width of anode, m
- D = distance between anode and tank bottom, m

$$R = \frac{10000 \, \text{ohm-cm}}{2 \cdot 2870 \, \text{cm} \cdot \tan(38.7)} \cdot \ln \left( \frac{2 \cdot 1\text{m} \cdot \tan(38.7)}{0.0064 \, \text{m}} \right) = 12.01 \, \text{ohms}$$

This calculation yields a resistance of approximately 12.01 ohms per average ribbon or 0.52 ohms for 23 ribbons in parallel. It is reasonable to assume that in 10,000 ohm-cm washed sand, the resistance will be between 0.3 and 0.5 ohms (0.4 ohms average). Should the sand actually be higher in resistivity than 10,000 ohm-

cm, the resistance will be proportionally higher. In order to be conservative assume a 1.2 ohm resistance between the tank bottom and the anode grid (30,000 ohm-cm sand).

### ESTIMATE OF RESISTANCE OF RIBBON TO BOTTOM

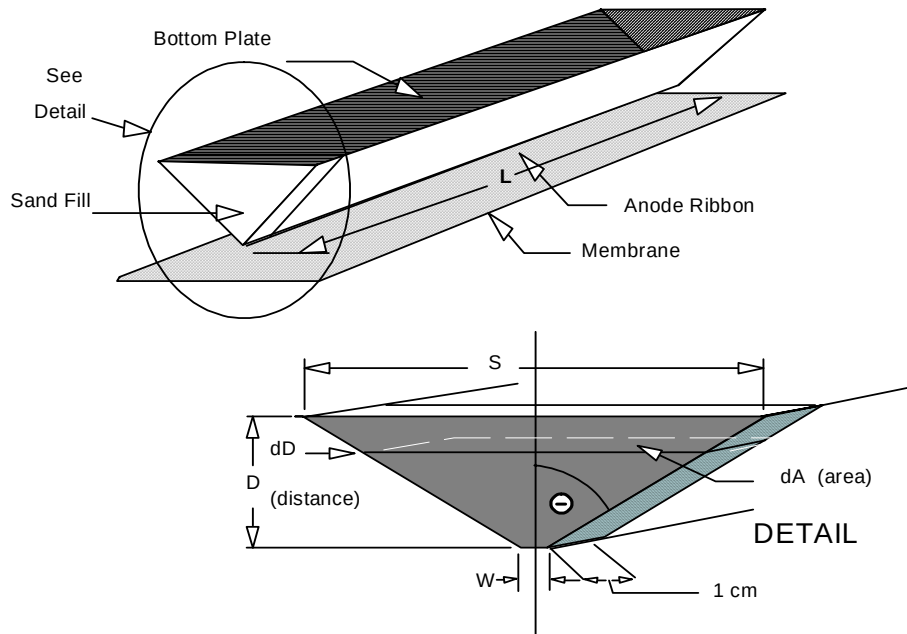


**Figure 6.6 Estimating Anode to Tank Resistance**

In a low-resistivity electrolyte attenuation in the ribbon would be significant. In the sand it is not a factor. Multiple connections to the anode are desirable for reliability. The spacing of cross connecting bars for this geometry is chosen to be approximately 9 meters. This provides four shorting bars across the anode grid and good redundancy in case occasional local failures occur in the anode ribbon.

The dimensions for cross connecting bar are:

|           |            |
|-----------|------------|
| Material  | - titanium |
| Width     | - 1.27 cm  |
| Thickness | - 0.1 cm   |

The number of cross connection connecting bars required:

$$N = d/s$$

where:

N = number of bars  
 d = tank diameter (36.6m)  
 s = bar spacing (9m)

$$N = 36.6 \text{ m} / 9 \text{ m} = 4$$

With the center bars located 4.5 meters on either side of the center of the tank, the total length of connector bars per quadrant from Table 6.3 is approximately 30 meters per quadrant (28.8 meters if taken from scaled drawing, (Figure 6.7). In addition, a cross feed between the connector bars is required. This cross feed would be 27 (3x9m) meters long. The total length of connector bar is about 147.4 meters.

**Table 6.3 Lengths of Cross Feed Bars**

| x(m) | y(m)          |
|------|---------------|
| 4.5  | 17.7          |
| 13.5 | 12.4          |
|      | 30.1/quadrant |

$$L = (4 \times 30.1 \text{ m}) + 27 \text{ m} = 147.4 \text{ m} (483.5 \text{ ft})$$

## ANODE GRID DESIGN

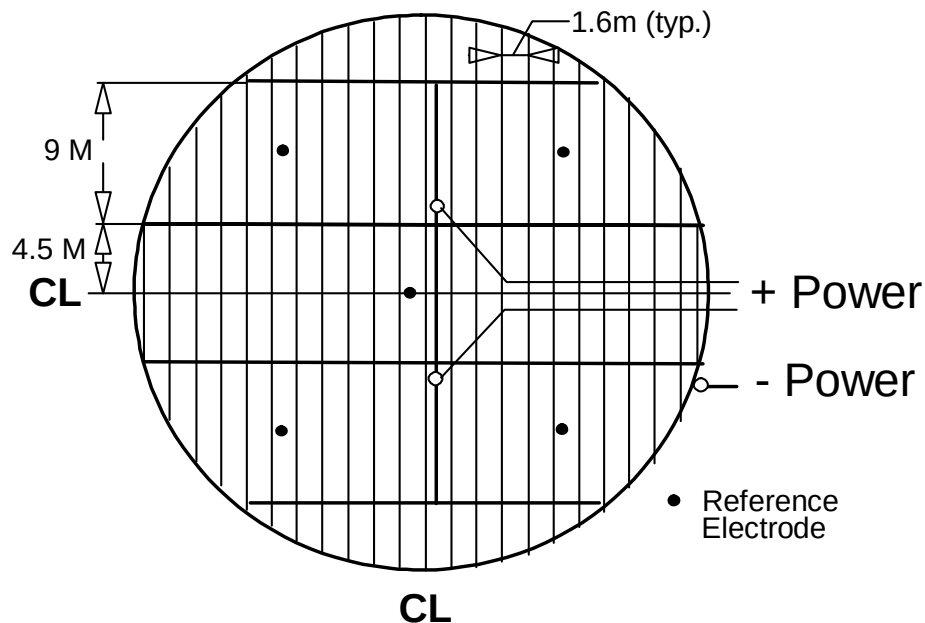


**Figure 6.7 Anode Layout**

The material cost for a mixed metal oxide coated titanium anode system is as follows:

|              |                       |               |
|--------------|-----------------------|---------------|
| Anode ribbon | 660m @\$10.50/m(1999) | \$6,930       |
| Cross bars   | 147.4m @\$5.70/m      | <u>\$ 840</u> |
| TOTAL        |                       | \$7,771       |

Rectifier and wiring to power the anode system are estimated at \$2,480. The total material cost for the impressed current system is approximately \$10,251.

The cost of materials for the impressed current system (not including the cost of AC service installation or operating power) is considerably less than that for galvanic anodes.

Figure 6.7 shows the proposed anode grid design to be installed approximately 10 centimeters above the membrane. Shown are five reference electrodes installed at intermediate points within the grid of the anode system. The reference electrodes should be close to the tank bottom, well above the anode grid.

The feeder wires attached to the connector bars and an attachment to the tank bottom are made at a location convenient for the installation of the rectifier unit.

The rectifier capacity would be given by :

$$E = IR$$

where:

E = maximum required voltage

I = current (10.5A)

R = resistance (1.2 ohms)

$$E = 10.5 \text{ A} \times 1.2 \text{ } \Omega = 12.6 \text{ volts}$$

Select the nearest standard rectifier, which is approximately 12 volts and 12 amperes.

Once the system and tank are installed, monitor the behavior of the cathodic protection system. Using the reference electrodes installed beneath the tank, conduct polarization tests and/or monitor polarization criteria.

## Existing Aboveground Tanks/Rectifier/Deep Anode

### Description

Four tanks, 23 meters (75 ft) in diameter and electrically isolated from connecting piping, are grouped in accordance with Figure 6.8. The tanks are approximately 23 meters (75 ft) apart. The geology in the area is suited to a deep anode system, with 2,500 ohm-cm soil present between 10m (33 ft) and 50m (164 ft) deep. A deep anode can be located 70 meters (230 ft) away from the nearest tank and surface piping. This provides the necessary separation to assure that the nearest tanks to the deep anode will not preferentially consume current. Design a deep anode cathodic protection system for the tank farm. The cathodic protection system should have a design life of 15 years.

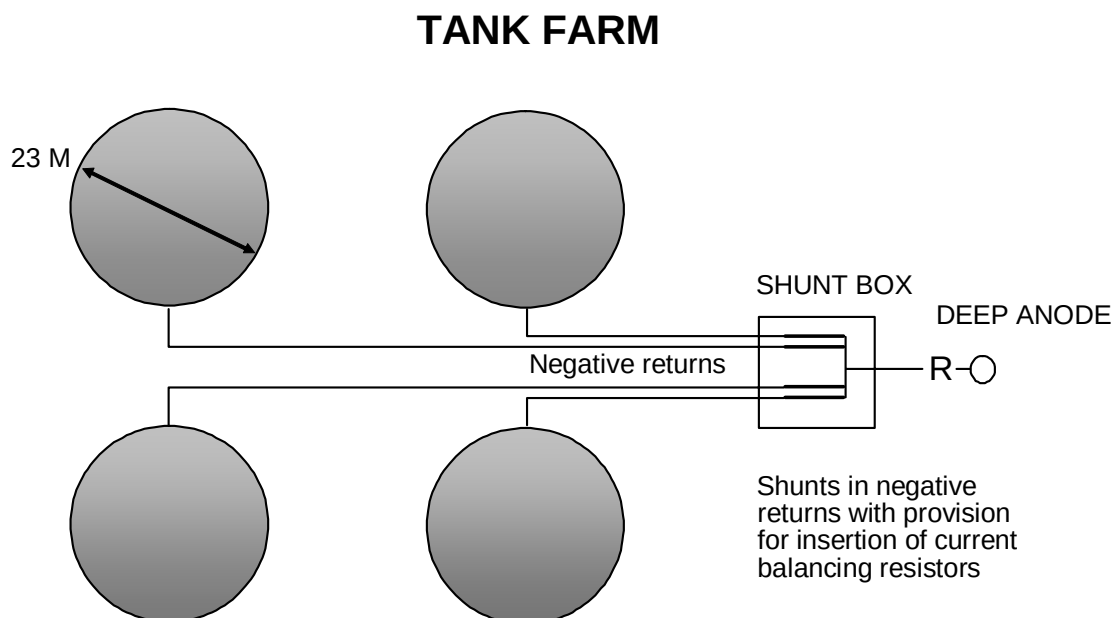


**Figure 6.8 Tank Farm with Deep Anode**



## Parameters

1. Assume current required is 0.5 microamperes per square centimeter ( $0.46\text{ma/ft}^2$ ) of tank bottom surface.
2. Provide individual negative returns from each tank and facilities for adjusting the quantity of current returned from each tank bottom. (Each tank is insulated from connecting piping. All connecting piping is on supports above grade.)
3. Determine that there are no problems concerning underground aquifers that might limit the use or the method of construction of a deep anode. Assume no such aquifer problem exists in this case.
4. To keep power costs down and to avoid hazardous voltages, design the deep anode system such that the maximum anode voltage will not exceed 18 volts at rated current output.
5. The design life of the cathodic protection system should be 15 to 20 years.

## Calculations

First calculate the surface area of the tanks:

$$A_s = \pi(d/2)^2$$

where:

$A_s$  = area of a single tank ( $\text{m}^2$ )  
 $d$  = tank diameter (23m)

$$A_s = 415\text{m}^2 (4,464 \text{ ft}^2) = 4.15 \times 10^6 \text{ cm}^2/\text{tank}$$

Estimate the current requirements:

$$I_T = A_i$$

where:

$I_T$  = current required /tank (A)  
 $A_s$  = area of a tank bottom ( $4.15 \times 10^6 \text{ cm}^2$ )  
 $i$  = current density required ( $5.0 \times 10^{-7} \text{ A/cm}^2$ )

$$I = 4.15 \times 10^6 \text{ cm}^2 \times 5.0 \times 10^{-7} \text{ A/cm}^2 = 2.08 \text{ A per tank}$$

$$I_T = 8.32 \text{ A (tank farm)}$$

Determine the required groundbed resistance for a maximum power supply voltage of 18 volts. Assume an operating polarized back voltage between the anode and tanks of 2.0 volts. Provide a safety factor of 2 to account for tank to earth resistance and wiring.



$$R = (E/I_T)/f$$

where:

R = total resistance between the tank farm and anode

E = net driving voltage (18 - 2 = 16 volts)

$I_T$  = total current (8.32A)

f = safety factor (2)

$$R = (16 \text{ V} / 8.32 \text{ A}) / 2 = 0.96 \text{ ohm}$$

Determine the active anode column length in 2,500 ohm-cm soil required to produce 0.96 ohm groundbed resistance. Use Figure 6.9, which is constructed using Dwight's formulas for a vertical anode with four different anode diameters.

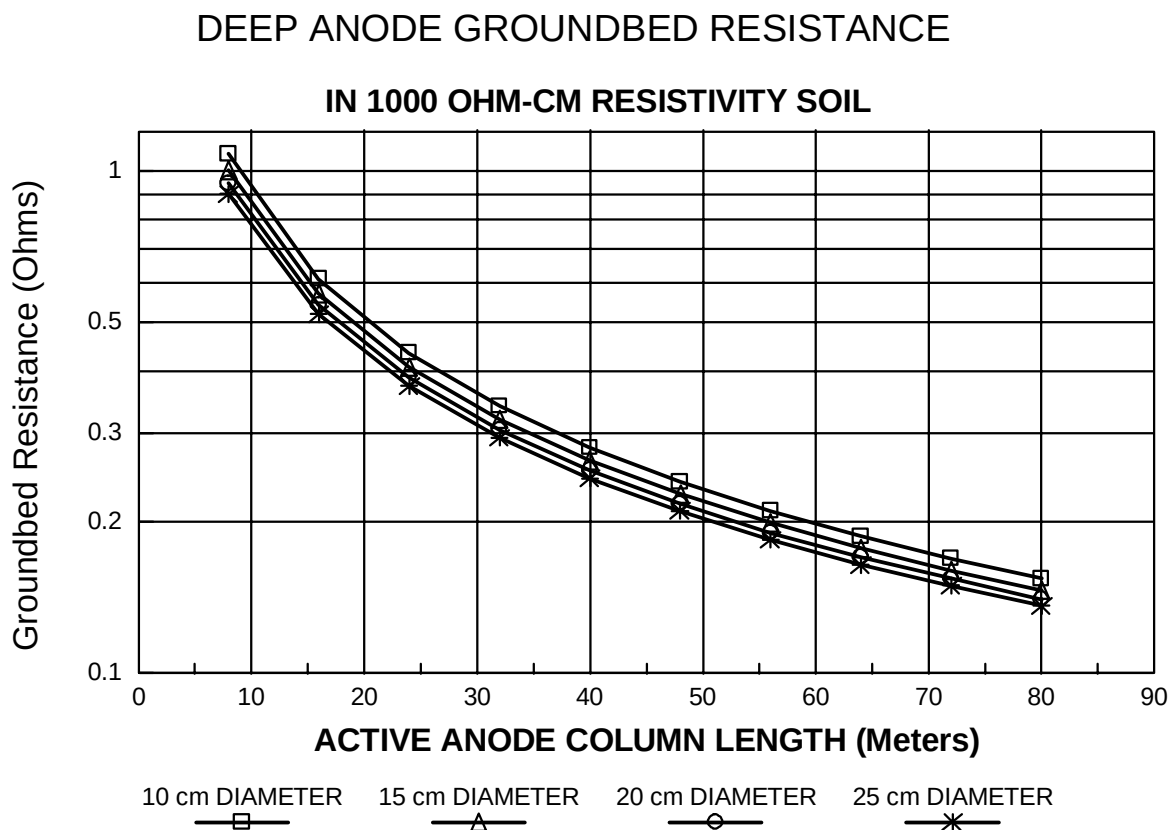


**Figure 6.9 Resistance to Remote Earth of Various Deep Anode Active Lengths**

Since the graph is for 1,000 ohm-cm soil, the actual groundbed resistance will be greater than that shown on the graph for a given length and diameter of anode column. The relationship is given by the formula:

$$R_x = f_c R_g$$

where:

- $R_x$  = the resistance in soil of x ohm-cm resistivity
- $R_g$  = the resistance shown on the graph at soil resistivity of 1000 ohm-cm
- $f_c$  =  $\rho_s/1000$  = resistivity correction factor
- $\rho_s$  = resistivity of actual soil (ohm-cm)

In this case, the correction factor is:

$$f_c = 2500/1000 = 2.5$$

$$R_g = R_x/f_c$$

$$R_g = 0.96 \, \Omega / 2.5 = 0.38 \, \text{ohm}$$

The active anode column length, which corresponds to 0.38 ohm in 1,000 ohm-cm soil, is between 24 and 30 meters in length, depending upon anode diameter. With this example we elect to use mixed metal oxide, tubular anodes on a single cable. The anodes are 122 cm (4 ft) long and 0.64 cm (0.25 in) in diameter. The current output rating is 1.8 amperes per anode. The minimum number of anodes required is:

$$N = I_T/I_a$$

where:

- $N$  = minimum number of anodes
- $I_T$  = total current (8.32A)
- $I_a$  = capacity of an anode (1.8A/anode)

$$N = 8.32 \, \text{A} / 1.8 \, \text{A} = 4.6 \, \text{anodes}$$

Five anodes in the deep groundbed would have adequate capacity.

Since the total length of the active anode must be about 27 meters (88.6 ft), this would mean that one 1.22 meter anode is required for each 5.4 meters of coke breeze in the groundbed. Experience suggests that spacing between the primary anodes should be no greater than two to three times the length of the active anode. For a 1.22m anode the maximum spacing between anodes should not exceed 3.7m. In this case, the spacing between active 1.22 meter anodes is 4.18m (5.40m - 1.22m). Increasing the number of anodes to 6 will reduce the spacing to 3.28m [(27/6) - 1.22]. The number of anodes required will be 6 anodes.



The maximum current density discharged from carbonaceous backfill should not exceed  $1.6 \text{ A/m}^2$  ( $150 \text{ mA/ft}^2$ ) of bore hole wall. If the bore hole is 15.2 cm (6 in) in diameter, the active anode will have an outer surface area of:

$$A_s = \pi dL$$

where:

$A_s$  = carbonaceous backfill/soil interface area ( $\text{m}^2$ )  
 $d$  = backfill diameter (0.152m)  
 $L$  = active anode length (27m)

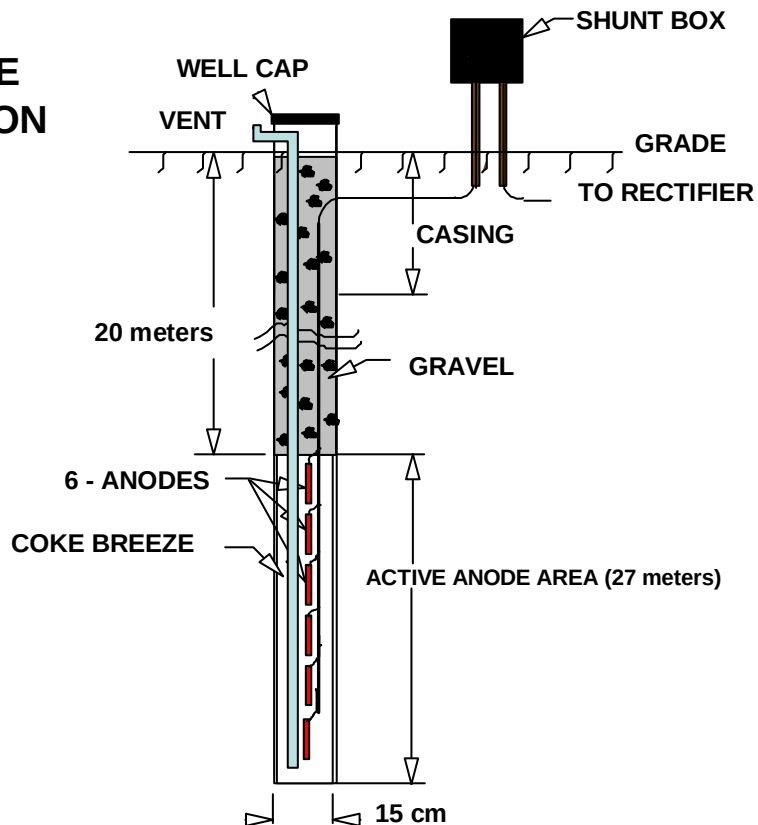
$$A_s = \pi \times 0.152 \text{ m} \times 27 \text{ m} = 12.9 \text{ m}^2 (138.8 \text{ ft}^2)$$

The current density is:

$$i = 8.32 \text{ A} / 12.9 \text{ m}^2 = 0.645 \text{ A/m}^2 (59.9 \text{ mA/ft}^2)$$

Figure 6.10 shows the deep anode design.

## DEEP ANODE INSTALLATION



### **Figure 6.10 Deep Anode Design**

#### **Negative Return Wiring**

The minimum wire size for mechanical reasons is selected as #8 AWG copper ( $2.10 \times 10^3$  ohms per meter). If the wire routing distance from the two tanks farthest from the rectifier is 70 meters, and that to the nearest tanks is 35 meters, there will be 0.15 ohm and 0.074 ohm of resistance respectively in the negative returns.

Depending on variations in resistance to remote earth of each of the four tank bottoms, the current from the groundbed may not equally divide among the four tanks. To control current distribution requires adjusting the resistance from the four tanks. Resistors (0.5 ohm with 5 amperes capacity) will generally provide adequate control. Once installed, current requirement tests should be performed to confirm proper rectifier sizing. It is generally desirable to adjust the resistance in the negative returns for test purposes, so that equal currents will be returned from each of the tanks involved.

# Well Casings Design Examples

## ***Existing/Solar/Surface Bed***

### ***Description***

A steel cased, wind powered, water well is located in a remote section of a cattle ranch. Cathodic protection is to be applied to the casing using a solar power source and surface anode. Given the following data, design the cathodic protection system.

### ***Data***

- Depth of well = 85.4 meters (280 ft)
- Diameter (O.D.) = 16.8 cm (6.625 in)
- Soil resistivity = 3500 ohm cm  $\pm$  1000 ohm cm to depth of 10 meters (32.8 ft)
- Semi arid conditions

### ***Procedure***

1. Estimate current requirement.
2. Design test groundbed for E log i test.
3. Determine anode-well separation.
4. Size photo voltaic power system.
5. Design anode suited to power source.

### ***Current requirements and anode location***

With wells, lack of access for local structure to soil potential measurements prevents use of many test techniques normally used for pipe line and near grade structures. E log i tests are generally the most feasible at grade electrochemical current requirement test measurement available for wells. On deep wells (oil and gas) down hole measurements are possible which permit the detection of small current flowing on a well casing. The procedures are very costly but are presently the most reliable method of cathodic protection testing.

For this case we chose to use E log i at grade measurements to determine the current required to protect the well casing.

First estimate the current required based on surface area and 2.0 micro amperes/cm<sup>2</sup>.

Surface area of well casing:

$$A_s = \pi dL$$

where:

$$\begin{aligned} d &= \text{diameter } 16.8 \text{ cm (6.625 in)} \\ L &= \text{length (depth) of casing } 8540 \text{ cm (280 ft)} \\ A_s &= \text{area (cm}^2\text{)} \\ A_s &= \pi \times 16.8 \text{ cm} \times 8540 \text{ cm} = 4.51 \times 10^5 \text{ cm}^2 \end{aligned}$$

Estimate current required:

$$I = A_s i$$

where:

$$\begin{aligned} I &= \text{total current required (amp)} \\ A_s &= \text{area (} 4.51 \times 10^5 \text{ cm}^2\text{)} \\ i &= \text{current density required (} 2.0 \times 10^{-6} \text{ amp/cm}^2\text{)} \end{aligned}$$

$$I = 4.51 \times 10^5 \text{ cm}^2 \times 2.0 \times 10^{-6} \text{ A/cm}^2 = 0.90 \text{ ampere}$$

To obtain a well-defined E log i plot require a total polarization shift from the native corrosion potential to the final test potential of between –100 and –150 mV. The slope of the E log i plot (Tafel constant) is usually about -120 mV per decade increase in test current. If 0.90 amperes is the expected current at the beginning of the E log i section of the plot, then a decade (ten fold) increase in current (9.0A) should produce an additional – 120 millivolts of polarization.

If we have a test power source capable of producing a maximum output of 10 amperes and 100 volts DC, the approximate resistance of a test groundbed must be:

$$R = E/I$$

where:

E = maximum power supply voltage (100V)

I = maximum desired test current (9 A)

R = test groundbed resistance (ohms)

$$R = 100/9.0 = 11 \text{ ohms}$$

Utility ground rods make useful test anodes.

Using Dwight's equation for a single vertical electrode, the resistance of a rod 1.53 meter (5 ft) long and 1.27 cm (0.5 in) in diameter is:

$$R = \frac{0.005\rho}{\pi L} \left( \ln \left( \frac{8L}{d} \right) - 1 \right)$$

where:

L = the length of the rod (1.53 m)

d = rod diameter (0.0127 m)

$\rho$  = average resistivity (3500 ohm cm)

R = resistance to remote earth (ohms)

$$R = \frac{0.005 \cdot 3500}{\pi \cdot 1.53} \left( \ln \left( \frac{8 \cdot 1.53\text{m}}{0.0127\text{m}} \right) - 1 \right) = 21.4\text{ohm}$$

To be certain that there will be adequate test current available from the power source, use 3 rods about 5 meters (16.4 ft) apart for the test anode.

The test anode must be placed far enough away from the well to be certain that the top and bottom of the well are exposed to about the same voltage gradient from the test anode.

The rise in earth potential, at any point, x, caused by current entering the earth is given by the equation<sup>3</sup>:

<sup>3</sup> Corrosion Handbook, H.H. Uhlig, Editor, 1948, p. 941, John Wiley & Sons, Inc., New York



$$E_r = \frac{0.005I\rho}{\pi L} \left( \ln \left( \frac{L + (L^2 + r^2)^{0.5}}{r} \right) \right)$$

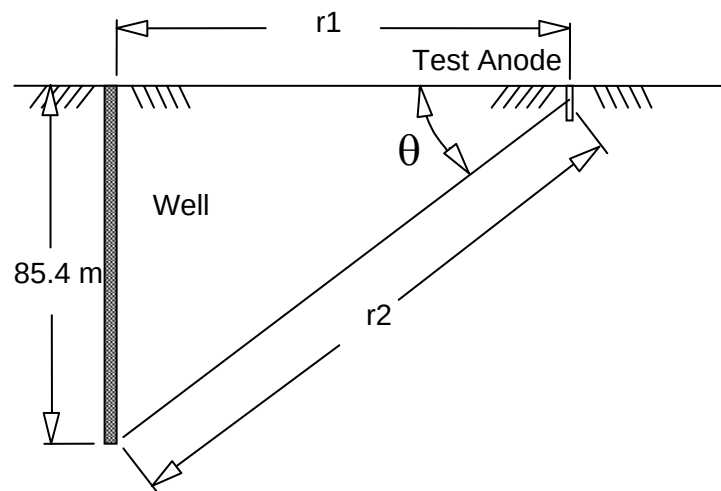
where:

- I = current delivered (by the anode) to the earth (A)
- $\rho$  = average resistivity of the earth (ohm-cm)
- L = length of rod below grade (meters)
- R = distance (meters) from the center of the anode to the point x
- $E_r$  = the voltage rise at x (volt) with respect to remote earth

If  $r$  is greater than about 10 times  $L$  then the equation reduces to:

$$E_r = \frac{0.0016I\rho}{r}$$

From this simplified formula, it is evident that the voltage rise ( $E_r$ ) is inversely proportional to the distance  $r$  from the current source (anode). Examine Figure 6.11 and note that, for a surface source (anode), the top of the well will always be closer to the anode than the bottom of the well. That is  $r_1$  will always be shorter than  $r_2$ .



$$r_1 = 85.4 / \tan \theta$$

$$r_2 = 85.4 / \sin \theta$$

Relationship of distance between top and bottom of 85.4 m well casing and a test anode at grade.

**Figure 6.11 Anode–Well Geometry**

If the angle,  $\theta$ , is  $60^\circ$ :

$$r_1 = 85.4 \text{ m} / \tan 60^\circ = 49.3 \text{ meters (162 ft)}$$

$$r_2 = 85.4 \text{ m} / \sin 60^\circ = 98.6 \text{ meters (323 ft)}$$

In 3500 ohm-cm soil the voltage rise at the top of the well per ampere of current from a single surface test anode 49.3 meters from the well will be:

$$E_r = \frac{0.0016 I \rho}{r}$$

where:

- I = current (1 A)
- $\rho$  = average resistivity (3500 ohm-cm)
- r = distance from the anode (49.3 m)
- $E_{rt}$  = voltage rise at top of well (volt)

$$E_{rt} = 0.0016 \times 3500/49.3 = 0.114 \text{ volt per amp}$$

The voltage rise at the bottom of the well 98.6 meters from the test anode will be:

$$E_{rb} = 0.0016 \times 3500/98.6 = 0.057 \text{ volt per amp}$$

The difference in the potential shift of the well to soil between the top and bottom is:

$$E_{rt} - E_{rb} = 0.114 \text{ V/A} - 0.057 \text{ V/A} = 0.057 \text{ V/A}$$

We know that a single test rod will have a resistance to remote earth of about 21 ohms (see above calculations). At one ampere of current the anode voltage rise will be:

$$E = IR$$

where:

- I = 1 ampere
- R = anode to remote earth resistance (21 ohms)
- E = voltage between the anode and remote earth (volts)

$$E = 1 \text{ A} \times 21 \Omega = 21 \text{ volts}$$

If the voltage rise at the top of the well is 0.114 volts/A. Then the top of the well is exposed to the percent of the anode voltage rise as follows:

$$\%V_a = E_{rt}/E \times 100$$

In other words, the well is outside about 99.5% of the voltage gradient surrounding the test anode 50 meters (164 ft) away.

The ratio of voltage rise at a point (r) distant from a vertical anode to the voltage rise of the anode measured to remote earth can be estimated using the ratio of the voltage rise equation at (I) amperes:



$$E_r = \frac{0.005I\rho}{\pi L} \left( \ln \left( \frac{L + (L^2 + r^2)^{0.5}}{r} \right) \right)$$

to (I) amperes times Dwight's equation for a vertical rod:

$$E = IR = I \left( \frac{0.005\rho}{\pi L} \right) \left( \ln \left( \frac{8L}{d} \right) - 1 \right)$$

Carrying out the division yields:

$$\frac{E_r}{IR} = \frac{\ln \left( \frac{L + (L^2 + r^2)^{0.5}}{r} \right)}{\ln \left( \frac{8L}{d} \right) - 1}$$

Therefore, the percentage of total anode voltage rise (%V<sub>a</sub>) at point r above remote earth is:

$$\%V_a = \frac{E_r}{IR} \cdot 100\% = \frac{\ln \left( \frac{L + (L^2 + r^2)^{0.5}}{r} \right)}{\ln \left( \frac{8L}{d} \right) - 1} \cdot 100\%$$

where:

%V<sub>a</sub> = percentage voltage rise above remote earth at point r

E<sub>r</sub> = voltage rise at distance r meters from the anode (volts)

IR = voltage rise of the anode to remote earth (volts)

L = length of anode (m)

d = diameter of the anode (m)

For this example using a single rod anode:

$$\begin{aligned} I &= 1 \text{ ampere} \\ L &= 1.53 \text{ meters} \\ d &= 1.27 \text{ cm (0.0127 m)} \\ r &= 50 \text{ m} \end{aligned}$$

$$\%V_a = \frac{\ln\left(\frac{1.53\text{m} + \left((1.53\text{m})^2 + (50\text{m})^2\right)^{0.5}}{50\text{m}}\right)}{\ln\left(\frac{8 \cdot 1.53\text{m}}{0.0127\text{m}}\right) - 1} \cdot 100\% = 0.52\%$$

Note that the formula is independent of resistivity and current. The formula permits estimates to be made of the relative "remoteness" of an anode with respect to structures in the area.

Figure 6.12 is an E log i plot of the polarization of the well in response to current applied between the well and the test anode array. The indicated minimum current required to control corrosion is about 0.70 ampere. The system should be designed to provide about 1.0 ampere.

Sometimes it is easier to consider what percentage of the total anode voltage rise the point r is outside (%V<sub>OUT</sub>), rather than within. In this case, we must subtract the percentage voltage rise at r (%V<sub>a</sub>) from the total percentage rise to remote earth of 100%. This equation is as follows:

$$\%V_{OUT} = 100\% - \left(\frac{E_r}{IR} \cdot 100\%\right) = 100\% - \left[ \frac{\ln\left(\frac{L + (L^2 + r^2)^{0.5}}{r}\right)}{\ln\left(\frac{8L}{d}\right) - 1} \cdot 100\% \right]$$

## E - Log I TEST

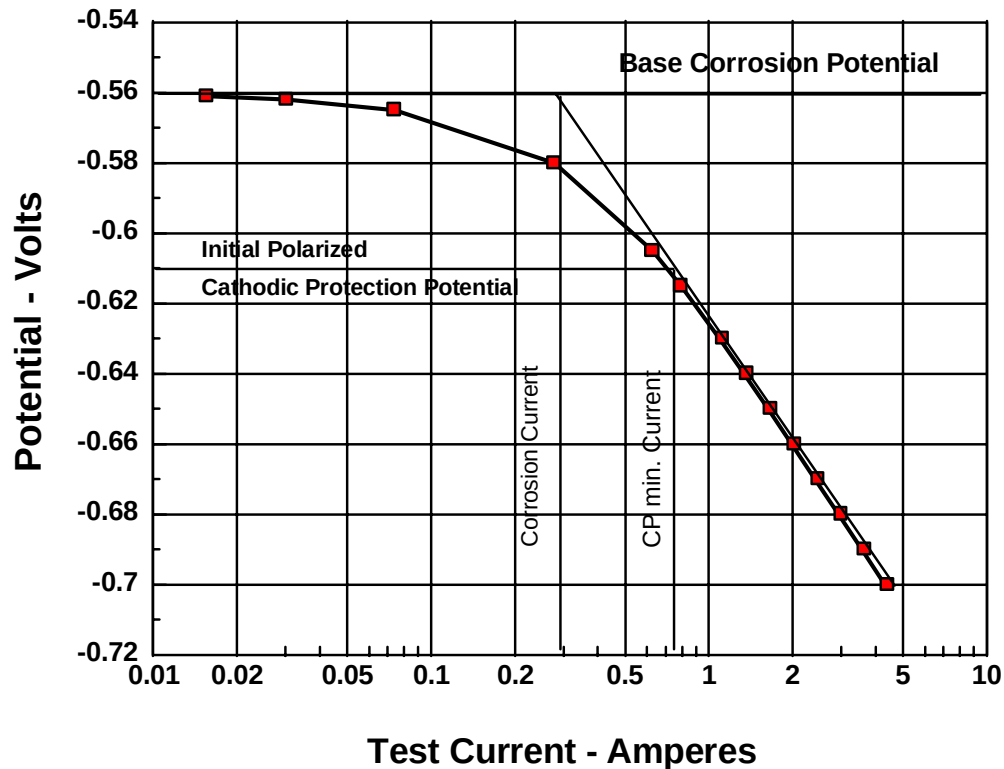


**Figure 6.12 E-log i Plot**

### Sizing Solar Power Supply

Manufacturers of solar arrays will generally provide design information to assist in calculating the size of the power supply. Solar radiation varies with location on the globe, weather and by season. Solar energy is converted into electricity by solar panels. The electric power produced during the time the sun is shining on the panels is stored in rechargeable batteries. The batteries serve as a reservoir while power is delivered at a steady rate to the cathodic protective control system.

If we design the permanent anode for a resistance of 10 ohms and a current capacity of 1.0 ampere, the voltage of the power source must be:

$$E = I (R_a + R_w + R_{ck}) + E_b$$

where:

- I = 1.0 amperes
- R<sub>a</sub> = 10 ohms
- R<sub>w</sub> = resistance of the well to earth (estimated at 0.5 ohms from Dwight's formula)
- R<sub>ck</sub> = wire and power supply circuit resistance (estimated at 1.0 ohm)
- E<sub>b</sub> = polarized backvoltage between anode and structure (2.0 volts)
- E = required minimum power supply output voltage

$$E = 1.0 \text{ A} (10 \Omega + 0.5 \Omega + 1.0 \Omega) + 2 \text{ V} = (1.0 \text{ A} \times 11.5 \Omega) + 2 \text{ V} = 13.5 \text{ volts}$$

A nominal 12 volt system would likely be adequate.

Power rating:

$$P = EI$$

where:

- E = output voltage (12 volts)
- I = current (1 ampere)
- P = Watts

$$P = 12 \text{ V} \times 1 \text{ A} = 12 \text{ watts}$$

**Energy Requirement:**

$$E = Pt$$

where:

- P = power (12 watts)
- t = hours/day (24 hrs/day)
- E = watt-hr. of energy/day
- E = 12 W x 24 hrs/day = 288 watt hrs/day

The solar power system must be able to provide at least this energy input during the worst case (winter) conditions at the site. Sufficient storage battery capacity must also be provided to average out the fluctuations in available energy.

Information to be provided to the solar power unit manufacturing includes:

1. Type of system (Cathodic Protection)
2. Geographic location (latitude and longitude)
3. System voltage (12 volts)
4. Current drain (1 ampere)
5. Ambient temperatures expected ( $^{\circ}\text{C}/^{\circ}\text{F}$ )
6. Estimate of number of consecutive no-sun days (worst case for site)
7. Special or unusual operating conditions

**Groundbed**

For this project we select pre-packaged graphite anodes for the groundbed. The anodes are 7.62 cm (3 in) diameter by 1.52 m (5 ft) long in 20 cm (8 in) diameter by 2.13 m (7 ft) long steel cylinders. The cylinders are pre-packaged with carbon backfill. Graphite is a good anode material under semi arid soil conditions.

Using Dwight's formula for a vertical anode:

$$R = \frac{0.005\rho}{\pi L} \left( \ln \left( \frac{8L}{d} \right) - 1 \right)$$

where:

- $\rho$  = soil resistivity (3500 ohm-cm)
- L = overall anode length (2.13 meters)
- d = outer anode diameter (.2 m)

$$R = (2.62 \, \Omega)(3.445) = 9.03 \, \text{ohm}$$





Since the result is less than the 10 ohms targeted, a single anode will have the necessary conductance. The current density from the primary anode at 1 ampere is:

$$i_a = I/(\pi dL)$$

where:

- I = current output (1A)
- d = graphite anode diameter (7.62 cm)
- L = anode length (152 cm)
- $i_a$  = anode current density A/cm<sup>2</sup>

$$i_a = 1 \text{ A}/(\pi \times 7.62 \text{ cm} \times 152 \text{ cm}) = 1 \text{ A}/3639 \text{ cm}^2 \\ = 0.000275 \text{ A/cm}^2$$

This current density is well below the 0.001 A/cm<sup>2</sup> maximum recommended by the manufacturer for graphite anodes. A single anode groundbed is therefore suitable. The anode should be located about the same distance from the well as was the test anode.

## ***Existing/Rectifier/Deep Anode***

### ***Description***

A group of three oil wells are located on a tract well away from other structures. The well heads are close together (about 30 meters apart) and diverge underground. The individual wells are isolated from each other and the gathering lines that transport the crude to a pipeline.

Tests of current requirements for cathodic protection of the wells have been made using E log i procedures. To make certain that local distortion of current distribution near the top of the wells did not overly influence the measurements, the reference electrode (a copper/copper sulfate half-cell) was placed, at grade, about 300 meters from the nearest well. The E log i tests indicate that the current requirements for the well casings is between 8 and 10 amperes per well. The design will assume 12A/well or a total design current of 36A.

Using the data provided below, design a deep anode rectifier powered cathodic protection system for the well field. Consider the gathering pipelines to be well coated with negligible exposed metal.

### ***Data***

Casing depth = 1,829 m (6,000 ft)

Casing diameter = 23 cm (9 in)

Average soil resistivity grade to 500 meter (1,640 ft) deep = 4,000 ohm-cm

Well log resistivities range = 400 ohm-cm to 10,000 ohm-cm

Service life = 20 years

Top 6 m (20 ft) of anode, to be cased

## **Procedure**

1. Design a deep anode to meet estimated current requirements and life expectancy.
2. Determine anode to well head separation required for suitable current distribution.
3. Determine rectifier requirements.

## **Anode Design**

For this design, we will select tubular high silicon iron anodes as the primary anode.

The weight of anode material required is:

$$W_T = C_r t I / f_u$$

where:

- $C_r$  = consumption rate (0.227 kg/A-yr.)  
 $t$  = design life (20 yrs.)  
 $I$  = average current required over design life (36A)  
 $f_u$  = utilization factor in coke (0.75)  
 $W_T$  = total weight of anode material required (kg)

$$W_T = (0.227 \text{ kg/A-yr}) \times 20 \text{ yr} \times 36 \text{ A} / 0.75 = 218 \text{ kg (480 lbs.)}$$

Select a standard tubular high silicon iron anode for the design. One typical large tubular anode of reasonable weight and size for deep anode use is 28.6 kg (63 lbs.), 6.75 cm (2.656 in) diameter and 2.13 m (84 in) long.

The number of these anodes required to give the needed weight of material is:

$$N = W_T / W_a$$

where:

$W_T$  = total weight of anode material required (218 kg)  
 $W_a$  = weight of an anode (28.6 kg)  
 $N$  = number of anodes required

$$N = 218 \text{ kg} / 28.6 \text{ kg} = 7.6 = 8 \text{ anodes}$$

High silicon iron anodes should meet the design consumption rate if current densities are less than or equal to  $5 \times 10^{-4} \text{ A/cm}^2$  (0.5A/ft<sup>2</sup>).

The total anode surface area for the 8 high silicon anodes is:

$$A_s = N\pi dL$$

where:

$N$  = number of anodes  
 $d$  = anode diameter 6.75 cm (2.656 in)  
 $L$  = anode length 213 cm (84 in)

$$A_s = 8\pi(6.75\text{cm})(213\text{cm}) = 36,134 \text{ cm}^2$$

Average current density is:

$$i_a = I/A_s$$

where:

$I$  = total current (36 A)  
 $A_s$  = anode surface area (36,134 cm<sup>2</sup>)  
 $i_a$  = anode current density amps/cm<sup>2</sup>

$$i_a = 36 \text{ A} / 36,134 \text{ cm}^2 = 9.96 \times 10^{-4} \text{ A/cm}^2$$

This current density is about twice the rated value. Therefore, the number of anodes should be doubled to a total of 16 anodes.

It is proposed to fill the active section of the deep anode with carbon backfill. The maximum discharge current density at the earth carbon interface in a deep anode system should be limited to about 1.6 A/m<sup>2</sup> (0.150 A/ft<sup>2</sup>) to prevent excessive gassing or drying.

To meet this requirement, the external surface area of the coke column should be:

$$A_{sc} = I_T / i_c$$



where:

$$\begin{aligned} I_T &= \text{total current (36 A)} \\ i_c &= \text{allowed current density (1.6 A/m}^2\text{)} \\ A_{sc} &= \text{outside surface area of coke column (m}^2\text{)} \end{aligned}$$

$$A_{sc} = 36 \text{ A} / 1.6 \text{ A/m}^2 = 22.5 \text{ m}^2$$

If the nominal diameter of the anode bore hole is 20 cm (8 in), the length of the coke column must be:

$$L = A_{sc} / \pi d$$

where:

$$\begin{aligned} A_{sc} &= \text{surface area of coke column (22.5 m}^2\text{)} \\ d &= \text{diameter of column (0.20 m)} \end{aligned}$$

$$L = 22.5 \text{ m}^2 / 0.628 \text{ m} = 35.8 \text{ m (117 ft)}$$

For a bore diameter of 30.5 cm (12 in):

$$L = 22.5 \text{ m}^2 / 0.958 \text{ m} = 23.5 \text{ m}$$

With the 30.5 cm (12 in) diameter coke column, the anode spacing for 16 anodes would be:

$$S = 23.5 \text{ m} / 16 = 1.5 \text{ meters}$$

With the 20 cm (8 in) diameter coke column, the anode spacing for 16 anodes would be:

$$S = 35.8 \text{ m} / 16 = 2.2 \text{ meters}$$

Depending upon the geology and costs involved a better solution might be the following:

Two deep anodes of 20 cm (8 in) diameter and 18 m (59 ft) coke column length.

Each deep anode would have 8-high silicon iron anodes on:

$$S = 18 \text{ m} / 8 = 2.25 \text{ m (7.4 ft) spacing}$$

Both of the alternatives have the same external coke column surface area (22.5 m<sup>2</sup>).



### Examine Anode Remoteness

Figures 6.13 through 6.15 are plots of the formula derived previously and given below for the 35.8 m long by 20 cm diameter anode, the 23.5 m long by 30.5 cm diameter anode, and the 18 m long by 20 cm diameter anode.

$$\%V_{\text{OUT}} = 100\% - \left( \frac{E_r}{IR} \cdot 100\% \right) = 100\% - \left[ \frac{\ln \left( \frac{L + (L^2 + r^2)^{0.5}}{r} \right)}{\ln \left( \frac{8L}{d} \right) - 1} \cdot 100\% \right]$$

where:

- $\%V_{\text{OUT}}$  = % voltage rise that r is outside
- $E_r$  = voltage rise at distance "r" meters from anode
- $IR$  = voltage of the anode measures to remote earth at current I Ampere
- $L$  = length of anode below grade (meters)
- $d$  = diameter of anode (m)
- $r$  = distance (m) from anode to point of measurement

To be certain that the tops of the wells are not subjected to more than 5% of the anode voltage gradient, the anode must be far enough away from the well head such that the well head is outside 95% of the anode. Remoteness is a function of coke column length and diameter. For the 35.8 m long by 20 cm diameter column (Table 6.4), the 95% point is located about 120 meters from the anode. Table 6.4 summarizes the 95% gradient data taken from Figures 6.13 through 6.15.

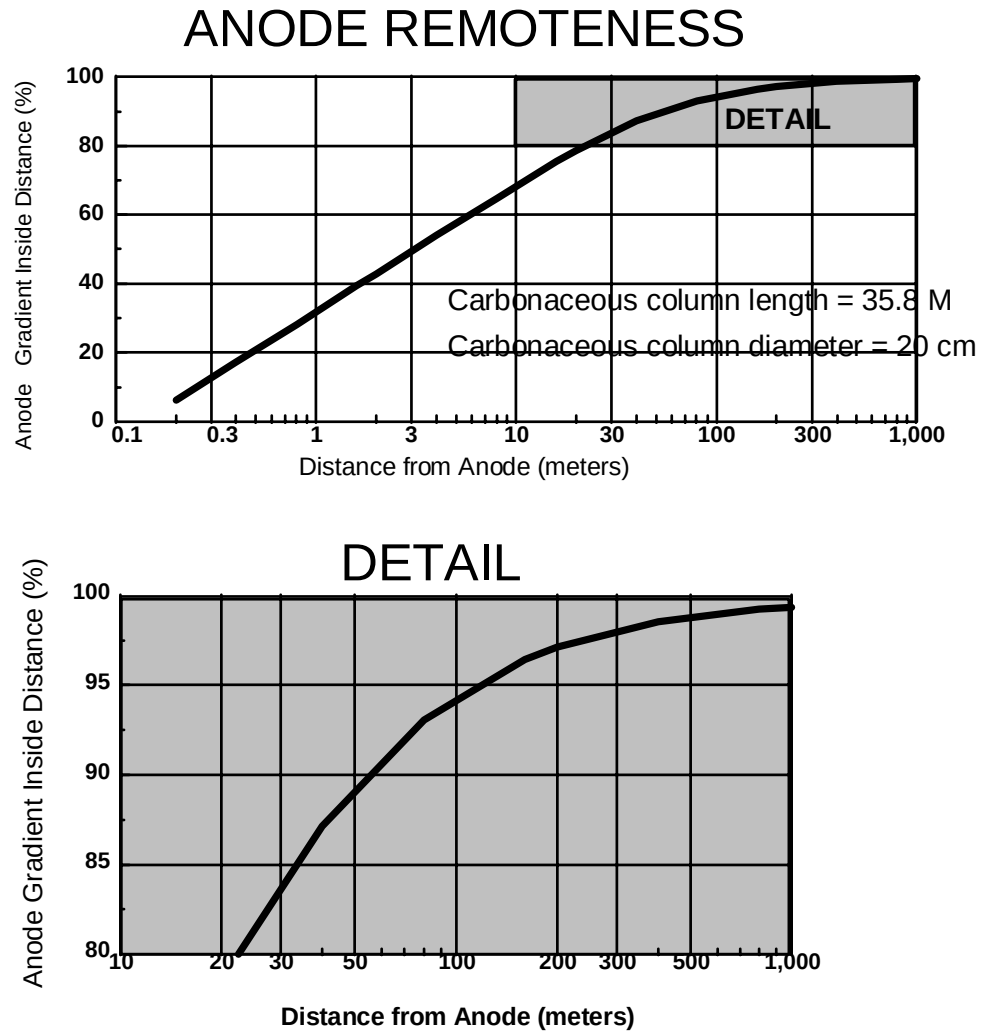


**Figure 6.13 Anode Remoteness, 35.8 M long by 20 cm diam.**  
**Anode**

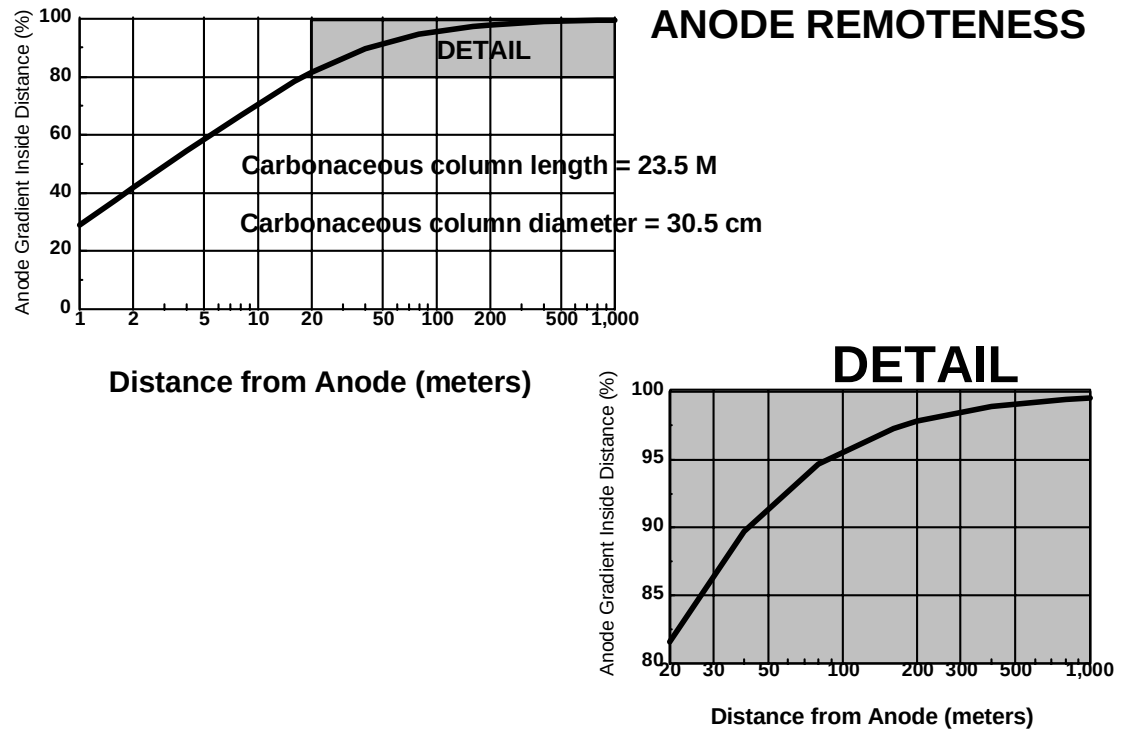


**Figure 6.14 Anode Remoteness, 23.5M long by 30cm diam.**  
**Anode**



## ANODE REMOTENESS

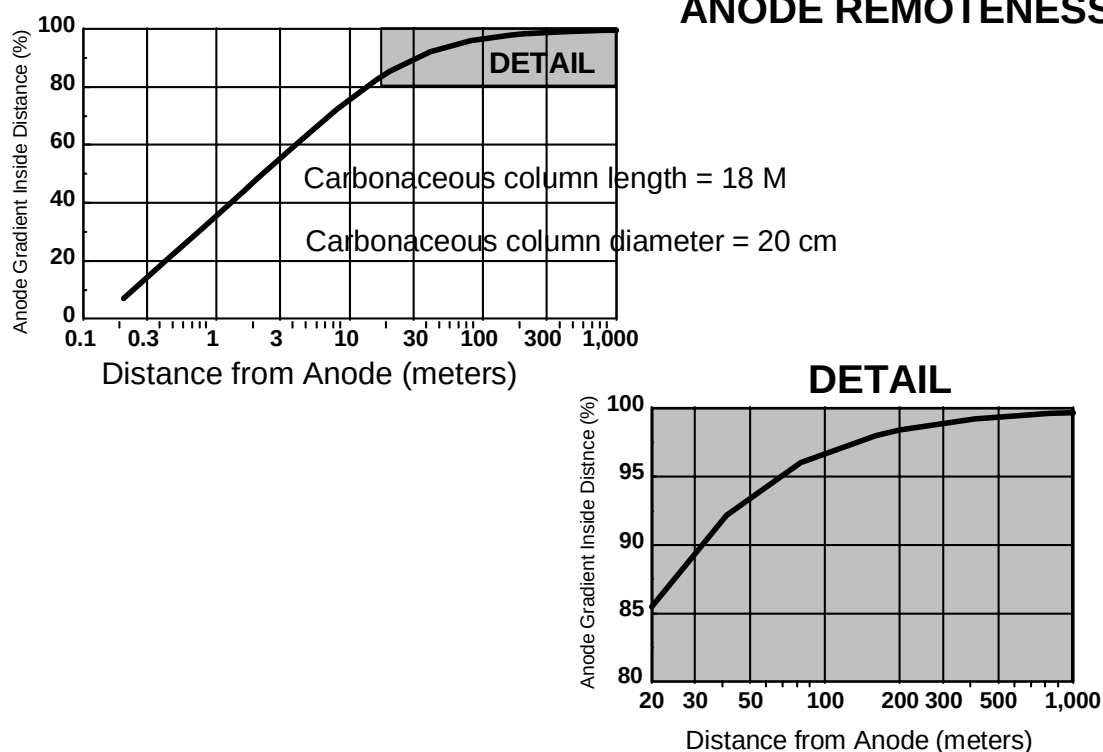


**Figure 6.15 Anode Remoteness, 18M long by 20cm diam.**  
**Anode**

**Table 6.4 Relative Remoteness of Anodes**

| Reference | Anode Diameter |      | Anode Length |      | 95% Voltage Gradient Anode to Well Distance |      | Approximate Resistance |
|-----------|----------------|------|--------------|------|---------------------------------------------|------|------------------------|
| Figure    | (cm)           | (in) | (m)          | (ft) | (m)                                         | (ft) | (ohms)                 |
| 13-13     | 20             | 8    | 35.8         | 117  | 120                                         | 394  | 1.11                   |
| 13-14     | 30.5           | 12   | 23.5         | 77   | 85                                          | 279  | 1.47                   |
| 13-15     | 20             | 8    | 18           | 59   | 70                                          | 230  | 1.97                   |
|           |                |      |              |      |                                             |      | 0.99                   |
|           |                |      |              |      |                                             |      | (2 anodes)             |

Of the three variations considered, the two deep anodes would require the lowest operating power (because of lower anode resistance) and might prove most reliable over the design life of the system. We choose to use a two (2) deep anode system configured as shown in Figures 6.16 and 6.17.

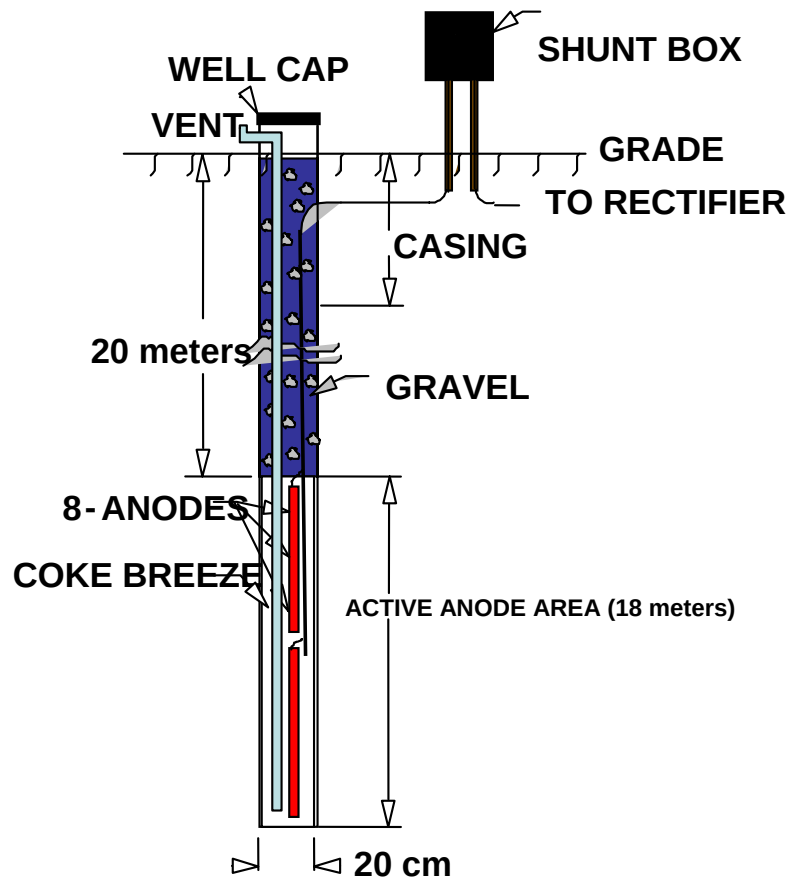
**DEEP ANODE  
INSTALLATION**

**Figure 6.16 Anode Design**

## GENERAL LAYOUT

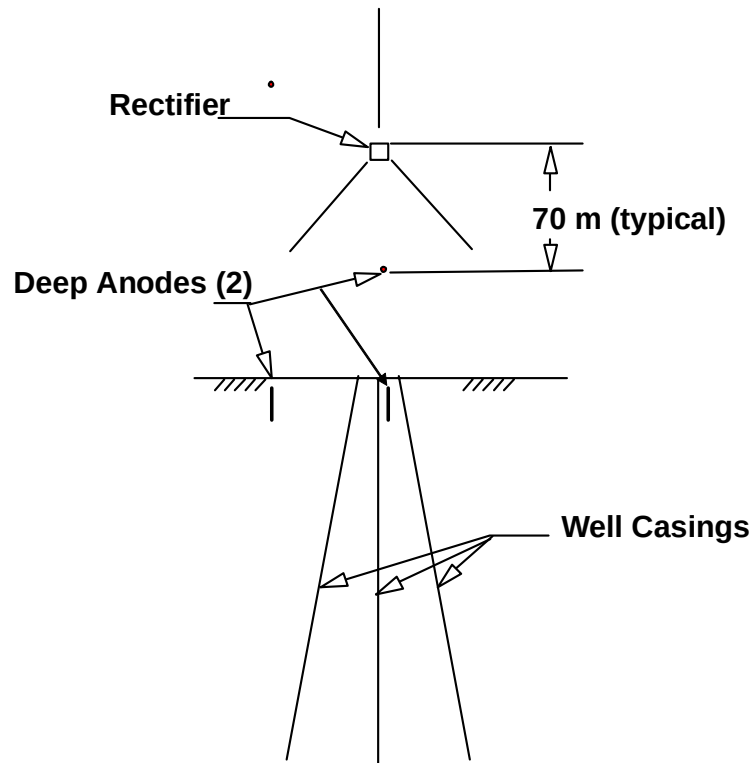


**Figure 6.17 Anode Placement**

Other factors that should be evaluated in most cases include:

1. Sub-soil geology which might impact drilling and performance of the anodes.
2. Relative costs of drilling, both bore size and depth.
3. Right-of-way for anode.

## ***Rectifier Voltage Requirements***

The circuit resistance for each of the deep anodes is now calculated.

$$R_T = R_a + R_w + R_u + R_c$$

where:

- $R_a$  = anode resistance to remote earth
- $R_w$  = wire resistance
- $R_u$  = unknown internal component resistances
- $R_c$  = cathode (well) to remote earth resistance
- $R_T$  = total circuit resistance

Anode resistance by Dwight's formula is:

$$R = \frac{0.005\rho}{\pi L} \left( \ln \left( \frac{8L}{d} \right) - 1 \right)$$

where:

- $\rho$  = 4,000 ohm-cm
- $L$  = 18 meters
- $d$  = 0.2 meters

$$R = (0.354 \Omega)(5.579) = 1.973 \text{ ohm}$$

$$R_a = 1.973 \text{ ohm}$$

If number 8 AWG copper wire ( $2.099 \times 10^{-3}$  ohm/m) is used for all anode runs:

$$R_w = R_1 + R_2 + R_3$$

where:

- $R_1$  = equivalent resistance of the 8 parallel down hole wires to the individual high silicon iron anodes.
- $R_1 = RL/8$
- $R$  = wire resistance ( $2.099 \times 10^{-3}$  ohm/m)
- $L$  = average length of 8 feed wires (27 m) (approximate)
- $R_1 = 7.08 \times 10^{-3}$  ohms
- $R_2$  = resistance of wire between deep anode and rectifier
- $R_2 = RL$

R = wire resistance ( $2.099 \times 10^{-3}$  ohm/m)  
 L = length of wire from anode to rectifier (70 m)

$$R_2 = 2.099 \times 10^{-3} \times 70 = 0.147 \text{ ohm}$$

$R_3$  = resistance of wire between rectifier and oil well

$R_3$  = RL  
 R = wire resistance ( $2.099 \times 10^{-3}$  ohm/m)  
 L = length of wire between rectifier and well head (20 m approx.)

$$R_3 = 2.099 \times 10^{-3} \times 20 = 0.042 \text{ ohm}$$

$$R_w = 0.007 + 0.147 + 0.042 = 0.196 \text{ ohm}$$

$R_u$  = assumed = 0.500 ohm

$R_c$  = assumed = 0.100 ohm

(Dwight's formula indicates resistance <0.05 ohm)

$$R_T = 1.973 + 0.196 + 0.500 + 0.100 = 2.769 \text{ ohms}$$

The maximum design current flow in each of the deep anode circuits is:

$$I = I_T/2$$

where:

$I_T$  = total design current (36 A)  
 I = single deep anode current (A)

$$I = 36 \text{ A}/2 = 18 \text{ A}$$

Rectifier Voltage

$$E = IR + E_p$$

where:

I = typical single deep anode current (18 A)  
 R = typical deep anode circuit resistance (2.769 ohms)  
 $E_p$  = polarized back voltage (Est. @ 2 V)

$$E = 18 \text{ A} \times 2.769 \Omega + 2 \text{ V} = 51.8 \text{ volts}$$

A standard rectifier with minimum 40 A and 60 volt capacity will provide adequate output for the system. Considering the power demand of this



system, if three-phase AC power is available operating efficiency would be significantly improved by using a three-phase rectifier.

## Summary

1. An example of a cathodic protection design for underground storage tanks which includes the following features:
  - Protective coating on tanks and piping
  - Electrical isolation from grounded structures
  - Sacrificial anode current source
2. An example of a cathodic protection design for underground storage tanks which includes the following features:
  - Negligible protective coating on the tanks
  - Electrical isolation from grounded structures
  - Rectifier powered, impressed current anode system
3. An example of a new aboveground storage tank cathodic protection design that includes the following features:
  - New construction, no protective coating on bottom plates
  - Dielectric secondary containment membrane
  - Distributed, ribbon type anode under bottom plates
  - Impressed current power source
4. An example of an existing aboveground storage tank cathodic protection design that includes the following features:
  - Existing tank farm
  - No dielectric secondary containment
  - Deep anode, rectifier powered cathodic protection
  - Return circuit control of current distribution to individual tank bottoms
5. An example of cathodic protection design for a shallow water well casing using a solar power source.
6. An example of cathodic protection design for a small group of oil wells utilizing impressed current deep anodes.

### Offshore Pipeline Design Examples

#### ***New/Bracelet/Zinc***

##### ***Description***

An electrically isolated 1525 meter (5000 ft.) section of 50.8 cm (20 in.) pipeline is to be installed offshore. Design a galvanic anode cathodic protection system for the pipeline using zinc bracelet type anodes.

##### ***Data***

Data for the design is as follows:

|                           |                                                                |
|---------------------------|----------------------------------------------------------------|
| Water depth, average      | 30 m (98.4 ft)                                                 |
| Length of pipeline        | 1525 m (5000 ft)                                               |
| Diameter of pipe          | 50.8 cm (20 in)                                                |
| Class of pipe             | ASA SCH 30                                                     |
| Wall thickness            | 1.27cm(0.500 in)                                               |
| Lineal resistance         | $6.800 \times 10^{-6}$ ohm/m( $2.073 \times 10^{-6}$ ohm/ft)   |
| Coating - dielectric tape | 3% exposed metal                                               |
| Environment around pipe   | 80% open seawater<br>30 ohm-cm<br>20% bottom mud<br>300 ohm-cm |
| Design life               | 20 years                                                       |



Design current density requirements:

|                                 |                                                            |
|---------------------------------|------------------------------------------------------------|
| Seawater                        | 6.5 $\mu\text{A}/\text{cm}^2$ (6 $\text{mA}/\text{ft}^2$ ) |
| Mud                             | 2.2 $\mu\text{A}/\text{cm}^2$ (2 $\text{mA}/\text{ft}^2$ ) |
| Anode material                  | Zinc (MIL-A-18001H)                                        |
| Current capacity                | 738 amp-hr/kg (360 amp-hr/lb.)                             |
| Consumption rate                | 11.9 kg/amp-yr (24 lb/amp-yr)                              |
| Utilization factor              | 0.9                                                        |
| Corrosion potential in seawater | -1.0 V Ag/AgCl                                             |
| Bracelet anode wt.              | 235 kg (518 lbs)                                           |

## Calculations

### ESTIMATE OF EXPOSED STEEL SURFACE AREA

$$A_s = \pi d L \% \text{bare}$$

where:

|        |                                                      |
|--------|------------------------------------------------------|
| $A_s$  | = Total exposed metal surface area ( $\text{cm}^2$ ) |
| $d$    | = Pipe diameter 50.8 cm (20 in)                      |
| $L$    | = Length of pipeline 152,500 cm (5000 ft)            |
| % bare | = Fraction of exposed metal 0.03 (3%)                |

$$A_s = \pi \times .508 \text{ m} \times 1525.00 \text{ m} \times 0.03 = 73 \text{ m}^2 (786 \text{ ft}^2)$$

Estimate of bare steel area in seawater

$$A_{sw} = 73 \text{ m}^2 \times 0.8 = 58.4 \text{ m}^2 (629 \text{ ft}^2)$$

Estimate of bare steel area in mud

$$A_m = 73 \text{ m}^2 \times 0.2 = 14.6 \text{ m}^2 (157 \text{ ft}^2)$$

## ***Estimate of maintenance cathodic protection current required***

### **SEAWATER**

$$I_{sw} = A_{sw} i_{sw}$$

where:

$I_{sw}$  = Current required in seawater (A)

$A_{sw}$  = Exposed steel in seawater ( $5.84 \times 10^5 \text{ cm}^2$ )

$i_{sw}$  = Current density required in seawater  
( $6.5 \times 10^{-6} \text{ A/cm}^2$ )

$$I_{sw} = 5.84 \times 10^5 \text{ cm}^2 \times 6.5 \times 10^{-6} \text{ A/cm}^2 = 3.80 \text{ A}$$

### **MUD**

$$I_m = A_m i_m$$

where:

$I_m$  = Current required in mud (A)

$A_m$  = Exposed steel in mud ( $1.46 \times 10^5 \text{ cm}^2$ )

$i_m$  = Current density required in mud ( $2.2 \times 10^{-6} \text{ A/cm}^2$ )

$$I_m = 1.46 \times 10^5 \text{ cm}^2 \times 2.2 \times 10^{-6} \text{ A/cm}^2 = 0.32 \text{ A}$$

### **TOTAL MAINTENANCE CURRENT REQUIRED**

$$I = I_{sw} + I_m = 3.80 + 0.32 = 4.12 \text{ A}$$

**ANODE CAPACITY REQUIRED**

$$C_a = It$$

where:

$$\begin{aligned} C_a &= \text{Electrochemical capacity (A-yr)} \\ I &= \text{Total current (4.12 A)} \\ t &= \text{Life expectancy (20 years)} \end{aligned}$$

$$C_a = 4.12 \text{ A} \times 20 \text{ yr} = 82.4 \text{ A-yr.}$$

**WEIGHT OF ZINC ANODES REQUIRED**

$$W = C_a C_r / f_u$$

where:

$$\begin{aligned} W &= \text{Weight of material (kg)} \\ C_a &= \text{Capacity required (82.4 A-yr.)} \\ C_r &= \text{Consumption rate for zinc in} \\ &\quad \text{seawater (11.9 kg/A-yr)} \\ f_u &= \text{Utilization factor (0.9)} \end{aligned}$$

$$W = 82.4 \text{ A-yr} \times 11.9 \text{ kg/A-yr} / 0.9 = 1090 \text{ kg}$$

**NUMBER OF ANODES REQUIRED**

$$N = W/W_a$$

where:

$$\begin{aligned} W &= \text{Total weight of zinc (1007 kg)} \\ W_a &= \text{Weight per anode 235 kg/anode} \end{aligned}$$

$$N = 1090/235 = 4.64$$

Choose the next higher number (5 anodes or one anode for every 305 meters of pipe). An anode would be installed (305/2) 152.5 meters from each end with a separation of 305 meters for anodes elsewhere.

**Attenuation**

Examine for the possibility of a problem with attenuation. In any highly conductive environment (seawater) attenuation may be a factor in the design of cathodic protection.



The resistance measured to remote earth of a bare pipeline of the dimension given in this example, is approximated by Dwight's formula for a horizontal electrode. Since only 3% of the pipe surface is bare, the diameter used in Dwight's equation should be 3% of the diameter of the pipe to approximate the resistance of the coated pipe to earth.

$$R = \frac{0.005\rho}{\pi L} \left( \ln\left(\frac{4L}{d}\right) + \ln\left(\frac{L}{h}\right) - 2 + \frac{2h}{L} \right)$$

where:

$\rho = 30$  ohm-cm (resistivity)

$L = 1525$  m (length of pipeline)

$d = 0.03 \times 0.508$ m (corrected diameter of pipe)

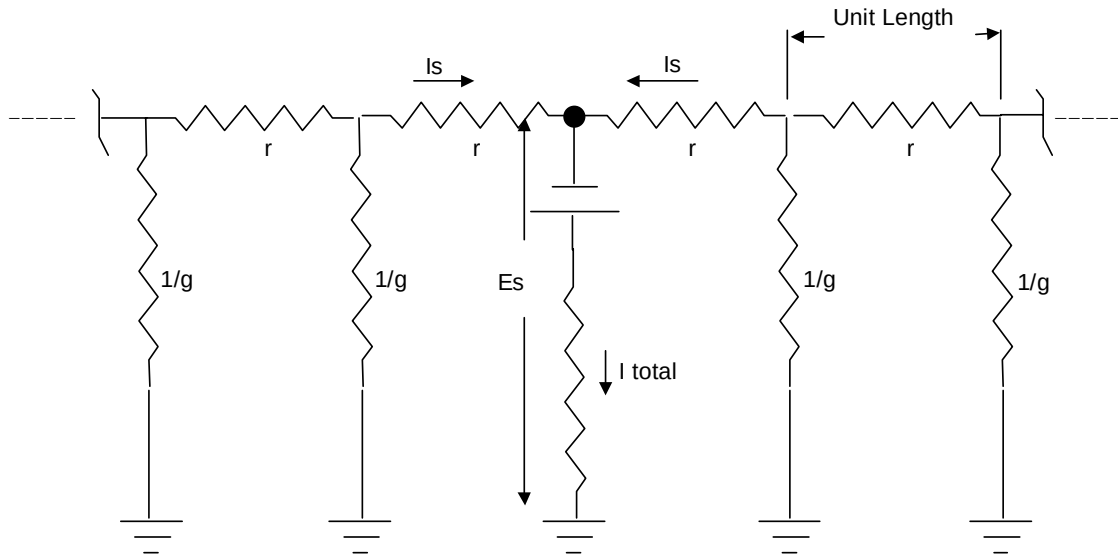
$h = 30$  m (depth of pipeline)

$$R = \frac{0.005 \cdot 30}{\pi \cdot 1525} \left( \ln\left(\frac{4 \cdot 1525}{0.01524}\right) + \ln\left(\frac{1525}{30}\right) - 2 + \frac{2 \cdot 30}{1525} \right) = 3.131 \times 10^{-5} (14.87) = 4.65 \times 10^{-4} \text{ ohms}$$

The resistance,  $4.65 \times 10^{-4}$  ohms, expressed as conductance is 2148 Siemens. Choosing 1m as the unit length and dividing the conductance of the pipeline by the total number of unit lengths gives the conductance per unit length.

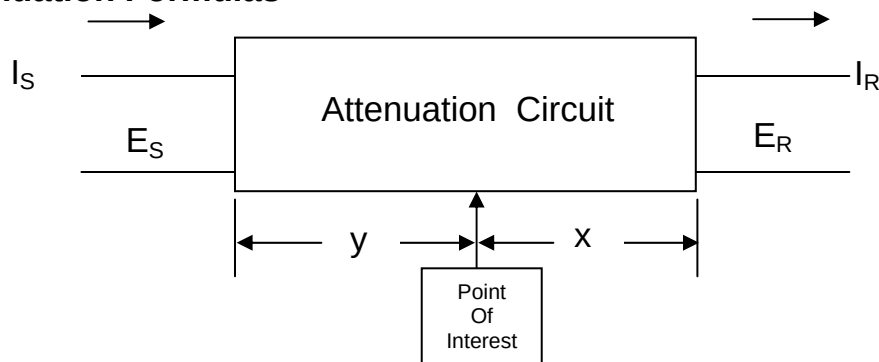
$$g = 2148 \text{ S} / 1525 \text{ m} = 1.41 \text{ S/m}$$

Using the attenuation formulas given in Figure 7.2, the equivalent circuit diagram in Figure 7.1 and steel pipe data from Tables 7.1 & 7.2, calculate the attenuation constant and characteristics resistance.



CIRCUIT DIAGRAM AT ANODE ATTACHMENT LOCATION

**Figure 7.1 Circuit Diagram**

**DC Attenuation Formulas**

$\alpha = \sqrt{rg}$  propagation or attenuation constant

$R_G = \sqrt{\frac{r}{g}}$  characteristic resistance (ohms)

$r =$  unit lineal resistance, ohms/unit length

$g =$  unit conductance to earth S/unit length

$x =$  number of unit lengths from receiving end

$y =$  number of unit lengths from sending end

| General Equations                                                           | Where:                                          |
|-----------------------------------------------------------------------------|-------------------------------------------------|
| 1. $E = E_r \cosh(\alpha x) + R_G I_r \sinh(\alpha x)$                      | $E_r$ = receiving end potential                 |
| 2. $I = I_r \cosh(\alpha x) + \left(\frac{E_r}{R_G}\right) \sinh(\alpha x)$ | $I_r$ = receiving end current                   |
| 3. $E = E_s \cosh(\alpha y) - R_G I_s \sinh(\alpha y)$                      | $E_s$ = sending end potential                   |
| 4. $I = I_s \cosh(\alpha y) - \left(\frac{E_s}{R_G}\right) \sinh(\alpha y)$ | $I_s$ = sending end current                     |
| 5. $R_{s0} = R_G \coth(\alpha x)$                                           | $R_{s0}$ = Resistance looking into open line    |
| 6. $R_G = \sqrt{R_{s0} R_{ss}}$                                             | $R_{ss}$ = Resistance looking into shorted line |

**Figure 7.2 Attenuation Equations**

**Table 7.1 Pipe Resistance Data****STEEL PIPE DATA FOR CORROSION CALCULATIONS**

Resistivity of Steel = 5.292E-06 Ohms-sq.in./in.

1.344E-05 Ohms-sqcm/cm

| Nominal<br>Size | Nominal<br>Size | Schedule<br>Number | O.D.   |      | Wall<br>Thickness |       | Weight<br>Per Ft. Per M |       | Linear<br>Resistance |           |
|-----------------|-----------------|--------------------|--------|------|-------------------|-------|-------------------------|-------|----------------------|-----------|
| Inch            | Cm              |                    | Inch   | Cm   | Inch              | Cm    | Lbs.                    | Kg.   | Ohms/Ft              | Ohms/m    |
| 4               | 10              | 40                 | 4.500  | 11.4 | 0.237             | 0.602 | 10.79                   | 4.90  | 2.001E-05            | 6.562E-05 |
| 6               | 15              |                    | 6.625  | 16.8 | 0.188             | 0.476 | 12.89                   | 5.85  | 1.675E-05            | 5.493E-05 |
| 6               | 15              |                    | 6.625  | 16.8 | 0.219             | 0.556 | 14.97                   | 6.80  | 1.442E-05            | 4.731E-05 |
| 6               | 15              |                    | 6.625  | 16.8 | 0.250             | 0.635 | 17.02                   | 7.73  | 1.268E-05            | 4.160E-05 |
| 6               | 15              | 40                 | 6.625  | 16.8 | 0.280             | 0.711 | 18.98                   | 8.62  | 1.138E-05            | 3.732E-05 |
| 6               | 15              | 80                 | 6.625  | 16.8 | 0.432             | 1.097 | 28.58                   | 12.97 | 7.556E-06            | 2.478E-05 |
| 6               | 15              | 120                | 6.625  | 16.8 | 0.562             | 1.427 | 36.40                   | 16.52 | 5.932E-06            | 1.946E-05 |
| 8               | 20              | 20                 | 8.625  | 21.9 | 0.250             | 0.635 | 22.37                   | 10.15 | 9.654E-06            | 3.167E-05 |
| 8               | 20              | 30                 | 8.625  | 21.9 | 0.277             | 0.704 | 24.70                   | 11.21 | 8.742E-06            | 2.867E-05 |
| 8               | 20              | 40                 | 8.625  | 21.9 | 0.322             | 0.818 | 28.56                   | 12.97 | 7.561E-06            | 2.480E-05 |
| 8               | 20              | 60                 | 8.625  | 21.9 | 0.406             | 1.031 | 35.64                   | 16.18 | 6.058E-06            | 1.987E-05 |
| 10              | 25              | 20                 | 10.750 | 27.3 | 0.250             | 0.635 | 28.04                   | 12.73 | 7.701E-06            | 2.526E-05 |
| 10              | 25              | 30                 | 10.750 | 27.3 | 0.307             | 0.780 | 34.25                   | 15.55 | 6.305E-06            | 2.068E-05 |
| 10              | 25              | 40                 | 10.750 | 27.3 | 0.365             | 0.927 | 40.49                   | 18.38 | 5.333E-06            | 1.749E-05 |
| 10              | 25              | 60                 | 10.750 | 27.3 | 0.500             | 1.270 | 54.74                   | 24.85 | 3.944E-06            | 1.294E-05 |
| 12              | 30              | 20                 | 12.750 | 32.4 | 0.250             | 0.635 | 33.38                   | 15.15 | 6.468E-06            | 2.122E-05 |
| 12              | 30              | 30                 | 12.750 | 32.4 | 0.330             | 0.838 | 43.78                   | 19.88 | 4.932E-06            | 1.618E-05 |
| 12              | 30              |                    | 12.750 | 32.4 | 0.375             | 0.953 | 49.57                   | 22.51 | 4.356E-06            | 1.429E-05 |
| 12              | 30              | 40                 | 12.750 | 32.4 | 0.406             | 1.031 | 53.53                   | 24.30 | 4.033E-06            | 1.323E-05 |
| 12              | 30              |                    | 12.750 | 32.4 | 0.500             | 1.270 | 65.43                   | 29.70 | 3.300E-06            | 1.082E-05 |
| 14              | 36              | 10                 | 14.000 | 35.6 | 0.250             | 0.635 | 36.72                   | 16.67 | 5.880E-06            | 1.929E-05 |
| 14              | 36              | 20                 | 14.000 | 35.6 | 0.312             | 0.792 | 45.62                   | 20.71 | 4.733E-06            | 1.552E-05 |
| 14              | 36              | 30                 | 14.000 | 35.6 | 0.375             | 0.953 | 54.58                   | 24.78 | 3.956E-06            | 1.298E-05 |
| 16              | 41              | 10                 | 16.000 | 40.6 | 0.250             | 0.635 | 42.06                   | 19.10 | 5.134E-06            | 1.684E-05 |
| 16              | 41              | 20                 | 16.000 | 40.6 | 0.312             | 0.792 | 52.28                   | 23.74 | 4.130E-06            | 1.355E-05 |
| 16              | 41              | 30                 | 16.000 | 40.6 | 0.375             | 0.953 | 62.59                   | 28.42 | 3.450E-06            | 1.132E-05 |
| 16              | 41              | 40                 | 16.000 | 40.6 | 0.500             | 1.270 | 82.78                   | 37.58 | 2.608E-06            | 8.555E-06 |

**Table 7.2 Pipe Resistance Data (Large Sizes)****STEEL PIPE DATA FOR CORROSION CALCULATIONS**

| Nominal<br>Size | Nominal<br>Size | Schedule<br>Number | O.D.   |       | Wall<br>Thickness |       | Weight<br>Per Foot<br>Per Meter |           | Linear<br>Resistance |           |
|-----------------|-----------------|--------------------|--------|-------|-------------------|-------|---------------------------------|-----------|----------------------|-----------|
|                 |                 |                    | Inch   | Cm    | Inch              | Cm    | Pounds                          | Kilograms | Ohms/Ft              | Ohms/m    |
| 18              | 46              | 10                 | 18.000 | 45.7  | 0.250             | 0.635 | 47.40                           | 21.52     | 4.555E-06            | 1.494E-05 |
| 18              | 46              | 20                 | 18.000 | 45.7  | 0.312             | 0.792 | 58.95                           | 26.76     | 3.663E-06            | 1.201E-05 |
| 18              | 46              | 30                 | 18.000 | 45.7  | 0.437             | 1.110 | 81.98                           | 37.22     | 2.634E-06            | 8.639E-06 |
| 18              | 46              |                    | 18.000 | 45.7  | 0.500             | 1.270 | 93.47                           | 42.43     | 2.310E-06            | 7.577E-06 |
| 20              | 51              | 10                 | 20.000 | 50.8  | 0.250             | 0.635 | 52.74                           | 23.94     | 4.094E-06            | 1.343E-05 |
| 20              | 51              | 20                 | 20.000 | 50.8  | 0.375             | 0.953 | 78.61                           | 35.69     | 2.747E-06            | 9.009E-06 |
| 20              | 51              | 30                 | 20.000 | 50.8  | 0.500             | 1.270 | 104.15                          | 47.28     | 2.073E-06            | 6.800E-06 |
| 24              | 61              | 10                 | 24.000 | 61.0  | 0.250             | 0.635 | 63.42                           | 28.79     | 3.404E-06            | 1.117E-05 |
| 24              | 61              | 20                 | 24.000 | 61.0  | 0.375             | 0.953 | 94.64                           | 42.96     | 2.282E-06            | 7.484E-06 |
| 24              | 61              |                    | 24.000 | 61.0  | 0.500             | 1.270 | 125.51                          | 56.98     | 1.720E-06            | 5.643E-06 |
| 30              | 76              |                    | 30.000 | 76.2  | 0.250             | 0.635 | 79.45                           | 36.07     | 2.718E-06            | 8.915E-06 |
| 30              | 76              |                    | 30.000 | 76.2  | 0.375             | 0.953 | 118.67                          | 53.88     | 1.820E-06            | 5.968E-06 |
| 30              | 76              |                    | 30.000 | 76.2  | 0.500             | 1.270 | 157.56                          | 71.53     | 1.370E-06            | 4.495E-06 |
| 36              | 91              |                    | 36.000 | 91.4  | 0.250             | 0.635 | 95.47                           | 43.34     | 2.262E-06            | 7.418E-06 |
| 36              | 91              |                    | 36.000 | 91.4  | 0.375             | 0.953 | 142.70                          | 64.79     | 1.513E-06            | 4.963E-06 |
| 36              | 91              |                    | 36.000 | 91.4  | 0.500             | 1.270 | 189.60                          | 86.08     | 1.139E-06            | 3.735E-06 |
| 42              | 107             |                    | 42.000 | 106.7 | 0.250             | 0.635 | 111.49                          | 50.62     | 1.937E-06            | 6.352E-06 |
| 42              | 107             |                    | 42.000 | 106.7 | 0.375             | 0.953 | 166.74                          | 75.70     | 1.295E-06            | 4.248E-06 |
| 42              | 107             |                    | 42.000 | 106.7 | 0.500             | 1.270 | 221.65                          | 100.63    | 9.742E-07            | 3.195E-06 |
| 48              | 122             |                    | 48.000 | 121.9 | 0.250             | 0.635 | 127.52                          | 57.89     | 1.693E-06            | 5.554E-06 |
| 48              | 122             |                    | 48.000 | 121.9 | 0.375             | 0.953 | 190.77                          | 86.61     | 1.132E-06            | 3.712E-06 |
| 48              | 122             |                    | 48.000 | 121.9 | 0.500             | 1.270 | 253.70                          | 115.18    | 8.511E-07            | 2.792E-06 |
| 54              | 137             |                    | 54.000 | 137.2 | 0.250             | 0.635 | 143.54                          | 65.17     | 1.504E-06            | 4.934E-06 |
| 54              | 137             |                    | 54.000 | 137.2 | 0.375             | 0.953 | 214.81                          | 97.52     | 1.005E-06            | 3.297E-06 |
| 54              | 137             |                    | 54.000 | 137.2 | 0.500             | 1.270 | 285.74                          | 129.73    | 7.557E-07            | 2.479E-06 |
| 60              | 152             |                    | 60.000 | 152.4 | 0.250             | 0.635 | 159.56                          | 72.44     | 1.353E-06            | 4.439E-06 |
| 60              | 152             |                    | 60.000 | 152.4 | 0.375             | 0.953 | 238.84                          | 108.43    | 9.040E-07            | 2.965E-06 |

$$\alpha = (rg)^{0.5}$$



$$R_G = (r/g)^{0.5}$$

where:

$r$  = per unit resistance of pipe ( $6.8 \times 10^{-6}$  ohm/m)

$g$  = per unit conductance of pipe (1.41 S/m)

$$\alpha = (6.8 \times 10^{-6} \Omega \times 1.41 \text{ S})^{0.5} = 3.10 \times 10^{-3}$$

$$R_G = (6.8 \times 10^{-6} \Omega / 1.41 \text{ S})^{0.5} = 2.20 \times 10^{-3} \text{ ohm}$$

Examine the situation of the middle anode on the pipeline. Equation 5 of Figure 7.2 will allow us to calculate the resistance looking in one direction from the anode, Figure 7.1.

$$R_{SO} = R_G \coth(\alpha x)$$

where:

$R_G$  = characteristic resistance ( $2.2 \times 10^{-3}$  ohm)

$\alpha$  = attenuation constant ( $3.1 \times 10^{-3}$ )

$x$  = the number of unit lengths between the end of the line and the anode location,  $1525 \text{ m} / 2$  (762.5 unit lengths)

$$R_{SO} = 2.2 \times 10^{-3} \coth(3.1 \times 10^{-3} \times 762.5)$$

$$R_{SO} = 2.24 \times 10^{-3} \text{ ohm to remote earth}$$

Since the input resistance at the center of the line looking in one direction is very close to the characteristic resistance (within 2%), this line is "electrically long" in each direction when viewed from the center of the line. Therefore, we would anticipate that attenuation could be a problem unless the anodes are properly spaced.

The bracelet anode closely resembles a sphere of radius 30 cm.

The resistance of a sphere measured to remote earth is<sup>1</sup>:

$$R_a = \frac{\rho}{4\pi r}$$

where:

- $\rho$  = Resistivity of the environment (30 ohm-cm)
- $r$  = Radius of the sphere (30 cm)
- $R_a$  = Resistance of anode to remote earth (ohm)

$$R_a = \frac{30 \text{ ohm-cm}}{4\pi \cdot 30 \text{ cm}} = 0.08 \text{ ohm}$$

If we assume a net driving potential between the anode and pipe of 0.5V [-1.0 – (-0.50)], anode potential minus steel potential to reference), the total current supplied by an anode is given by:

$$I = E / (R_{so}/2 + R_a)$$

$$I = 0.5 \text{ V} / [(2.24 \times 10^{-3} \Omega/2) + 0.080 \Omega] = 6.16 \text{ A} \text{ (3.08 A in each direction)}$$

Use Equation 2 (Figure 7.2) to calculate the voltage change of the pipe to remote earth at the receiving end with 3.08A returned to the anode at the center from the direction of the voltage measurement.

$$I = I_r \cosh(\alpha x) + (E_r/R_G) \sinh(\alpha x)$$

where:

- $I_r$  = 0
- $X$  = 762.5 units
- $I$  = 3.08A
- $\alpha$  =  $3.1 \times 10^{-3}$
- $R_G$  =  $2.2 \times 10^{-3}$  ohm.

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\*Jerry Cochran, "A Correlation of Anode-to-Electrolyte Resistance Equations Used in Cathodic Protection", NACE Corrosion 82, Paper No. 169

Rearranging the equation and solving for  $E_r$ .

$$E_r = IR_G / \sinh(\alpha x)$$

$$E_r = 3.08 \times 2.2 \times 10^{-3} / \sinh(3.1 \times 10^{-3} \times 762.5)$$

$$E_r = 0.00678 / \sinh(2.364)$$

$$E_r = 0.00129V$$

The voltage attenuation curve can then be determined. In this case the attenuation is considerable, as shown below.

The voltage between pipe and remote earth at the anode is (Equation 1, Figure 7.2):

$$E = E_r \cosh(\alpha x) + R_G I_r \sinh(\alpha x)$$

where:

$$\begin{aligned} E_r &= \text{Voltage shift at the open end (0.00129 volt)} \\ \alpha &= \text{Attenuation constant } 3.1 \times 10^{-3} \\ x &= \text{Distance of the source from the open end (762.5 units)} \\ R_G &= \text{Characteristic resistance } (2.2 \times 10^{-3} \text{ ohm}) \\ E &= 0.00129 \cosh(2.36) + 0 \\ E &= 0.00689 \text{ volt} \end{aligned}$$

There is  $[.00689 - 0.00129 / 0.00689 = 0.81]$  an 81% voltage attenuation along the pipe from the center anode, less from each of the other anodes. Therefore, maximum spacing between the anodes will be an important consideration.

## ***Existing/Rectifier/Sled***

### ***Description***

A 20.3 cm (8 in.) diameter coated steel pipeline crosses a seawater bay. The crossing is 3201 meters (10,500 ft) wide. The pipeline is electrically isolated from connecting pipelines on either shore with insulating flanges. Given the data below, design a cathodic protection system for the bay crossing.

### ***Data***

Data provided by field tests and pipeline design records.

|                                                                |                                                                  |
|----------------------------------------------------------------|------------------------------------------------------------------|
| Water depth, average                                           | 12 m (40 ft)                                                     |
| Length of pipeline section                                     | 3201m(10,500 ft)                                                 |
| Diameter of pipe                                               | 20.3 cm ( 8 in)                                                  |
| Class of pipe                                                  | (ASA Sch 40)                                                     |
| Wall thickness                                                 | 0.818 cm (0.322 in)                                              |
| Lineal resistance                                              | $2.480 \times 10^{-5}$ ohm/m<br>( $7.561 \times 10^{-6}$ ohm/ft) |
| Coating—epoxy                                                  | % of exposed metal unknown                                       |
| Environment around pipe                                        | Seawater and bottom sand 30 ohm-cm                               |
| Design life of CP                                              | 20 years                                                         |
| Electric power available on both shorelines.                   |                                                                  |
| Construction—welded steel with flanged valves on either shore. |                                                                  |

### ***Cathodic protection test data***

1. Test anode located electrically remote from pipe. No significant anode gradient in vicinity of pipe).
2. Tests at the point of current application (Figure 7.3) indicates a potential shift between pipe and a remote reference electrode of  $-0.15$  volt is required to adequately polarize the pipeline at the point of test.

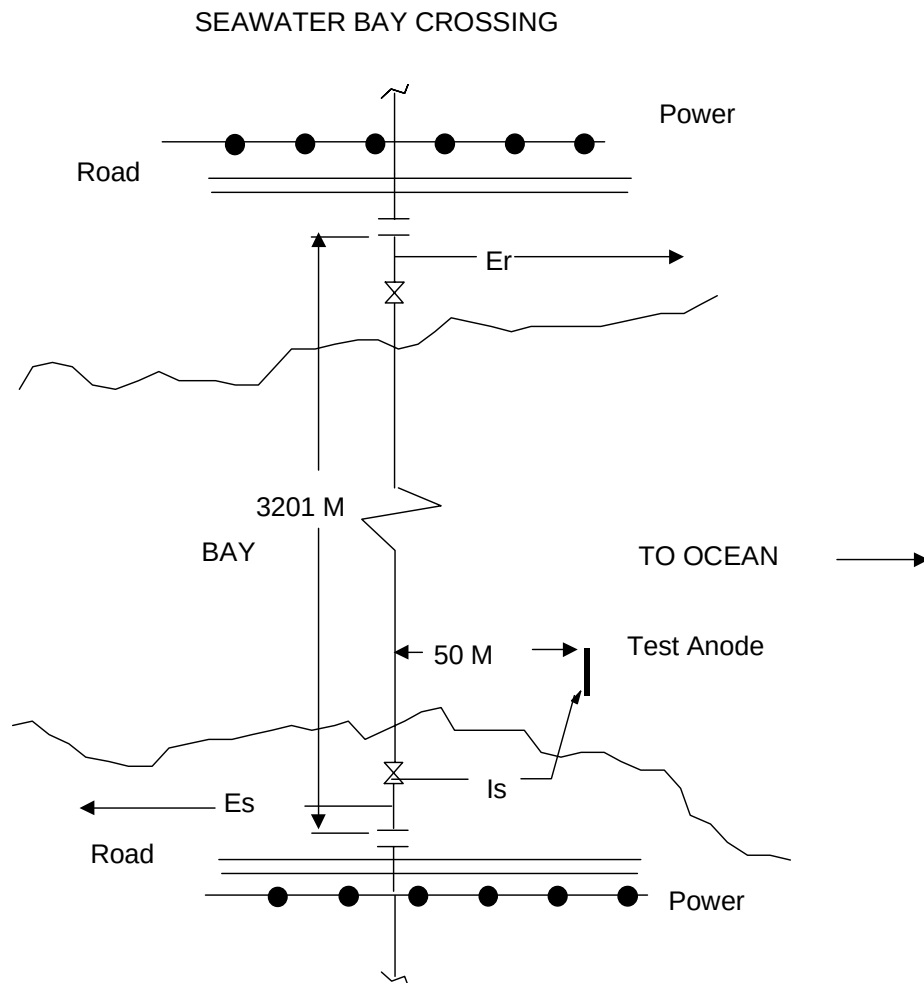


**Figure 7.3 Test Arrangement**

3. The voltage shift between pipe and a "remote" reference electrode on the same shore as the test anode is  $-0.05$  volt/ampere.
4. The voltage shift between pipe and a "remote" reference electrode on the opposite shore from the test anode is  $-0.01$  volt/ampere.

## Approach

1. Determine the electrical attenuation parameters of the pipeline section.
2. Determine the number and capacity of cathodic protection current sources required to protect the section of pipeline.
3. Design the anode(s) and power source(s) needed.

## Calculations

Calculate the attenuation constant and characteristic resistance of the pipeline section using the general equations from Figure 7.2.

Given from test data:

|         |   |                                                                                               |
|---------|---|-----------------------------------------------------------------------------------------------|
| $I_s$   | = | 1 ampere                                                                                      |
| $E_s$   | = | 0.05 volt                                                                                     |
| $E_r$   | = | 0.01 volt                                                                                     |
| $I_r$   | = | 0 amp (assumed good isolating flanges)                                                        |
| $x = y$ | = | 3201 m (distance between test current source and receiving end measurement on opposite shore) |

From Equation 3 (Figure 7.2)

$$E = E_s \cosh(\alpha y) - R_G I_s \sinh(\alpha y)$$

where:

|          |   |                                                                             |
|----------|---|-----------------------------------------------------------------------------|
| $E_s$    | = | source voltage shift (0.05V)                                                |
| $I_s$    | = | source current (1.0A)                                                       |
| $\alpha$ | = | attenuation constant                                                        |
| $y$      | = | number of 1 meter unit lengths from the sending end to location of E (3201) |
| $E$      | = | receiving end voltage shift (0.01V)                                         |
| $R_G$    | = | characteristic resistance                                                   |

The only unknowns in applying Equation 3 are the characteristic resistance,  $R_G$ , and the attenuation constant,  $\alpha$ .

From Equation 5 (Figure 7.2)

$$R_{s0} = R_G \coth(\alpha x)$$

Solving for  $R_G$ ,



$$R_G = R_{s0}/\coth(\alpha x)$$

where:

$$\begin{aligned} R_{s0} &= \text{resistance looking into open end of line (source)} \\ R_{s0} &= E_s/I_s = 0.05 \text{ ohm} \end{aligned}$$

For  $x = y = 3201$  units

$$R_G = 0.05/\coth(\alpha y)$$

Using the trigonometric identity:  $\coth(\alpha y) = \cosh(\alpha y)/\sinh(\alpha y)$ :

$$R_G = 0.05 \sinh(\alpha y)/\cosh(\alpha y)$$

Substituting  $R_G$  and the other knowns in Equation 3 (Figure 7-2), we will attempt to determine the attenuation constant.

$$E = E_s \cosh(\alpha y) - R_G I_s \sinh(\alpha y)$$

$$0.01 = 0.05 \cosh(\alpha y) - (0.05 \sinh(\alpha y)/\cosh(\alpha y))(\sinh(\alpha y))$$

$$0.01 = 0.05 \cosh(\alpha y) - 0.05 \sinh^2(\alpha y)/\cosh(\alpha y)$$

Multiplying both sides of the equation by  $\cosh(\alpha y)$  and factoring

$$0.01 \cosh(\alpha y) = 0.05 [\cosh^2(\alpha y) - \sinh^2(\alpha y)]$$

Divide both sides of the equation by 0.01.

$$\cosh(\alpha y) = 5 [\cosh^2(\alpha y) - \sinh^2(\alpha y)]$$

Now, substitute the trigonometric identity:  $\cosh^2 \alpha y - \sinh^2 \alpha y = 1$

The equation now simplifies to:  $\cosh(\alpha y) = 5$

Taking the inverse hyperbolic cosine of both sides of the equation (i.e.,  $\cosh^{-1}$  or  $\operatorname{arccosh}$ ) and solving for the attenuation constant,  $\alpha$ :

$$\begin{aligned} \cosh^{-1}(\cosh(\alpha y)) &= \cosh^{-1}(5) \\ \alpha y &= 2.2924 \end{aligned}$$

$$\alpha = 2.2924/3201 = 7.162 \times 10^{-4}$$

Now, determine the characteristic resistance,  $R_G$ :

$$R_G = 0.05/\coth 2.2924$$

$$R_G = 0.05/1.02$$

$$R_G = 0.049 \text{ ohms}$$

From attenuation formulas for  $\alpha$  and  $R_G$  solve for  $r$  and  $g$ .

$$\alpha = (rg)^{0.5}$$

$$\alpha^2 = rg$$

$$r = \alpha^2/g \quad \text{and,}$$

$$R_G = (r/g)^{0.5}$$

$$R_G^2 = r/g \quad \text{since } r = \alpha^2/g, \text{ substitute for } r$$

$$R_G^2 = \alpha^2/g^2$$

$$g^2 = \alpha^2/R_G^2$$

$$g = (\alpha^2/R_G^2)^{0.5}$$

$$g = 0.0146 \text{ Siemens/unit}$$

$$r = \alpha^2/g$$

$$r = 3.513 \times 10^{-5} \text{ ohm/unit}$$

The unit lineal resistance includes several flanged joints at valves. The unit lineal resistance of the pipeline section,  $r$ , is higher than the book value given for this size and class of pipe ( $2.480 \times 10^{-5}$  ohm/m). See Tables 7.1 & 7.2.

From Equation 3 (Figure 7.2) plot the voltage shift profile for the bay crossing from the side at  $y = 0$  to the far side at  $y = 3201$  m. Use 1 ampere for the source current so that the profile will be on a rationalized basis.

$$E = E_s \cosh(\alpha y) - R_G I_s \sinh(\alpha y)$$



where:

|          |   |                                                                 |
|----------|---|-----------------------------------------------------------------|
| $E_s$    | = | source voltage (0.05V)                                          |
| $I_s$    | = | source current (1A)                                             |
| $R_G$    | = | characteristics resistance (0.049 ohm)                          |
| $\alpha$ | = | attenuation constant ( $7.162 \times 10^{-4}$ )                 |
| $y$      | = | number of unit lengths (meters) from the source side of the bay |
| $E$      | = | voltage shift at location $y$ (volt)                            |

Figure 7.4 is the plot of the data.

## ATTENUATION ON PIPELINE

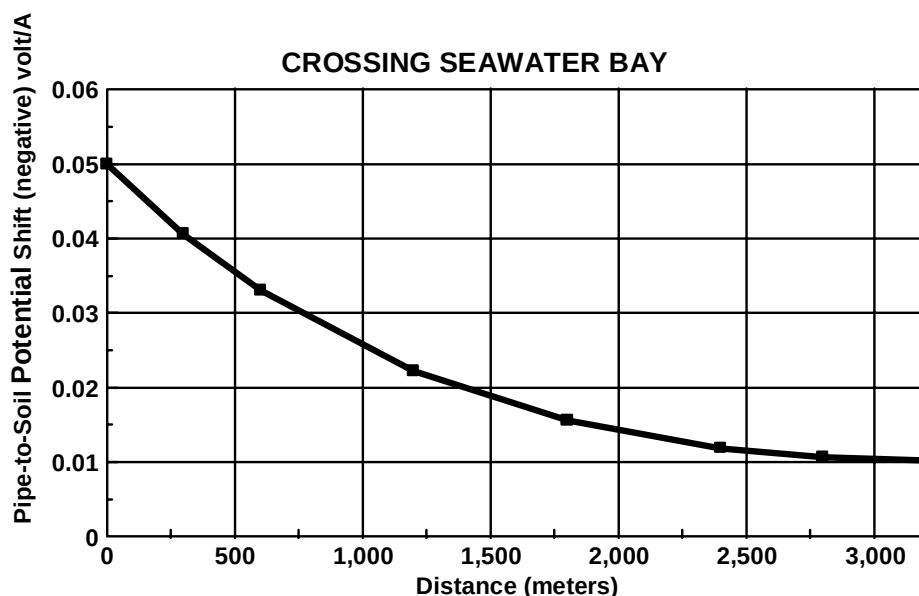


**Figure 7.4 Pipe- to-Soil Potential Attenuation**

The data clearly show that moving the pipe-to-soil potential the required – 0.15 volts all the way across the bay from a single power source is not wise. Each ampere of current applied at the source side of the bay crossing moves the potential of the pipe on the far side of the crossing by only –0.01 volt. To achieve a –0.15 volt shift in pipe to soil potential (remote earth) requires a current source of the following magnitude:  $I_s = E_r/R_{r,s}$

where:

- $R_{r,s}$  = the pipe-to-soil potential shift (electrical coupling) caused at the receiving end per ampere of current applied at the source (-0.01 V/A)
- $I_s$  = the source current (A)
- $E_r$  = potential shift at receiving side (-0.15V)
- $I_s = -0.15/-0.01 = 15A.$

## ATTENUATION ON PIPELINE

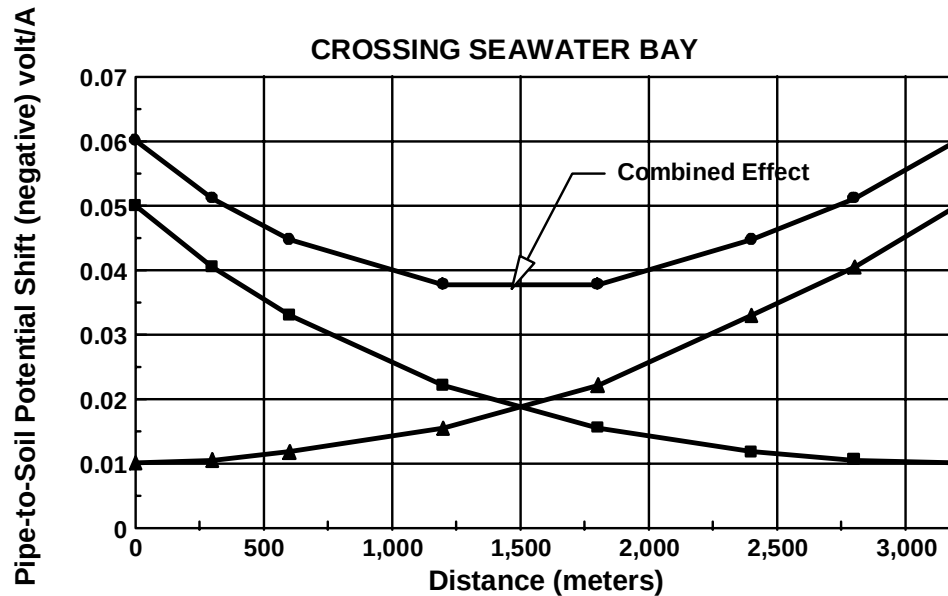


**Figure 7.5 Profile – Two Sources**

Application of 15 amperes will result in a pipe-to-soil potential shift at the source of:

$$E_s = I_s R_{s,s}$$

where:

$I_s$  = source current (15A)

$R_{s,s}$  = pipe-to-soil potential shift (electrical coupling) caused at the sending end per ampere of source current (-0.05 V/A)

$E_s$  = potential shift at sending side (volts)

$$E_s = 15 \times (-0.05) = 0.75 \text{ volt}$$

This is over five (5) times the potential shift required for protection of the pipe at the source side of the bay crossing.

Examine a design with two power sources, one on each side of the bay crossing. Assume that the general network parameters are similar for a remote anode on the far (receiving) side of the crossing as on the original (source) test side.

Figure 7.5 is a plot of the potential profile with two current sources (one on each side of the crossing). Note that the minimum potential shift is now at the center of the crossing and has a value of -0.035V for the combined effect of 1A from each power source (-0.0175 V/A from each source).

To achieve a -0.15 volt shift at the center of the crossing will require:

$$E_c = I_s R_{c,s} + I_r R_{c,r}$$

where:

- $I_s$  = current from the original source side of the crossing (A)
- $I_r$  = current from the original receiving side (A)
- $R_{c,s}$  = electrical coupling for potential shift at the center caused by current  $I_s$  (-0.0175 V/A)
- $R_{c,r}$  = electrical coupling of potential shift at the center caused by current  $I_r$  (-0.0175 V/A)
- $E_c$  = total shift in pipe-to-soil potential at the center of the crossing (-0.15 volt required)

If  $I_s$  is to equal  $I_r$  (equal currents from both sources) and

$R_{c,s} = R_{c,r} = R_{c,l} = 0.0175 \text{ V/A}$  then:

$$E_c = 2IR_{c,l}$$

$$I = E_c / (2R_{c,l})$$

$$I = -0.15 \text{ V} / 0.035 \Omega$$

$$I = 4.3 \text{ A (from each of 2 power sources)}$$

The total required current is reduced to about 8.6A from 15A required from a single source. The potential shift at the shorelines with operation at 4.3A per source is:

$$\begin{aligned} E_s &= I_s R_{s,s} + I_r R_{s,r} \\ E_r &= I_s R_{r,s} + I_r R_{r,r} \end{aligned}$$

$E_s$  and  $E_r$  = pipe-to-soil potential shift at either shore line (V)  
 $I_s$  and  $I_r$  = current from each power source potential (4.3A)  
 $R_{x,y}$  = electrical couplings at location X caused by current source Y

$$\begin{aligned} R_{s,s} &= R_{r,r} = -0.05 \text{ V/A} \\ R_{s,r} &= R_{r,s} = -0.01 \text{ V/A} \\ E_s &= 4.3 \text{ A } (-0.05 \Omega) + 4.3 \text{ A } (-0.01 \Omega) \\ E_s &= -0.26 \text{ volt} \end{aligned}$$

Similarly:

$$E_r = -0.26 \text{ volt}$$

The voltage shift at the shore line locations (-0.26 volt) is only 1.7 times the required value compared with 5 times for a single source.

## **Anode Design**

Older coated pipelines in offshore service are subject to many forces that can further reduce the effectiveness of the protective coating. With a pipeline such as in this example, providing for increased future demand on the cathodic protection system is good practice. Also avoidance of excessive over protection will help to lessen the stress on the remaining protective coating. We choose to design the cathodic protection using the two source approach.

Electric power is available on both sides of the bay crossing. A small rectifier powered sled type anode will readily meet the requirements. Sleds for impressed current systems are generally fabricated using non-metallic structural members to avoid corrosion by interference currents associated with the anode operation. If wood is used to support the active anodes, some form of anchoring is necessary to avoid flotation and movement with ocean currents and tides. The purpose of the sled is to support and protect the active anodes. The anodes can be silicon iron, platinized titanium or niobium, mixed metal oxide or graphite blocks.

For this design we choose tubular high silicon iron anodes. The design parameters are:



|                                 |                                               |
|---------------------------------|-----------------------------------------------|
| Anode discharge current density | 1.6ma/cm <sup>2</sup> (1.5A/ft <sup>2</sup> ) |
| Consumption rate                | 0.4kg/A-yr(0.9lb./A-yr)                       |
| Utilization factor              | .6                                            |
| Design current                  | 5A/sled                                       |
| Design life                     | 20 years                                      |

$$\text{Surface area of anodes: } A_s = I / i$$

where:

$I$  = total current output (5A)  
 $i$  = optimum design current density (0.0016A/cm<sup>2</sup>)  
 $A_s$  = total anode surface area (cm<sup>2</sup>)

$$A_s = 5 \text{ A} / 0.0016 \text{ A/cm}^2 = 3125 \text{ cm}^2 (3.36 \text{ ft}^2) = 0.3125 \text{ m}^2$$

Minimum weight of anode material:

$$W = C_r t I / f_u$$

where:

$C_r$  = rate of consumption (0.4 kg/A-yr)  
 $t$  = design life (20 yrs)  
 $I$  = design current (5A)  
 $f_u$  = utilization factor (0.6)  
 $W$  = weight of anode material (kg)

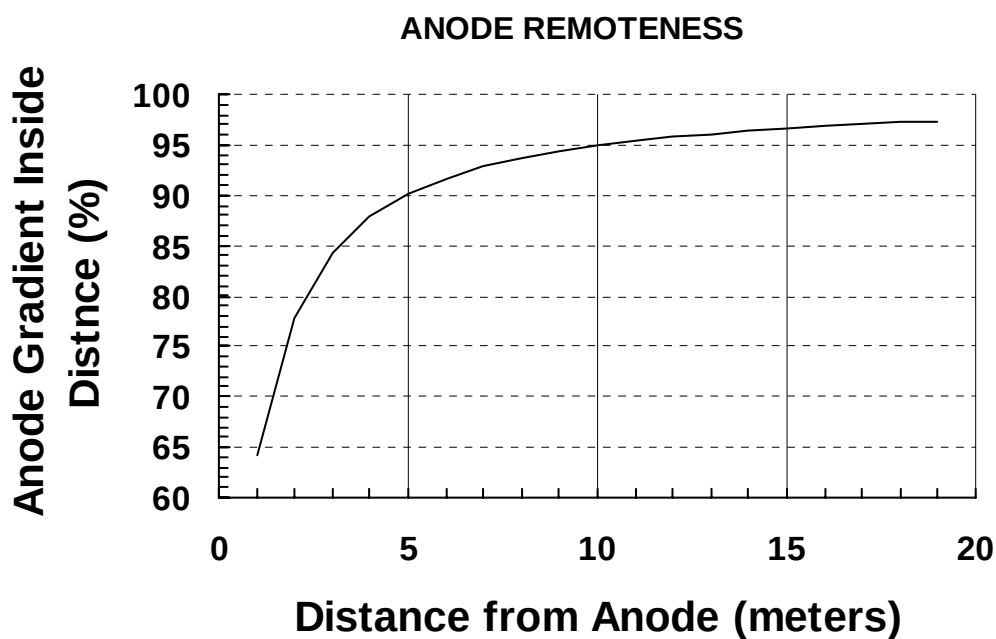
$$W = 0.4 \text{ kg/A-yr} \times 20 \text{ yr} \times 5 \text{ A} / 0.6$$

$$W = 66.7 \text{ kg}$$

Two (2) 39 kg, 9.5 cm diameter by 2.134 meter long anodes will provide adequate material for a 20 year life. The surface area of each anode is 6400 cm<sup>2</sup> (6.9 ft<sup>2</sup>). The discharge surface is about 4 times the design value. This should not be a significant problem for this type of anode since low current density is generally more acceptable than excess current density. The 0.6 utilization factor is conservative.

Each sled design will consist of two 39 kg tubular anodes mounted on a wooden frame with provisions to anchor the sled sufficiently off shore to prevent accidental damage by small boats. The anode leads will be trenched to the rectifier site.

### **Remoteness**



Anode Length = 213.4 cm

Anode Diameter = 9.5 cm

**Figure 7.6 Anode Remoteness**

To minimize anode gradient at the pipeline the separation of the anode sled from the pipe should be enough to assure that the pipe is outside 95% of the anode voltage gradient. Figure 7.6 is a remoteness curve for a single 9.5 cm diameter 2.13 m long anode. This should approximate the configuration of the sled located in water 2 m deep. This chart indicates that the anode sleds should be located at least 10 meters from the pipeline.

A reasonable size for the anode sleds is 2.5 m by 1.5 m with the two anodes placed side by side 1 m apart.

### **Power Supply**

Use the Sunde formula to estimate the resistance of the anodes to remote earth.

$$R_N = \frac{0.005\rho}{\pi NL} \left( \ln\left(\frac{8L}{d}\right) - 1 + \frac{2L}{s} \ln(0.656N) \right)$$

where:

- $R_N$  = grounded resistance (ohm)
- $\rho$  = 30 ohm-cm average resistivity
- $N$  = number of anodes in parallel (2)
- $L$  = length of an anode (2.134m.)
- $d$  = anode diameter (0.095 m.)
- $s$  = spacing of anodes (1 m.)

$$R_N = (0.01119) [\ln(180) - 1 + 4.268 \ln(1.312)] \text{ ohm}$$

$$R_N = 0.06 \text{ ohm}$$

In this case both the anode to earth resistance and the pipe to earth resistance are small. If AWG No. 8 copper wire is used for the anode feeds and the sleds are placed 50 m from the pipeline and rectifier, the parallel resistance of the two anode feed wires will be:



$$R_W = rL/2$$

where:

- $r$  = unit resistance of number 8 wire ( $2.061 \times 10^{-3}$  ohm/m)
- $L$  = length of wire (50 m)
- $R_W$  = resistance of two anode lead wires in parallel
- $R_W = 2.061 \times 10^{-3} \Omega/\text{m} \times 50 \text{ m}/2 = 0.052 \Omega$

The total circuit resistance is:

$$R_T = R_N + R_W + R_X + R_P$$

where:

- $R_N$  = resistance to remote earth of the anodes (0.060 ohm)
- $R_W$  = resistance of anode wires (0.052 ohm)
- $R_X$  = miscellaneous internal resistances in power supply and pipe connector (estimated) (0.1 ohm)
- $R_P$  = resistance of pipe to remote earth at point of attachment (0.05 ohm)

$$R_T = 0.060 + 0.052 + 0.100 + 0.050 = 0.262 \text{ ohms}$$

Allowing 2.0 volts for the polarized back voltage between the pipe and anode, the rectifier voltage required for the design is:

$$E_o = IR_T + 2.0$$

where:

- $I$  = rectifier design current (5A)
- $R_T$  = pipeline–anode circuit resistance (0.262 ohms)

$$E_o = 5 \text{ A} \times 0.262 \Omega + 2.0 \text{ V} = 3.31 \text{ V}$$

This design consists of two rectifier (one on either shore). The nearest off the shelf commercial rectifiers are rated at 8A, 8 volts. The anodes will consist of two high silicon iron tubular units mounted on sleds anchored 50 m from the pipeline.

# Offshore Jacket Example

## ***New/Stand-off/Aluminum***

### ***General***

Offshore structures are often complex. Unlike pipelines and tanks the geometry is a maze of columns and trusses which present a formidable challenge for cathodic protection design. Those working in the offshore field of corrosion control frequently rely on some form of computer program to assist in design work. This is particularly the case where impressed current cathodic protection systems are involved. Students interested in pursuing application of computer programs in the design of offshore cathodic protection systems should find *Computers in Corrosion Control*, Volume 2<sup>2</sup> a valuable reference. The following example of cathodic protection design on an offshore jacket is a non-computerized approach to the problem. Additional information on offshore platforms can be found in NACE International RP0176-94<sup>3</sup>.

### ***Description***

Figure 7.7 shows an overall schematic diagram of a launch tripod jacket for installation in the Gulf of Mexico. Surface areas listed in the figure have been obtained from the engineering drawings for the jacket. The right column gives areas of structural members in the vertical members of each bay. Those in the left column are areas of horizontal members and the vertical members within about 1 meter of each joint between bays. In addition to the structure shown there will be piling below mudline and six (6) producing wells.

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<sup>2</sup> "Computers in Corrosion Control", Volume 2, A. C. Van Order, R. C. Erbar, D. Wilson, NACE International, Houston

<sup>3</sup> RP0176-94, "Corrosion Control of Steel Fixed Offshore Platforms Associated with Petroleum Production", NACE International, Houston.



## Requirements Specific to the Design

1. Design life of C.P. system to be 20 years.
2. Current density for cathodic protection in water zone, use  $6.46 \text{ uA/cm}^2$  ( $6 \text{ mA/ft}^2$ ) (maintenance),  $28 \text{ uA/cm}^2$  ( $26 \text{ mA/ft}^2$ ) (start-up)
3. Current density for cathodic protection in the mud zone, use  $1.08 \text{ uA/cm}^2$  ( $1 \text{ mA/ft}^2$ )
4. Provide an additional 2 amperes of cathodic protection design current for each well casing. (A total of 12 amperes for the 6 wells at this jacket).
5. The structure shall have a minimum potential of  $-0.80 \text{ V}$  measured versus a silver/silver chloride reference electrode. The average native potential is assumed to be  $-0.56 \text{ volt}$  versus a silver/silver chloride reference electrode.
6. Cathodic protection shall be provided by aluminum alloy galvanic anodes.

### LIFT TRIPOD JACKET

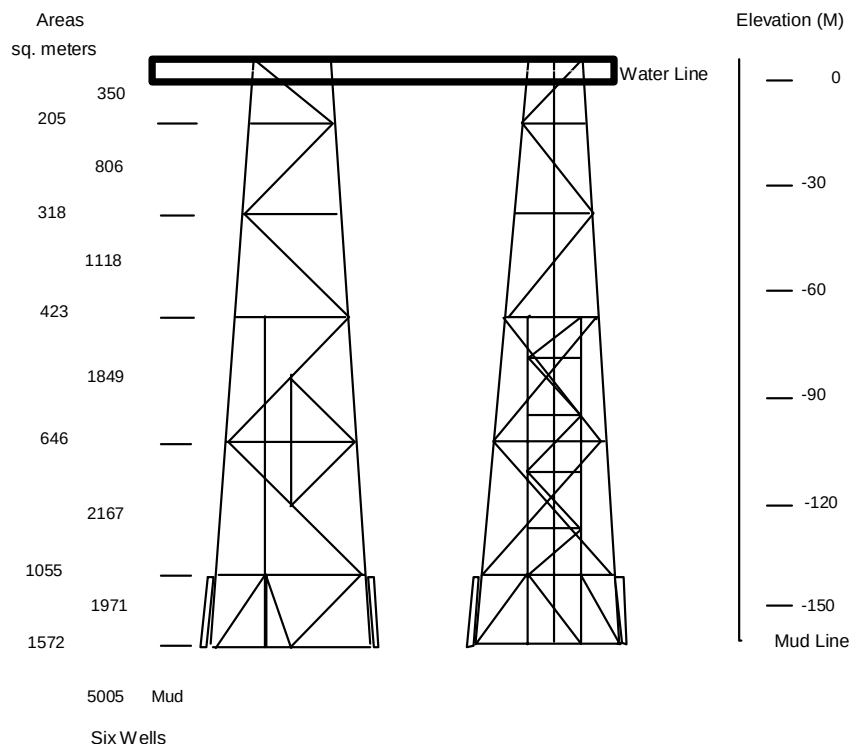


**Figure 7.7 Schematic Diagram of Jacket**

Anodes exposed to water only shall have the following composition by weight:

|                    |   |                    |
|--------------------|---|--------------------|
| Zinc               | = | 0.35% – 0.50%      |
| Silicon            | = | 0.10% max.         |
| Mercury            | = | 0.035% – 0.048%    |
| Aluminum           | = | remainder          |
| Potential shall be | = | 1.05V vs. Ag/Ag Cl |

Anodes exposed to partial or total contact with mud shall have the following composition by weight.

|                    |   |                     |
|--------------------|---|---------------------|
| Zinc               | = | 3.0%                |
| Silicon            | = | 0.1%                |
| Indium             | = | 0.015%              |
| Aluminum           | = | remainder           |
| Potential shall be | = | 1.09 V vs. Ag/Ag Cl |

7. Anode consumption rates used in the design calculations shall be:

|                 |   |                            |
|-----------------|---|----------------------------|
| Seawater anodes | – | 3.1 kg/A-yr (6.8 lb./A-yr) |
| Mudline anodes  | – | 3.4 kg/A-yr (7.6 lb./A-yr) |

8. Utilization factor 0.9
9. Anode distribution shall be in direct proportion to the current requirements based on surface areas present in the zone of influence.
10. Anodes shall not be installed across structural joints or mounted so as to protrude outside the structure where damage might occur.

### **Approach**

1. Determine the total surface areas in seawater and mud zones which are to receive cathodic protection.
2. Calculate the start-up (initial) and maintenance current required to protect the structure.
3. Calculate the minimum weight of anode material required for a 20-year service life.
4. Estimate effective anode to structure resistances.
5. Determine number and size of anodes required.

### **Surface Areas**

Surface areas are derived from the jacket design drawings and are summarized on Figure 7.7.

$$A_{sw} = \text{surface area in seawater (12,480 m}^2\text{)}$$

$$A_{sm} = \text{surface area in mud (5,005 m}^2\text{)}$$

### **Current Required**

Current required is given by the formula:

$$I = iA_s$$

where:

$$i = \text{current density required (A/m}^2\text{)}$$

$$A_s = \text{surface area (m}^2\text{)}$$

In seawater:

$$i = 0.28 \text{ A/m}^2 \text{ (start-up)}$$

$$i = 0.065 \text{ A/m}^2 \text{ (maintenance)}$$

$$A_{sw} = 12,480 \text{ m}^2$$

$$I = 0.28 \text{ A/m}^2 \times 12,480 \text{ m}^2 = 3494.4 \text{ A (start-up)}$$

$$I = 0.065 \text{ A/m}^2 \times 12,480 \text{ m}^2 = 811.2 \text{ A (maintenance)}$$

In mud:

$$i = 0.0108 \text{ A/m}^2$$

$$A_{sm} = 5005 \text{ m}^2$$

$$I = 0.0108 \text{ A/m}^2 \times 5005 \text{ m}^2 = 54.1 \text{ A}$$

For wells:

$$I = 12 \text{ A (given for six wells)}$$

Total Current Required

$$I_{\text{Start-up}} = 3494.4 + 54.1 + 12 = 3560.5 \text{ A}$$

$$I_{\text{Maintenance}} = 811.2 + 54.1 + 12 = 877.3 \text{ A}$$

### **Weight of Anode Material**

The weight of material required is given by the formula.

$$W = C_r t I / f_u$$

where:



$C_r$  = rate of consumption (kg/A-yr)  
 $t$  = design life (yr)  
 $I$  = current (A)  
 $f_u$  = utilization factor (0.9)  
 $W$  = weight of material (kg)

Weight required for initialization:

Assume full polarization will be achieved in one month (0.083 yr). Neglect difference in consumption rates among different aluminum alloys.

$C_r$  = 3.1 kg/A-yr  
 $t$  = 0.083 yr  
 $I$  = 3560A  
 $f_u$  = 0.9

$$W = 3.1 \text{ kg/A-yr} \times 0.083 \text{ yr} \times 3560 \text{ A} / 0.9 = 1018 \text{ kg}$$

Weight required for maintenance:

$C_r$  = 3.1 kg/A-yr  
 $t$  = 20 – 0.083 = 19.9 yr  
 $I$  = 877A  
 $f_u$  = 0.9

$$W = 3.1 \text{ kg/A-yr} \times 19.9 \text{ yr} \times 877 \text{ A} / 0.9 = 60,113 \text{ kg}$$

Total weight of anode material required:

$$W = 60,113 \text{ kg} + 1018 \text{ kg} = 61,131 \text{ kg} (134,488 \text{ lbs.})$$

### ***Anode-to-Structure Resistance.***

Galvanic anodes used in offshore applications have heavy steel cores that are welded directly to the structure. Connection resistance is low enough to be insignificant. Also, the large size of the structure makes structure to remote earth resistance negligible. The only significant resistance is that of the anode to remote earth.

Rapid buildup of calcareous deposits in the immediate vicinity of an anode overcomes proximity effects. The deposits and surface over-voltage (polarization) act like a protective coating and make the anode appear "remote" from the structure.

NACE<sup>4</sup> recommends use of Dwight's equation for a vertical anode in calculating the anode resistance to remote earth.

$$R = \frac{0.005\rho}{\pi L} \left( \ln \left( \frac{4L}{r} \right) - 1 \right)$$

where:

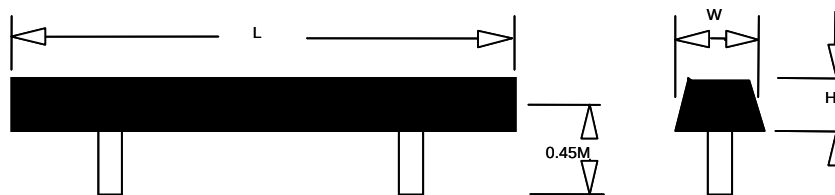
- $\rho$  = resistivity of environment (ohm-cm)
- $L$  = length of anode (m)
- $r$  = anode radius (circumference /  $2\pi$ ) (m)
- $R$  = resistance of anode to remote earth (ohms)

Figure 7.8 shows the dimensions of several sizes of anodes suitable for this structure. The calculated resistance to remote earth in 20 ohm-cm Gulf of Mexico seawater is shown in a column next to the anodes. As the anode is consumed the effective radius decreases. NACE recommends using  $r/2$  for derating the anode.

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<sup>4</sup> NACE Standard RP0176 (1983 Revision) Recommended Practice - Corrosion Control of Steel, Fixed Offshore Platforms Associated with Petroleum Production, NACE Houston, TX

## TYPICAL OFFSHORE ANODES



$$r = 2(H + W)/2 \quad \pi = (H + W)/\pi$$

$$R = 0.005 \cdot \rho / \pi L [\ln(4L/r) - 1]$$

$$\rho = 20 \text{ ohm} \cdot \text{cm}$$

| Type     | Weight of |      |       |       |      |       |       | Derated | Values |
|----------|-----------|------|-------|-------|------|-------|-------|---------|--------|
| Design . | Aluminum  |      | $W$   | $H$   | $L$  | $r$   | $R$   | $r$     | $R$    |
|          | kg        | lbs. | m     | m     | m    | m     | ohm   | m       | ohm    |
| A        | 148       | 325  | 0.165 | 0.152 | 2.44 | 0.101 | 0.047 | 0.050   | 0.056  |
| B        | 329       | 725  | 0.241 | 0.216 | 2.44 | 0.145 | 0.042 | 0.073   | 0.051  |
| C        | 375       | 825  | 0.305 | 0.280 | 1.52 | 0.186 | 0.052 | 0.093   | 0.067  |
| D        | 415       | 915  | 0.305 | 0.267 | 1.83 | 0.182 | 0.047 | 0.091   | 0.059  |
| E        | 454       | 1000 | 0.305 | 0.254 | 2.13 | 0.178 | 0.043 | 0.089   | 0.053  |
| F        | 490       | 1080 | 0.305 | 0.229 | 2.44 | 0.170 | 0.040 | 0.085   | 0.049  |
| G        | 536       | 1180 | 0.305 | 0.229 | 2.74 | 0.170 | 0.037 | 0.085   | 0.045  |
| H        | 572       | 1260 | 0.305 | 0.229 | 3.05 | 0.170 | 0.034 | 0.085   | 0.041  |
| I        | 612       | 1348 | 0.305 | 0.229 | 3.35 | 0.170 | 0.032 | 0.085   | 0.039  |

**Figure 7.8 Anode Sizes**

### Number and Size of Anodes Required

Assume negligible mutual effects among anodes (the output of any anode is not affected by the output of other anodes on a short time basis).

Weight basis.

$N$  = Total weight required/anode weight

$N$  = 61,131 kg/anode weight



Current basis. By Ohm's law:

$$\begin{aligned} I_a &= E/R_a \text{ and } N = I_T/I_a \text{ therefore,} \\ N &= I_T R_a/E \end{aligned}$$

where:

$$E = (E_a - E_s) = \text{Open circuit (start-up potential)}$$

$$E_a = \text{open circuit anode to reference electrode potential} \\ (-1.05\text{V})$$

$$E_s = \text{native structure to reference electrode potential} \\ (-0.56\text{V})$$

$$E = -1.05 \text{ V} + 0.56 \text{ V} = 0.49 \text{ V}$$

$$I_a = \text{Start-up current from a typical anode (A)}$$

$$R_a = \text{Single anode resistance (ohm)}$$

$$I_T = \text{Total start-up current (3560 A)}$$

Current basis (maintenance current).

$$E = \text{Polarized potential between anodes and structure}$$

$$E = -1.05 \text{ V} + 0.80 \text{ V} = -0.25 \text{ V}$$

$$I_T = \text{Total maintenance current (877A)}$$

Table 7.3 summarizes the calculations on a weight, start-up current, and maintenance current basis for each of the various size anodes shown in Figure 7.8. With the exception of the Type A (148kg) anode, the start-up current basis requires the greatest number of anodes. Cost of installation vs. material cost is one factor in the selection of anode type. Installation costs will be a dominant factor if divers are required during installation. Another factor is the number of anodes required to effectively distribute current over the structure.

In this problem the ratio of the number of anodes required to provide adequate start-up current to the number required for minimum total anode weight for the specified service life is about 3:1 for anode types C through I. There are, therefore, no material cost savings in using the lighter anodes vs. heavy anodes. On this basis, the minimum number of anodes, which would provide adequate coverage, would be the choice. Type H or I anodes appear best suited to the problem.

**Table 7.3 Number of Anodes Required**

| Type   | Weight of Aluminum | Derated Resistance | Number of Anodes Required |               |             |
|--------|--------------------|--------------------|---------------------------|---------------|-------------|
|        |                    |                    | Weight                    | Current Basis |             |
| Design | kg                 | ohm                | Basis                     | Start-up      | Maintenance |
| A      | 148                | 0.056              | 413                       | 407           | 196         |
| B      | 329                | 0.051              | 186                       | 371           | 179         |
| C      | 375                | 0.067              | 163                       | 488           | 235         |
| D      | 415                | 0.059              | 147                       | 429           | 207         |
| E      | 454                | 0.053              | 135                       | 385           | 186         |
| F      | 490                | 0.049              | 125                       | 356           | 172         |
| G      | 536                | 0.045              | 114                       | 327           | 158         |
| H      | 572                | 0.041              | 107                       | 299           | 144         |
| I      | 612                | 0.039              | 100                       | 283           | 137         |

The total number of anodes must be distributed on the basis of surface areas of the zones on the jacket. The total surface of jacket steel in seawater is 12,480 m<sup>2</sup>. Of the total start-up current (3560A), 3494A relates to the seawater surfaces. This represents 98% of the current. From this only 2% of the current (and number of anodes) relates to the mud zone and wells. For Type I anodes, the number of anodes dedicated to the mud zone is:

$$N_m = 0.02 \times 283 = 5.66 \text{ anodes}$$

Six (6) anodes will be added to the bottom seawater zone. The remaining 277 anodes will be distributed in proportion to the surface area of the various zones on the jacket.

Table 7.4 lists the relative surface areas of the jacket and the anode distribution to the nearest whole anode.

**Table 7.4 Surface Areas and Anodes Required by Elevation**

| <b>Elevation</b> | <b>Area</b>       | <b>Relative Fraction of Area</b> | <b>Number of Anodes</b> |
|------------------|-------------------|----------------------------------|-------------------------|
| <b>Meters</b>    | <b>Sq. Meters</b> |                                  |                         |
| 0 to -14         | 350               | 0.028                            | 8                       |
| -14              | 205               | 0.016                            | 4                       |
| -14 to -38       | 806               | 0.065                            | 18                      |
| -38              | 318               | 0.025                            | 7                       |
| -38 to -69       | 1118              | 0.090                            | 25                      |
| -69              | 423               | 0.034                            | 9                       |
| -69 to -105      | 1849              | 0.148                            | 41                      |
| -105             | 646               | 0.052                            | 14                      |
| -105 to -143     | 2167              | 0.174                            | 48                      |
| -143             | 1055              | 0.085                            | 24                      |
| -143 to -160     | 1971              | 0.158                            | 44                      |
| -160             | 1572              | 0.126                            | 35 + 6 = 41             |
| <b>Totals</b>    | <b>12,480</b>     | <b>1.000</b>                     | <b>283</b>              |

Since the structure is a tripod, slight adjustments can be made to make the design symmetrical. The anodes in the bottom zone must be made of the aluminum-indium alloy because of possible exposure to mud.

The design could be further fine tuned by considering different size anodes for each zone. Another approach might involve using aluminum anodes for the long-term maintenance current requirements while employing magnesium anodes or a temporary impressed current system for start-up requirements. The student is encouraged to explore such approaches.

## Summary

1. An example of an offshore pipeline with distributed galvanic anodes and attenuation problems.
2. An example of an impressed current, sled, design for an offshore pipeline with an attenuation problem.
3. An example of a galvanic anode cathodic protection system for an offshore jacket.

### Water Tanks Design Examples

#### ***Existing/Rectifier/Silicon Iron***

##### ***Description***

The protective coating on a large elevated water storage tank has deteriorated. The tank is located in an area where winter icing is not a problem. Design an impressed current cathodic protection system using silicon iron anodes. Consider the tank to be bare. Use the data listed below in preparing the design.

##### ***Data***

- |                                                                                                                                                                            |                                        |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------|
| 1. Tank capacity                                                                                                                                                           | 1,893 m <sup>3</sup> (500,000 gallons) |
| 2. Height of tank from ground to bottom of bowl                                                                                                                            | 35 m (115 ft)                          |
| 3. Tank diameter                                                                                                                                                           | 17.08 m (56 ft)                        |
| 4. Water level in tank.                                                                                                                                                    | 10.7 m (35 ft)                         |
| 5. Overall depth of tank                                                                                                                                                   | 11.9 m (39 ft)                         |
| 6. Height of vertical shell                                                                                                                                                | 3.35 m (11 ft)                         |
| 7. Riser pipe diameter                                                                                                                                                     | 1.52 m (60 in)                         |
| 8. Shape of tank                                                                                                                                                           | Ellipsoidal, top and bottom            |
| 9. Estimated current requirement                                                                                                                                           | 4 $\mu\text{A}/\text{cm}^2$            |
| 10. Power available                                                                                                                                                        | 120/240 V 60 Hz. single phase          |
| 11. Design life                                                                                                                                                            | 10 yrs                                 |
| 12. Average water resistivity                                                                                                                                              | 4,000 ohm-cm                           |
| 13. Assumed anode deterioration rate at manufacturers rated current density                                                                                                | 0.454 kg/A-yr (1 lb./A-yr)             |
| 14. Assumed utilization factor                                                                                                                                             | -50%                                   |
| 15. Assume negligible cathode (tank) to water resistance                                                                                                                   |                                        |
| 16. Assume that the protective coating in the tank will continue to deteriorate. The cathodic protection design should be based on 100% of the wetted surfaces of the tank |                                        |

## Approach

1. Calculate the wetted surface areas in the tank.
2. Estimate the current needed to protect the wetted walls of the tank bowl and the riser pipe.
3. Calculate the weight of anode material (silicon iron) needed to provide a 10-year service life.
4. Based on the number of anode units required by weight of material to protect the bowl side wall, the bowl bottom and the riser, calculate the position of the anodes (anode locations) which will best distribute current to the surfaces.
5. Estimate the electrical resistance of the various anode units.
6. Determine power supply requirements.

## Calculations

### CALCULATE THE WETTED SURFACE OF THE TANK BOWL:

Figure 8.1 gives the formulas for calculating the surface areas of an ellipsoidal tank.

The total surface area of the ellipsoid sections (top and bottom) of the tank is given by the formula:

$$A_{se} = 2\pi a^2 + \frac{\pi b^2}{e} \ln \left( \frac{1+e}{1-e} \right)$$

where:

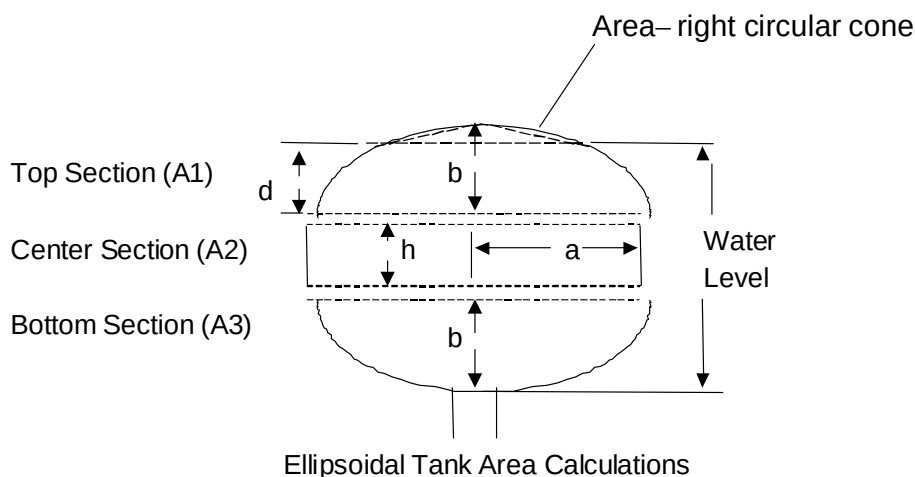
$A_{se}$  = surface area of ellipsoid

$a$  = semi-major axis of ellipsoidal tank (8.54 m)

$b$  = semi-minor axis of ellipsoidal tank (4.27 m)

$e = [(a^2 - b^2)^{0.5}] / a = (0.866)$

$$A_{se} = 2\pi(8.54\text{m})^2 + \frac{\pi(4.27\text{m})^2}{0.866} \ln \left( \frac{1+0.866}{1-0.866} \right) = 632.4\text{m}^2$$



Area of Ellipsoid (Full Top + Bottom Sections) =  $A_{se}$

$$A_{se} = 2\pi a^2 + (\pi b^2/e) \ln [(1+e)/(1-e)]$$

$$\text{where } e = [(a^2 - b^2)^{0.5}] / a$$

Area of Conical Surface of Right Circular Cone =  $A_{sc}$

$$A_{sc} = \pi r(r^2 + h^2)^{0.5}$$

$$\text{where } h = b - d$$

$r$  = radius at high water line

$$r = a (1 - d^2/b^2)^{0.5}$$

Area of Center Cylinder Section =  $A_2$

$$A_2 = 2\pi ah$$

$$\text{Area of Top Section (A1)} = \frac{1}{2} A_{se} - A_{sc}$$

$$\text{Area of Bottom Section (A3)} = \frac{1}{2} A_{se} - \pi R^2$$

**Figure 8.1 Tank Bowl Calculations**

The water level in the top ellipsoidal section of the tank is:

$$d = L_w - h - b$$

where:

- $d$  = height of water level in top ellipsoidal section (m)
- $L_w$  = level of water in the tank (10.7m)
- $h$  = height of vertical shell (3.35m)
- $b$  = semi-minor axis of ellipsoidal tank (4.27 m)

$$d = 10.7 \text{ m} - 3.35 \text{ m} - 4.27 \text{ m} = 3.08 \text{ m}$$

The non-wetted surface of the top ellipsoidal section is a mathematical integral and cannot be reduced to a simple formula. If the diameter of the water level in the tank (upper ellipsoidal section) is large compared with

the height of the center of the top of the tank above the water level, the surface area above the water level is approximately equal to that of a right circular cone. The formula for that surface area is given by:

$$A_{sc} = \pi r (r^2 + h_c^2)^{0.5}$$

where:

$r$  = radius of the tank at the water level (base of a right circular cone) in meters

$h_c$  = height of the center of the tank above the water level (b - d), 1.19m

From the equation for an ellipse:

$$\frac{r^2}{a^2} + \frac{d^2}{b^2} = 1$$

Solve for  $r$ ,

$$r = a \left( 1 - \frac{d^2}{b^2} \right)^{0.5}$$

where:

$a$  = semi-major axis of ellipsoidal tank (8.54 m)

$b$  = semi-minor axis of ellipsoidal tank (4.27 m)

$d$  = height of water level in top ellipsoidal section (3.08m)

$$r = 8.54\text{m} \left( 1 - \frac{(3.08\text{m})^2}{(4.27\text{m})^2} \right)^{0.5} = 5.92\text{m}$$

Now solve for the surface area of the right circular cone,  $A_{sc}$

$$A_{sc} = \pi \times 5.92\text{m} \times ((5.92\text{m})^2 + (1.19\text{m})^2)^{0.5}$$

$$A_{sc} = 112.2\text{ m}^2$$



The wetted surface area of the top ellipsoidal section of the tank ( $A_1$ ) is given by:

$$A_1 = (A_{se}/2) - A_{sc}$$

where:

$$\begin{aligned} A_{se} &= \text{the total ellipsoidal surface area of the tank (632.4m}^2\text{)} \\ A_{sc} &= \text{the approximate surface area above the water level (112.2m}^2\text{)} \end{aligned}$$

$$A_1 = 316.2 \text{ m}^2 - 112.2 \text{ m}^2 = 204 \text{ m}^2$$

The wetted surface area of the center cylinder section ( $A_2$ ) is given by:

$$A_2 = 2\pi ah$$

where:

$$\begin{aligned} a &= \text{semi-major axis of ellipsoidal tank (8.54 m)} \\ h &= \text{height of vertical shell (3.35 m)} \end{aligned}$$

$$A_2 = 2\pi (8.54 \text{ m} \times 3.35 \text{ m}) = 179.8 \text{ m}^2$$

The wetted surface area of bottom section ( $A_3$ ) is given by:

$$A_3 = A_{se}/2 - \pi r_p^2$$

where:

$$\begin{aligned} r_p &= \text{radius of the riser pipe (0.76 m)} \\ A_{se} &= \text{the total ellipsoidal surface area of the tank (632.4m}^2\text{)} \end{aligned}$$

$$A_3 = 632.4 \text{ m}^2/2 - \pi(0.76 \text{ m})^2 = 314.4 \text{ m}^2$$

Total wetted area of tank:

$$A_T = A_1 + A_2 + A_3$$

$$A_T = 204 \text{ m}^2 + 179.8 \text{ m}^2 + 314.4 \text{ m}^2 = 698.2 \text{ m}^2$$

**AREA OF RISER PIPE**

$$A_{sR} = 2\pi r_p h_p$$

where:

$$\begin{aligned} r_p &= \text{radius of riser pipe (0.76 m)} \\ h_p &= \text{height of riser pipe (35 m)} \end{aligned}$$

$$A_{sR} = 2 \times \pi \times 0.76 \text{ m} \times 35 \text{ m} = 167.1 \text{ m}^2$$

***Calculation of maximum design current for cathodic protection based on 4 microamperes/cm<sup>2</sup> of bare surface area***

**TANK BOWL**

$$\begin{aligned} I_B &= i A_T \\ I_B &= 4.0 \times 10^{-6} \text{ A/cm}^2 \times 6.982 \times 10^6 \text{ cm}^2 = 27.9 \text{ A} \end{aligned}$$

**RISER**

$$\begin{aligned} I_R &= i A_{sR} \\ I_R &= 4.0 \times 10^{-6} \text{ A/cm}^2 \times 1.671 \times 10^6 \text{ cm}^2 = 6.68 \text{ A} \end{aligned}$$

***Calculation of minimum weight of anode material (high silicon iron)***

**TANK BOWL ANODES**

$$W = t C_r I / f_u$$

where:

$$\begin{aligned} W &= \text{weight of anode material (kg.)} \\ t &= \text{design life (10 years)} \\ C_r &= \text{anode deterioration rate (0.454 kg/A-yr)} \\ I &= \text{maximum design current (27.9 A)} \\ f_u &= \text{assumed anode utilization factor (0.5)} \end{aligned}$$

$$W = (10 \text{ yr} \times 0.454 \text{ kg/A-yr} \times 27.9 \text{ A}) / 0.5 = 253 \text{ kg.}$$

**RISER ANODES**

$$W = tC_r I / f_u$$

where:

|                |                                            |
|----------------|--------------------------------------------|
| W              | = weight of anode material (kg.)           |
| t              | = design life (10 years)                   |
| C <sub>r</sub> | = anode deterioration rate (0.454 kg/A-yr) |
| I              | = maximum design current (6.68 A)          |
| f <sub>u</sub> | = assumed anode utilization factor (0.5)   |

$$W = (10 \text{ yr} \times 0.454 \text{ kg/A-yr} \times 6.68 \text{ A}) / 0.5 = 60.7 \text{ kg.}$$

In circular water storage tanks, the anodes are generally arranged in circular arrays to provide uniform current distribution. Shepard and Graeser<sup>1</sup> developed some useful empirical design parameters for anodes in water tanks. The bottom of an anode (or string of anodes) should be about as far above the tank bottom as the anode is from the side wall. If more than one anode string is utilized, the radius of the main anode group should be such that the distance between the tank wall and an anode is approximately one-half of the distance between anodes. There are many possible combinations of anode length, separation, number and weight of material that could provide satisfactory performance. The optimum radius of the main anode group (that which covers the side walls and part or all of the bottom) is given by the formula:

$$r = \frac{dN}{2(\pi + N)}$$

where:

|   |                                                                            |
|---|----------------------------------------------------------------------------|
| r | = radius of the main tank anode array (m)                                  |
| d | = tank diameter (17.08 m)                                                  |
| N | = assumed number of anode units (10) to keep weight/unit reasonable (25kg) |

$$r = \frac{17.08 \text{ m} \cdot 10}{2(\pi + 10)} = 6.5 \text{ m}$$

From Shepard and Graeser, the distance from the tank wall and from the bottom should be about equal. This distance is about one-half the circumferential distance between anodes as noted above. See Figure 8.2.

<sup>1</sup> E. R. Shepard and Henry J. Graeser, Jr., **CORROSION** Vol. 6, November 1950, pp 360-375

$$s_a = (2\pi r)/N$$

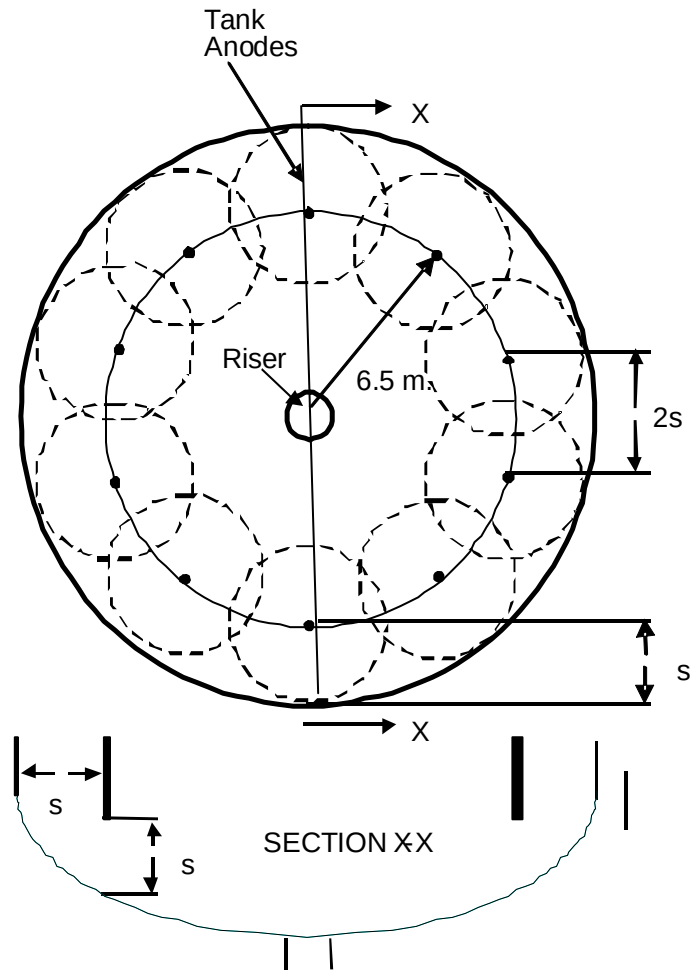
where:

- $s_a$  = Circumferential spacing between anodes (m)
- $r$  = radius of anode ring (6.5 m)
- $N$  = assumed number of anode units (10)
- $s_s$  = anode distance to tank wall and to tank bottom

$$s_a = (2 \times \pi \times 6.5 \text{ m})/10 = 4.08 \text{ m}$$

$$s_s = s_a/2 = 4.08 \text{ m}/2 = 2.04 \text{ m}$$

The length of the cord between anodes is about equal to the circumferential spacing (4.0m).



View of Main Anode Locations  
Showing Space Relationships

**Figure 8.2 Bowl Anode Locations**

### ***Selection of size of main anodes***

A circular array of 10 anode strings has been assumed. The minimum weight of anode material in each string of anodes is:

$$W_s = W/N$$

where:

- $W_s$  = the weight of material in a group (kg/group)  
 $W$  = total weight of material in main array (253kg.)  
 $N$  = number of anode strings in the array

$$W_s = 253 \text{ kg}/10 \text{ string} = 25.3 \text{ kg/string}$$

### THE AVERAGE CURRENT DISCHARGE PER STRING

$$I_s = I/N$$

where:

- $I_s$  = current per string (A)  
 $I$  = total current to protect the bowl (27.9 A)  
 $N$  = number of anode strings in the array

$$I_s = 27.9/10 = 2.79 \text{ A}$$

### MAXIMUM LENGTH OF ANODE GROUP

The height of the tank (floor to roof) at the location of the main anode circle (6.5 m from the center of the tank) can be calculated by beginning with the formula for an ellipse:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

where:

- $x$  = radial distance from the center of the tank (6.5 m)  
 $a$  = semi-major axis = radius of the tank (8.54 m)  
 $y$  = distance above and below the major axis of the ellipse (m)  
 $b$  = semi-minor axis of the ellipse (4.27 m)

Rearranging the formula to solve for  $y$  (the distance above and below the vertical section of the tank to the shell at the anode ring):

$$y = \left( \left( 1 - \frac{x^2}{a^2} \right) b^2 \right)^{0.5}$$

$$y = \left( \left( 1 - \frac{(6.5\text{m})^2}{(8.54\text{m})^2} \right) (4.27\text{m})^2 \right)^{0.5} = 2.77\text{m}$$

The height of the tank at the string location is then calculated from the relationship:

$$h_s = 2y + h$$

where:

- $h_s$  = height of tank 6.5 meters from center (m)
- $y$  = distance above and below the major axis of the ellipse at 6.5 meters from the center (2.77m)
- $h$  = the vertical shell height (3.35 m)

$$h_s = (2 \times 2.77 \text{ m}) + 3.35 \text{ m} = 8.9 \text{ m}$$

### ***Length of anode string to maintain symmetry***

$$L = h_s - 2s$$

where:

- $L$  = length of anode group (m)
- $h_s$  = height of tank 6.5 meters from center (8.9m)
- $s$  = distance above floor (same as anode to wall) (2.04m)

$$L = 8.9 \text{ m} - (2 \times 2.04 \text{ m}) = 4.8 \text{ m}$$

These calculations require that a minimum of 25.3 kg of anode material, which can discharge 2.79A, be 4.8 m long. If one examines a list of available high silicon iron anodes, the 11.35 kg 3.81 cm (1.5 in) x 1.524m (60 in) anode can deliver 1.0A in fresh water. The minimum number of these anodes that can deliver the required current is:

$$N = I_s / I_r$$

where:

$N$  = number of anodes per string  
 $I_s$  = current to a string (2.79 A)  
 $I_r$  = current rating of the anode (1.0 A)

$N = 2.79 \text{ A} / 1.0 \text{ A} = 2.79 = 3 \text{ anodes}$

Since 3 anodes weigh 34.1 kg (3 x 11.35 kg), which is more than the 25.6 kg. minimum required, there will be ample material in the anodes. The length of a string of 3 anodes will be 4.6m (3 x 1.524m). For practical purposes during installation, each anode could be hung from a separate wire.

### Stub Anodes

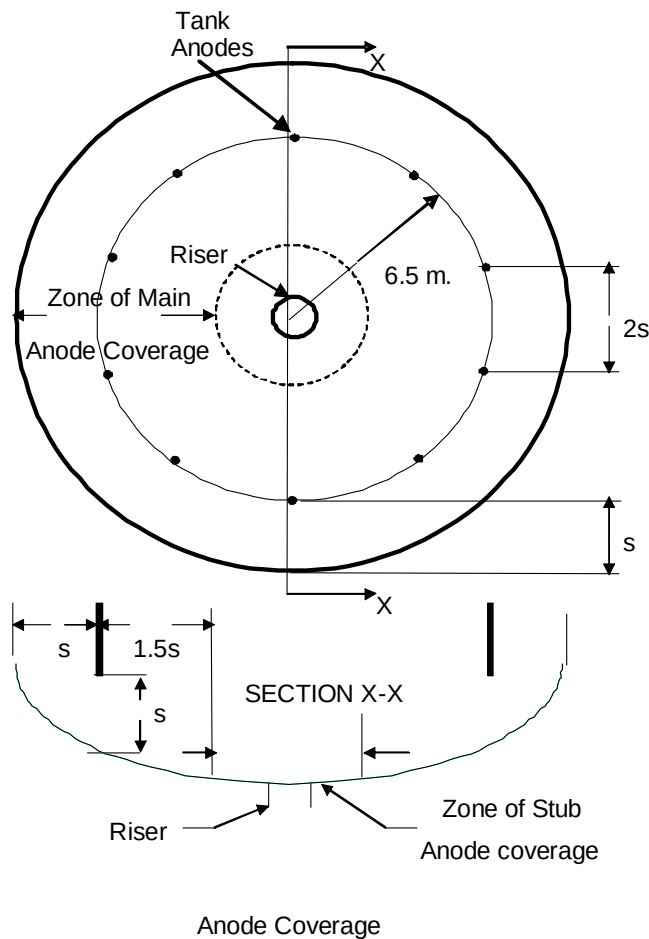


**Figure 8.3 Anode Coverage**

Experience has shown that the main anode array will cover the bottom of the tank from the wall to a distance inside the anode ring equal to about

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1.5 times the distance from the lower end of the anode to the bottom of the tank. See Figure 8.3.

A possible explanation rests in the geometry. If the bottom of one of the main anodes is taken as the apex of a right circular cone of which the side is at an angle of  $60^\circ$  to the vertical, the distance measured from the anode along the side of the cone to the intersection with the floor is twice the distance from the bottom of the anode to the floor. In this case the surface of the tank bottom out at the perimeter of the imagined cone would be exposed to about one-half of the voltage present directly under the anode. Therefore the current density would be about one-half that under the anode. In a  $60^\circ$  cone, the radius of the base is 1.73 times the height of the cone (the distance from the bottom of the anode to the floor of the tank). Using an anode spacing in the main ring equal to twice the space from anode to floor and anode to wall provides an overlap from one anode to the next where the additive effects from adjacent anodes will provide adequate current density for protection without over protecting the region directly under an anode. Although the calculated radius of the cone is 1.73 times the height, a more conservative factor of 1.5 will be used because the assumption of an inverse relationship between current density and distance is only approximate.

In this case the area is represented by an annular region extending from the vertical tank wall to a circle 3.1 m ( $1.5 \times 2.04$  m) in from the main anode circle. This circle has a radius:

$$r_i = d/2 - s - 1.5s = d/2 - 2.5s$$

where:

- $r_i$  = inner radius of main anode coverage (m)
- $d$  = tank diameter (17.08m)
- $s$  = the distance of the main anode ring from the wall (2.04m)

$$r_i = 17.08 \text{ m}/2 - 2.5(2.04 \text{ m}) = 3.4 \text{ m}$$

Anodes, which are referred to as "stub" anodes are required to cover the remaining area from the riser pipe (radius 0.76 m) to the above inner radius of coverage by the main anodes. The width of this annular area is:

$$w = r_i - r_p$$

where:

- $w$  = width of annulus covered by stub anodes (m)
- $r_i$  = inner radius of main anode coverage (3.4 m)



$$r_p = \text{radius of riser pipe (0.76 m)}$$

$$w = 3.4 \text{ m} - 0.76 \text{ m} = 2.64 \text{ m}$$

As with the projected cone of coverage idea discussed above, the height of the stub anodes above the floor to cover this area is:

$$s_s = w/3$$

$$s_s = 2.64 \text{ m}/3 = 0.88 \text{ m}$$

To maintain symmetry with the main anodes and coverage between the main anodes, 10 stub anodes will be used in a ring of radius:

$$r_s = w/2 + r_p$$

where:

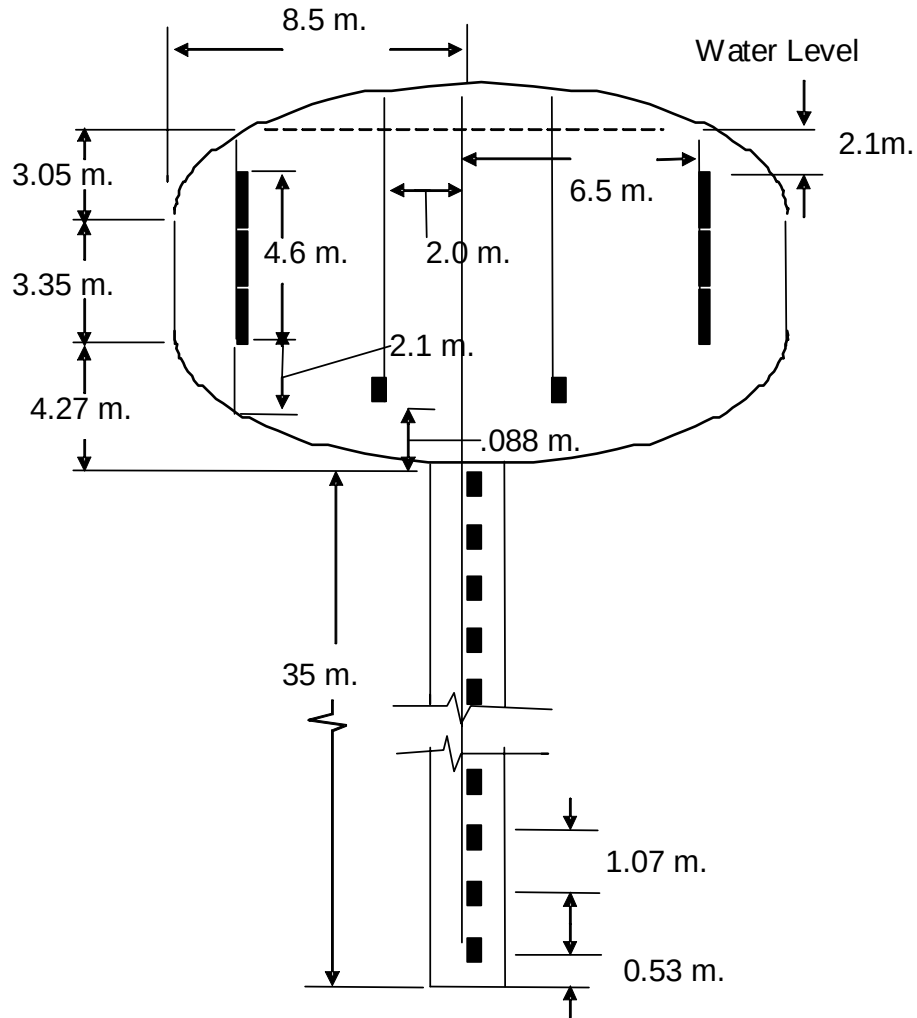
$$r_s = \text{radius of stub anodes array (m)}$$

$$w = \text{width of annulus covered by stub anodes (2.64 m)}$$

$$r_p = \text{radius of riser pipe (0.76 m)}$$

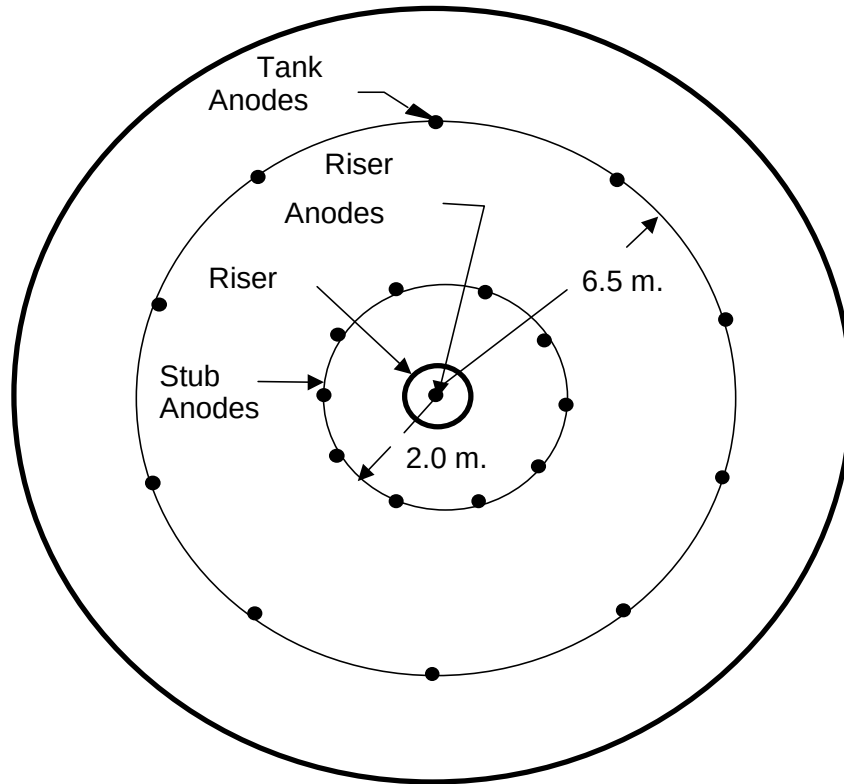
$$r_s = 2.64 \text{ m}/2 + 0.76 \text{ m} = 2.08 \text{ m}$$

The configuration with rounded off dimensions is shown in Figures 8.4 and 8.5.



Anode Configuration for Best Coverage

**Figure 8.4 Anode Configuration for Best Coverage**



Plan View of Anode Locations

**Figure 8.5 Plan View of Anode Placement**

The area of the tank wetted surface covered by the stub anodes is:

$$A_s = \pi(r_i^2 - r_p^2)$$

where:

$A_s$  = area covered by stub anodes ( $\text{m}^2$ )  
 $r_i$  = inner radius of main anode coverage (3.4 m)

$$A_s = \pi(11.56 \text{ m} - 0.58 \text{ m}) = 34.49 \text{ m}^2 (344,900 \text{ cm}^2)$$

### **Maximum current required from stub anodes**

$$I_s = 4.0 \times 10^{-6} \text{ A/cm}^2 \times 3.449 \times 10^5 \text{ cm}^2 = 1.38 \text{ A}$$

Since this current does not have to be supplied by the main anodes, the current supplied by the main anode array is:

$$I_m = I_B - I_s$$

where:

- $I_m$  = current from main anode array (A)
- $I_B$  = total current to bowl (27.9 A)
- $I_s$  = current to stub anode array (1.38 A)

$$I_m = 27.9 \text{ A} - 1.38 \text{ A} = 26.5 \text{ A}$$

Use of the 4.09kg, 6.35cm (2.5 in) x 22.9cm (9 in) anodes for the stub array will work. Each 6.35 cm x 22.9 cm anode is rated at 0.250 A Ten anodes can provide 2.5 A, well above the required 1.38A.

### **Resistance calculations**

Calculation of anode to electrolyte resistance for cylindrical anodes in circular tanks is frequently estimated using a formula developed by E. R. Shepard<sup>2</sup>.

$$R = \frac{0.366\rho}{L} \text{Log}\left(\frac{d_T}{d_a}\right)$$

where:

- $R$  = anode to tank resistance (ohms)
- $\rho$  = liquid (water) resistivity (ohm-cm)
- $d_T$  = tank diameter (m)
- $d_a$  = anode diameter (m)
- $L$  = length of single anode (cm)

If there are more than 3 strings of anodes, a modified Shepard formula has been proposed in Department of Defense publications and found to be in good agreement with actual results<sup>3</sup>:

<sup>2</sup> E. R. Shepard and Henry J. Graeser, Jr., **CORROSION** Vol. 6, November 1950, pp 360-375

<sup>3</sup> Department of Defense, **MILITARY HANDBOOK - ELECTRICAL ENGINEERING CATHODIC PROTECTION**, MIL-HDBK-1004/10 31, January 1990



$$R = \frac{0.366\rho}{L} \text{Log}\left(\frac{d_T}{a}\right)$$

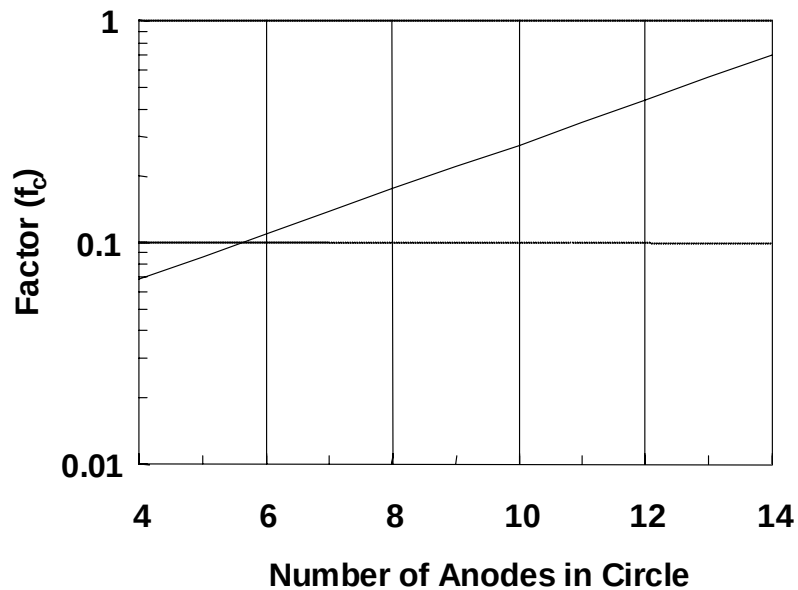
where:

$R, \rho, L$  and  $d_T$  have the meaning and dimension of the Shepard formula.

$$a = f_c d_s$$

$f_c$  = factor given by Figure 8.6

$d_s$  = diameter of the anode string array (m)



Factor to Calculate Equivalent Diameter of Anodes  
In a Circular Tank

**Figure 8.6 Correction Factor for Number of Anodes**

**RESISTANCE OF MAIN ANODE ARRAY**

Since there are more than three anodes in the main bowl anode array, use the modified Shepard formula:

$$R = \frac{0.366\rho}{L} \text{Log} \left( \frac{d_T}{a} \right)$$

where:

- $\rho$  = resistivity (4,000 ohm-cm)
- $d_T$  = tank diameter (17.08 m)
- $a$  =  $f_c d_s$
- $d_s$  = diameter of anode string array (13 m)
- $f$  = factor for 10 anode array, Figure 8.6 (0.275)
- $a$  =  $0.275 \times 13 \text{ m} = 3.58 \text{ m}$
- $L$  = length of anode material ( $3 \times 152.4 \text{ cm}$ ) = 457.2 cm

$$R = \frac{0.366 \cdot 4000 \text{ ohm-cm}}{457.2 \text{ cm}} \text{Log} \left( \frac{17.08 \text{ m}}{3.58 \text{ m}} \right) = 2.17 \text{ ohms}$$

Also from MIL-HDBK-1004/10, when the ratio of the length of anode material to the anode diameter ( $L/d_a$ ) is less than 100, a correction factor must be used to adjust the resistance. The correction factor is obtained from Figure 8.7.

For the chosen anode group:

- $L$  = 457.2 cm
- $d_a$  = 3.81 cm
- $L/d_a$  = 120

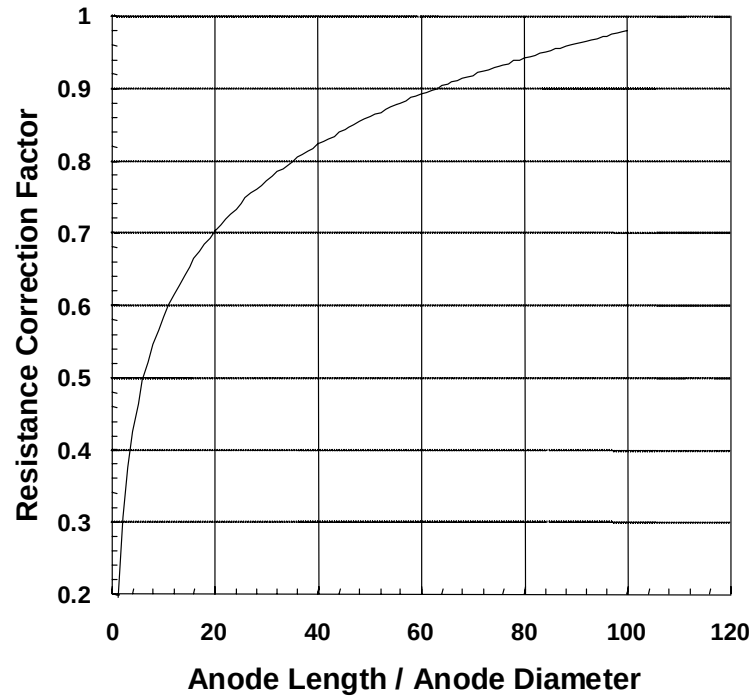
No correction factor is required since  $L/d_a$  ratio is greater than 100.

The resistance of the main anode array is:

$$R_m = 2.17 \text{ ohms}$$

The resistance of the stub anode array is:

$$R = \frac{0.366\rho}{L} \text{Log}\left(\frac{d_T}{a}\right)$$



ANODE RESISTANCE CORRECTION FACTOR

**Figure 8.7 Resistance Correction Factor**

where:

- $\rho$  = resistivity (4,000 ohm-cm)
- $d_T$  = tank diameter (17.08 m)
- $a$  =  $f_c d_s$
- $d_s$  = diameter of anode string array (4.16m)
- $f_c$  = factor for 10 anode array, Figure 8.6 (0.275)
- $a$  =  $0.275 \times 4.16 \text{ m} = 1.14 \text{ m}$
- $L$  = length of anode material (1 x 22.9 cm) = 23 cm

$$R = \frac{0.366 \cdot 4000 \text{ ohm-cm}}{23 \text{ cm}} \text{Log}\left(\frac{17.08 \text{ m}}{1.14 \text{ m}}\right) = 74.8 \text{ ohms}$$



For the chosen anode group:

$$L = 23 \text{ cm}$$

$$d_a = 6.35 \text{ cm}$$

$$L/d_a = 3.6$$

A correction factor is needed. From Figure 8.7, the correction factor is about 0.4.

The corrected resistance of the stub anode array is:

$$R_s = 0.4 \times 74.8 \text{ ohms} = 29.9 \text{ ohms}$$

If No. 10 AWG wire is used as the main feeds to the two anode arrays, the resistance to be added to each anode array will be negligible (about 0.2 ohm for an estimated 60 meters of wire to each array).

### ***Bowl Power Requirements***

#### **MAIN ARRAY**

$$E_m = I_m R_m f$$

where:

- $E_m$  = driving voltage required by array (V)
- $I_m$  = current required by array (26.5A)
- $R_m$  = resistance of array and feed wires (about 2.4Ω)
- $f$  = assumed safety factor (1.5)

$$E_m = 26.5 \text{ A} \times 2.4 \text{ } \Omega \times 1.5 = 95.4 \text{ volts}$$

**STUB ARRAY**

$$E_s = I_s R_s f$$

where:

- $E_s$  = driving voltage required by array (V)
- $I_s$  = current required from array (1.38A)
- $R_s$  = resistance of array and feed wires (29.9Ω)
- $f$  = assumed safety factor (1.5)

$$E_s = 1.38 \text{ A} \times 29.9 \text{ } \Omega \times 1.5 = 61.9 \text{ volts}$$

Since there is a difference in the driving voltage needed for each array, the bowl requires either two separate power supplies or an adjustable resistor in the stub anode circuit to reduce the voltage to that array. If a resistor is to be used, it should have enough resistance to drop the current to half the expected value. This provides for the possibility of adjustments later if needed. The rating is:

$$R_x = \frac{E_m - E_s}{\frac{I_s}{f}}$$

where:

- $R_x$  = control resistance (ohms)
- $E_m$  = max. main array voltage (assume 100 volts rectifier)
- $E_s$  = min expected stub voltage (25 volts)
- $f$  = the factor required to drop the current to one half the estimated value (0.5)
- $I_s$  = stub anode current (1.38A)

$$R_x = \frac{100\text{V} - 25\text{V}}{\frac{1.38\text{A}}{0.5}} = 109\text{ohms}$$

Power rating:

$$P = (I_s)^2 R_x = (1.38 \text{ A})^2 \times 109 \text{ } \Omega = 208 \text{ watts}$$

## ***Riser Anode Design***

The distance of the riser anode from the wall of the riser is the radius (0.76 m). Using geometry to estimate anode end-to-end spacing, a maximum spacing of 2 times the distance from the anode to the riser wall is determined. In order to be more conservative, the end-to-end spacing factor used will be 1.5 times this distance.

$$S_{ee} = 1.5r_r$$

where:

$$\begin{aligned} S_{ee} &= \text{end-to-end anode spacing (m)} \\ r_r &= \text{the riser radius (0.76 m)} \end{aligned}$$

$$S_{ee} = 1.5 \times 0.76 \text{ m} = 1.14 \text{ m}$$

For the riser, 5.1 cm (2.0 in) x 22.9 cm (9 in) anodes will be used. The number of anodes required is:

$$N = h / (S_{ee} + L)$$

where:

$$\begin{aligned} N &= \text{number of anodes in string} \\ h &= \text{height of riser (35 m)} \\ S_{ee} &= \text{anode spacing (1.14 m)} \\ L &= \text{anode length (0.229 m)} \end{aligned}$$

$$N = 35 \text{ m} / (1.14 \text{ m} + 0.229 \text{ m}) = 25.6 = 26 \text{ anodes}$$

The average current to be delivered from each anode is:

$$I_a = I_R / N$$

where:

$$\begin{aligned} I_a &= \text{current from one anode (A)} \\ I_R &= \text{total current required in the riser (6.68A)} \\ N &= \text{number of anodes in string (26)} \\ I_a &= 6.68 \text{ A}/26 = 0.257\text{A} \end{aligned}$$

For this service, 5.1 cm (2.0 in) x 22.9 cm (9 in) anodes are conservatively rated by the manufacturer at 0.200 A. The anodes weigh 2.27 kg. The total weight of the anode string will be:

$$W = 2.27 \text{ kg} \times 26 = 59.02 \text{ kg}$$

This weight is less than the minimum (60.7 kg.) required for the design life of 10 years. Additional anodes are required for the design life.

$$N = 60.7 \text{ kg}/2.27 \text{ kg} = 26.7 = 27 \text{ anodes}$$

Using the minimum number of anodes required for the 10 year life (27 anodes), the adjusted end-to-end spacing is:

$$S_{ee} = h/N - L = 35 \text{ m}/27 - 0.229 \text{ m} = 1.07 \text{ m}$$

### RISER ANODE RESISTANCE

The active length of the riser anode material is:

$$L = 27 \times 22.9 \text{ cm} = 618 \text{ cm}$$

With a single anode string use the standard Shepard formula:

$$R_R = \frac{0.366\rho}{L} \text{Log} \left( \frac{d_R}{d_a} \right)$$

where:

$$\begin{aligned} R_R &= \text{riser anode to riser pipe resistance (ohms)} \\ \rho &= \text{liquid (water) resistivity (4,000 ohm-cm)} \\ d_R &= \text{riser diameter (1.52m)} \\ d_a &= \text{anode diameter (0.051m)} \\ L &= \text{active length of anode material (618 cm)} \end{aligned}$$

$$R_R = \frac{0.366 \cdot 4000 \text{ ohm-cm}}{618 \text{ cm}} \text{Log} \left( \frac{1.52 \text{ m}}{0.051 \text{ m}} \right) = 3.49 \text{ ohm}$$

Checking the L/d ratio for the riser anode string to see if a correction factor is needed:

$$L/d_a = 618 \text{ cm}/5.1 \text{ cm} = 121$$

Since the ratio is greater than 100, there is no correction factor.

As with the bowl anodes, the resistance of the No. 10 AWG feeder wire is not significant.

The driving voltage required for the riser anodes is:

$$E_R = I_R R_R f$$

where:

- $E_R$  = driving voltage (V)
- $I_R$  = riser current (6.68 A)
- $R_R$  = riser anode circuit resistance (3.49Ω)
- $f$  = assumed safety factor (1.5)

$$E_R = 6.68 \text{ A} \times 3.49 \text{ } \Omega \times 1.5 = 34.97 \text{ volts}$$

This voltage is only about 35% that of the bowl power supply. The power wasted in dropping the voltage from the maximum 100 volts to 34.97 volts is:

$$P = E_x I_R$$

where:

- $P$  = power lost (watts)
- $E_x$  = voltage dropped across resistor (100 – 34.97 = 65.03 volts)
- $I_R$  = riser current (6.68A)

$$P = 65.03 \text{ V} \times 6.68 \text{ A} = 434.4 \text{ watts}$$

Continuous waste of this power is unreasonable. Therefore, a separate power supply for the riser anode system is justified.

Since there is no indication of significant variation in current requirements for this tank, conventional single-phase bridge type rectifiers would be a good choice. Once the cathodic protection system is installed the current

requirements must be verified and monitored with time. It is desirable to have permanent reference electrodes installed in the tank to facilitate testing.

In regions where winter ice formation is a problem, the design must be modified to prevent destruction of the anode systems. Various floatation systems have been employed to control ice damage. Each situation must be examined for the design variables and costs involved.

## ***New/Rectifier/Platinized Niobium***

### ***Description***

A new seawater holding tank is to be constructed of mild steel. The tank will be coated with a coal tar epoxy, which is compatible with cathodic protection. Design a cathodic protection system for the tank using platinized niobium wire anodes. The system must control corrosion even if one third of the coating fails. Use the data, which follows, in preparing the design.

### ***Data***

|                                               |                                                      |
|-----------------------------------------------|------------------------------------------------------|
| 1. Tank diameter                              | 2 meters (6.6 ft)                                    |
| 2. Water level in tank                        | 3.9 meters (12.8 ft)                                 |
| 3. Overall depth of tank                      | 4 meters (13.1 ft)                                   |
| 4. Shape of tank                              | Cylindrical                                          |
| 5. Estimated current requirement              | 14 microamperes/square centimeter of exposed surface |
| 6. Power available                            | 120/240 V 60 Hz. single phase                        |
| 7. Design life                                | 10 years                                             |
| 8. Average water resistivity                  | 27 ohm-cm                                            |
| 9. Assumed consumption of the platinum        | $1.2 \times 10^{-5}$ kg/A-yr                         |
| 10. Assumed anode utilization factor          | 50%                                                  |
| 11. Diameter of platinized niobium wire anode | 0.157 cm                                             |
| 12. Weight of platinum on anode wire          | $1.37 \times 10^{-6}$ kg/cm of wire                  |

## Calculations

### WETTED SURFACE AREA OF TANK WALL

$$A_{sw} = \pi dh$$

where:

$$\begin{aligned} A_{sw} &= \text{wetted surface area of tank (cm}^2\text{)} \\ d &= \text{diameter of tank (200 cm)} \\ h &= \text{wetted height of tank (390 cm)} \end{aligned}$$

$$A_{sw} = \pi \times 200 \text{ cm} \times 390 \text{ cm} = 2.45 \times 10^5 \text{ cm}^2$$

### SURFACE AREA OF TANK BOTTOM

$$A_{sb} = \pi r^2$$

where:

$$\begin{aligned} A_{sb} &= \text{area of tank bottom (cm}^2\text{)} \\ r &= \text{radius of tank bottom (100 cm)} \end{aligned}$$

$$A_{sb} = \pi \times (100 \text{ cm})^2 = 3.1416 \times 10^4 \text{ cm}^2$$

### TOTAL AREA OF TANK

$$A_s = A_{sw} + A_{sb}$$

where:

$$\begin{aligned} A_s &= \text{wetted area of tank (cm}^2\text{)} \\ A_{sw} &= \text{area of tank wall (} 2.45 \times 10^5 \text{ cm}^2\text{)} \\ A_{sb} &= \text{area of tank bottom (} 3.1416 \times 10^4 \text{ cm}^2\text{)} \end{aligned}$$

$$A = 2.45 \times 10^5 \text{ cm}^2 + 3.1416 \times 10^4 \text{ cm}^2 = 2.764 \times 10^5 \text{ cm}^2$$



**MAXIMUM EXPOSED METAL SURFACE ( $A_m$ )**

$$A_m = 0.33 \times 2.764 \times 10^5 \text{ cm}^2 = 9.12 \times 10^4 \text{ cm}^2 (98 \text{ ft}^2)$$

**ESTIMATED TOTAL MAXIMUM CURRENT REQUIRED:**

$$I = iA_m$$

where:

- $I$  = design current (A)
- $i$  = required current density ( $1.4 \times 10^{-5} \text{ A/cm}^2$ )
- $A_m$  = maximum exposed metal surface ( $9.12 \times 10^4 \text{ cm}^2$ )

$$I = 1.4 \times 10^{-5} \text{ A/cm}^2 \times 9.12 \times 10^4 \text{ cm}^2 = 1.28 \text{ A}$$

**MINIMUM WEIGHT OF PLATINUM REQUIRED:**

$$W = tC_r I / f_u$$

where:

- $W$  = weight of anode material (kg.)
- $t$  = design life (10 years)
- $C_r$  = anode deterioration rate ( $1.2 \times 10^{-5} \text{ kg/A-yr}$ )
- $I$  = maximum design current (1.28 A)
- $f_u$  = assumed anode utilization factor (0.5)

$$W = (10 \text{ yr} \times 1.2 \times 10^{-5} \text{ kg/A-yr} \times 1.28 \text{ A}) / 0.5 = 3.1 \times 10^{-4} \text{ kg}$$

**TOTAL LENGTH OF PLATINUM ANODE REQUIRED**

$$L_p = W/w$$

where:

- $L_p$  = length of active platinized anode (cm)
- $W$  = weight of platinum required ( $3.1 \times 10^{-4} \text{ kg}$ )
- $w$  = weight of platinum per cm of wire ( $1.371 \times 10^{-6} \text{ kg/cm}$ )

$$L_p = 3.1 \times 10^{-4} \text{ kg} / 1.371 \times 10^{-6} \text{ kg/cm} = 226 \text{ cm (7.4 ft)}$$

Platinum wire anodes for water tanks can be constructed as shown in Figure 8.8. One unit length of anode assembly consists of 45 cm of active platinized niobium wire plus 12 cm of insulated copper bus wire. The unit length is 57 cm. The active platinum anode is 79% of the unit length.

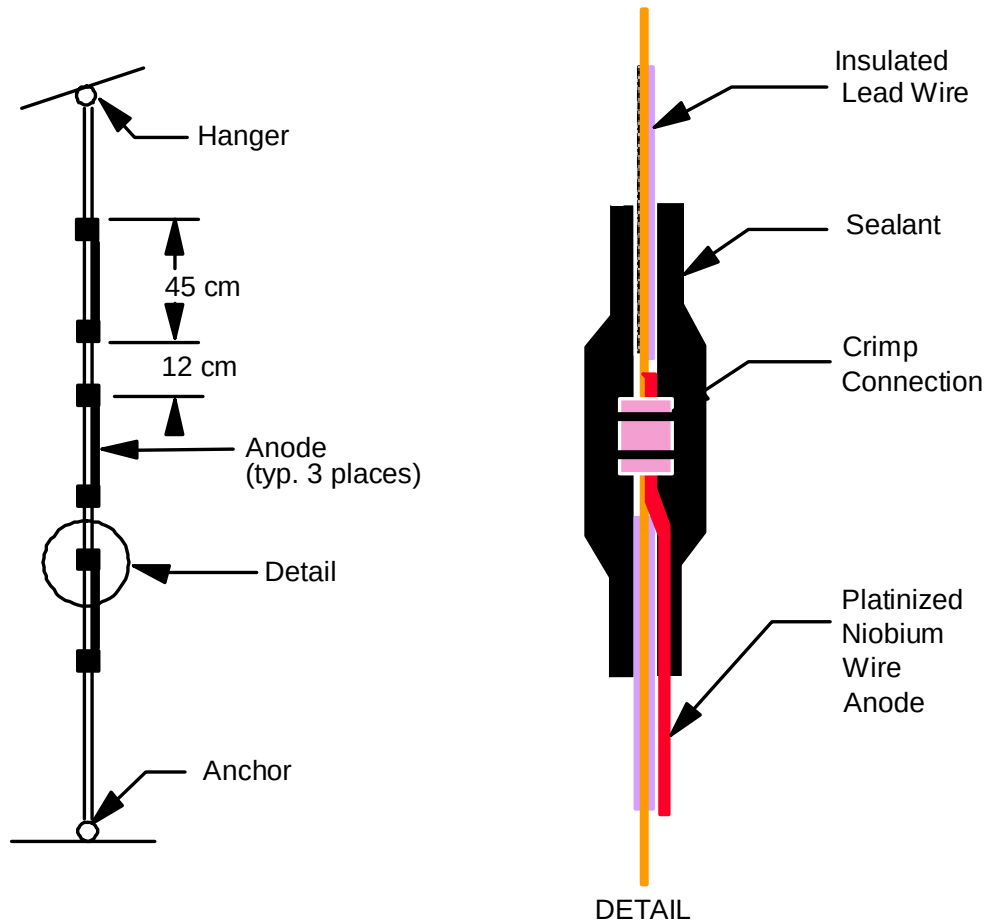


**Figure 8.8 Anode Connection**

**TOTAL LENGTH OF ANODE REQUIRED**

$$L = L_p/0.79$$

where:

$$\begin{aligned} L &= \text{total length of anode (cm)} \\ L_p &= \text{total length of platinized wire (226 cm)} \end{aligned}$$

$$L = 226 \text{ cm}/0.79 = 286 \text{ cm (9.4 ft)}$$

**NUMBER OF ANODE STRINGS REQUIRED:**

$$N = L/h$$

where:

$$\begin{aligned} N &= \text{number of anode strings} \\ L &= \text{total length of anode (286 cm)} \\ h &= \text{wetted height of tank (390 cm)} \end{aligned}$$

$$N = 286 \text{ cm}/390 \text{ cm} = 0.73 = 1 \text{ string}$$

**BOTTOM COVERAGE**

The maximum separation of the anode (lowest active element) from the bottom is:

$$s = h - L$$

where:

$$\begin{aligned} s &= \text{separation between bottom and lowest anode element (cm)} \\ L &= \text{total length of anode (286 cm)} \\ h &= \text{wetted height of tank (390 cm)} \\ S &= 390 \text{ cm} - 286 \text{ cm} = 104 \text{ cm (3.4 ft)} \end{aligned}$$

**TOTAL BOTTOM ZONE COVERED**

$$Z_b = 1.5s$$

where:

$Z_b$  = radius of zone covered by single anode (cm)

$S$  = separation between bottom and lowest anode element (104 cm)

$$Z_b = 1.5 \times 104 \text{ cm} = 156 \text{ cm (5.1 ft)}$$

The radius of the tank bottom is 100 cm. The protection of the bottom could be accomplished with a single anode group in the center of the tank.

The anode configuration is shown in Figure 8.9.

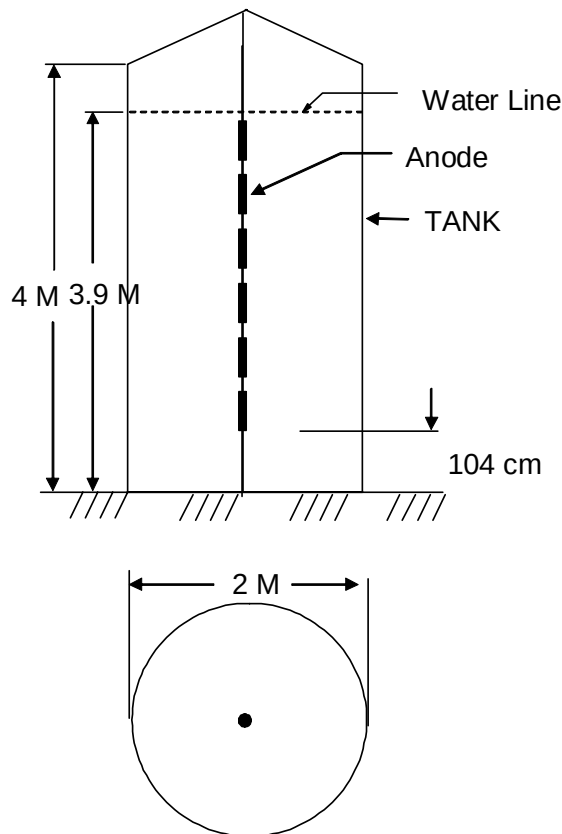


**Figure 8.9 Anode Configuration**

## Resistance Calculations

The active length of anode material is:

$$L = 6 \times 45 \text{ cm} = 270 \text{ cm}$$

With a single anode use the standard Shepard formula:

$$R = \frac{0.366\rho}{L} \text{Log}\left(\frac{d_T}{d_a}\right)$$

where:

- R = anode to tank resistance (ohms)
- $\rho$  = liquid (water) resistivity (27 ohm-cm)
- $d_T$  = tank diameter (200 cm)
- $d_a$  = anode diameter (0.157 cm)
- L = active length of anode material (270 cm)

$$R = \frac{0.366 \cdot 27 \text{ ohm-cm}}{270 \text{ cm}} \text{Log}\left(\frac{200 \text{ cm}}{0.157 \text{ cm}}\right) = 0.114 \text{ ohm}$$

The  $L/d_a$  ratio for the riser anode string is:

$$L/d_a = 270 \text{ cm} / 0.157 \text{ cm} = 1720$$

Since the ratio is greater than 100, there is no correction factor required.

If No. 8 AWG copper wire is used for the feeder from the power source to the anode ring (an estimated length of 8 meters) the resistance of the wire will be:

$$R_F = L_F r$$

where:

- $R_F$  = resistance of feeder wire (ohms)
- $L_F$  = length of feeder (8 m)
- R = unit resistance of No 8 wire (0.002 ohm/m)

$$R_F = 8 \text{ m} \times 0.002 \text{ } \Omega/\text{m} = 0.016 \text{ } \Omega$$

A well-coated tank will exhibit significant cathode to electrolyte resistance. Once the coating begins to fail, the resistance will drop. In this case



assume the worst condition (33% coating failure). The exposed surface area is very large compared with the anode system; the tank to electrolyte resistance ( $R_E$ ) is expected to be insignificant.

The driving voltage required for the main anodes is:

$$E_M = I_M R_T$$

where:

- $E_M$  = driving voltage (V)
- $I_M$  = main current (1.28 A)
- $R_T$  = main anode circuit resistance:  
 $R_T = (R_M + R_F + R_E)$
- $R_M$  = main anode resistance (0.114 ohm)
- $R_F$  = feeder wire resistance (0.016 ohm)
- $R_E$  = tank to electrolyte resistance (assumed <0.01 ohm)
- $R_T = 0.114 + 0.016 + 0.00 = 0.13$  ohms

$$E_M = 1.28 \text{ A} \times 0.13 \Omega = 0.1664 \text{ volt}$$

In this case, the back voltage produced by the anode to steel tank galvanic potential plus polarization of the anode and the tank will be greater than the potential needed to overcome the circuit resistance. Assume a back voltage of 2.0 volts. An 8 volt 4 ampere rectifier would be a candidate power supply.

## Discussion

Coated water tanks that are cathodically protected with impressed current systems generally require automatic potential control. To avoid excessive electrical stress on the coating, the potential set point should not exceed – 900 millivolts vs. a saturated copper-copper sulfate reference electrode. The reference electrode which senses the potential of the tank should be located close to the tank wall in an area as remote as possible from any anode. One approach is to install the reference next to a small bare steel coupon, which is welded to the tank or is otherwise electronically connected to the tank through a wire. The coupon represents a deliberate fault in the coating and provides a surface responsive to flow of the cathodic protection current.

Paint and other thin coatings behave as membranes. Water can permeate the coating and ultimately reach the base metal. If skips and voids or improper surface preparation are present at the coating metal interface, water can collect over an appreciable area of the surface. If there are differences in the ion concentrations present in the liquid at the

steel coating interface and that in the bulk solution on the outside of the coating (a likely occurrence), osmotic effects can develop. These osmotic effects can further force water molecules and ions through the protective coating. The build-up in pressure at the coating steel interface will ultimately result in blistering and coating failure.

Application of cathodic protection to a coated steel surface immersed in water, places further electrical stresses across the coating membrane. Electro-osmosis has a tendency to force water toward the cathode (the steel base), thus exerting a pressure, which can cause blistering of the coating. A coating system with inadequate adhesion to the base will blister from the pressure of water driven through the coating membrane by the applied cathodic potentials.

Successful application of cathodic protection in aqueous environments of pH less than 9, will invariably result in a rise in pH at the metal interface. This is due to electrochemical reduction of hydrogen ions from the water in contact with the metal surface. It is not uncommon for the pH at the interface of steel, in a properly cathodically protected situation, to be much greater than 9. For a coating to be compatible with cathodic protection, it must be able to resist an alkaline environment. Many paints and coatings are not resistant to alkalis. The increase in pH, caused by cathodic protection, can accelerate the deterioration of an improperly applied coating, even though the coating itself is compatible with the conditions produced by cathodic protection. The rapid and extensive deterioration resulting from applying cathodic protection to an improperly applied coating is frequently blamed on the cathodic protection. However, the deterioration is generally due to improper application of the coating.

# Vessel Design Examples

## ***Condenser Waterbox/Impressed Current System***

### ***Description***

The main surface condensers at a power plant have been re-fitted with titanium tubes and tube sheets. The water boxes are constructed of epoxy coated steel. The cooling water is seawater with a conductivity between 29,000 and 40,000 micro Siemens (25 and 35 ohm-cm resistivity).

Titanium is an active metal (like aluminum), which rapidly forms a highly protective film in seawater. It is this film that permits the use of titanium as a substrate for platinum and mixed metal oxide impressed current anodes. In the presence of aerated seawater, titanium exhibits a relatively noble (cathodic) potential, which is generally between +0.200 and -0.200 volt vs. a silver/silver chloride reference. In seawater, steel (at a potential of -0.5 to -0.7 volts vs. silver/silver chloride) will undergo rapid corrosion when directly connected to a large titanium surface.

There is justified concern that the coated steel waterbox will corrode at an unacceptable rate at coating faults and penetration of the steel box will result. Application of cathodic protection for the water boxes can be used to polarize the titanium to a more active potential (-0.550 to -0.650 volt with respect to a silver/silver chloride reference electrode). This will eliminate the otherwise harmful galvanic potential difference between the titanium and the steel.

Cathodic polarization of the titanium must not be sufficiently negative to produce hydrogen at the titanium surface. If hydrogen is produced, the titanium can form hydrides, which make the metal brittle and can result in tube cracking and other forms of mechanical failure. The equation for the potential at which hydrogen ions in water can be reduced to hydrogen gas at one atmosphere of pressure (from Pourbaix<sup>4</sup>) is:

$$E_o = 0.000 - 0.0591 \text{ pH (volt vs. SHE)}$$

Referenced to a silver/silver chloride electrode in seawater the equation becomes:

$$E_o = (0.000 - 0.0591 \text{ pH}) - 0.254 \text{ volt}$$

<sup>4</sup> Marcel Pourbaix, **Atlas of Electrochemical Equilibria in Aqueous Solutions**, NACE, Houston, Texas USA.



At a pH of 8.0 (normal for seawater) the potential for production of hydrogen is:

$$E_o = (-0.0591 \times 8) - 0.254$$

$$E_o = -0.727 \text{ volt vs. silver/silver chloride}$$

Polarizing the titanium to between  $-0.550$  and  $-0.650$  vs. silver/silver chloride will not result in formation of titanium hydrides. This potential will eliminate the galvanic potential difference between the titanium and the steel.

Given the following data, design an impressed current cathodic protection system for the water boxes on this condenser. Anodes shall have a nominal 10 year life expectancy.

### **Data**

1. From laboratory tests at flow rates matching those in the condenser tubes, 1.8 m/sec (6 ft/sec), the current density required to polarize titanium to  $-0.650$  v. to a silver/silver chloride reference is about 75 microamp/cm<sup>2</sup>.
2. From laboratory studies the effective distance that polarization occurs down a tube is about 5 tube diameters.
3. There are 5140 titanium tubes entering each waterbox. Tube diameter is 2.22 cm (7/8 in).
4. Consider average water resistivity is 30 ohm-cm
5. All large connecting pipes to the condenser have a protective coating within five pipe diameters of the condenser. Conservatively estimate 10% of all coated steel surfaces as exposed metal. Assume all surfaces beyond 5 pipe diameters will not receive significant current density.
6. Assume waterbox dimensions are as indicated in Figure 8.10. For this problem inlet and outlet tube sheets are mirror images of each other.
7. Water velocity through the condenser tubes is 1.83 m/sec (6 ft/sec).

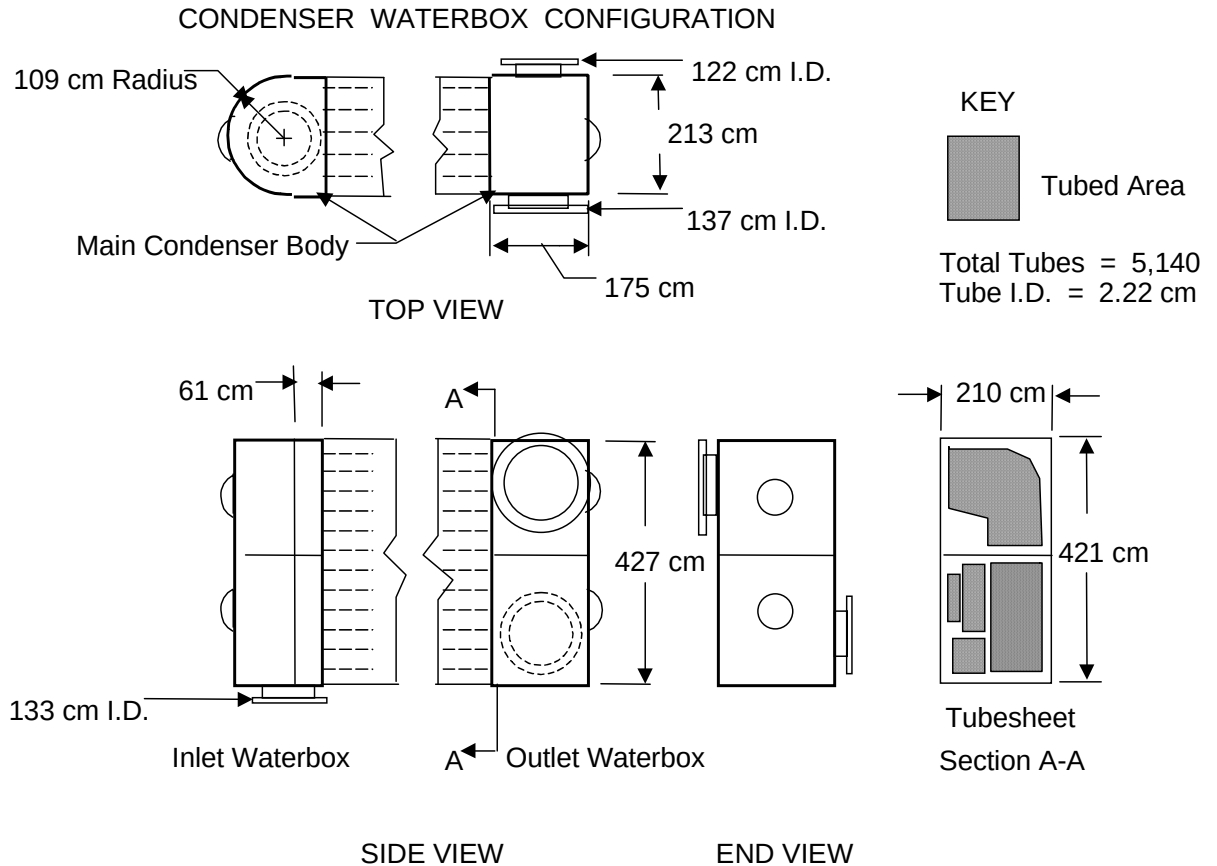


**Figure 8.10 Diagram of Condenser Waterbox**

### **Procedure**

1. Calculate surface areas.
2. Estimate current required to meet criteria.
3. Select anodes.
4. Estimate minimum number of anodes to meet life and current distribution requirements.
5. Estimate rectifier rating.

## Calculations

### SURFACE AREAS

Effective area of titanium tubes which will receive current (5 tube diameters into tube).

$$A_{st} = \pi d(5d)N$$

where:

d = tube diameter (2.22 cm)

$A_{st}$  = area of inner surface of a tube affected by cathodic current flow ( $\text{cm}^2$ )

N = number of tubes in tube sheet (5,140)

$$A_{st} = \pi \times 2.22 \text{ cm} \times 5 \times 2.22 \text{ cm} \times 5140$$

$$A_{st} = 397,913 \text{ cm}^2 (428 \text{ ft}^2)$$

### AREA OF EXPOSED TITANIUM ON TUBE SHEET

$$A_{ss} = A_{so} - A_{sx}$$

where:

$A_{so}$  = overall tube sheet area  
 $421 \times 210 = 88,410 \text{ cm}^2 (95.2 \text{ ft}^2)$

$A_{sx}$  = open cross section of tubes  
 $(\pi(d/2))^2 \times N$

d = I.D. of tubes (2.22. cm)

N = number of tubes (5,140)

$A_{sx} = \pi \times (2.22 \text{ cm}/2)^2 \times 5140 = 19,896 \text{ cm}^2 (21.4 \text{ ft}^2)$

$$A_{ss} = 88,410 \text{ cm}^2 - 19,896 \text{ cm}^2 = 68,514 \text{ cm}^2 = (73.7 \text{ ft}^2)$$

Total effective area of titanium receiving cathodic current (per waterbox).

$$A_{St} = A_{st} + A_{ss}$$

where:

$A_{st}$  = effective area of inner surface of titanium tubes  
(397,913 cm<sup>2</sup>)

$A_{ss}$  = exposed surface of tube sheet (68,514 cm<sup>2</sup>)

$$A_T = 397,913 \text{ cm}^2 + 68,514 \text{ cm}^2 = 466,427 \text{ cm}^2 (502 \text{ ft}^2)$$

### EFFECTIVE SURFACE OF STEEL IN WATER BOXES.

For large diameter connecting piping, assume surfaces to have the equivalent of five diameters of straight pipe attached to each opening.

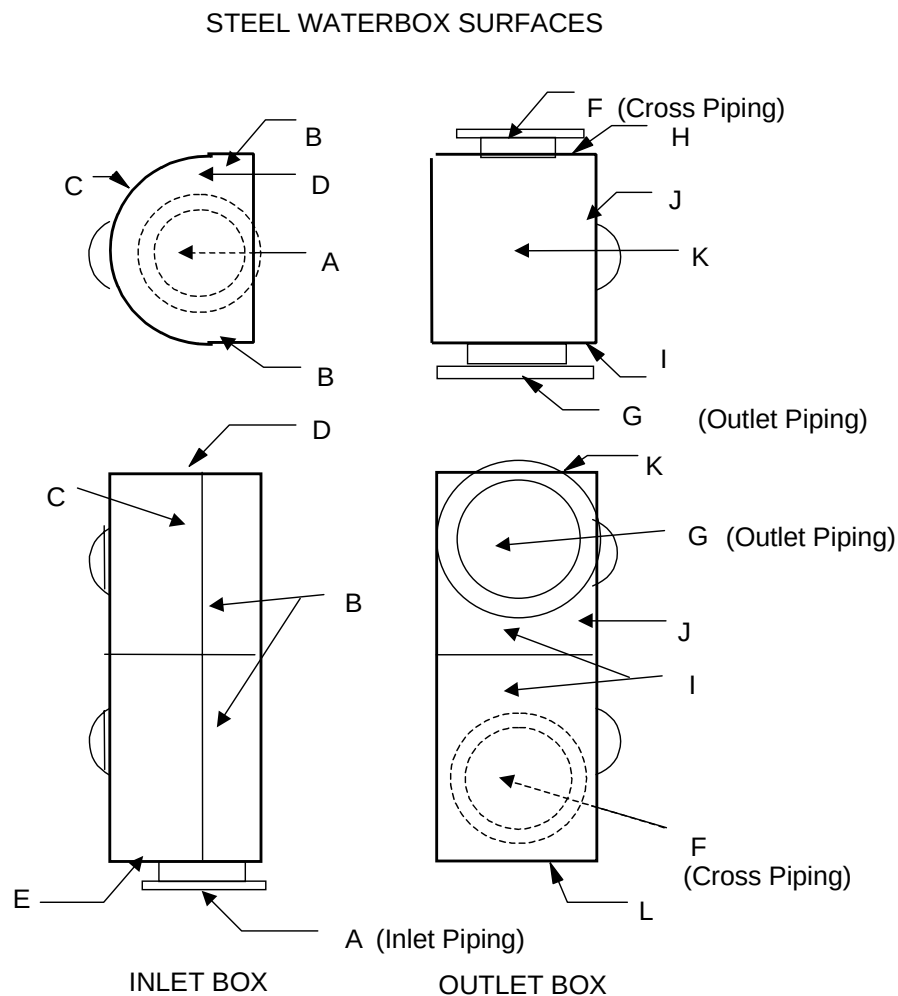


**Figure 8.11 Steel Surfaces**

Inlet pipe connection (A) is 133 cm I.D. (52 in).

Assume length of pipe = 5 x 133 cm = 665 cm

$$A_{SA} = \pi dL$$

where:

$$\begin{aligned} d &= \text{pipe diameter (133 cm)} \\ L &= \text{effective length of pipe (665 cm)} \end{aligned}$$

$$A_{SA} = \pi \times 133 \text{ cm}^2 \times 665 \text{ cm}^2 = 277,858 \text{ cm}^2$$

Vertical Walls

Rectangular surfaces (B) 2 each:

$$A_{SB} = wL \times 2$$

where:

$$\begin{aligned} w &= \text{width (61 cm)} \\ L &= \text{height of box (427 cm)} \end{aligned}$$

$$A_B = 61 \text{ cm} \times 427 \text{ cm} \times 2 = 52,094 \text{ cm}^2 (56 \text{ ft}^2)$$

Half cylinder surface (C):

$$A_{SC} = \pi rL$$

where:

$$\begin{aligned} r &= \text{radius of curvature (109 cm)} \\ L &= \text{height of box (427 cm)} \end{aligned}$$

$$A_C = \pi \times 109 \text{ cm} \times 427 \text{ cm} = 146,219 \text{ cm}^2 (157 \text{ ft}^2)$$

Top of box (D) (Rectangle + half circle):

$$A_{SD} = wL + 0.5\pi r^2$$

where:

$$\begin{aligned} w &= \text{width (61 cm)} \\ L &= \text{length (213 cm)} \end{aligned}$$

$$r = \text{radius of curvature (109 cm)}$$

$$A_{SD} = (61 \text{ cm} \times 213 \text{ cm}) + (0.5 \times \pi \times (109 \text{ cm})^2)$$

$$A_{SD} = 12993 \text{ cm}^2 + 18663 \text{ cm}^2 = 31,656 \text{ cm}^2 (34 \text{ ft}^2)$$

Bottom of box (E):

$$A_{SE} = A_{SD} - \pi d^2/4$$

where:

$$\begin{aligned} A_{SD} &= \text{total area of bottom (top) (31,656 cm}^2\text{)} \\ d &= \text{inlet pipe diameter (133 cm)} \end{aligned}$$

$$A_E = 31,656 \text{ cm}^2 - \pi \times (133 \text{ cm})^2/4 = 17,763 \text{ cm}^2 (19 \text{ ft}^2)$$

#### **TOTAL AREA OF COATED STEEL IN INLET BOX AND PIPING**

$$A_{SIB} = A_{SA} + A_{SB} + A_{SC} + A_{SD} + A_{SE}$$

$$A_{SIB} = 277,858 + 52,094 + 146,219 + 31,656 + 17,763$$

$$A_{SIB} = 525,590 \text{ cm}^2 (566 \text{ ft}^2)$$

$$\text{Area of assumed 10\% exposed steel} = 52,559 \text{ cm}^2 (56.6 \text{ ft}^2)$$

#### **TOTAL EXPOSED AREA OF ALL METAL (STEEL AND TITANIUM) INLET WATERBOX**

$$A_{STIB} = 0.1 A_{SIB} + A_{ST}$$

$$A_{STIB} = 52,559 + 466,427$$

$$A_{STIB} = 518,986 \text{ cm}^2 (559 \text{ ft}^2)$$

**OUTLET BOX (FIGURE 8.11)****CROSS PIPE CONNECTION (F)**

This is a short connection to the adjacent condenser waterbox. It has a bare metal gate valve in the connection. Assume exposed metal area is equal to the area of the pipe I.D.

$$A_{SF} = \pi d^2/4$$

where:

d = pipe diameter (122 cm)

$$A_{SF} = \pi \times (122 \text{ cm})^2/4$$

$$A_{SF} = 11,690 \text{ cm}^2 (12.6 \text{ ft}^2)$$

Outlet piping (G) is 175 cm I.D. (69 in):

Assume five pipe diameters of coated steel (5 x 175 cm = 875 cm).

$$A_{SG} = \pi dL$$

where:

d = pipe diameter (175 cm)

L = effective length of pipe (875 cm)

$$A_{SG} = \pi \times 175 \text{ cm} \times 875 \text{ cm} = 481,056 \text{ cm}^2 (518 \text{ ft}^2)$$

**SIDE OF BOX (H):**

$$A_{SH} = wL - \pi d^2/4$$

where:

w = depth of box (175 cm)

L = height of box (427 cm)

d = cross pipe I.D. (122 cm)

$$A_{SH} = (175 \text{ cm} \times 427 \text{ cm}) - [\pi \times (122 \text{ cm})^2/4]$$

$$A_{SH} = 74,725 \text{ cm}^2 - 11,690 \text{ cm}^2 = 63,035 \text{ cm}^2 (67.9 \text{ ft}^2)$$

**SIDE OF BOX (I)**

$$A_{SI} = wL - \pi d^2/4$$

where:

$$\begin{array}{lll} w & = & \text{depth of box (175 cm)} \\ L & = & \text{height of box (427 cm)} \\ d & = & \text{outlet pipe I.D. (175 cm)} \end{array}$$

$$A_{SI} = (175 \text{ cm} \times 427 \text{ cm}) - [\pi \times (175 \text{ cm})^2/4]$$

$$A_{SI} = 74,725 \text{ cm}^2 - 24,053 \text{ cm}^2 = 50,672 \text{ cm}^2 (54.5 \text{ ft}^2)$$

**FACE (J)**

$$A_{SJ} = wL$$

where:

$$\begin{array}{lll} w & = & \text{width of box (213 cm)} \\ L & = & \text{height of box (427 cm)} \end{array}$$

$$A_{SJ} = 213 \text{ cm} \times 427 \text{ cm} = 90,951 \text{ cm}^2 (97.9 \text{ ft}^2)$$

**TOP OF BOX (K)**

$$A_{SK} = wL$$

where:

$$\begin{array}{lll} w & = & \text{width of box (213 cm)} \\ L & = & \text{depth of box (175 cm)} \end{array}$$

$$A_{SK} = 213 \text{ cm} \times 175 \text{ cm} = 37,275 \text{ cm}^2 (40.1 \text{ ft}^2)$$

**BOTTOM OF BOX (L)**

$$A_{SL} = A_{SK} = 37,275 \text{ cm}^2 (40.1 \text{ ft}^2)$$



**TOTAL AREA OF COATED STEEL IN OUTLET BOX AND PIPING**

$$A_{SOB} = A_{SF} + A_{SG} + A_{SH} + A_{SI} + A_{SJ} + A_{SK} + A_{SL}$$

11,690

481,056

63,035

50,672

90,951

37,275

37,275

$$A_{SOB} = 771,954 \text{ cm}^2 (831 \text{ ft}^2)$$

[Area of assumed 10% exposed steel = 77,195 cm<sup>2</sup> (83.1 ft<sup>2</sup>)]

Total effective area of all metal (steel and titanium) outlet waterbox.

$$A_{STOB} = 0.1 A_{SOB} + A_{ST}$$

$$A_{STOB} = 77,195 \text{ cm}^2 + 466,427 \text{ cm}^2$$

$$A_{STOB} = 543,622 \text{ cm}^2 (585 \text{ ft}^2)$$

**Summary of Exposed Areas****INLET WATERBOX**

$$A_{STIB} = 518,986 \text{ cm}^2 (559 \text{ ft}^2)$$

**OUTLET WATERBOX**

$$A_{STOB} = 543,622 \text{ cm}^2 (585 \text{ ft}^2)$$

**Estimate current required to meet criteria for exposed areas**

From given laboratory studies, current density (c) required to polarize titanium to -0.650 v (silver/silver chloride) is 75 micro A/cm<sup>2</sup>. Assume the same current density is required to equalize potentials of all steel and titanium surfaces in the waterboxes.

**INLET WATERBOX**

CP 4—Cathodic Protection Specialist Course Manual

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10/01/2004

$$I_{IB} = iA_{STIB}$$

$$I_{IB} = 75 \times 10^{-6} \text{ A/cm}^2 \times 518,986 \text{ cm}^2$$

$$I_{IB} = 38.9 \text{ A}$$

### OUTLET WATERBOX

$$I_{OB} = i A_{STOB}$$

$$I_{OB} = 75 \times 10^{-6} \text{ A/cm}^2 \times 543,622 \text{ cm}^2$$

$$I_{OB} = 40.8 \text{ A}$$

### Anode Selection

This design requires control of the polarized potential on the titanium surfaces. This means that the cathodic protection must be an impressed current system operated under potential control. For service in waterboxes of this type, bayonet (rod) anodes are convenient. These anodes (either platinum clad titanium or niobium or mixed metal oxide coated titanium) work well in the highly conductive seawater. The size of the anodes is small and the effect on the cooling water flow patterns is minimal.

### Minimum Active Anode Surface Area

Figure 8.12 is a graph derived from published consumption rates of platinum clad anodes in fresh and seawater.

For a design life of 10 years for the anodes, the consumption rate is given by:

$$C_r = tk/t$$

where:

$$\begin{aligned} tk &= \text{thickness of platinum (microns)} \\ t &= \text{time (yr.)} \end{aligned}$$

for,  $tk = 6.35 \text{ microns (250 micro-inch)}$  (a common thickness)  
and,  $t = 10 \text{ years}$

$$C_r = 6.35 \text{ microns} / 10 \text{ yr} = 0.635 \text{ microns/yr}$$

## Consumption Rate of Platinum

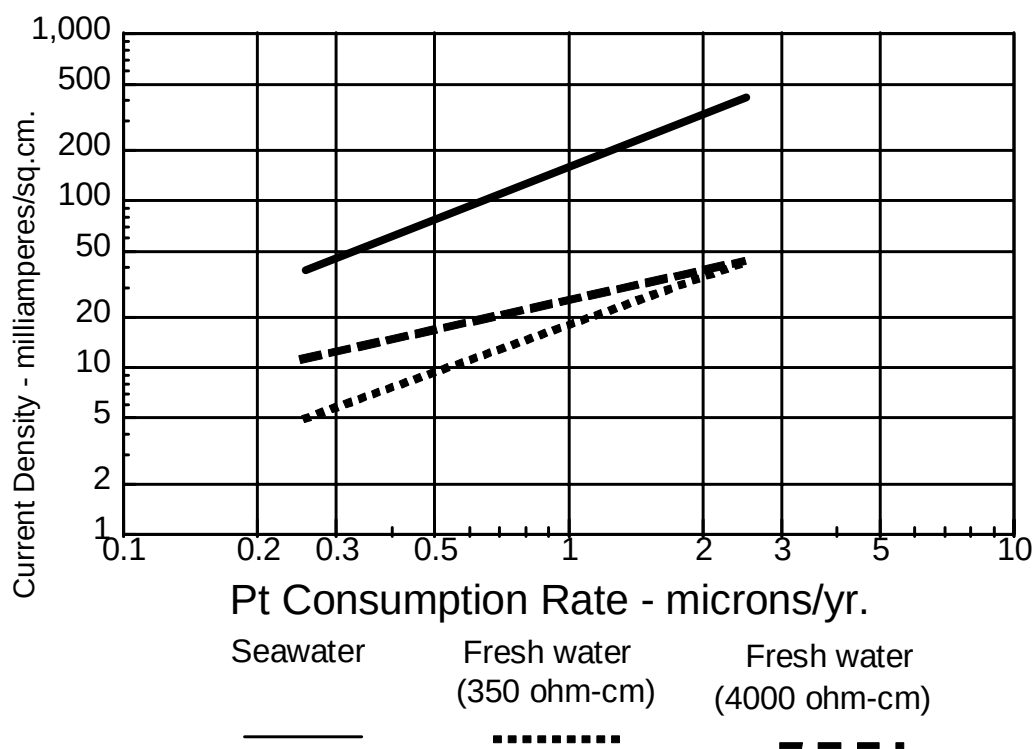


**Figure 8.12 Consumption Rate of Platinum**

From Figure 8.12, in seawater, this consumption rate corresponds to a maximum current density of about 100 milliamperes/cm<sup>2</sup> (0.1A/cm<sup>2</sup>) of platinum surface.

Assuming a design current of 50A (125% of outlet box estimated current requirement) for each waterbox, the total active anode surface required would be

$$A_A = I/i_a$$

where:

$$\begin{aligned} I &= \text{required current (50A)} \\ i_a &= \text{current density (0.1A/cm}^2\text{)} \end{aligned}$$

$$A_A = 50/0.1 = 500 \text{ cm}^2$$

Platinum clad titanium or niobium rods are available in diameters of 0.635 cm (0.25 in), 0.953 cm (0.375 in) and 1.27 cm (0.500 in). For mechanical

reasons (flow rates in the water boxes) we select the 1.27 cm (0.500 in) rods. The total length of rod required in each waterbox will be:

$$L = A_A / \pi d$$

where:

$$\begin{aligned} d &= \text{rod diameter (1.27 cm)} \\ A_A &= \text{total active area (500 cm}^2\text{)} \end{aligned}$$

$$L = 500 \text{ cm}^2 / \pi(1.27 \text{ cm}) = 125 \text{ cm}$$

### **Velocity**

The water velocity through the tubes in the condenser is given as 1.83 m/sec. (6 ft/sec). The corresponding flow rate is:

$$F = VA_x$$

where:

$$\begin{aligned} V &= \text{water velocity (1.83 m/s)} \\ A_x &= \text{total cross section area of condenser tubes} \\ &\quad \text{previously calculated (19,896 cm}^2\text{) or 1.99 m}^2 \\ F &= \text{flow rate (m}^3\text{/s)} \end{aligned}$$

$$F = 1.83 \text{ m/s} \times 1.99 \text{ m}^2 = 3.64 \text{ m}^3\text{/s}$$

The velocity of water through the inlet pipe of the inlet waterbox is calculated.

$$V = F / (\pi d^2 / 4)$$

where:

$$\begin{aligned} F &= \text{flow rate (3.64 m}^3\text{/s)} \\ d &= \text{inlet pipe diameter (1.33 m)} \end{aligned}$$

$$V = 3.64 \text{ m}^3\text{/s} / (\pi \times (1.33\text{m})^2 / 4) = 2.62 \text{ m/s}$$

Since this is the smallest pipe entering or leaving the condenser, (excluding the 122 cm diameter cross connection) 2.62 m/s is the highest mean velocity. At high flow rates, the maximum velocity ( $V_{MAX}$ ) is between 1.2 and 1.4 times the mean velocity<sup>5</sup>.

In this case assume:

$$V_{MAX} = 1.4 \times 2.62 = 3.7 \text{ m/s (12 ft/s)}$$

***Calculation of forces on a rod type anode subjected to hydraulic drag.***

Figure 8.13 is a diagram of a rod anode anchored at the waterbox wall through an insulating fittings. Figure 8.14 is a graph summarizing the effect of mechanical forces operating on titanium based probe anodes with the variables of velocity, rod diameter and length of rod extending from the wall of a structure (wall of a waterbox). Note that 8.14 includes a safety factor of 3. Should the probes be used in a vessel that has heavy vibration, a factor of 5 should be applied.

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<sup>5</sup> Chemical Engineers' Handbook, 3rd Ed., pp. 399, J. H. Perry, McGraw-Hill Book Company, Inc., NY

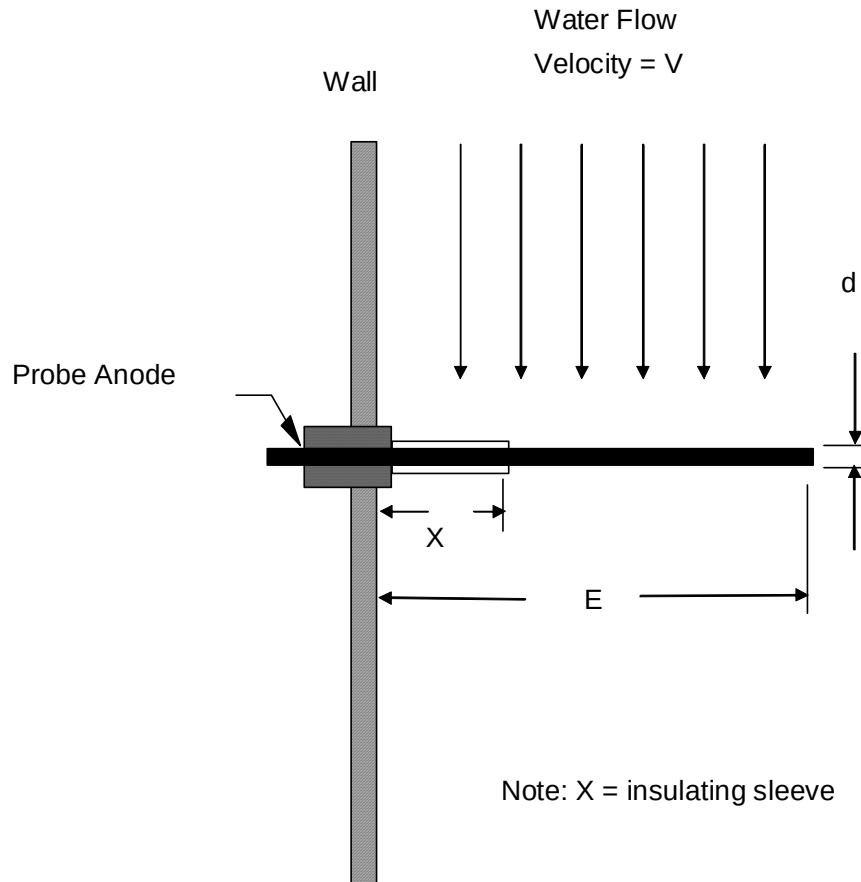


**Figure 8.13 Diagram of Probe Anode**

The maximum velocity in the inlet waterbox has been calculated at 3.7 m/s (12 ft/s). From Figure 8.14 at a seawater velocity of 4 m/sec, a 1.27 cm (0.5 in) diameter probe anode should not be longer than about 55 cm (22 in).

In most cases an insulating sleeve "x" cm long (Figure 8.13) is installed on the bayonet anode to provide separation of the active element from the wall of the vessel. A common length for "x" is about 8 cm (3 in). If we elect to set  $x = 8$  cm then the minimum number of 55 cm (22 in) long anodes in each waterbox can be determined from the equation:

$$N (L_{MAX} - X) = L_A$$

$$N = L_A / (L_{MAX} - X)$$

where:

$L_A$  = total length of exposed active anode rod (125 cm)  
 $X$  = length of insulating sleeve (8 cm)  
 $L_{MAX}$  = maximum safe length of rod extension from wall (55 cm)

$$N = 125 \text{ cm} / (55 \text{ cm} - 8 \text{ cm}) = 2.66$$

### BAYONET ANODE

#### SAFE OPERATING PARAMETERS

Environment = Seawater

Safety factor = 3.0

Rod material = Titanium

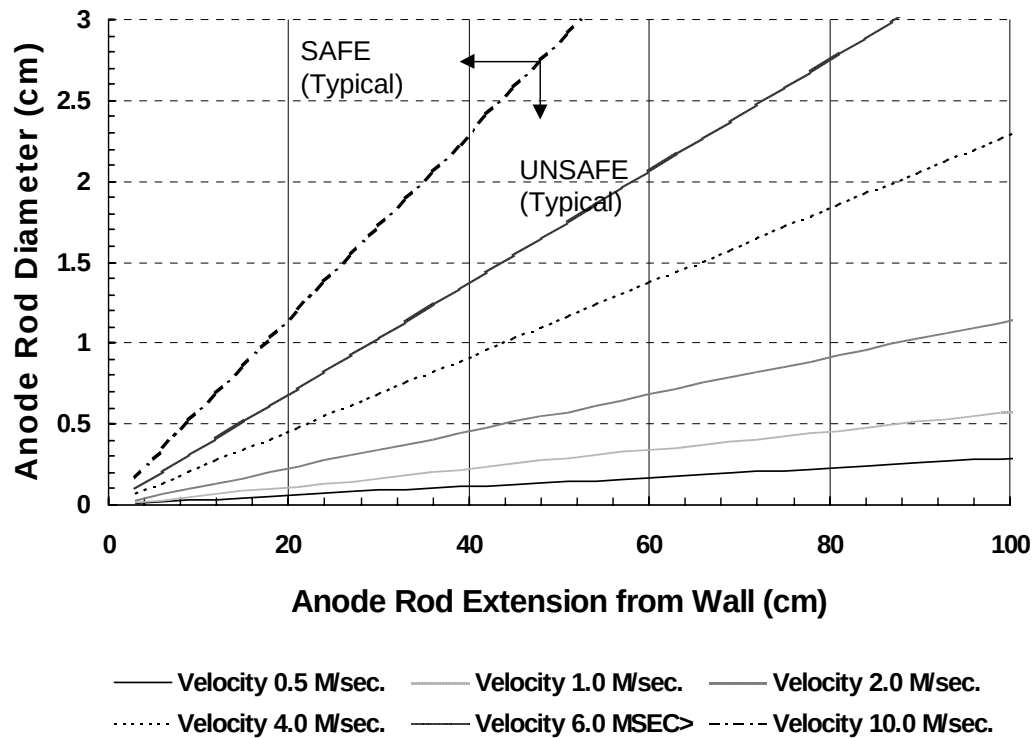


**Figure 8.14 Probe Anode Operating Parameters**

The next whole number of anodes is 3. Three anodes in each box allow for only one anode in each tubed area and one in the middle zone. For better backup in case of damage to an anode, at least two anodes should be in both the upper and lower tubed areas. Adding another anode for the zone between the tubed areas yields a total of 5 anodes per box.

Since there are more anodes, the active length of each anode can be reduced. Assuming N has 5 anodes, we can solve the above equation for  $L_{MAX}$ :

$$L_{MAX} = X + L_A/N$$

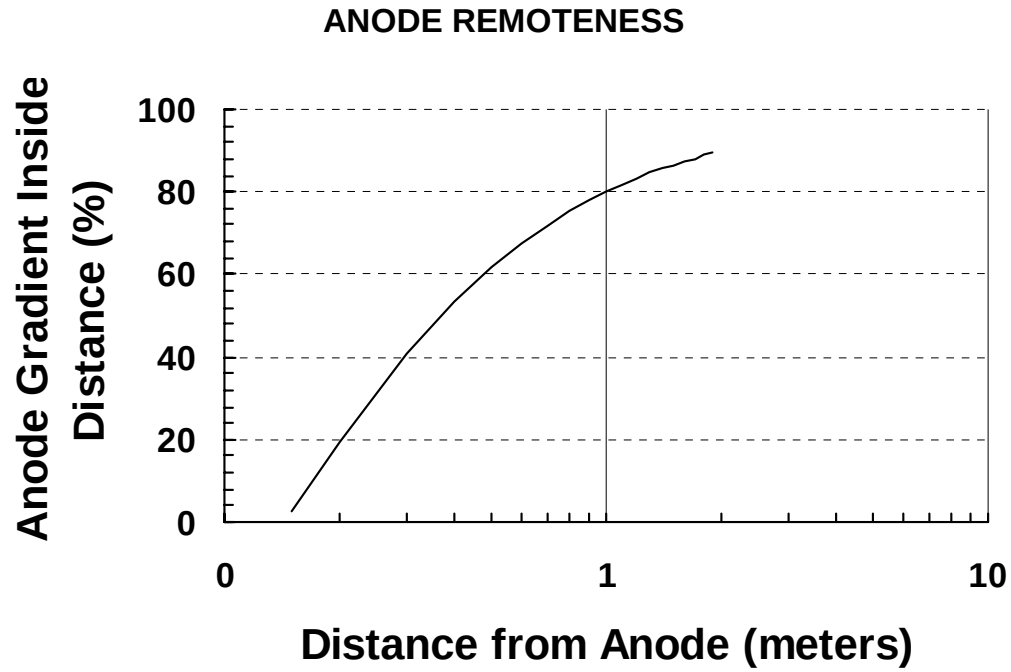
$$L_{MAX} = 8 \text{ cm} + 125 \text{ cm}/5 = 33 \text{ cm}$$

Each anode has an overall extension of 33 cm with 25 cm of active anode and 8 cm of insulating sleeve. If we allow a 20% safety factor (in case one anode is damaged) we should specify an active length of  $1.2 \times 25 = 30$  cm and an overall length of 38 cm.

### ***Examine Anode Remoteness***

Figure 8.15 is plot of the effective anode remoteness for a 30 cm long 1.27 cm diameter anode placed against a non-conducting (coated) surface. The dimensions of the waterboxes severely limit the separation of anodes from the bare titanium tube sheets. In the inlet waterbox the maximum separation of the anodes from the tube sheet is 170 cm (1.7 m) or 67 inches. Figure 8.15 indicates that the tube sheet will be outside 80% of the above gradient if the anodes are at least 1 meter (39 in) away from the tube sheet. Variations in current density reaching the tube sheet because of differences in anode gradient would be less than 10% (the difference between the gradient at 1.7 m and 1 m). The object then is to locate the probe anodes in a pattern on the coated steel walls of the water boxes such that the closest anode is no nearer the tube sheet than about 1 meter (39 in). Figure 8.16 shows one possible arrangement in which the anodes are relatively evenly distributed and which meet the 1 meter criteria.





Anode Length = 30cm

Anode Diameter = 1.27cm

***Figure 8.15 Anode Remoteness***

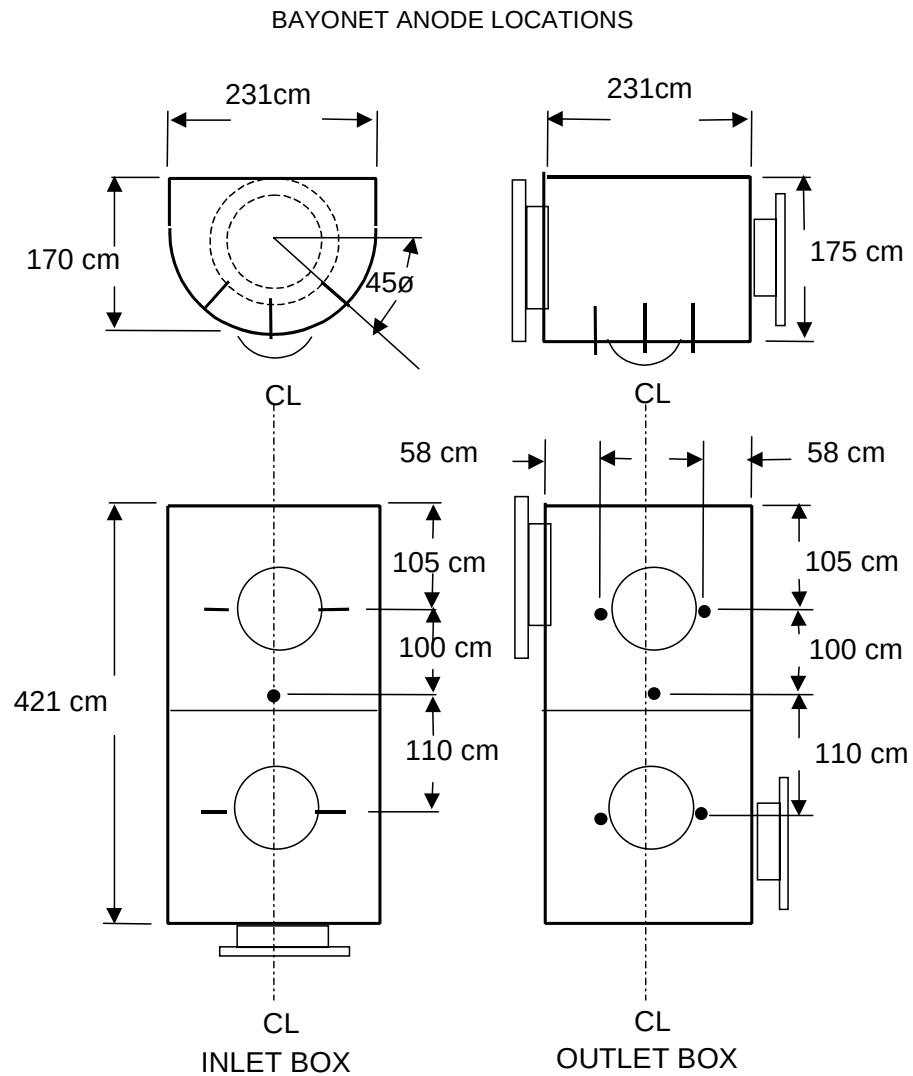


**Figure 8.16 Anode Configuration**

## ***Rectifier Rating and Control***

Estimate the approximate anode resistance using Dwight's formula for a vertical anode.

$$R = \frac{0.005\rho}{\pi L} \left( \ln \left( \frac{8L}{d} \right) - 1 \right)$$

where:

$$\begin{aligned} \rho &= 30 \text{ ohm-cm} \\ L &= 0.30 \text{ meters} \\ d &= 0.0127 \text{ m} \end{aligned}$$

$$R = \frac{0.005 \frac{\text{m}}{\text{cm}} \cdot 30 \text{ ohm-cm}}{\pi 0.30 \text{ m}} \left( \ln \left( \frac{8 \cdot 0.30 \text{ m}}{0.0127 \text{ m}} \right) - 1 \right) = 0.675 \text{ ohm per anode}$$

The approximate resistance of 5 anodes in parallel is:

$$R = 0.675 \Omega / 5 = 0.135 \text{ ohm}$$

The voltage required to provide 50A per waterbox is by Ohm's law.

$$E = IR$$

where:

$$\begin{aligned} I &= \text{design current (50A)} \\ R &= \text{anode to waterbox resistance (0.135}\Omega\text{)} \end{aligned}$$

$$E = 50 \text{ A} \times 0.135 \Omega = 6.75 \text{ V}$$

Taking into account back potential and polarization of the anodes and waterbox, select a potential controlled rectifier with separate units for each waterbox having a rating of 50A (10A per anode) and 12 volt maximum voltage.

## Location and Type of Reference Electrodes

The cathodic protection system must hold the potential of the titanium tube sheet at no more than -650V vs. silver/silver chloride. The reference used to control the power supply should be located at the tube sheet in a location which is nearest to an anode. Other references are desirable at additional locations to verify effectiveness of the cathodic protection.

References are available which can be fitted into a tube opening. This prevents the use of such tubes for cooling. However, the large number of tubes (over 5000) in this type of condenser makes this a negligible problem. Figure 8.17 shows a typical tube mounted reference electrode (silver/silver chloride) and suggested locations for installing these in the typical waterbox.

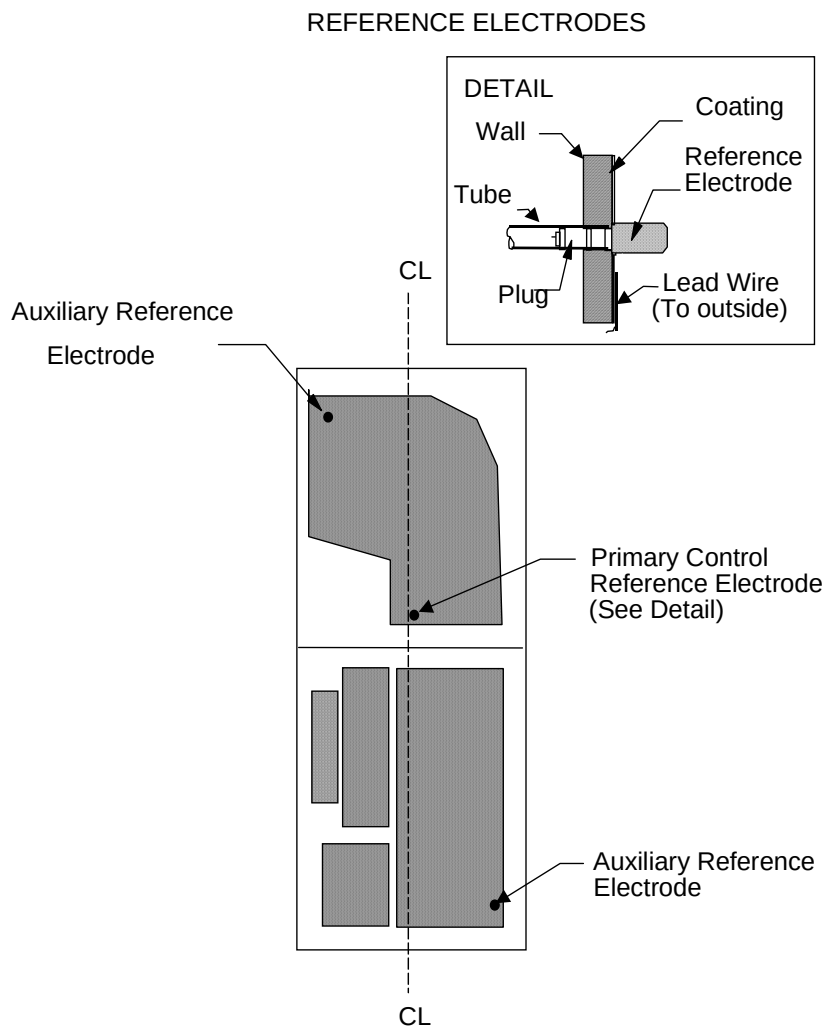


**Figure 8.17 Reference Electrodes**

## Small Production Thickener/Aluminum Anodes

### ***Existing Structure – Some Protective Coating***

#### ***Description***

Figure 8.18 shows a small thickener used to separate sediment from a process stream. The unit consists of polymer lined concrete tank 9.1 meters (30 ft) in diameter and 2.4 meters (8 ft) high. The thickener has a long and a short rake arm made of carbon steel with wooden blades. (see Figure 8.19) The rake arms have a coating which is not fully effective in controlling corrosion. The liquid in the process stream contains a high salt concentration with a resistivity of about 20 ohm-cm.

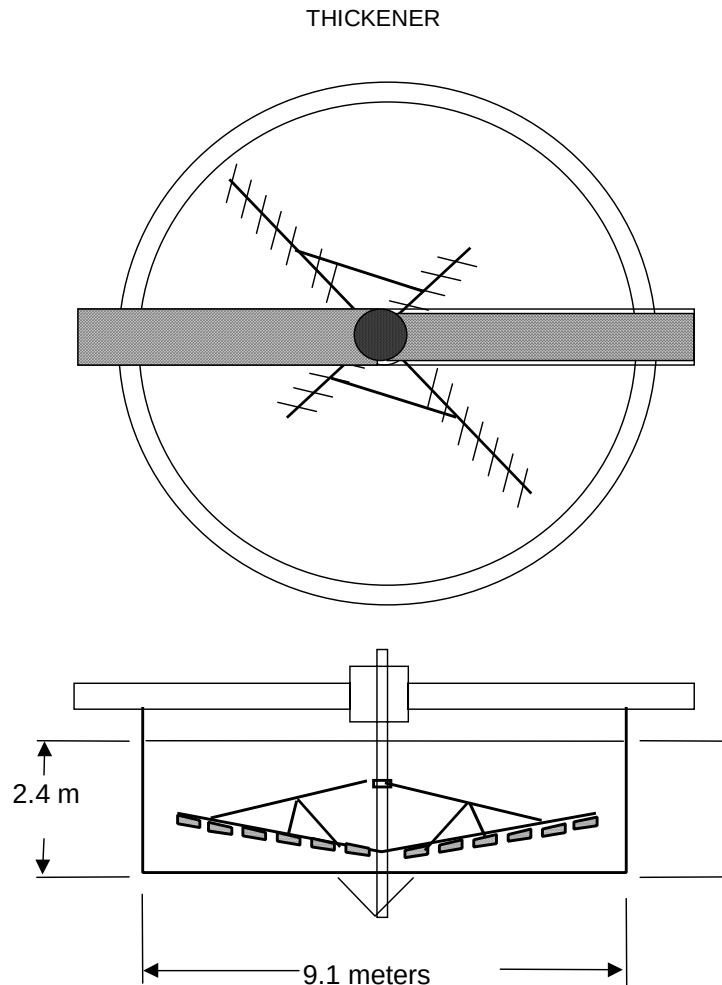
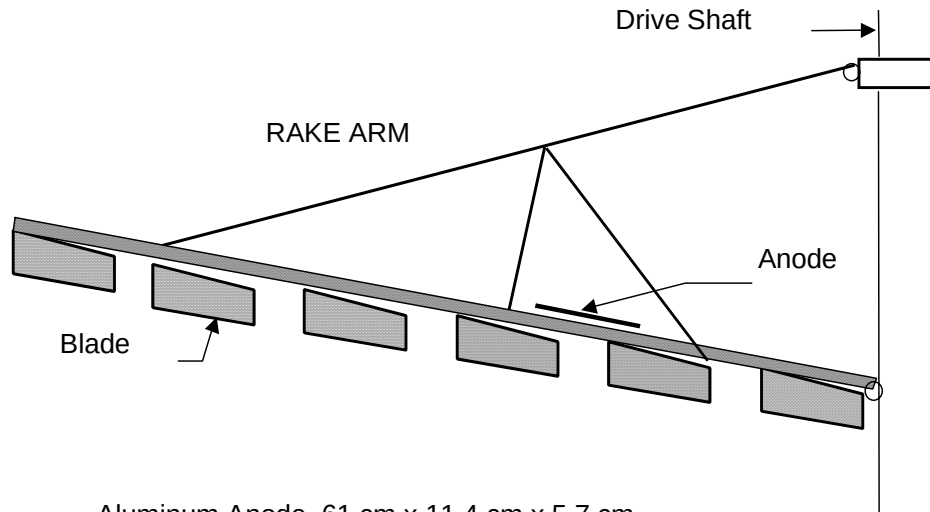


***Figure 8.18 Thickener***

Design a galvanic anode system which will control corrosion on the rake arms. The anodes should have a life of about 3 years.

THICKENER RAKE ARM  
CATHODIC PROTECTION



Aluminum Anode 61 cm x 11.4 cm x 5.7 cm

Alloy Composition

Zinc - 3.0%

Silicon - 0.1%

Indium - 0.015%

Aluminum - Remainder

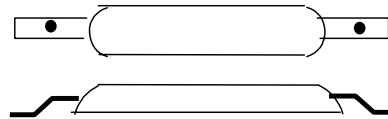


**Figure 8.19 Rake Arm**

## Parameters

1. Total surface area of steel in the long rake arm, the short rake arm and the immersed section of the drive shaft at 9 m<sup>2</sup>.
2. Laboratory tests indicate that a current density of 25 micro-amperes/cm<sup>2</sup> is required to protect steel under the flow conditions in the thickener.

## Analysis

Since the tank is lined with a dielectric material, the only components in the unit that are metallic are the rake arms and the drive shaft. The high salt content and low resistivity of the environment suggest the use of aluminum anodes for protection. Aluminum alloys have a high amp-hr capacity to weight ratio and can easily be mounted to the main arms of the unit. If the anodes are provided with steel straps for bolting to the rake arms, they can be easily replaced during normal maintenance of the thickeners. Standard 9.1 kg (20 lb.) hull type anodes should be well suited to this equipment. The rake arm in the vicinity of the anodes ( $\pm 1$  meter) should be coated with a suitable epoxy or other dielectric material to increase the "throw" of current from the anodes.

## Calculations

### ESTIMATE CURRENT REQUIRED FOR PROTECTION.

$$I_T = i_c A_s$$

where:

$$\begin{aligned} i_c &= \text{estimated current density (25 x 10}^{-6} \text{ A/cm}^2\text{)} \\ A_s &= \text{exposed area to be protected (9 m}^2\text{, 90,000 cm}^2\text{)} \end{aligned}$$

$$I_T = 25 \times 10^{-6} \text{ A/cm}^2 \times 90,000 \text{ cm}^2 = 2.25 \text{ A}$$

**ESTIMATE WEIGHT OF ALUMINUM ALLOY REQUIRED FOR 3 YEAR LIFE**

$$W = It/C_a f_u$$

where:

- I = current required over life (2.25 A)
- t = time (3 yr x 8760 hr/yr = 26,280 hr)
- C<sub>a</sub> = current capacity of aluminum - indium alloy (2533 A-hr/kg)
- f<sub>u</sub> = utilization factor (0.85)

$$W = 2.25 \text{ A} \times 26,280 \text{ hr} / (2533 \text{ A-hr/kg} \times 0.85) = 27.5 \text{ kg}$$

Number of 9.1 kg anodes required;

$$N = 27.5 \text{ kg} / 9.1 \text{ kg} = 3.02$$

For symmetry use 4 anodes (one per rake arm).

**ESTIMATE THE MAXIMUM CURRENT OUTPUT FOR ANODES**

From Dwight's equation for a horizontal anode:

$$R = \frac{0.005\rho}{\pi L} \left( \ln\left(\frac{4L}{d}\right) + \ln\left(\frac{L}{h}\right) - 2 + \frac{2h}{L} \right)$$

where:

- ρ = 20 ohm-cm (resistivity)
- L = 0.61 m (length of anode)
- d = .08 m (approximate diameter of anode)
- h = 2 m (approximate depth of anode)

The resistance for one anode is:

$$R = \frac{0.005 \frac{\text{m}}{\text{cm}} \cdot 20 \text{ ohm-cm}}{\pi \cdot 0.61 \text{ m}} \left( \ln\left(\frac{4 \cdot 0.61 \text{ m}}{0.08 \text{ m}}\right) + \ln\left(\frac{0.61 \text{ m}}{2 \text{ m}}\right) - 2 + \frac{2 \cdot 2 \text{ m}}{0.61 \text{ m}} \right) = 0.35 \text{ ohm}$$



Four anodes in parallel (neglecting mutual effects) is:

$$R_T = 0.35 \text{ ohm}/4 = 0.089 \text{ ohm}$$

There are other formulas for estimating the resistance of small anodes in production vessels. All are approximations because of confined geometry and distribution of coating faults.

#### **ESTIMATED TOTAL CURRENT OUTPUT BY OHM'S LAW.**

$$I = E/R$$

where:

- E = initial galvanic potential between anode and unpolarized steel (assume steel @  $-0.55 \text{ V CSE}$ , anode @  $-1.15 \text{ V CSE}$ )
- E =  $-0.60 \text{ volt}$
- R = circuit resistance (neglecting rake arms to liquid resistance,  $R = 0.089 \text{ ohm}$ )
- I =  $0.6 \text{ V}/0.089 \text{ } \Omega = 6.7 \text{ A}$

This current should assure rapid polarization of the steel. As the potential of the steel approaches that of the anode ( $-1.15 \text{ volt CSE}$ ) the current will decrease to the level required to sustain polarization.

With process equipment, there are many geometric and operating variables, which may influence actual performance. Most of the general formulas used to estimate resistances are in error to some degree because of the close geometry involved. All systems should be thoroughly evaluated after installation.

## Summary

1. An example of a cathodic protection design for a large water storage tank with the following features:
  - Little effective protective coating
  - Impressed current silicon iron anodes
  - Elevated elliptical bowl with riser pipe
  - Example includes main anode array, stub anode array and riser anode
2. An example of cathodic protection design for a small seawater holding tank with platinized niobium impressed current anodes.
3. An example cathodic protection design for the waterboxes of a large surface condenser in a power plant. Features of note include:
  - protective coating on steel waterbox walls
  - titanium tubes and tubesheet (subject to degradation by hydrogen produced by cathodic protection)
  - design of bayonet type anodes to resist mechanical stress caused by fluid flow
  - potential controlled power supply
4. An example of cathodic protection design for a small process thickener using galvanic anodes.

# CHAPTER 9

## STEEL REINFORCING IN CONCRETE STRUCTURES

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### Introduction

Reinforcing in concrete structures can refer to either standard reinforcing bars or high strength steel tendons (prestressed or post-tensioned concrete). Cathodic protection (CP) for steel reinforcing in concrete can be either the impressed current or galvanic type. The function of the anode in a cathodic protection system for reinforced concrete is to distribute current uniformly to all embedded steel. Impressed current CP employs a rectifier and an anode to force all of the steel reinforcement into functioning as a cathode, resulting in no corrosion activity on the steel surface. On the other hand, a galvanic CP system does not require a rectifier because the source of the current is the anode. When two different metals (steel and galvanic anode) are electrically connected to each other, a galvanic cell is established. As a result, electrical current flows naturally from the galvanic anode to the steel through the concrete electrolyte. Since reinforcing in concrete tends to close to the surface and densely packed, the anode usually covers the entire surface of the concrete or separate anodes are closely spaced.

### *Existing Structures*

#### *Impressed Current Systems*

##### CONCRETE OVERLAY TITANIUM MESH CP SYSTEM

The catalyzed titanium mesh anode system consists of an expanded titanium mesh with a mixed metal oxide catalyst applied to the concrete surface.(Figure 9.1)

The mesh anodes are fastened to the prepared concrete surface using plastic fasteners after the damaged concrete is repaired.

The titanium mesh is connected to a bare titanium current distributor bar using a spot-welder. The anode mesh is then overlaid with a cementitious material, such as standard portland cement concrete mix or shotcrete.



A catalyzed titanium mesh anode system was first introduced in 1985 and is the most commonly used CP system for deck surfaces that are exposed to the de-icing salt environment. The titanium mesh system is known to be the most durable system to protect bridge deck structures.



**Figure 9.1 Titanium mesh anode system**

This system is also beneficial to protect concrete piles or columns. After damaged concrete is repaired, the titanium mesh anodes are installed on the concrete surfaces by wrapping around the piles or columns. The anodes are then embedded in a cementitious material using shotcrete or non-metallic concrete forms.

## TITANIUM RIBBON MESH SLOTTED CP SYSTEM

This system involves the use of a MMO coated titanium ribbon and a non-shrink cementitious grout as the slot backfill. Ribbon mesh sizes are typically 13-mm and 19-mm wide. Slot spacing is dependent on steel density, but is typically 200-400 mm on center. A typical concrete slot is 10-mm wide by 25-mm deep for the 13-mm wide anode and 32-mm deep for the 19-mm wide anode. In areas of spalled and delaminated concrete, the ribbon can be attached to exposed rebar with plastic clips, and covered with shotcrete. Titanium current distributor bars provide continuity between the strips and are spot-welded to the ribbon mesh in the transverse direction. This system has been especially useful for concrete structures that cannot tolerate the additional dead load of a concrete overlay or where bonding of the overlay for mesh encapsulation is a concern. Sufficient cover over the rebar must be present, or the steel must be located with a rebar locator so the slots can be installed between the bars.

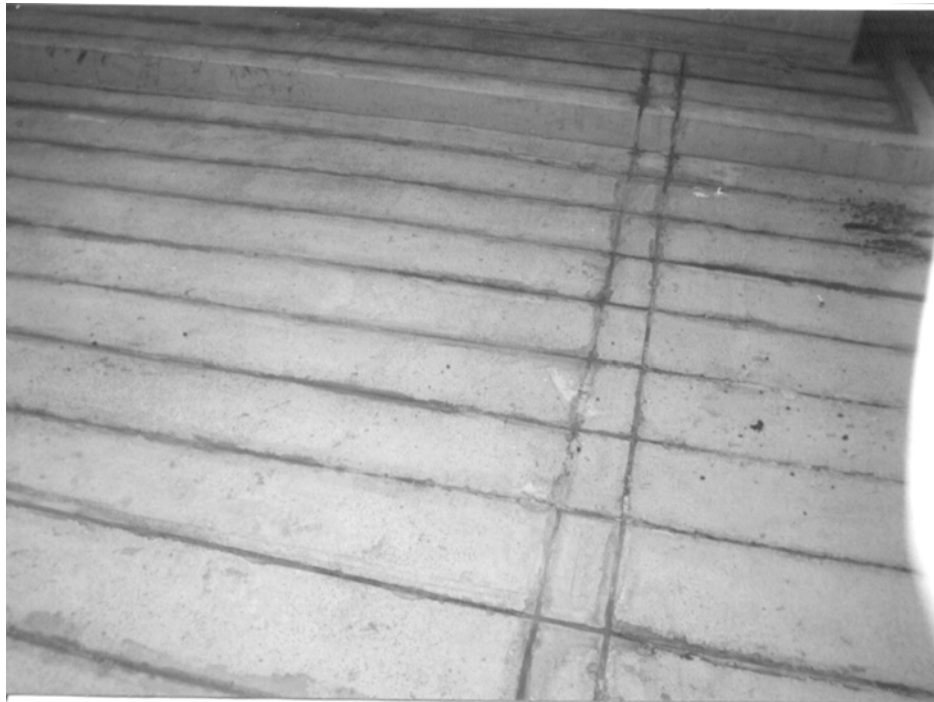


***Figure 9.2 Slotted anode CP system***

## DISCRETE ANODE CP SYSTEM

The discrete anode system is one of the most cost-effective systems for beams, piles and columns. The anodes are relatively easy to install and do not require extensive saw cutting or use of concrete overlays. The discrete anodes are typically inserted into drilled holes that are 20-25 mm in diameter and backfilled with a non-shrink cementitious grout. The length and spacing of the anode is dependent on the steel density and protection requirements for cathodic protection. Several systems are available. These include a discrete titanium ribbon mesh system, ceramic anodes and platinized titanium wire with a carbon rich backfill. Current densities at the anode-concrete interface should be limited to  $220 \text{ mA/m}^2$ ; otherwise degradation of the cement paste at the anode-concrete interface may result.

## THERMALLY SPRAYED ZINC SYSTEM

The technique of zinc metallizing as used in cathodic protection of reinforced concrete was first developed by the California Department of Transportation in 1983. The process of metallizing involves the melting of a metal or alloy in wire form, typically with a high amperage arc, and spraying the molten metal onto the concrete with compressed air. The zinc coating is typically applied to a dry film thickness of 300-400 microns. A metal pad embedded in the concrete is used to connect the anode to the rectifier. Testing arc sprayed zinc systems through electrochemical aging has shown that bond strengths actually increase with time due to secondary mineralization of the zinc reaction products. Arc sprayed zinc impressed current cathodic protection (ICCP) systems are also subject to short circuits from exposed or partially embedded rebar chairs.

## THERMALLY SPRAYED TITANIUM SYSTEM

Thermally sprayed titanium anodes for cathodic protection of reinforced concrete have been applied to several structures in the field on a trial basis. A liquid chemical catalyst is applied to the anode surface to allow the anode to discharge current. The first installation was in 1994 on the Depoe Bay Bridge in Oregon. The results of the field trials to date indicate that the systems are operating at relatively low current levels and are achieving criteria for cathodic protection of steel in concrete. Arc sprayed titanium is somewhat more difficult to apply than arc sprayed zinc, due to the hardness of the wire and subsequent wear of the spray tips. Titanium, however, is relatively inert in the environment and there are no known environmental impacts using this type of system. In theory, the anode has very long life expectancy (i.e., >100 years) and it is possible that the liquid catalyst may be reapplied to the titanium surface in the future, if needed.

## **CONDUCTIVE COATING SYSTEM**

Conductive coatings using a high carbon loading were one of the first anode systems used on concrete structures. One of the advantages of a conductive coating is its ability to be applied easily to irregular surfaces, such as deck soffits and bridge piers. The paint is sprayed, rolled or brush applied to the surface at a thickness of approximately 300 microns DFT. Platinized niobium current distributor wires are typically spaced at 3-6 m intervals. The conductive coating is rolled directly over these wires or the wires are embedded in conductive mastic. The conductive coating is black, so a decorative paint is required as an overcoat. Conductive paint systems are particularly subject to short circuits from exposed or partially embedded rebar chairs that exist on the underside of structural elements. Furthermore long term durability in marine environments is suspect, especially in areas subject to surface wetting.

## **TITANIUM ANODE INTEGRAL PILE JACKET CP SYSTEM**

Another system known as the integral pile jacket CP system has been used on many concrete bridge pilings in Florida. This system uses a prefabricated fiberglass jacket, which is supplied with the mesh anode attached to the inside of the jacket using special offsets. The jacket system is mounted to the piles using compression bands and the void between the jacket and concrete surface is filled with a cementitious grout. The systems installed with pile jackets have been successful in controlling corrosion on bridge piles in the splash and tidal zones. The jackets have the additional benefit of acting as electrical insulators, thus preventing the flow of current through seawater to submerged steel. Since the catalyzed titanium anodes have extremely low consumption rates and long life expectancy (i.e. > 75 years), life cycle costs are generally favorable regarding their use. Figure 9-3 shows an example of a titanium mesh integral pile jacket system on a bridge in Florida.



**Figure 9.3 Titanium anode in a pile jacket**

## **Galvanic CP Systems**

### **GENERAL**

All galvanic CP systems require a metallic connection to the reinforcing steel. The type of connection depends on the construction. Where high-strength steel is used, such as in pre-stressed or post-tensioned construction, the attachment is generally done mechanically. In other situations brazing or other thermal methods may be used.

### **THERMALLY SPRAYED ZINC SYSTEM**

Thermally sprayed zinc has also been used as a sacrificial anode for atmospherically exposed reinforced concrete structures. Pure zinc is applied to the concrete surface using standard metallizing equipment (e.g., flame spray, electric arc). As with all galvanic anode systems, the presence of embedded metal near the surface that would short out and render ineffective an impressed current anode system has no detrimental effect on a galvanic anode system. Metallized zinc has been applied at about 300 microns (12 mils) thick. The current from thermally sprayed zinc shows a substantial decrease with time in dry areas. Zinc is useful for surfaces that are slightly moist so that the metal remains active. No sacrificial anode coating should be used on surfaces that are subject to continuous immersion since the anode will quickly become depleted due to current dis-





charge to metal outside the embedded concrete intended to be protected. The system must provide a suitable connection to the reinforcing.

### THERMALLY SPRAYED ALUMINUM ALLOY

The alloy, which contains aluminum, zinc and indium, is produced in cored wire form, which consists of an outer aluminum sheath and a hollow core filled with alloyed powder. The alloy is applied onto concrete surfaces using arc spray equipment (Figure 9.4). The electric arc spray system simultaneously feeds two wires at a uniform speed through a spray gun. Upon application of a voltage across the wires, an arc is formed, which subsequently melts the wires. The molten alloy is then propelled onto the concrete surface using pneumatic air pressure. The recommended anode coating thickness is approximately 300 microns (12 mils).

Expected life of the aluminum alloy anode is 10 to 15 years, depending on the surrounding environment. Corrosion protection (galvanic) current output from the anode fluctuates with relative humidity, temperature, and wetness of the concrete. Therefore, the anode installed on a concrete structure exposed to highly corrosive environment (high temperature and high relative humidity) expected to be shorter anode life.



**Figure 9.4 Arc spray application of galvanic anode**

### ZINC/HYDROGEL SYSTEM

This material consists of a 0.25-mm thick zinc sheet with an ionically conductive adhesive (hydrogel) backing. No special equipment or engineering skills is required for installation of this anode. The release paper is simply removed from the backing and the laminate is pressed onto the concrete surface. The surface of the concrete should be relatively smooth and



clean for this application. The edges should be sealed with silicon caulking to prevent moisture ingress. The system has been installed on several bridge substructure projects and condominium balconies along the coast of Florida.

### **ZINC MESH INTEGRAL PILE JACKET**

The zinc mesh integral pile jacket system is designed to protect the tidal and splash zones of bridge pilings. The system consists of snap-together fiberglass jackets with expanded zinc mesh fastened to the inside face of the jacket assembly. The annular space between the jacket and the pile is then filled with a cementitious grout. Since the system is pre-assembled, installation is quite simple.

## ***New Structures***

### **TITANIUM RIBBON MESH CP SYSTEM**

Catalyzed titanium ribbon mesh anodes are also well suited for CP of new concrete structures. The anodes are fastened to the reinforcement cage during assembly using special non-metallic rebar clips, as shown in Figure 9.5. Each ribbon mesh anode is connected to bare titanium current distributor bars to deliver protection current from a rectifier. The ribbon mesh anode is spot-welded to the current distributor bars in the field. The anode spacing is calculated based on the required protection current density at the rebar and the anticipated current distribution pattern. Care should be taken to ensure that the anodes are not too widely spaced. Using higher current output at too great a spacing leads to an unacceptably uneven current distribution across the reinforcement cage. Typical anode spacing is between 200 to 400 mm on centers.

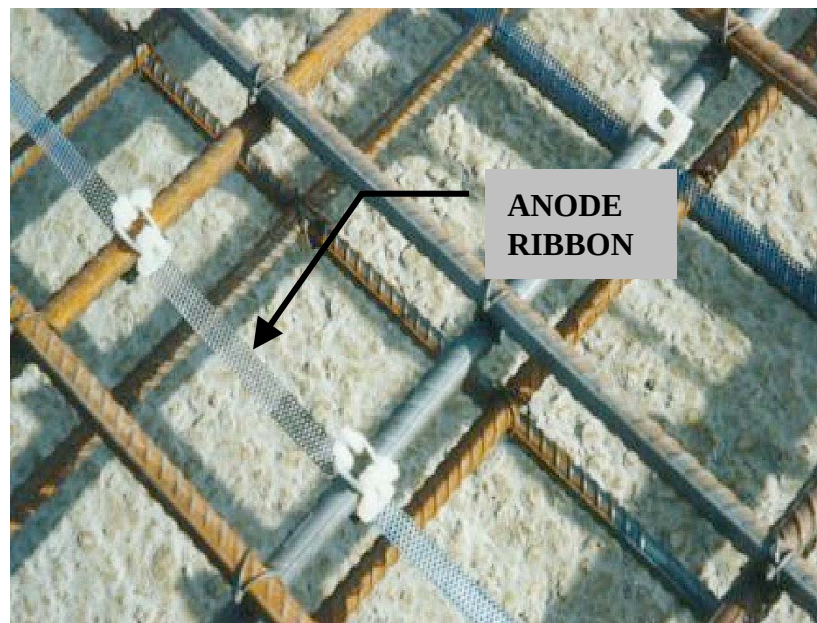


***Figure 9.5 Titanium anode installed in new structure***

## TITANIUM MESH CP SYSTEM

Titanium mesh can also be installed for new concrete beams, piles and columns. After a reinforcement cage is assembled the titanium mesh is attached to the outer layer of reinforcing steel using plastic cable straps. To prevent electrical shorts between the anodes and the reinforcement, plastic mesh spacers are installed directly on the exposed rebar cage prior to the titanium mesh anodes installation. The titanium mesh is spot-welded to a bare titanium current distributor bar for the later electrical connection. After the cathodic prevention system is installed, the structural member is completed by placing concrete in forms.

To avoid concrete segregation by the titanium mesh, several small holes are cut in the mesh. Typically, the 50 mm (2 inches) in diameter holes are spaced at approximately every 300 mm (12 inches) on centers to improve the concrete flow during the concrete placement.

# Design Examples for Concrete Bridge Deck Protection

## **General**

The design of a cathodic protection system for a bridge deck combines both specific and empirical parameters. The major specific parameters needed are:

1. The dimensions of the deck and associated plans.
2. The reinforcing pattern and schedule embedded in the deck.
3. The results from a bridge condition survey, normally includes:
  - reinforcing steel bar (rebar) potentials.
  - chloride ion concentrations.
  - rebar depth of cover.
  - rebar and other metallic embedment electrical continuity.
  - concrete delamination areas.
  - concrete resistivity.
4. The availability, location, and type of AC power.
5. The required design life for the cathodic protection system.

The major empirical input is the estimation of direct current required to achieve adequate cathodic protection levels. The current requirement impacts the choice of anode system(s), the amount of anode material required, the size of the rectifier unit, and the wiring size and configurations. Because cathodic protection design for reinforced concrete structures is quite different from other structures included in this course, the example chosen is more general in concept than other designs presented to this point.

## ***Current Requirements***

Typically, current requirements are based upon a current density per square meter of steel surface or per square meter of bridge deck. Current densities calculated on the basis of the area of steel usually use the total surface area of reinforcing steel in the bridge deck to determine the surface area of steel. If the current flow is not equally distributed to the entire reinforcing steel in the deck, some of the rebars are not sufficiently protected from corrosion. The proportion of current flow to each rebar is a function of the concrete conductivity, the depth of cover over each rebar, and the rebar pattern. With such a complex function to consider, the design engineer must: compare the structure under design with structures of the same type from which the empirical current requirements were derived. If substantial differences exist, site-specific data or another empirical current requirement may be needed.

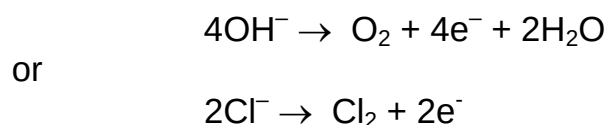
Current requirement values based on the area of deck surface make the assumption that the reinforcing steel pattern is uniform across the surface and that the ratio of the deck surface area to steel surface area is constant. The designer must review the structural drawings of each bridge deck to determine the rebar pattern and schedule. For a typical double mat rebar construction bridge deck, the surface area of the rebar steel will average about 85 percent of the surface area of the bridge deck.

The typical range of current densities used in estimating current requirements is from 5 to 20 mA/m<sup>2</sup> (0.5 to 2.0 mA/ft<sup>2</sup>) of steel. On the basis of the above rebar-to-deck area, the ratio would be 4.3 to 17 mA/m<sup>2</sup> (0.43 to 1.7 mA/ft<sup>2</sup>) of deck surface. In actual operation, the current requirements are more typically about 7.5 to 15 mA/m<sup>2</sup> (0.75 to 1.5 mA/ft<sup>2</sup>) of steel. In the design stage of a cathodic protection system, higher current should be used, considering the design safety-factor aspect and unexpected high current discharge at localized areas of the system, and the higher current in the initial stages of operation.

### Example

Consider a bridge deck with a surface area of 1,000 m<sup>2</sup> (10,000 ft<sup>2</sup>). An examination of the rebar pattern indicates that the steel-to-deck surface area ratio is one to one. A conservative estimate of the total cathodic protection current required is 20 amperes, (1,000 m<sup>2</sup> x 0.02 amperes/m<sup>2</sup>).

Once the total current requirement is established, the amount of anode material is determined. For mixed metal oxide coated titanium mesh type of anode material, the current density per square meter of the anode is typically limited to a maximum of 110 mA/m<sup>2</sup> (10 mA/ft<sup>2</sup>) of anode surface. The electrochemical action at the surface of the anode is of either the oxidation of hydroxyl or chloride ions. The results are the generation of either water and oxygen or chlorine.



The reaction and rate of oxidation are a direct function of anode current density. Experience has shown that the concrete can diffuse the oxidation products (oxygen and water) as they are produced at anode current densities of less than 110 mA/m<sup>2</sup>. To prevent concrete damage due to the generation of chlorine at the anode-concrete interface, the operating anode current density should be less than 110 mA/m<sup>2</sup>. Considering the remaining life of the concrete bridge deck, a minimum design life of at least 40 years at 110 mA/m<sup>2</sup> is required.

The following examples indicate the procedure for calculating the amount of each anode material. There are three types of titanium mesh anodes available. The current rating varies with the mesh. Ratings based on area of mesh are:

Type 150 (current rating: 18.8 mA/m<sup>2</sup> at 110 mA/m<sup>2</sup> of anode material)

Type 210 (current rating: 24.4 mA/m<sup>2</sup> at 110 mA/m<sup>2</sup> of anode material)

Type 300 (current rating: 37.8 mA/m<sup>2</sup> at 110 mA/m<sup>2</sup> of anode material)

If 20 mA/m<sup>2</sup> of deck area is the required design capacity and the mixed metal oxide mesh anode is limited to 110 mA/m<sup>2</sup> of anode surface area, use Type 210 mesh.

### Anode Zones

The cathodic protection anodes are usually segmented into zones of influence along the deck. Segmenting into zones permits the bridge engineer



to control the level of cathodic protection with greater precision than for an anode system interconnected over the entire deck. Defects, failures, or short circuits can be identified and located more rapidly within a zone than within the entire system. The size of a zone is one of the parameters that the designer needs to specify.

At first glance, the designer may choose to specify a large number of small zones for the benefits of improved control. However, there are cost factors to consider. Excessive zoning will increase system costs. Each zone will require a separate rectifier control circuit and power feed from the rectifier to the deck anode and system ground. Cable and conduit costs must also be evaluated. Typically, a zone will require at least one reference electrode, preferably two for redundancy with associated cable and conduit which also add to the cost per zone.

The practical size of anode zones depends upon the area of the deck and the variation of rebar surface area per square meter of deck area. A typical guideline is presented in Table 9.1.

**Table 9.1 Suggested anode zone sizes**

| <u>Deck area (m<sup>2</sup>)</u> | <u>Average Zone Area</u> | <u>Maximum Zone Area</u> |
|----------------------------------|--------------------------|--------------------------|
| 0 – 5,000                        | 400 m <sup>2</sup>       | 750 m <sup>2</sup>       |
| 5,000 – 10,000                   | 750 m <sup>2</sup>       | 1,000 m <sup>2</sup>     |
| 10,000 +                         | 1,000 m <sup>2</sup>     | 1,200 m <sup>2</sup>     |



## ***Power distribution***

After the amount of anode material has been determined, the next consideration is the effective distribution of the power to the anode system. Each of the anode systems has a finite longitudinal resistance to the flow of current. The internal anode resistance causes a non-uniform discharge of current along the anode. Unless the current is distributed evenly, either the anode current densities will exceed  $110 \text{ mA/m}^2$  or portions of the bridge deck will not receive adequate current. Bare titanium current distributor bars that are attached to the anode mesh system provide uniform current distribution.

The resistance of titanium current distributor bars and titanium mesh anode causes voltage losses in the anode system. As the voltage drives the current from the anode to the reinforcing steel, a significant drop in voltage results in a corresponding drop in current. An uneven current distribution from the anode surface could result in one or more of the following:

1. Insufficient current density to the steel for those areas most remote from the anode's power feed points.
2. Excessive current discharge from the anodes nearest the power feed points.
3. Degradation of the concrete.
4. Reduced anode life.

Voltage losses are an inherent part of an electrical network. As a guideline, the voltage losses should be minimized to about 10 percent of the initial voltage.

Calculation of the voltage drops along the entire mesh anode systems is a complex exercise in electrical network analysis. The detail required to perform this analysis is beyond the scope of this problem, but some approximation techniques can be used to provide guidelines for the spacing of current distributors in the anode system.

Over the length of the anode, current is discharged continuously. Because of the voltage drops inherent along the anode, the current will not be uniform, but the average current along the entire length will be one-half of the total. The voltage drop in the anode segment can be approximated by:

$$V = \frac{1}{2} I \times R \quad (1)$$

where:

$V$  = Voltage drop across an anode

$I$  = Current discharge from the anode

$R$  = Lineal resistance of the anode conductor

In general, the acceptable voltage-drop for titanium mesh anode is less than 300 mV.

### **Example – Anode System Layout For Mixed Metal Oxide Mesh Anode (Type 210)**

Given:

1. Bridge deck size (1,000 m<sup>2</sup>: 10 m by 100 m)
2. Two zones (500 m<sup>2</sup> for each zone)
3. Type 210 mesh anode resistance: 1.2 m wide (0.046 ohm/m lengthwise)
4. Titanium current distributor bar (0.049 ohm/meter)

Since the titanium mesh is 1.2 m wide, a total of 8 rows of the mesh can be laid out in the longitudinal direction of the bridge deck with 5 cm opening between the anodes.

- a) Assume that a single current distributor is laid out at the center of each zone in the transverse direction of the deck and the electrical lead wire from a rectifier is connected at the beginning of the distributor bar, as shown in Figure 9.6. The length of the distributor bar is 10 m and the maximum distance from the distributor bar and the end of the mesh is 25 m.

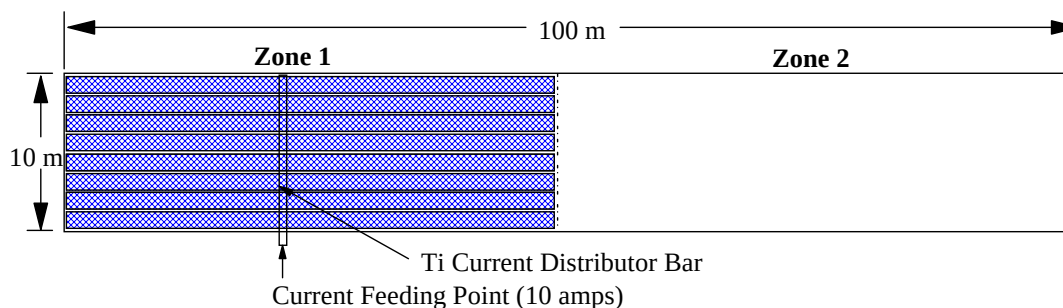


**Figure 9.6**

The total design current  $I_{\text{anode}}$  for one zone (500 m<sup>2</sup>) is:

$$I_{\text{anode}} = 20 \text{ mA/m}^2 \times 500 \text{ m}^2 = 10,000 \text{ millamps or 10 amps for each zone}$$

Voltage drop  $V_{\text{bar}}$  in the distributor bar is:

$$V_{\text{bar}} = 1/2 \times 10,000 \text{ mA} \times (0.049 \text{ ohm/m} \times 10 \text{ m}) = 2,450 \text{ mV}$$

The amount of current that flows in the half portion of a single titanium mesh is:

$$1/2 \times (10,000 \text{ mA} / 8 \text{ rows}) = 625 \text{ mA}$$

The voltage drop,  $V_{\text{anode}}$ , in the anode mesh from the distributor bar to the end of the mesh (25 m in length) is:

$$V_{\text{anode}} = 1/2 \times 625 \text{ mA} \times (0.046 \text{ ohm/m} \times 25 \text{ m}) = 359 \text{ mV}$$

Therefore, the total voltage-drop,  $V_{\text{total}}$ , in the mesh system is:

$$V_{\text{total}} = V_{\text{bar}} + V_{\text{anode}} = 2,809 \text{ mV}$$

This is above the criterion of 300 mV.

- b) Now, assume that five current distributor bars are used to feed the current to the mesh anode, as shown in Figure 9.7.

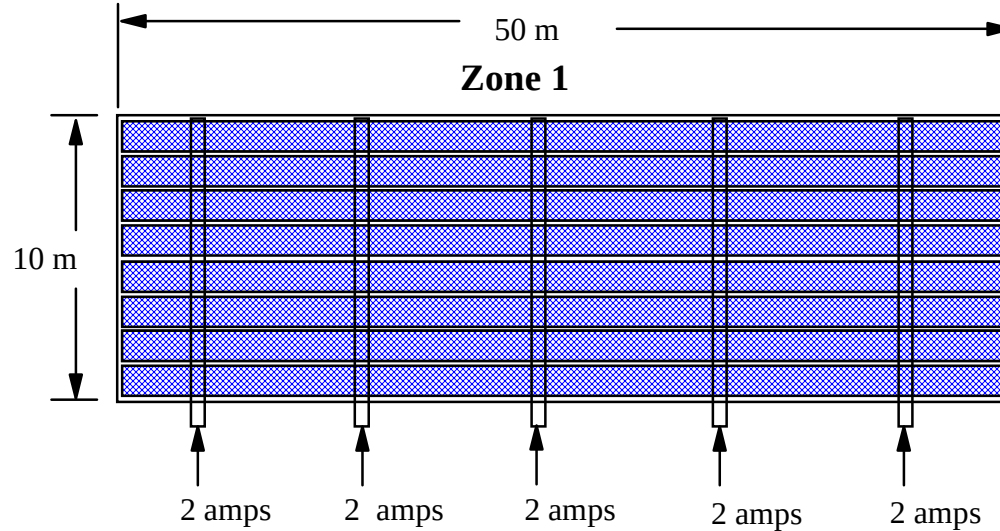


**Figure 9.7**

In this situation, the amount of current that is fed to each distributor bar is:

$$10,000 \text{ mA} / 5 \text{ bars} = 2,000 \text{ mA or 2 amps}$$

Voltage drop  $V_{\text{bar}}$  in the distributor bar is:

$$V_{\text{bar}} = 1/2 \times 2,000 \text{ mA} \times (0.049 \text{ ohm/m} \times 10 \text{ m}) = 490 \text{ mV} > 300 \text{ mV}$$

c) To further reduce the voltage drop for the distributor bar, there are two options:

Option 1: Use double distributor bars. This will reduce the resistance by half.

Option 2: The location of the electrical wire connection moves to the center of the distributor bar, if possible. This will reduce the length of the distributor bar and current flow becomes half.

In the case of Option 1 (Figure 9.8),

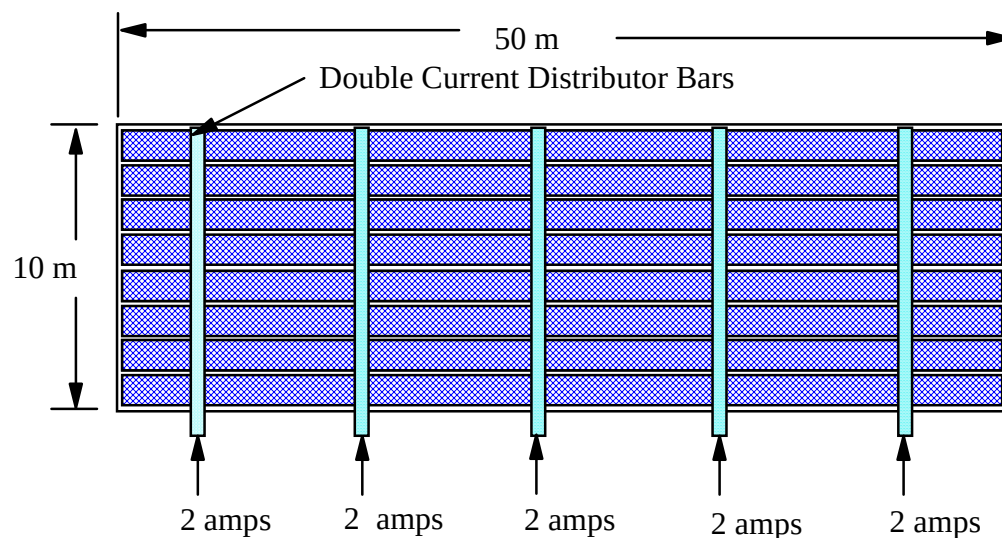


**Figure 9.8**

$$V_{\text{bar}} = 1/2 \times 2,000 \text{ mA} \times (0.049 \text{ ohm/m} \times 10 \text{ m}) / 2 \text{ bars} = 245 \text{ mV}$$

The amount of current from the distributor bar to the end of one titanium mesh is:

$$(2,000 \text{ mA} / 8 \text{ rows}) \times 1/2 = 125 \text{ mA}$$

The voltage drop,  $V_{\text{anode}}$ , in the anode mesh from the distributor bar to the end of the mesh (5 m in length) is:

$$V_{\text{anode}} = 1/2 \times 125 \text{ mA} \times (0.046 \text{ ohm/m} \times 5 \text{ m}) = 14 \text{ mV}$$

Therefore, the total voltage-drop,  $V_{\text{total}}$ , in the mesh system is:

$$V_{\text{total}} = V_{\text{bar}} + V_{\text{anode}} = 259 \text{ mV} < 300 \text{ mV}$$

In the case of Option 2 (Figure 9.9),

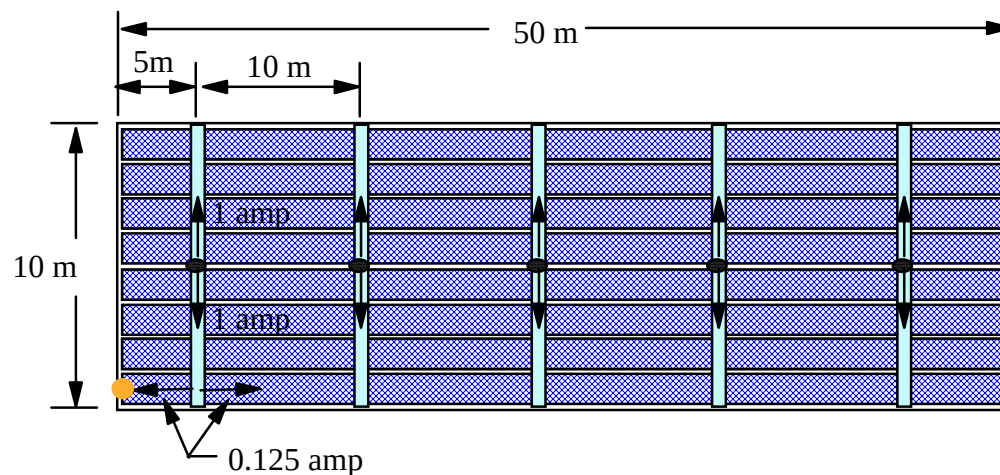


**Figure 9.9**

$$V_{\text{bar}} = 1/2 \times 1,000 \text{ mA} \times (0.049 \text{ ohm/m} \times 5 \text{ m}) = 123 \text{ mV}$$

The amount of current from the distributor bar to the end of one titanium mesh is:

$$(1,000 \text{ mA} / 4 \text{ rows}) \times 1/2 = 125 \text{ mA}$$

The voltage drop,  $V_{\text{anode}}$ , in the anode mesh from the distributor bar to the end of the mesh (5 m in length) is:

$$V_{\text{anode}} = 1/2 \times 125 \text{ mA} \times (0.046 \text{ ohm/m} \times 5 \text{ m}) = 14 \text{ mV}$$

Therefore, the total voltage-drop,  $V_{\text{total}}$ , in the mesh system is:

$$V_{\text{total}} = V_{\text{bar}} + V_{\text{anode}} = 137 \text{ mV} < 300 \text{ mV}$$

In this situation, the total voltage drop is less than 300 mV. Therefore, we can reduce the number of the distributor bars from 5 to 3, resulting in:

$$V_{\text{total}} = 244 \text{ mV}$$

## ***Rectifier sizing***

The next design item is the cathodic protection rectifier and wiring to the anode power feeds. The basic design of a rectifier will revolve around the type of output control, the AC power input, the DC power output, and accessory options. The AC and DC wiring parameters include current carrying capacity (ampacity), the longitudinal resistance, and insulation type.

The rectifier AC input is usually determined by the available power in the vicinity of the bridge. The rectifier DC output is determined by the total design current per zone (including any safety factors) and the voltage required to obtain that current. The voltage is a function of the anode to rebar resistance plus the resistance of the DC wiring circuit. Anode to rebar resistances will vary depending upon the anode configuration, rebar surface area, and concrete temperature and resistivity but historically range from 50 to 200 ohms for a square meter of deck. Since the resistances for a square meter operate in parallel, the anticipated resistance per zone is calculated by dividing the resistance for each square meter by the total square meters in the zone. For a given deck, this range of values can be observed during seasonal fluctuations.

For a 1,000-m<sup>2</sup> bridge deck divided into 2 equal zones (500 m<sup>2</sup>), the resistance between the anode and the reinforcing steel for one zone ranges from 0.1 to 0.4 ohm. At 0.4 ohm resistance, the voltage to supply 10 amperes to a zone is 4 volts ( $E = IR$ ).

The designer must bear in mind that the rectifier voltage used previously in the anode design as a basis for the 300 mV anode voltage drop is the voltage at the point of connection between the power feed and the furthest point of the anode. Any voltage losses in the positive or negative circuit wiring between the rectifier and the anode feed connection should be

added to the maximum DC voltage for the rectifier design. Wiring voltage losses should be minimized to avoid unnecessary power consumption. For design purposes, voltage losses in the wiring circuit should be limited to ten percent of the voltage required at the anode feed connection. Specific examples for calculating and accounting for these wiring voltage losses are presented in the DC wiring section of this chapter.

The designed output voltage for the rectifier unit circuit is the total volts required to drive the cathodic protection current from the anode to the reinforcing steel plus the voltage losses in the positive and negative wiring from the rectifier plus a safety factor.

The rectifier voltage design for the example presented includes the following components:

- |                                       |   |                                                                       |
|---------------------------------------|---|-----------------------------------------------------------------------|
| a) Voltage required at the anode      | = | 4.0 volts.                                                            |
| b) Voltage losses in the anode system | = | 0.244 volts                                                           |
| c) Voltage losses in DC wiring        | = | <u>0.4 volts</u> (10 percent of a) – assumed – to be calculated below |
| d) Voltage required at the rectifier  | = | 4.644 volts (sum of a, b, and c).                                     |
| e) Add 50 percent safety factor       | = | <u>2.322 volts</u> (50 percent of d).                                 |
| f) Rectifier design voltage           | = | 6.966 volts                                                           |

The rectifier would contain 2 circuits (one per zone). Each circuit would provide a minimum 10 volts and 10 amperes. A 50 percent factor has been added to the voltage capacity of the rectifier. At this point, the designer should consult his catalogue references of rectifier manufacturers. Most manufacturers produce a standard line of various rated rectifier units. The specification of nonstandard ratings could needlessly increase the costs of a rectifier.

The next major design decision is the type of rectifier control. This includes:

- **Constant Voltage Mode.** In constant voltage mode, the rectifier DC output voltage is held at a constant value. Changes in the concrete (e.g., moisture, chloride content, temperature) will affect the electrical resistance of the concrete, resulting in changes in the DC current output.
- **Constant Current Mode.** If fluctuations in the DC current output are a concern, a constant current rectifier can be used to supply a controlled constant current output.

A rectifier unit may contain internal meters, plug receptacles for test instruments, alarm circuits, hour usage meters, etc. These items are in-



tended to provide either system operating information to the owner/operator or to facilitate future monitoring by the owner/operator. However, they are also potential maintenance items. For a general-purpose rectifier, the fewer accessory items included, the fewer repair costs and down time are incurred. In specifying a rectifier unit, only specify the options that are required for providing cathodic protection current and cost-effective maintenance of the system.

The designer should have considered the location of the unit when choosing a means to monitor the rectifier. In place of the individual meters, he might have chosen to have plug-in jacks installed for use with a hand held meter or, even better, to extend these jacks to a more conveniently mounted small junction box. Another option would be remote monitoring using telephone connections to a modem within the rectifier as an automatic means of surveillance. A rectifier is a simple device, which can function for many years. Some options may tend to increase maintenance costs. Each option should be carefully evaluated in terms of its specific cost effectiveness.

## ***DC Wiring***

The DC power wiring connects the positive output terminal(s) of the rectifier to the anode and the negative terminal(s) of the rectifier to the reinforcing steel. The current flow in this wiring creates a voltage drop. If the voltage drops are excessive, the voltage available between the system anode and the rebar may be insufficient to provide the needed DC protective current from the anodes to the reinforcing. The voltage drops can be calculated using Ohm's Law,  $E = IR$ , for various gauges of cable.

## Examples

The voltage drops for single circuits with various size cables are presented in the following calculations:

**Given I, design current per circuit = 10 amperes maximum**

D1 = distance to anode power feed from rectifier = 50 m

D2 = distance to zone negative from rectifier = 50 m

D = total distance = D1 + D2 = 100 m

### Selection of cable size

In general, the typical resistance of various cable sizes for 100 m at 20° C is:

|                  |            |
|------------------|------------|
| AWG No. 2/0 wire | 0.026 ohms |
| AWG No. 1/0 wire | 0.032 ohms |
| AWG No. 2 wire   | 0.051 ohms |
| AWG No. 4 wire   | 0.082 ohms |
| AWG No. 6 wire   | 0.13 ohms  |
| AWG No. 8 wire   | 0.21 ohms  |
| AWG No. 10 wire  | 0.33 ohms  |
| AWG No. 12 wire  | 0.52 ohms  |
| AWG No. 14 wire  | 0.83 ohms  |

**If #10 AWG copper cable is used:**

R = 0.34 ohms/100m (resistance of #10 AWG wire)

D = 50 m + 50 m = 100 m

E = 10 amperes x (0.34 ohms/100 m) x 100 m (Ohm's Law)

E = 3.4 volts (> 0.4 volts or 10% of voltage required at anode)

**If #1/0 AWG copper cable is used:**

$$R = 0.032 \text{ ohms/100 m (resistance of \#1/0 AWG wire)}$$

$$D = 100 \text{ m}$$

$$E = 10 \text{ amperes} \times (0.032/100 \text{ m}) \text{ (Ohm's Law)}$$

$$E = 0.32 \text{ volts (< 0.4 volts)}$$

Therefore, #1/0 AWG wire is selected in this example. When the anode-rebar resistance (0.4-ohm) and the wire resistance (0.032-ohm) are added, the total resistance is 0.43 ohm. Therefore, the particular zone would be designed for a minimum of 4.3 DC volts and 10 DC amperes. In practice, a greater voltage and current are specified as a safety factor. The amount of safety factor used by the engineer will depend upon the precision of the design data used in his calculations. In general, a factor of 50 percent is used in design practice, which are 8 volts 15 amperes in this case.

The basic calculation methods have been presented. The design engineer can fine-tune the balance between power costs, conduit costs, cable costs, and rectifier costs by comparing the various alternates available. Specific economic analysis is not covered in this chapter due to the differences in design life, in the cost of capital, and accounting practices of the various agencies that will use the technical contents of this review. The assumption is made that the design engineer is familiar with economic analysis or that the design engineer has references on economic analysis available.

***Reference cells***

To adjust and evaluate a cathodic protection system, reference cells provide an indication of the effectiveness of the cathodic protection system. Cathodic protection current is used to maintain the energy level of the reinforcing steel. Reference cells permanently embedded within the bridge deck provide a means to measure the energy level as the potential difference between the steel and the reference electrodes.

The following are types of electrodes that may be employed:

Copper-Copper Sulfate ( $\text{Cu-CuSO}_4$ )  
Silver-Silver Chloride ( $\text{Ag-AgCl}$ ).  
Manganese Dioxide ( $\text{MnO}_2$ ).

For permanent installation in bridge decks,  $\text{Cu-CuSO}_4$  are rarely used because of their unreliable long term stability in embedded concrete. The current recommended reference cell is the  $\text{Ag-AgCl}$  or  $\text{MnO}_2$  cell.

After the type of reference cell is specified, the number and location of the references must be selected. Bearing in mind that the primary function of a reference cell is to indicate levels of cathodic protection, the cells should be placed in those areas which have the highest probability for corrosion or which require greater amounts of cathodic protection current. Reference cells should be located at:

- a) Locations of high chloride levels.
- b) Locations of dense rebar patterns.
- c) Locations remote from anode power feeds or at the midpoint between anode power feeds.

The number of reference cells is somewhat discretionary. Each anode zone should have at least one reference electrode. If the zones are small ( $500 \text{ m}^2$  or less), one reference cell may suffice. However, large zones ( $500\text{-}1,200 \text{ m}^2$ ) may have variations in rebar pattern or chloride levels that warrant the placement of a couple of reference cells. The bridge engineer should also consider some redundancy in the number of reference cells. As a guide, one reference cell per  $500 \text{ m}^2$  of deck surface should provide for adequate monitoring of potential levels and for initial startup of the cathodic protection systems.

## Summary

Once the design of the cathodic protection system is completed, the following items will have been determined:

- A) The number and size of anode zones.
- B) Anode type required.
- C) Quantity of anode materials required.
- D) Size and spacing on the deck for each anode panel or segment.
- E) Location of power feeds into the anode system.
- F) The rectifier rating and options.
- G) The size of the DC wiring.
- H) The number and location of reference cells.

# APPENDIX A

## GLOSSARY

# GLOSSARY

## A

**ACTIVE** (1) The negative direction of electrode potential. (2) A state of a metal that is corroding without significant influence of reaction product.

**ACTIVE POTENTIAL** A potential more anodic (negative) than the standard hydrogen potential.

**AERATION CELL** See Differential Aeration Cell

**AMPHOTERIC METAL** A metal that is susceptible to corrosion in both acid and alkaline environments.

**ANAEROBIC** Free of air or uncombined oxygen.

**ANION** A negatively charged ion that migrates through the electrolyte toward the anode under the influence of a potential gradient.

**ANODE** The electrode of an electrochemical cell at which oxidation occurs. Electrons flow away from the anode in the external circuit. Corrosion usually occurs and metal ions enter the solution at the anode.

### ANODE CORROSION

**EFFICIENCY** The ratio of the actual corrosion (mass loss) of an anode to the theoretical corrosion

(mass loss) calculated from the quantity of electricity that has passed between the anode and cathode using Faraday's law.

**ANODIC POLARIZATION** The change of the electrode potential in the noble (positive) direction caused by current across the electrode/electrolyte interface. (*See Polarization.*)

**ATTENUATION** Electrical losses in a conductor caused by current flow in the conductor.

**AUXILIARY ELECTRODE** An electrode usually made from a noncorroding material, which is commonly used in polarization studies to pass current to or from a test electrode.

## B

**BACKFILL** Material placed in a hole to fill the space around the anodes, vent pipe, and buried components of a cathodic protection system.

**BITUMINOUS COATING** An asphalt or coal-tar compound used to provide a protective coating for a surface.

**BLAST CLEANING** Cleaning with propelled abrasives.

## C

### **CALCAREOUS COATING**

A layer consisting of calcium carbonate and other salts deposited on the surface. When the surface is cathodically polarized as in cathodic protection, this layer is the result of the increased pH adjacent to the protected surface.

**CALCAREOUS DEPOSIT** See *Calcareous Coating*.

**CATHODE** The electrode of an electrochemical cell at which reduction is the principal reaction. Electrons flow toward the cathode in the external circuit.

### **CATHODIC CORROSION**

Corrosion resulting from a cathodic condition of a structure, usually caused by the reaction of an amphoteric metal with the alkaline products of electrolysis.

**CATHODIC DISBONDMENT** The destruction of adhesion between a coating and the coated surface caused by products of a cathodic reaction.

### **CATHODIC POLARIZATION**

The change of the electrode potential in the active (negative) direction caused by current across the electrode/electrolyte interface. (See *Polarization*.)

**CATHODIC PROTECTION** A technique to reduce the corrosion of a metal surface by making that surface

the cathode of an electrochemical cell.

**CATHOLYTE** The electrolyte adjacent to the cathode of an electrochemical cell.

**CATION** A positively charged ion that migrates through the electrolyte toward the cathode under the influence of a potential gradient.

**CELL** See *Electrochemical/Cell*

**CONCENTRATION CELL** An electrochemical cell, the electromotive force of which is caused by a difference in concentration of some component in the electrolyte. (This difference leads to the formation of discrete cathodic and anodic regions.)

### **CONCENTRATION**

**POLARIZATION** That portion of polarization of a cell produced by concentration changes resulting from passage of current through the electrolyte.

**CONTINUOUS ANODE** A single anode with no electrical discontinuities.

**CORROSION** The deterioration of a material, usually a metal, that results from a reaction with its environment.

### **CORROSION POTENTIAL**

( $E_{corr}$ ) The potential of a corroding surface in an electrolyte relative to a reference electrode under open-circuit conditions (also known



*as rest potential, open-circuit potential, or freely corroding potential.*

**CORROSION RATE** The rate at which corrosion proceeds.

**CORROSION RESISTANCE** Ability of a material, usually a metal, to withstand corrosion in a given system.

**CORROSIVENESS** The tendency of an environment to cause corrosion.

**COUNTER ELECTRODE** See *Auxiliary/Electrode*.

**COUPLE** See *Galvanic Coup/e*.

**CURRENT DENSITY** The current to or from a unit area of an electrode surface.

**CURRENT EFFICIENCY** The ratio of the electrochemical equivalent current density for a specific reaction to the total applied current density.

## **D**

**DC DECOUPLING DEVICE** A device used in electrical circuits that allows the flow of alternating current (AC) in both directions and stops or substantially reduces the flow of direct current (DC).

**DEEP GROUNDBED** One or more anodes installed vertically at a nominal depth of 15 m (50 ft) or more below the earth's surface in a

drilled hole for the purpose of supplying cathodic protection.

**DEPOLARIZATION** The removal of factors resisting the current in an electrochemical cell.

**DIELECTRIC SHIELD** An electrically nonconductive material, such as a coating, sheet or pipe, that is placed between an anode and an adjacent cathode, usually on the cathode, to improve current distribution in a cathodic protection system.

**DIFFERENTIAL AERATION CELL** An electrochemical cell, the electromotive force of which is due to a difference in air (oxygen) concentration at one electrode as compared with that at another electrode of the same material.

**DIFFUSION-LIMITED CURRENT DENSITY** The current density that corresponds to the maximum transfer rate that a particular species can sustain because of the limitation of diffusion (often referred to as *limiting current density*).

**DISBONDMENT** The loss of adhesion between a coating and the substrate.

**DRAINAGE** Conduction of electric current from an underground or submerged metallic structure by means of a metallic conductor.

**DRIVING POTENTIAL** Difference in potential between the anode and the steel structure.

## **E**

**ELECTRICAL ISOLATION** The condition of being electrically separated from other metallic structures or the environment.

**ELECTROCHEMICAL CELL** A system consisting of an anode and a cathode immersed in an electrolyte so as to create an electrical circuit. The anode and cathode may be different metals or dissimilar areas on the same metal surface.

**ELECTROCHEMICAL EQUIVALENT** The mass of an element or group of elements oxidized or reduced at 100% efficiency by the passage of a unit quantity of electricity.

**ELECTROCHEMICAL POTENTIAL** The partial derivative of the total electrochemical free energy of a constituent with respect to the number of moles of this constituent where all other factors are kept constant. It is analogous to the chemical potential of a constituent except that it includes the electrical as well as chemical contributions to the free energy.

**ELECTRODE** A conductor used to establish contact with an electrolyte and through which current is transferred to or from an electrolyte.

**ELECTRODE POTENTIAL** The potential of an electrode in an electrolyte as measured against a reference electrode. (The electrode potential does not include any resistance losses in potential in either the electrolyte or the external circuit. It represents the reversible work to move a unit of charge from the electrode surface through the electrolyte to the reference electrode.)

**ELECTROLYTE** A chemical substance containing ions that migrate in an electric field.

**ELECTROMOTIVE FORCE SERIES** A list of elements arranged according to their standard electrode potentials, the sign being positive for elements whose potentials are cathodic to hydrogen and negative for those anodic to hydrogen.

## **ELECTROLYSIS**

The passage of an electric current an electrolyte with subsequent migration of positively and negatively charged ions to the negative and positive electrodes.

## **ELECTRONEGATIVE**

Tending to migrate to the positive pole in electrolysis.

## **ELECTROPOSITIVE**

Tending to migrate to the negative pole in electrolysis.

**EMBRITTLEMENT** Loss of ductility of a material resulting from a chemical or physical change.

**EMF SERIES** See *Electromotive Force Series*.

**END EFFECT** The more rapid loss of anode material at the end of an anode, compared with other surfaces of the anode, resulting from higher current density.

**ENVIRONMENT** The surroundings or conditions (physical, chemical, mechanical) in which a material exists.

**EPOXY** Type of resin formed by the reaction of aliphatic or aromatic polyols (like bisphenol) with epichlorohydrin and characterized by the presence of reactive oxirane end groups.

**EQUILIBRIUM POTENTIAL** The potential of an electrode in an electrolyte at which the forward rate of a given reaction is exactly equal to the reverse rate; the electrode potential with reference to a standard equilibrium, as defined by the Nernst equation.

**EXCHANGE CURRENT** The rate at which either positive or negative charges are entering or leaving the surface when an electrode reaches dynamic equilibrium in an electrolyte.

**EXTERNAL CIRCUIT** The wires, connectors, measuring devices, current sources, etc., that are used to

bring about or measure the desired electrical conditions within an electrochemical cell. It is this portion of the cell through which electrons travel.

## F

**FAULT CURRENT** A current that flows from one conductor to ground or to another conductor due to an abnormal connection (including an arc) between the two. A fault current flowing to ground may be called a ground fault current.

**FORCED DRAINAGE** Drainage applied to underground or submerged metallic structures by means of an applied electromotive force or sacrificial anode.

**FOREIGN STRUCTURE** Any metallic structure that is not intended as a part of a system under cathodic protection.

## G

**GALVANIC ANODE** A metal that provides sacrificial protection to another metal that is more noble when electrically coupled in an electrolyte. This type of anode is the electron source in one type of cathodic protection.

**GALVANIC CORROSION** Accelerated corrosion of a metal because of an electrical contact with a more noble metal or nonmetallic conductor in a corrosive electrolyte.

**GALVANIC COUPLE** A pair of dissimilar conductors, commonly metals, in electrical contact in an electrolyte.

**GALVANIC CURRENT** The electric current between metals or conductive nonmetals in a galvanic couple.

**GALVANIC SERIES** A list of metals and alloys arranged according to their corrosion potentials in a given environment.

**GROUND BED** One or more anodes installed below the earth's surface for the purpose of supplying cathodic protection.

## H

**HALF-CELL** A pure metal in contact with a solution of known concentration of its own ion, at a specific temperature, develops a potential that is characteristic and reproducible; when coupled with another half-cell, an overall potential that is the sum of both half-cells develops.

**HOLIDAY** A discontinuity in a protective coating that exposes unprotected surface to the environment.

**HYDROGEN BLISTERING** The formation of subsurface planar cavities, called hydrogen blisters, in a metal resulting from excessive

internal hydrogen pressure. Growth of near-surface blisters in low-strength metals usually results in surface bulges.

**HYDROGEN EMBRITTLEMENT** A loss of ductility of a metal resulting from absorption of hydrogen.

**HYDROGEN-INDUCED CRACKING** Stepwise internal cracks that connect adjacent hydrogen blisters on different planes in the metal, or to the metal surface (also known as *stepwise cracking*).

**HYDROGEN OVERVOLTAGE** Overvoltage associated with the liberation of hydrogen gas.

**HYDROGEN STRESS CRACKING** Cracking that results from the presence of hydrogen in a metal in combination with tensile stress. It occurs most frequently with high-strength alloys.

## I

**IMPRESSED CURRENT** An electric current supplied by a device employing a power source that is external to the electrode system. (An example is direct current for cathodic protection.)

**ION** An electrically charged atom or group of atoms.

## L

**LINE CURRENT** The direct current flowing on a pipeline.

**LONG-LINE CURRENT** Current though the earth between an anodic and a cathodic area that returns along an underground metallic structure.

**LUGGIN PROBE** A small tube or capillary filled with electrolyte, terminating close to the metal surface of an electrode under study, which is used to provide an ion-conducting path without diffusion between the electrode under study and a reference electrode.

## M

**MIXED POTENTIAL** A potential resulting from two or more electrochemical reactions occurring simultaneously on one metal surface.

## N

**NATURAL DRAINAGE** Drainage from an underground or submerged metallic structure to a more negative (more anodic) structure, such as the negative bus of a trolley substation.

**NEGATIVE RETURN** A point of connection between the cathodic protection negative cable and the protected structure.

**NERNST EQUATION** An equation that expresses the exact electromotive force of an electrochemical cell in

terms of the activities of products and reactants of the cell.

**NERNST LAYER** The diffusion layer at the surface of an electrode in which the concentration of a chemical species is assumed to vary linearly from the value in the bulk solution to the value at the electrode surface.

**NOBLE** The positive direction of electrode potential, thus resembling noble metals such as gold and platinum.

**NOBLE METAL** (1 ) A metal that occurs commonly in nature in the free state. (2) A metal or alloy whose corrosion products are formed with a small negative or a positive free-energy change.

**NOBLE POTENTIAL** A potential more cathodic (positive) than the standard hydrogen potential.

## O

**OPEN-CIRCUIT POTENTIAL** The potential of an electrode measured with respect to a reference electrode or another electrode in the absence of current.

**OVERVOLTAGE** The change in potential of an electrode from its equilibrium or steady-state value when current is applied.

**OXIDATION** (1 ) Loss of electrons by a constituent of a chemical reaction. (2) Corrosion of a metal that

is exposed to an oxidizing gas at elevated temperatures.

**OXYGEN CONCENTRATION CELL** See *Differential Aeration Cell*.

## P

**PASSIVATION** A reduction of the anodic reaction rate of an electrode involved in corrosion.

**PASSIVATION POTENTIAL** See *Primary Passive Potential*.

**PASSIVE** (1 ) The positive direction of electrode potential. (2) A state of a metal in which a surface reaction product causes a marked decrease in the corrosion rate relative to that in the absence of the product.

**PASSIVE-ACTIVE CELL** An electrochemical cell, the electromotive force of which is caused by the potential difference between a metal in an active state and the same metal in a passive state.

**PASSIVITY** The state of being passive.

## pH

The negative logarithm of the hydrogen ion activity written as:

$$\text{pH} = -\log_{10} (a_{\text{H}^+})$$

where  $a_{\text{H}^+}$  = hydrogen ion activity = the molar concentration of hydrogen ions multiplied by the mean ion-activity coefficient.

## PIPE-TO-ELECTROLYTE

**POTENTIAL** The potential difference between the pipe metallic surface and electrolyte that is measured with reference to an electrode in contact with the electrolyte.

**PITTING** Localized corrosion of a metal surface that is confined to a small area and takes the form of cavities called pits.

**POLARIZATION** The change from the open-circuit potential as a result of current across the electrode/electrolyte interface.

**POLARIZATION CELL** A DC decoupling device consisting of two or more pairs of inert metallic plates immersed in an aqueous electrolyte. The electrical characteristics of the polarization cell are high resistance to DC potentials and low impedance of AC.

**POLARIZATION CURVE** A plot of current density versus electrode potential for a specific electrode/electrolyte combination.

**POLARIZATION DECAY** The decrease in electrode potential with time resulting from the interruption of applied current.

## POLARIZATION RESISTANCE

The slope ( $dE/di$ ) at the corrosion potential of a potential (E)-current density (i) curve. (The measured slope is usually in good agreement with the true value of the polarization

resistance when the scan rate is low and any uncompensated resistance is small relative to the polarization resistance.)

**POLARIZED POTENTIAL** The potential across the structure/electrolyte interface that is the sum of the corrosion potential and the cathodic polarization.

**POTENTIAL-pH DIAGRAM** A graphical method of representing the regions of thermodynamic stability of species for metal/electrolyte systems (also known as *Pourbaix diagram*).

**POURBAIX DIAGRAM** See *Potential-pH Diagram*.

## R

**REDUCTION** Gain of electrons by a constituent of a chemical reaction.

**REFERENCE ELECTRODE** An electrode whose open-circuit potential is constant under similar conditions of measurement, which is used for measuring the relative potentials of other electrodes.

**REFERENCE HALF-CELL** See *Reference Electrode*

**REMOTE EARTH** A location on the earth far enough from the affected structure that the soil potential gradients associated with currents entering the earth from the affected structure are insignificant.

**REST POTENTIAL** See *Corrosion Potential*/.

**REVERSIBLE POTENTIAL** See *Equilibrium Potential*.

## S

**SACRIFICIAL PROTECTION** Reduction of corrosion of a metal in an electrolyte by galvanically coupling it to a more anodic metal (a form of cathodic protection).

**SHALLOW GROUNDBED** One or more anodes installed either vertically or horizontally at a nominal depth of less than 15 m (50 ft) for the purpose of supplying cathodic protection.

**STANDARD ELECTRODE POTENTIAL** The reversible potential for an electrode process when all products and reactions are at unit activity on a scale in which the potential for the standard hydrogen reference electrode is zero.

**STRAY CURRENT** Current through paths other than the intended circuit.

**STRAY-CURRENT CORROSION** Corrosion resulting from current through paths other than the intended circuit, e.g., by any extraneous current in the earth.

## T

**TAFEL PLOT** A plot of the relationship between the change in potential (E) and the logarithm of the

current density ( $\log \sim$  of an electrode when it is polarized in both the anodic and cathodic directions from its open-circuit potential.

**TAFEL SLOPE** The slope of the straight-line portion of the E log Curve on a Tafel plot. (The straight-line portion usually occurs at more than 50 mV from the open-circuit potential.)

## **W**

**WORKING ELECTRODE** The test or specimen electrode in an electrochemical cell.



# APPENDIX B

## VARIABLE LIST

# VARIABLE LIST

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a = length of semi-major axis of ellipse or Shepard correction factor  
A = cross-sectional area  
 $A_s$  = surface area  
b = length of semi-minor axis of ellipse  
 $C_a$  = capacity  
 $C_r$  = consumption rate  
d = diameter or distance  
E = voltage, potential, or energy  
 $E_{a,oc}$  = potential of the anode, open circuited  
 $E_{a,p}$  = potential of the anode, polarized  
 $E_{c,oc}$  = potential of the cathode, open circuited  
 $E_{c,p}$  = potential of the cathode, polarized  
 $E_{corr}$  = corrosion potential  
 $E_r$  = potential at receiving end  
 $E_s$  = potential at sending end  
f = safety factor  
 $f_c$  = correction factor  
 $f_u$  = utilization factor  
F = Faraday's constant or flow rate  
g = conductance per unit length  
g' = specific conductance  
G = conductance  
h = depth or height  
i = current density  
 $i_0$  = exchange current density  
 $I_r$  = current at receiving end  
 $I_s$  = current at sending end  
I = current  
 $I_{corr}$  = corrosion current  
ID = inside diameter  
L = length  
M = atomic weight  
n = number of electrons  
N = number  
OD = outside diameter  
r = resistance per unit length or radius  
r' = specific resistance  
R = resistance  
 $R_{a,b}$  = Coupling factor at location **a** due to current injection at location **b**  
 $R_E$  = resistance of electrolyte path  
 $R_G$  = characteristic resistance  
 $R_M$  = resistance of metal path  
 $R_{so}$  = input resistance to transmission line with receiving end open circuited  
 $R_{ss}$  = input resistance to transmission line with receiving end short circuited  
s = spacing  
t = time  
tk = thickness  
V = voltage or potential or velocity  
w = width or weight  
W = weight  
 $X_r$  = distance from electrode to point X  
x = number of unit lengths from Point of Interest to receiving end  
y = number of unit lengths from Point of Interest to sending end  
 $\Delta I$  = change in current  
 $\Delta V$  = change in voltage  
 $\alpha$  = attenuation constant  
 $\eta$  = polarization  
 $\rho$  = resistivity  
%bare = percent of surface bare  
% $V_a$  = percentage of anode voltage rise  
% $V_{OUT}$  = percentage of total rise point r is outside

## APPENDIX C

### Steel Pipe Data for Corrosion Calculations

**APPENDIX C**  
**STEEL PIPE DATA FOR CORROSION CALCULATIONS**  
Resistivity of steel = 5.292E-06 ohms-in/1.344E-05 ohms-cm

| Nominal<br>Size | Nominal<br>Size | Schedule<br>Number | OD     |      | Wall<br>Thickness |       | Weight<br>Per ft Per m |       | Linear Res<br>Per ft Per m |           |
|-----------------|-----------------|--------------------|--------|------|-------------------|-------|------------------------|-------|----------------------------|-----------|
| Inch            | Cm              |                    | Inch   | Cm   | Inch              | Cm    | lbs                    | kg    | ohms                       | ohms      |
| 4               | 10              | 40                 | 4.500  | 11.4 | 0.237             | 0.602 | 10.79                  | 4.90  | 2.001E-05                  | 6.582E-05 |
| 6               | 15              |                    | 6.625  | 16.8 | 0.188             | 0.476 | 12.89                  | 5.85  | 1.675E-05                  | 5.493E-05 |
| 6               | 15              |                    | 6.625  | 16.8 | 0.219             | 0.556 | 14.97                  | 6.80  | 1.442E-05                  | 4.731E-05 |
| 6               | 15              |                    | 6.625  | 16.8 | 0.250             | 0.635 | 17.02                  | 7.73  | 1.268E-05                  | 4.160E-05 |
| 6               | 15              | 40                 | 6.625  | 16.8 | 0.280             | 0.711 | 18.98                  | 8.62  | 1.138E-05                  | 3.732E-05 |
| 6               | 15              | 80                 | 6.625  | 16.8 | 0.432             | 1.097 | 28.58                  | 12.97 | 7.556E-06                  | 2.478E-05 |
| 6               | 15              | 120                | 6.625  | 16.8 | 0.562             | 1.427 | 36.40                  | 16.52 | 5.932E-06                  | 1.946E-05 |
| 8               | 20              | 20                 | 6.625  | 21.9 | 0.250             | 0.635 | 22.37                  | 10.15 | 9.654E-06                  | 3.167E-05 |
| 8               | 20              | 30                 | 6.625  | 21.9 | 0.277             | 0.704 | 24.70                  | 11.21 | 8.742E-06                  | 2.867E-05 |
| 8               | 20              | 40                 | 6.625  | 21.9 | 0.322             | 0.616 | 28.58                  | 12.97 | 7.561E-06                  | 2.480E-05 |
| 8               | 20              | 60                 | 6.625  | 21.9 | 0.406             | 1.031 | 35.64                  | 16.18 | 6.058E-06                  | 1.987E-05 |
| 10              | 25              | 20                 | 10.750 | 27.3 | 0.250             | 0.635 | 28.04                  | 12.73 | 7.701E-06                  | 2.526E-05 |
| 10              | 25              | 30                 | 10.750 | 27.3 | 0.307             | 0.780 | 34.25                  | 15.55 | 6.305E-06                  | 2.068E-05 |
| 10              | 25              | 40                 | 10.750 | 27.3 | 0.365             | 0.927 | 40.49                  | 18.38 | 5.333E-06                  | 1.749E-05 |
| 10              | 25              | 60                 | 10.750 | 27.3 | 0.500             | 1.270 | 54.74                  | 24.85 | 3.944E-06                  | 1.294E-05 |
| 12              | 30              | 20                 | 12.750 | 32.4 | 0.250             | 0.635 | 33.38                  | 15.15 | 6.468E-06                  | 2.122E-05 |
| 12              | 30              | 30                 | 12.750 | 32.4 | 0.330             | 0.638 | 43.78                  | 19.88 | 4.932E-06                  | 1.618E-05 |
| 12              | 30              |                    | 12.750 | 32.4 | 0.375             | 0.953 | 49.57                  | 22.51 | 4.356E-06                  | 1.429E-05 |
| 12              | 30              | 40                 | 12.750 | 32.4 | 0.406             | 1.031 | 53.53                  | 24.30 | 4.033E-06                  | 1.323E-05 |
| 12              | 30              |                    | 12.750 | 32.4 | 0.500             | 1.270 | 65.43                  | 29.70 | 3.300E-06                  | 1.082E-05 |
| 14              | 36              | 10                 | 14.000 | 35.6 | 0.250             | 0.635 | 36.72                  | 16.67 | 5.880E-06                  | 1.929E-05 |
| 14              | 36              | 20                 | 14.000 | 35.6 | 0.312             | 0.792 | 45.62                  | 20.71 | 4.733E-06                  | 1.552E-05 |
| 14              | 36              | 30                 | 14.000 | 35.6 | 0.375             | 0.953 | 54.58                  | 24.78 | 3.956E-06                  | 1.298E-05 |
| 16              | 41              | 10                 | 16.000 | 40.6 | 0.250             | 0.635 | 42.06                  | 19.10 | 5.134E-06                  | 1.684E-05 |
| 16              | 41              | 20                 | 16.000 | 40.6 | 0.312             | 0.792 | 52.28                  | 23.74 | 4.130E-06                  | 1.355E-05 |
| 16              | 41              | 30                 | 16.000 | 40.6 | 0.375             | 0.953 | 62.59                  | 28.42 | 3.450E-06                  | 1.132E-05 |
| 16              | 41              | 40                 | 16.000 | 40.6 | 0.500             | 1.270 | 82.78                  | 37.58 | 2.608E-06                  | 8.555E-06 |

# STEEL PIPE DATA FOR CORROSION CALCULATIONS

| Nominal<br>Size | Nominal<br>Size | Schedule<br>Number | OD     |       | Wall<br>Thickness |       | Weight<br>Per ft Per m |        | Linear Res<br>Per ft Per m |           |
|-----------------|-----------------|--------------------|--------|-------|-------------------|-------|------------------------|--------|----------------------------|-----------|
| Inch            | Cm              |                    | Inch   | Cm    | Inch              | Cm    | lbs                    | kg     | ohms                       | ohms      |
| 18              | 46              | 10                 | 18.000 | 45.7  | 0.250             | 0.635 | 47.40                  | 21.52  | 4.555E-06                  | 1.494E-05 |
| 18              | 46              | 20                 | 18.000 | 45.7  | 0.312             | 0.792 | 56.95                  | 26.76  | 3.663E-06                  | 1.201E-05 |
| 18              | 46              | 30                 | 18.000 | 45.7  | 0.437             | 1.110 | 61.98                  | 37.22  | 2.634E-06                  | 8.639E-06 |
| 18              | 46              |                    | 18.000 | 45.7  | 0.500             | 1.270 | 93.47                  | 42.43  | 2.310E-06                  | 7.577E-06 |
| 20              | 51              | 10                 | 20.000 | 50.8  | 0.250             | 0.635 | 52.74                  | 23.94  | 4.094E-06                  | 1.343E-06 |
| 20              | 51              | 20                 | 20.000 | 50.8  | 0.375             | 0.953 | 78.61                  | 35.69  | 2.747E-06                  | 9.009E-06 |
| 20              | 51              | 30                 | 20.000 | 50.8  | 0.500             | 1.270 | 104.15                 | 47.28  | 2.073E-06                  | 6.800E-06 |
| 24              | 61              | 10                 | 24.000 | 61.0  | 0.250             | 0.635 | 63.42                  | 28.79  | 3.404E-06                  | 1.117E-05 |
| 24              | 61              | 20                 | 24.000 | 61.0  | 0.375             | 0.953 | 94.64                  | 42.96  | 2.282E-06                  | 7.484E-06 |
| 24              | 61              |                    | 24.000 | 61.0  | 0.500             | 1.270 | 125.51                 | 56.98  | 1.720E-06                  | 5.643E-06 |
| 30              | 76              |                    | 30.000 | 76.2  | 0.250             | 0.635 | 79.45                  | 36.07  | 2.718E-06                  | 8.915E-06 |
| 30              | 76              |                    | 30.000 | 76.2  | 0.375             | 0.953 | 118.67                 | 53.88  | 1.820E-06                  | 5.968E-06 |
| 30              | 76              |                    | 30.000 | 76.2  | 0.500             | 1.270 | 157.56                 | 71.53  | 1.370E-06                  | 4.495E-06 |
| 36              | 91              |                    | 36.000 | 91.4  | 0.250             | 0.635 | 95.47                  | 43.34  | 2.262E-06                  | 7.418E-06 |
| 36              | 91              |                    | 36.000 | 91.4  | 0.375             | 0.953 | 142.70                 | 64.79  | 1.513E-06                  | 4.963E-06 |
| 36              | 91              |                    | 36.000 | 91.4  | 0.500             | 1.270 | 189.60                 | 86.08  | 1.139E-06                  | 3.735E-06 |
| 42              | 107             |                    | 42.000 | 106.7 | 0.250             | 0.635 | 111.49                 | 50.62  | 1.937E-06                  | 6.352E-06 |
| 42              | 107             |                    | 42.000 | 106.7 | 0.375             | 0.953 | 166.74                 | 75.70  | 1.295E-06                  | 4.248E-06 |
| 42              | 107             |                    | 42.000 | 106.7 | 0.500             | 1.270 | 221.65                 | 100.63 | 9.742E-06                  | 3.195E-06 |
| 46              | 122             |                    | 48.000 | 121.9 | 0.250             | 0.635 | 127.52                 | 57.89  | 1.693E-06                  | 5.554E-06 |
| 46              | 122             |                    | 48.000 | 121.9 | 0.375             | 0.953 | 190.77                 | 86.61  | 1.132E-06                  | 3.712E-06 |
| 46              | 122             |                    | 48.000 | 121.9 | 0.500             | 1.270 | 253.70                 | 115.18 | 8.511E-06                  | 2.792E-06 |
| 54              | 137             |                    | 54.000 | 137.2 | 0.250             | 0.635 | 143.54                 | 65.17  | 1.504E-06                  | 4.934E-06 |
| 54              | 137             |                    | 54.000 | 137.2 | 0.375             | 0.953 | 214.81                 | 97.52  | 1.005E-06                  | 3.297E-06 |
| 54              | 137             |                    | 54.000 | 137.2 | 0.500             | 1.270 | 285.74                 | 129.73 | 7.557E-06                  | 2.479E-06 |
| 60              | 152             |                    | 60.000 | 152.4 | 0.250             | 0.635 | 159.56                 | 72.44  | 1.353E-06                  | 4.439E-06 |
| 60              | 152             |                    | 60.000 | 152.4 | 0.375             | 0.953 | 238.84                 | 108.43 | 9.040E-06                  | 2.965E-06 |

## APPENDIX D

### US/Metric Conversions for Units Commonly Used in Corrosion-related Literature

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## U.S. Customary/Metric Conversions for Units Commonly Used in Corrosion-Related Literature

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|                                |                                                                     |                       |                                            |
|--------------------------------|---------------------------------------------------------------------|-----------------------|--------------------------------------------|
| 1 A/ft <sup>2</sup>            | = 10.76 A/m <sup>2</sup>                                            | 1 kg/mm <sup>2</sup>  | = 9.807 MPa                                |
| 1 acre                         | = 4,047 m <sup>2</sup> = 0.4047 ha                                  | 1 kilocalorie         | = 4.184 kJ                                 |
| 1 A-h/lb                       | = 2.205 A-h/kg                                                      | 1 knot                | = 0.515 m/s                                |
| 1 Angstrom                     | = 10 <sup>-4</sup> μm = 10 <sup>-10</sup> m = 0.1 nm                | 1 ksi                 | = 6.895 MPa                                |
| 1 atm                          | = 101.325 kPa                                                       | 1 lb                  | = 453.6 g = 0.4536 kg                      |
| 1 bar                          | = 100 kPa                                                           | 1 lb/ft <sup>2</sup>  | = 47.88 Pa                                 |
| 1 bbl, oil (U.S.)              | = 159.0 L                                                           | 1 lb/ft <sup>3</sup>  | = 0.01602 g/cm <sup>3</sup>                |
| 1 bpd (oil)                    | = 159 L/d                                                           | 1 lb/100 U.S. gal     | = 1.1981 g/L                               |
| 1 BTU                          | = 1,055 J                                                           | 1 lb/1,000 bbl        | = 2.852 mg/L                               |
| 1 BTU/ft <sup>2</sup>          | = 11,360 J/m <sup>2</sup>                                           | 1 mA/in. <sup>2</sup> | = 0.155 mA/cm <sup>2</sup>                 |
| 1 BTU/ft <sup>2</sup> /h       | = 3.152 W/m <sup>2</sup> (K-factor)                                 | 1 mA/ft <sup>2</sup>  | = 10.76 mA/m <sup>2</sup>                  |
| 1 BTU/ft <sup>2</sup> /h/F     | = 5.674 W/m <sup>2</sup> -K                                         | 1 MBPD (oil)          | = 159 kL/d                                 |
| 1 BTU/ft <sup>2</sup> /h/F/in. | = 0.144 W/m-K                                                       | 1 mile                | = 1.609 km                                 |
| 1 BTU/h                        | = 0.2931 W                                                          | 1 sq. mile            | = 2.590 km <sup>2</sup>                    |
| 1 cfm                          | = 28.3 L/min = 0.0283 m <sup>3</sup> /min = 40.75 m <sup>3</sup> /d | 1 mi.(naut.)          | = 1.852 km                                 |
| 1 cup                          | = 236.6 mL                                                          | 1 mil                 | = 0.0254 mm = 25.4 μm                      |
| 1 cycle/s                      | = 1 Hz                                                              | 1 MMCFD               | = 2.83 x 10 <sup>4</sup> m <sup>3</sup> /d |
| 1 ft                           | = 0.3048 m                                                          | 1 mm mercury          | = 0.1333 kPa                               |
| 1 ft <sup>2</sup>              | = 0.0929 m <sup>2</sup> = 929 cm <sup>2</sup>                       | 1 mph                 | = 1.609 km/h                               |
| 1 ft <sup>3</sup>              | = 0.02832 m <sup>3</sup> = 28.32 L                                  | 1 mpy                 | = 0.0254 mm/y = 25.4 μm/y                  |
| 1 ft-lb (force)                | = 1.356 J                                                           | 1 N/mm <sup>2</sup>   | = 1 Pa                                     |
| 1 ft-lb (torque)               | = 1.356 N-m                                                         | 1 oz                  | = 28.35 g                                  |
| 1 ft/s                         | = 0.3048 m/s                                                        | 1 oz fluid (Imp.)     | = 28.41 mL                                 |
| 1 gal (Imp.)                   | = 4.546 L = 0.004546 m <sup>3</sup>                                 | 1 oz fluid (U.S.)     | = 29.57 mL                                 |
| 1 gal (U.S.)                   | = 3.785 L = 0.003785 m <sup>3</sup>                                 | 1 oz/ft <sup>2</sup>  | = 2.992 Pa                                 |
| 1 gal/bag (U.S.)               | = 89 mL/kg (water/cement ratio)                                     | 1 oz/U.S. gal         | = 7.49 g/L                                 |
| 1 grain                        | = 0.06480 g = 64.80 mg                                              | 1 part/1,000 bbl      | = 2.32 mg/L                                |
| 1 grain/ft <sup>3</sup>        | = 2.212 g/m <sup>3</sup>                                            | 1 psi                 | = 0.006895 MPa = 6.895 kPa                 |
| 1 grain/100 ft <sup>3</sup>    | = 22.12 mg/m                                                        | 1 qt (Imp.)           | = 1.1365 L                                 |
| 1 hp                           | = 0.7457 kW                                                         | 1 qt (U.S.)           | = 0.9464 L                                 |
| 1 microinch                    | = 0.0254 μm = 25.4 nm                                               | 1 teaspoon (tsp)      | = 4.929 mL                                 |
| 1 in.                          | = 2.54 cm = 25.4 mm                                                 | 1 ton (short)         | = 907.2 kg                                 |
| 1 in. <sup>2</sup>             | = 6.452 cm <sup>2</sup>                                             | 1 torr                | = 133.3 Pa                                 |
| 1 in. <sup>3</sup>             | = 16.387 cm <sup>3</sup> = 0.01639 L                                | 1 U.S. bag cement     | = 42.63 kg (94 lb)                         |
| 1 in.-lb (torque)              | = 0.113 N-m                                                         | 1 yd                  | = 0.914 m                                  |
| 1 in. mercury                  | = 3.387 kPa                                                         | 1 yd <sup>2</sup>     | = 0.8361 m <sup>2</sup>                    |
| 1 in. water                    | = 248.8 Pa                                                          | 1 yd <sup>3</sup>     | = 0.7646 m <sup>3</sup>                    |

---

### Do Not Use

are  
candle  
candlepower  
fermi  
gamma  
micron  
millimicron  
mho  
γ (mass)  
λ (volume)

### Use Instead

1 are = 1 dam<sup>2</sup> = 100 m<sup>2</sup>  
1 candle = 1 cd  
1 candlepower = 1 cd  
1 fermi = 1 fm = 10<sup>-15</sup> m  
1 gamma = 1 nT  
1 micron = 1 μm = 10<sup>-6</sup> m  
1 millimicron = 1 nm = 10<sup>-9</sup> m  
1 mho = 1 S  
1 γ = 1 μg  
1 λ = mm<sup>3</sup> = 1 μL = 1 mm<sup>3</sup>

### Miscellaneous Units Not to Be Used

calorie  
conventional millimeter of mercury  
grade (1 grade = (π/200) rad)  
kilogram-force  
langley (1 langley = 1 cal/cm<sup>2</sup>)  
metric carat  
metric horsepower  
millimeter, centimeter, or meter of water  
standard atmosphere (1 atm = 101.325 kPa)  
technical atmosphere (1 at = 98.0665 kPa)

## APPENDIX E

### Useful Equations



## APPENDIX E

### GENERAL EQUATIONS

#### A) Ohm's Law:

$$E = IR \quad \text{or} \quad V = IR$$

where:

- V = voltage drops at a sink (volts)
- E = source voltage (volts)
- I = current (amperes)
- R = resistance (ohms)

#### B) Kirchhoff's Laws:

- for a series circuit – voltage law

$$\Sigma \text{ EMFs} = IR_1 + IR_2 + \dots + IR_n$$

- for a parallel circuit – current law

$$\Sigma I\text{'s entering a junction} = \Sigma I\text{'s leaving a junction}$$

#### C) Electrical Resistance of a Material:

$$R = \rho \frac{L}{A}$$

where:

- R = resistance (ohms)
- $\rho$  = electrical resistivity (ohm-m)
- L = length (m)
- A = cross-sectional area (m<sup>2</sup>)

D) Electrode Resistance:

- i) Dwight's Modified Equation for a single electrode positioned vertically from the earth's surface when  $L \gg d$ .

$$R = \frac{\rho}{2\pi L} \left( \ln\left(\frac{8L}{d}\right) - 1 \right)$$

where:  $R$  = resistance (ohms)  
 $\rho$  = resistivity (ohm-m)  
 $L$  = length of electrode (m)  
 $d$  = diameter of electrode (m)

- ii) Dwight's Modified Equation for a horizontal electrode (pipe, rod or continuous groundbed).

$$R = \frac{\rho}{2\pi L} \left( \ln\left(\frac{4L}{d}\right) + \ln\left(\frac{L}{h}\right) - 2 + \frac{2h}{L} \right)$$

where:  $R$  = resistance (ohms)  
 $\rho$  = resistivity (ohm-m)  
 $L$  = length of electrode (m)  
 $d$  = diameter of electrode (m)  
 $h$  = depth below grade (m)

- iii) Sunde Equation for a number of electrodes connected in parallel and spaced apart.

$$R_N = \frac{\rho}{2\pi N L} \left\{ \ln\left(\frac{8L}{d}\right) - 1 + 2\frac{L}{s} \ln(0.656 N) \right\}$$

where:  $R_N$  = resistance to remote earth of  $N$  electrodes (ohms)  
 $\rho$  = earth resistivity (ohm-m)  
 $L$  = length of single electrode (m)  
 $d$  = diameter of anode (m)  
 $s$  = spacing between electrodes (m)  
 $N$  = number of electrodes

- iv) Resistance of a sphere:

$$R = \frac{\rho}{4\pi r}$$

where:  $\rho$  = solution resistivity (ohm-m)  
 $r$  = radius of sphere (m)

v) Resistance of a Cylindrical Anode in a Circular Tank for  $L \geq 100 d$

$$R = \frac{0.366 \rho}{L} \log_{10} \left( \frac{d_T}{d_a} \right) \quad \text{or} \quad R = \frac{\rho}{2 \pi L} \ln \left( \frac{d_T}{d_a} \right)$$

where:  $\rho$  = solution resistivity (ohm-m)  
 $d_T$  = tank diameter (m)  
 $d_a$  = anode diameter (m)  
 $L$  = length of anode (m)

E) Voltage Rise in Earth Caused by Anode Current at a Distance  $r$  from the Anode:

$$E_R = \frac{I \rho}{2 \pi L} \left\{ \ln \left( \frac{L + \sqrt{L^2 + r^2}}{r} \right) \right\}$$

for:  $r \geq 10L$

then: 
$$E_R = \frac{0.16 I \rho}{r}$$

where:  $L$  = length of anode (m)  
 $\rho$  = earth resistivity (ohm-m)  
 $r$  = distance from anode (m)  
 $I$  = anode current (A)

F) Area Protected by Anode:

i) Length of Bare Structure Receiving Protection

$$L = 2 d \tan 60^\circ$$

where:  $d$  = perpendicular distance between anode and structure  
 $L$  = length of structure receiving protection

ii) Radius of Circle Receiving Protection from a Stub Anode

$$Z_b = 1.5 s$$

where:  $Z_b$  = radius of circle (m)  
 $s$  = distance from end of stub anode to structure (m)

G) Anode Life Calculations:

i) Using Consumption Rate

$$t = \frac{W f_u e}{I_a C_r}$$

where:  $W$  = weight of anode material (kg)  
 $I_a$  = anode output current (A)  
 $C_r$  = consumption rate (kg / A-yr)  
 $f_u$  = utilization factor  
 $e$  = efficiency factor  
 $t$  = time (yrs)

ii) Using Anode Capacity

$$t = \frac{W C_a f_u e}{I_a} \times \frac{\text{yr}}{8766 \text{ hrs}}$$

where:  $W$  = weight of anode material (kg)  
 $I_a$  = anode output current (A)  
 $C_a$  = anode capacity (A-hr / kg)  
 $f_u$  = utilization factor  
 $e$  = efficiency factor  
 $t$  = time (yrs)

H) Radius of Anode Strings in Circular Tank:

$$r = \frac{d N}{2(\pi + N)}$$

where:  $r$  = radius of anode array (m)  
 $d$  = diameter of tank (m)  
 $N$  = number of anode strings

l) Attenuation Equations for Long Structures Having Leakage Conductance (pipelines, distributed groundbeds):

i) Attenuation Constant ( $\alpha$ )

$$\alpha = \sqrt{r g}$$

where:  $\alpha$  = attenuation constant per unit length  
 $r$  = lineal resistance of a unit length of the structure (ohm)  
 $g$  = conductance per unit length of structure (S)

ii) Characteristic Resistance ( $R_G$ )

$$R_G = \sqrt{\frac{r}{g}}$$

where:  $R_G$  = characteristic resistance of structure having infinite length (ohm)

iii) Voltage and Current Response at any Point 'y' Distance or Units Away From Source

$$\begin{aligned} E_Y &= E_S \cosh(\alpha y) - I_S R_G \sinh(\alpha y) \\ I_Y &= I_S \cosh(\alpha y) - \frac{E_S}{R_G} \sinh(\alpha y) \end{aligned}$$

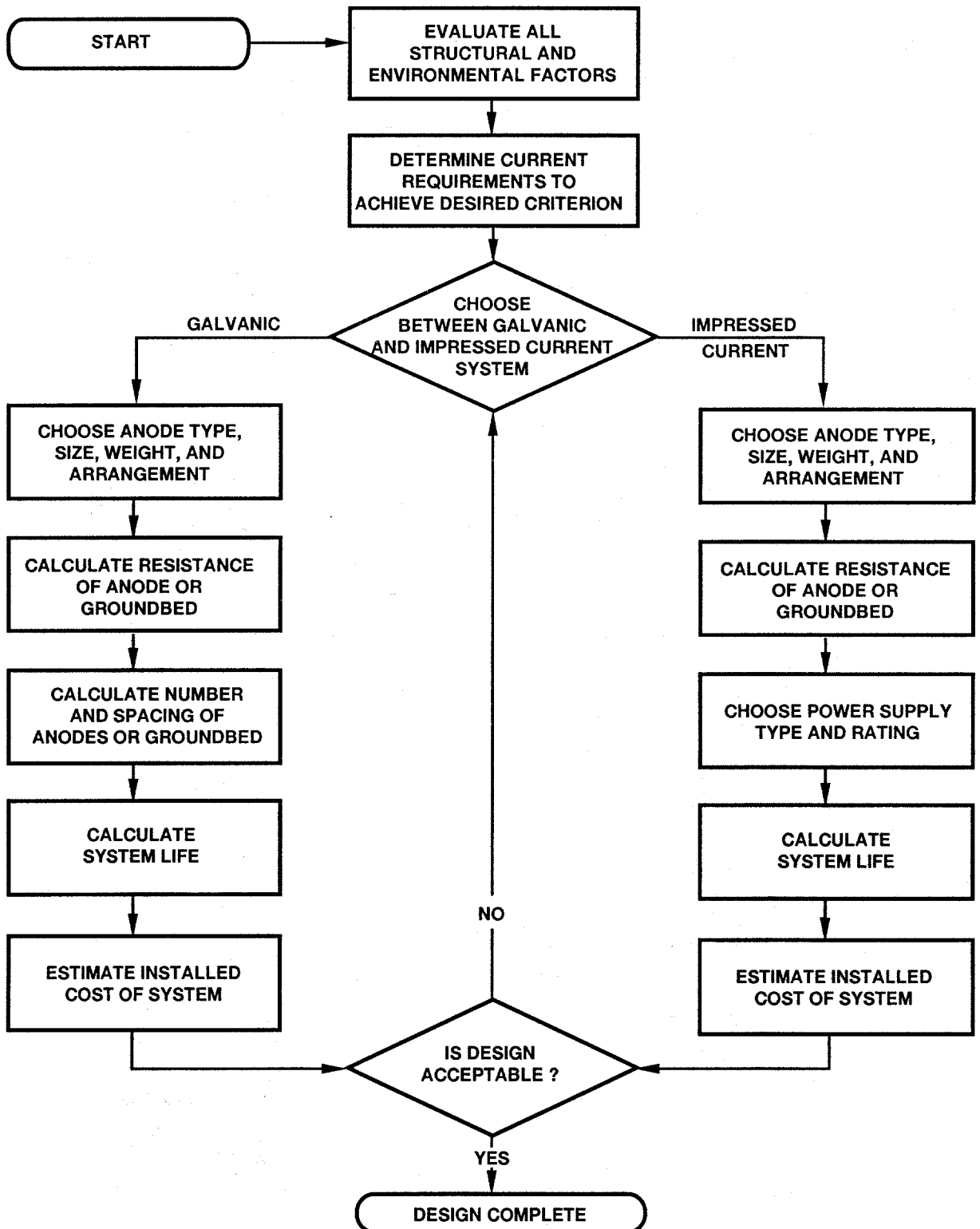
where:  $E_S$  = source voltage between structure and remote earth  
 $I_S$  = source current between structure and remote earth  
 $R_S$  = resistance to remote earth looking into structure at voltage or current source  
 $y$  = number of unit lengths from source end  
 $\alpha$  = attenuation constant  
 $R_G$  = characteristic resistance

where:  $R_{SO} = R_G \coth(\alpha y)$

## APPENDIX F

### Typical Cathodic Protection Design Procedure

# TYPICAL CATHODIC PROTECTION DESIGN PROCEDURE



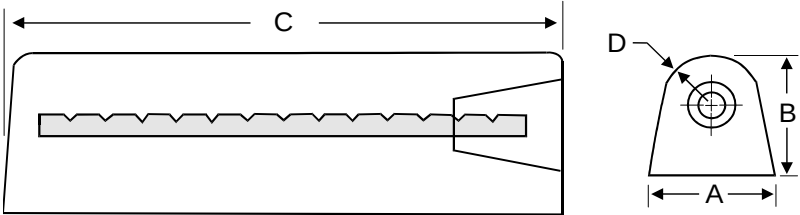
## APPENDIX G

### Anode Specifications



**Table I**  
**Packaged Magnesium Anodes**

\*The first number in the anode designation refers to the weight in pounds. The letter indicates the anode shape. The final number represents the approximate width in inches.



| ANODE TYPE* | MAGNESIUM CASTING DIMENSIONS (in.) |        |          |         | PACKAGE DIMENSIONS (in.) & WEIGHT (lb.) |       |              |           |
|-------------|------------------------------------|--------|----------|---------|-----------------------------------------|-------|--------------|-----------|
|             | A                                  | B      | C        | D       | Length                                  | Width | Backfill Wt. | Total Wt. |
| 3D3         | 3-1/2"                             | 3-3/4" | 5"       | 1-1/2"  | 6-1/2"                                  | 6"    | 6#           | 9#        |
| 5D3         | 3-12"                              | 3-3/4" | 8-1/2"   | 1-1/2"  | 13-1/2"                                 | 6"    | 9#           | 14#       |
| 9D3         | 3-1/2"                             | 3-3/4" | 13-5/16" | 1-1/2"  | 17"                                     | 6"    | 15#          | 24#       |
| 9D2         | 2-3/4"                             | 3"     | 27"      | 1-1/8"  | 17"                                     | 6"    | 15#          | 24#       |
| 17D3        | 3-1/2"                             | 3-3/4" | 25-7/8"  | 1-1/2"  | 30"                                     | 6"    | 25#          | 42#       |
| 17D2        | 2-3/4"                             | 3"     | 50"      | 1-1/8"  | 60"                                     | 6"    | 25#          | 42#       |
| 20D2        | 2-3/4"                             | 3"     | 59-3/4"  | 1-1/8"  | 62"                                     | 5"    | 50#          | 70#       |
| 24D4        | 4-3/4"                             | 4-1/2" | 22-1/4"  | 2"      |                                         |       |              |           |
| 32D3        | 3-1/2"                             | 3-3/4" | 45-1/4"  | 1-1/2"  | 48"                                     | 6"    | 40#          | 72#       |
| 32D5        | 5-1/2"                             | 5-3/4" | 20-9/16" | 2-7/16" | 30"                                     | 8"    | 38#          | 70#       |
| 40D3        | 3-1/2"                             | 3-3/4" | 59-3/4"  | 1-1/2"  | 62"                                     | 6"    | 50#          | 90#       |
| 48D5        | 5-1/2"                             | 5-3/4" | 31-1/16" | 2-7/16" | 34"                                     | 8"    | 48#          | 96#       |

**Table II**  
**Zinc Packaged Ground Anodes**

| TYPE | WEIGHT | SIZE               |
|------|--------|--------------------|
| ZA5  | 5      | 1.4" × 1.4" × 110" |
| ZA6  | 6      | 1.4" × 1.4" × 112" |
| ZA9  | 9      | 1.4" × 1.4" × 118" |
| ZA12 | 12     | 1.4" × 1.4" × 224" |
| ZA18 | 18     | 1.4" × 1.4" × 336" |
| ZA24 | 24     | 2" × 2" × 24"      |
| ZA30 | 30     | 1.4" × 1.4" × 660" |
| ZA48 | 48     | 2" × 2" × 48"      |
| ZA60 | 60     | 2" × 2" × 60"      |

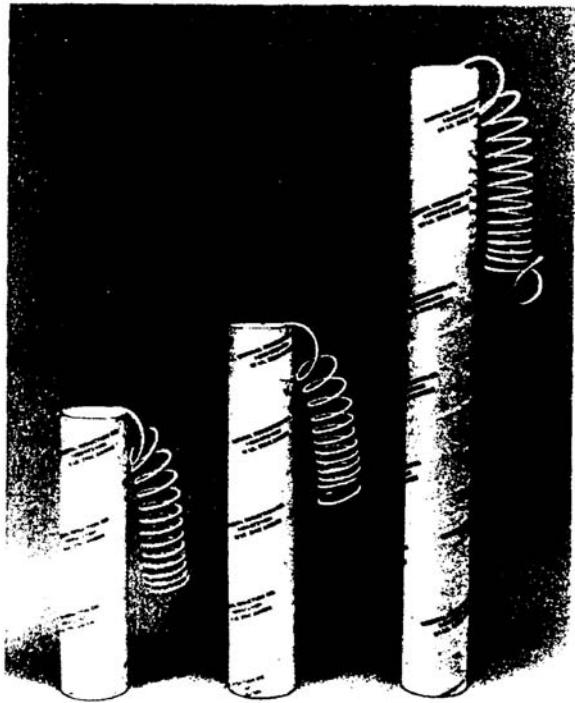
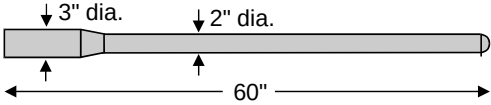
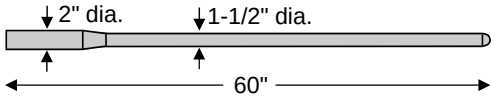
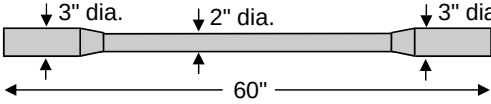
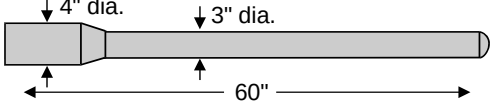
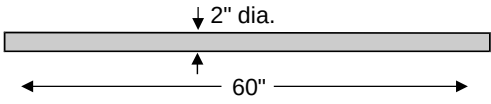


**Table IIIB**  
**High Silicon Iron Solid Chill Cast Anodes**

| TYPE | STYLE               | DIMENSIONS                                                                         | WEIGHT<br>(lbs.) | AREA<br>(sq.ft.) |
|------|---------------------|------------------------------------------------------------------------------------|------------------|------------------|
| EHA  | 1 (PIN)<br>2 (LEAD) |  | 44               | 2.6              |
| EHK  | 2 (LEAD)            |  | 26               | 2.0              |
| EHM  | 1 (PIN)<br>2 (LEAD) |  | 60               | 2.7              |
| EHR  | 1 (PIN)<br>2 (LEAD) |  | 110              | 4.0              |
| SHA  | 2 (LEAD)            |  | 43               | 2.6              |

**SHIPPING INFORMATION**

|            | SOLID ANODES PER CRATE |             | GROSS WEIGHT (lbs.) |             |
|------------|------------------------|-------------|---------------------|-------------|
| Anode Type | Small Crate            | Large Crate | Small Crate         | Large Crate |
| EHA, SHA   | 50                     | 80          | 2350                | 3720        |
| EHM        | 45                     | --          | 2800                | --          |
| EHK        | 70                     | 126         | 1990                | 3502        |
| EHR        | 24                     | --          | 2740                | --          |

**Table IV**  
**Concentric Stranded Copper Single Conductors**  
**Direct Burial Service Suitably Insulated**

| Size<br>AWG | Overall Diameter<br>Not including<br>Insulation<br>(inches) | Approx. weight<br>Not Including<br>Insulation<br>(lbs./M ft.) | Maximum<br>Breaking<br>Strength<br>(lbs.) | Maximum<br>D.C. Resistance<br>@ 20°C<br>Ohms/1000 ft. | Max. Allowable<br>D.C. Current<br>Capacity<br>(Amperes) |
|-------------|-------------------------------------------------------------|---------------------------------------------------------------|-------------------------------------------|-------------------------------------------------------|---------------------------------------------------------|
| 14          | 0.0726                                                      | 12.68                                                         | 130                                       | 2.5800                                                | 15                                                      |
| 12          | 0.0915                                                      | 20.16                                                         | 207                                       | 1.6200                                                | 20                                                      |
| 10          | 0.1160                                                      | 32.06                                                         | 329                                       | 1.0200                                                | 30                                                      |
| 8           | 0.1460                                                      | 50.97                                                         | 525                                       | 0.6400                                                | 45                                                      |
| 6           | 0.1840                                                      | 81.05                                                         | 832                                       | 0.4030                                                | 65                                                      |
| 4           | 0.2320                                                      | 128.90                                                        | 1320                                      | 0.2540                                                | 85                                                      |
| 3           | 0.2600                                                      | 162.50                                                        | 1670                                      | 0.2010                                                | 100                                                     |
| 2           | 0.2920                                                      | 204.90                                                        | 2110                                      | 0.1590                                                | 115                                                     |
| 1           | 0.3320                                                      | 258.40                                                        | 2660                                      | 0.1260                                                | 130                                                     |
| 1/0         | 0.3730                                                      | 325.80                                                        | 3350                                      | 0.1000                                                | 150                                                     |
| 2/0         | 0.4190                                                      | 410.90                                                        | 4230                                      | 0.0795                                                | 175                                                     |
| 3/0         | 0.4700                                                      | 518.10                                                        | 5320                                      | 0.0631                                                | 200                                                     |
| 4/0         | 0.5280                                                      | 653.30                                                        | 6453                                      | 0.0500                                                | 230                                                     |
| 250 MCM     | 0.5750                                                      | 771.90                                                        | 7930                                      | 0.0423                                                | 255                                                     |

**Table V**  
**Typical Platinum Clad Niobium (Copper-cored) Anode Specification**

| Diameter<br>inches | %<br>Nb | Nb Thickness<br>inches | Resistance<br>microhm/ft | Pt Thickness<br>μ-in. (2X)** | Anode Life*<br>AY/ft. (2X) |
|--------------------|---------|------------------------|--------------------------|------------------------------|----------------------------|
| .750               | 20      | .038                   | 22                       | 300                          | 373                        |
| .500               | 20      | .025                   | 50                       | 200                          | 166                        |
| .375               | 20      | .019                   | 89                       | 150 (300)                    | 93 (186)                   |
| .250               | 20      | .013                   | 201                      | 100 (200)                    | 41 (82)                    |
| .188               | 20      | .009                   | 356                      | 75 (150)                     | 22 (44)                    |
| .125               | 20      | .006                   | 806                      | 50 (100)                     | 10 (20)                    |
| .125               | 40      | .013                   | 1025                     | 50 (100)                     | 10 (20)                    |
| .093               | 40      | .010                   | 1822                     | 38 (75)                      | 5.5 (11)                   |
| .063               | 40      | .007                   | 4102                     | 25 (50)                      | 2.5 (5)                    |

\*Based on 0.08 g/Amp-Year

\*\*Double Platinum Thickness

# APPENDIX H

## Protective Coatings Supplement

## ***Composition of Liquid/Liquifiable Coatings***

Conventional coatings have two major components:

- Pigment
- Vehicle (combination of resin and solvent)

Miscellaneous components can also be included for specific reasons.

### ***Vehicle***

A vehicle is the liquid base of the coating and consists of a solvent, binder, and any required liquid additives. The solvent is usually referred to as the volatile vehicle. The binder generally refers to the resin or resin blend that provides the film-forming portion. Binder and pigment compose the dried film coating. The binder or resin is usually referred to as the non-volatile vehicle. Most coatings are named after the film-forming resin (binder).

### ***Solvents (Volatile Vehicle)***

Most coatings contain solvents. Solvents are added to coatings for a number of reasons, including:

- Dissolve the base resin - A solvent is needed to make a solution of the resin to allow its use as a coating vehicle. Many synthetic resins, such as alkyd resin and epoxy resin, are solids.
- Easier application - A solvent is used to make the coating easier to apply. In such cases, the solvent is usually referred to as a thinner. The solvent also controls the evaporation rate and improves the quality of the final film.

## **PRINCIPAL GROUPS OF SOLVENTS**

Principal groups of solvents include:

- Aliphatic hydrocarbons
- Aromatic hydrocarbons
- Ketones
- Esters
- Alcohol
- Glycol ethers
- Water

### ***Non Volatile Vehicle***

The non-volatile vehicle contains the coating resin (binder), pigment, and non-EPA 24 solvents. The non-volatile vehicle is the primary film-forming constituent of the coating. To create a protective coating film on a substrate, the resins must convert from pliant liquid form (which allows application) to cohesive solid form, which adheres to and protects the surface. It is this capability to change from one form to the other that identifies resins suitable for use in coatings.

Generally, the name given to a coating material is that of its principal resin. Resins may be natural organic materials or synthetic materials. Common resins include:

- Acrylic
- Alkyd
- Asphalt
- Chlorinated rubber
- Coal tar
- Drying oil
- Epoxy
- Phenolic
- Polyvinylchloride
- Silicone
- Urethane
- Vinyl
- Siloxirane

### ***Co-Reaction Cure Coatings***

Co-reaction, or addition polymerization, is achieved when a curing agent is added to the base material so that there is an end-to-end addition of monomers to form long-chain molecules.

Types of co-reaction cure coatings, which require the addition of an activator to the base material, include:

- Epoxy
- Coal tar epoxy
- Zinc-rich epoxy
- Epoxy emulsion
- Polyester epoxy
- Phenolic (epoxy-modified)
- Rubber sheet lining
- Urethane (moisture-cure)
- Urethane (two component)
- Inorganic zinc, post-cure, waterbase
- Chlorosulfonated polyethylene
- Vinyl esters
- Polyesters
- Silicone (polysiloxane)

Many coatings are formulated strictly for atmospheric exposures while others are designed for soil and liquid environments. For those who may have the need, NACE offers a Coating Inspector Training and Certification Program that goes into detail on this topic. The following coating types are those most frequently used in soil or immersion service where cathodic protection may be present or considered.

### ***Tar and Mastic***

Throughout much of the twentieth century, coal tar and asphalt were the most common types of coating systems used on structures buried in the ground, exposed to fresh water or seawater, and subjected to the splash zone on marine structures. These heavy build barrier coatings were applied in both hot and cold formulations, many times with inclusion of glass and/or felt to add strength. The relatively low cost and effectiveness made these materials popular. Today there are thousands of pipelines and other structures still in service, which have tar and mastic coating systems. Unfortunately these materials have properties which are toxic and hazardous to handle. The use of these materials on new construction is no longer considered acceptable in many areas. However, the cathodic protection specialist will be dealing with structures coated with systems containing coal tar and asphalt for years to come.



## ***Tapes***

A variety of tape type protective coatings are employed for the protection of metal surfaces from corrosion. Many are used for either underground or atmospheric service.

Initially tapes for underground service were of a hot applied variety. This was consistent with the hot applied coal tar and asphalt enamels in common use at the time. These tapes were essentially a fabric, generally woven of glass or other strong material, filled with a coal tar, asphalt or wax compound that was flashed on a primed metal surface with a torch.

Most tapes used today are plastic polymers applied cold with some sort of bonding agent or adhesive. These tapes have high dielectric properties and come in a variety of widths. They can be applied by hand or by machine.

One problem with the plastic tapes can be the high dielectric resistance. If, for some reason, the bonding agent fails an open void can develop between the metal surface and the tape. Corrosion may initiate in such spaces and the plastic body of the tape may shield the active areas from cathodic protection.

## ***Extruded Plastic***

Organic polymers can be extruded on metal surfaces concurrently with mastic compound that bonds the coating to the metal surface. Some of these systems are concentric extrusions others are formed using plastic extruded in tape form. Like the polymer tapes, the coatings have a high dielectric rating that can result in very low electrical conductance between the base metal and the environment. On long pipelines, this means little attenuation of cathodic protection even in very conductive environments.

## ***Catalytic Curing Polymers***

Over the years, many different catalytic curing coating systems have been developed for corrosion protection. Most require careful surface preparation to avoid later failure. A common use for this class of coating is for field patching and coating of joints on pipelines. Field conditions will definitely impact the final quality of the coating and it is important to follow the manufacturer's recommendations if the results are to be satisfactory.

## ***Fusion Bonded Polymers***

Environmental regulations have lead to the development of new coatings with little or no volatile organic content. Fusion bonded polymer coatings fall into this class of coating. Some of the early fusion bonded coatings have suffered from poor surface preparation an inadequate temperature control during the application process. As a consequence, the coatings have blistered in service and provided questionable levels of protections.

Fusion bonded epoxy coating is gaining popularity as a coating for buried pipelines. The coating has relatively high water adsorption for an organic barrier coating. This suggests that over time this class of coating may show higher than expected electrical conductivity. Manufacturers claim that some leakage is a good thing since it permits passage of cathodic protection current through to surfaces where undercutting or blisters have developed. Until some extended experience has been gained with these materials, cathodic protection designs for pipelines employing them should anticipate this effect.

## ***Compatibility Issues***

Coatings used in connection with cathodic protection must “exhibit coating stability”. That is, they must have effective resistance and bond for a long period of time. Effective resistance is affected by a number of factors, including coating thickness and the environmental conditions. If the effective resistance of the coating is not sufficient, more electric current will be needed, increasing energy costs. Electric current requirements also increase if the coating does not bond well to the surface.

## ***Cathodic Disbondment***

There have been many arguments through the years concerning coating failures that are associated with cathodically protected structures. Some coating systems are not suited to cathodic protection. The can not stand up to the chemical conditions produced at a cathodically protected surface. A compatible coating applied to an improperly prepared surface will fail sooner with cathodic protection than without it.

## ***pH Rise***

Under steady state conditions, steel held at a potential -0.850 volt in an aqueous electrolyte will produce a pH slightly greater than 9.0. At potentials more negative, the pH rises one point for each -59 mV change in polarized potential. Some coating systems can not tolerate pH values in this alkaline range. They will simply lose the bond to the metal and blister or peel off.

## ***Gas Evolution***

Ideally, reduction of dissolved oxygen is the charge transfer reaction at a cathodically protected surface at the usually accepted potential for corrosion control. In reality there will be times when reduction of hydrogen ions to form hydrogen gas takes place. The gas production if trapped at the coating metal interface may put mechanical stress on the coating bond. Unless the structure is grossly over protected, hydrogen gas production should not be a problem.

## ***Factors to be Considered***

### ***Type of Exposure***

Coating systems should be selected with regard to “zones of usage,” which define the type of environment to which the substrate will be exposed.

The operating conditions of a particular structure may be a major factor in coating selection. For example, if a structure were operating at high temperatures and exposed to acid fumes, the coating selected would have to withstand both conditions to be effective. Specific zones of exposure must also be considered when addressing operating conditions.

Upset conditions refer to a change in equipment operations that could damage or destroy a coating. For example, a vat properly coated on its interior to hold an acid might have an exterior coating that is mildly resistant. Should the vat overflow, the exterior coating would fail. In this case, the upset condition would suggest selection of a highly resistant coating for the exterior surface of the vat as well.

### ***Substrate***

Substrate type and condition affect the chemical compatibility, thermal compatibility, flexing, and adhesion of the coating. For example, a wide variety of coatings could be used on a ferrous metal substrate that is abrasive blast cleaned. However, coatings with good wetting properties may need to be selected if the surface is cleaned mechanically.

### ***Ambient Conditions During Application***

The following ambient conditions can affect coating selection:

Temperature -The manufacturer’s data sheet usually provides the ambient temperature range at which a coating can be effectively applied. At higher

ambient temperatures, some coatings may not adhere to the surface correctly or may have a shorter pot life.

**Relative humidity** - Some coatings, such as certain types of inorganic zinc coatings, require high humidity to cure. However, most coatings are negatively affected by high humidity. The upper relative humidity limit at which a coating can be effectively applied is usually included in the manufacturer's data sheet.

**Dew point** - Dew point is a function of temperature and relative humidity. It is the temperature at which water will condense at a given relative humidity. Unless the substrate temperature is 5¼F (3¼C) higher than the dew point, surface preparation and coating application should not occur. Also, if the ambient temperature reaches the dew point before a coating cures, the application should be delayed.

## ***Environmental Regulations***

In some areas, governmental regulations to protect the environment may restrict the use of certain coating materials or application techniques, such as:

**Abrasive blasting** - If dry abrasive blast cleaning is restricted and the steel surface is cleaned in the air, by hand or mechanically, a coating that wets the surface well should be selected. In this situation, this type of coating would be more effective than a coating that needs a high level of surface preparation.

**Solvent emission** - If solvent emission is regulated, water born coatings, coatings with a high solid/low volatile solvent ratio, or coatings that are formulated with approved solvents must be used.

**Contact with potable water and/or foodstuffs** - Regulations also exist that govern types of coatings that can be used in contact with potable water or food.

## **OLDER COATINGS**

Some old coatings contain hazardous materials such as asbestos and PCBs. Before removing or disposing of old coatings determine whether the materials present are considered hazardous. If present, handling of hazardous materials may be subject to a variety of regulations.

## ***Surface Preparation***

Methods and standards of surface preparation should be specified. Requirements vary with many projects, but all parts of the cleaning process

should be addressed in the specifications for a coating project including:

- Pre-inspection (a procedure to inspect for, mark, and correct all fabrication defects)
- Pre-cleaning (removal of contaminants, such as oil, grease, dirt, and so on by solvent cleaning to a known standard [e.g., SSPC Surface Preparation Specification No. 1 Solvent Cleaning])
- Cleaning operations to referenced standards (NACE, SSPC, ISO)

Additional information included might address abrasives, equipment, techniques, and restrictions in regard to surface preparation.

## ***General Causes of Coating Defects and Failures***

Coating failures may occur for many reasons. The service life of a coating system may be influenced by a variety of factors including the following causes.

### ***Improper Selection of Coating System***

A major cause of failure is improper selection of the type of coating to be used. Selection may be based on several criteria, including:

- Known performance of coatings for similar applications
- Known chemical composition and physical properties of the coating
- Results of exposure tests on coatings under anticipated environment/service conditions.

Although there are many high-performance coatings used in a wide variety of situations, no one coating or type of coating is resistant to all environments or service situations (atmospheric, aqueous, or chemical). Therefore, many types of coatings have been developed for service under special conditions.

Sometimes a coating may be selected because of appearance, availability, or some other reason without consideration of the service situation. In a case like this, a premature coating failure may occur.

### ***Environmental Conditions***

An important consideration in selection of a coating system is environment, the conditions in which the coating system will be expected to perform. Consider:

- Temperature range
- Chemicals present

- Mechanical stresses

### ***Workpiece Factors***

Structural design and manufacturing flaws can complicate the procedures required to achieve a successful coating system.

The coating specifier may not be responsible for the work of designers, engineers, and/or fabricators. However, he should be able to point out problems, which may arise as a result of the way in which the workpiece has been designed and manufactured. He should also be able to provide assistance in finding a solution to such problems.

Some of the problems with the design and resulting physical structure make it virtually impossible to achieve continuous coating. These include:

- Inaccessibility to some areas by brush or spray gun
- Dissimilar metals in contact with each other, which may create galvanic action that expedites coating failure
- Solvents that may not escape from applied film in areas that prevent complete drying, such as narrow crevices
- Sharp edges, angles, weld spatters, and skip welds which are all difficult to cover well

In any case, the person selecting the coating system should be alert to any structural design and/or manufacturing flaws, and attempt to have them corrected, or select the best possible coating system for the situation.

### ***Inadequate Surface Preparation***

Experience indicates that the majority of all coating failures can be attributed, at least in part, to inadequate surface preparation. Contributing factors may include:

- Improper customer-supplied specifications
- Failure of the contractor to follow proper specifications
- Inadequate inspection:
  1. Of the prepared surface to make sure that it meets the surface preparation standard specified .
  2. For compounds prevalent in industrial areas which could contaminate the surface

Any of the above can result in insufficient/incorrect profile. They can also cause

incomplete removal of materials, such as those listed below, which prevent adhesion of coating to the surface.

- Dirt
- Grease
- Rust
- Oil
- Mill scale

## APPENDIX I

### D.C. Network Analysis



# DC Network Analysis

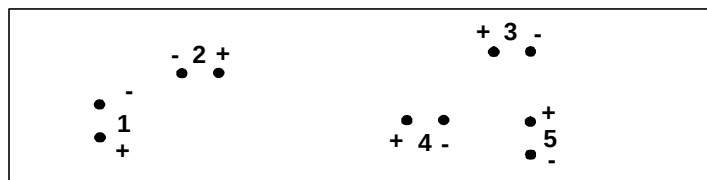
## Electrical Coupling

Buried metallic structures become a part of a complex electrical network. Each metallic element is a potential conductor of electricity having finite electrical resistance within itself and relative to other structures.

In analysis of such circuits, the concept of the electrical coupling is an extremely valuable tool. When an electric current is made to flow in any part of an electrical network, it will exert some effect on all other parts of the network.

Consider Figure 1. This figure represents the external terminals of a “black box” which contains an electrical network the circuit details of which are not known. If a direct current is impressed at terminal No.1, its effects can be detected at all of the other terminals in the network. At terminal No.2, which represents an electrical shunt in the network, the effect of current at terminal No.1 is designated as  $R_{2,1}$ . Since terminal No.2 is a shunt (calibrated resistance), it normally will have a calibration factor such as 1 ampere per millivolt. It is possible then to convert the electrical potential that appears at terminal No.2 into amperes of current.

At terminal No.3, which represents a potential measuring terminal between a structure in the network and a ground reference, the voltage which appears at terminal No.3 as the result of current applied at terminal No.1 can be represented by the coupling value  $R_{3,1}$ . It is measured in volts per ampere. Similarly, couplings from current  $I_1$  at terminal No.'s 4 and 5 are represented by the symbols  $R_{4,1}$  and  $R_{5,1}$ . If a current is impressed at terminal No. 5 with the polarity indicated, a series of electrical couplings can be obtained for the other terminals in the network.



| TERMINAL | DESCRIPTION                                    |
|----------|------------------------------------------------|
| 1        | Terminals attached to 2 different elements     |
| 2        | Shunt in a branch of one element               |
| 3        | Voltage terminal between an element and ground |
| 4        | Voltage terminal between an element and ground |
| 5        | Terminals attached to 2 different elements     |

**Figure 1 Network "black box"**

**Table 1** gives some typical values which might appear as the result of current applied, first at terminal No. 1 and then at terminal No. 5.

**Table 1- Network Constants (See Figure 1)**

| Current Applied at Terminal No. 1 | Current Applied at Terminal No. 5 |
|-----------------------------------|-----------------------------------|
| $R_{1,1} = +5.00V/A$              | $R_{1,5} = -2.50V/A$              |
| $R_{2,1} = +0.0008V/A = 0.8A/A$   | $R_{2,5} = +0.0004V/A = 0.4A/A$   |
| $R_{3,1} = +2.00V/A$              | $R_{3,5} = -2.20V/A$              |
| $R_{4,1} = -0.10V/A$              | $R_{4,5} = +0.50V/A$              |
| $R_{5,1} = -2.50V/A$              | $R_{5,5} = +2.50V/A$              |

In network analysis, it is important to assign polarities to the terminals and keep these polarities throughout the analysis.

## Application to Cathodic Protection Design

Transform the network of Figure 1 to a typical cathodic protection problem. Figure 1-15, illustrates the use of network analysis in cathodic protection design. Terminal No.1 now represents the output terminal of a cathodic protection rectifier. Terminal No.2 is a voltage drop test station on pipeline A, which is to have cathodic protection applied to it. Terminal No.3 is a pipe-to-soil reference test station located on pipeline A at a crossing with pipeline B. Terminal No.4 is a similar pipe-to-soil

test station on pipeline B at the mutual crossing. Terminal No.5 is a pair of wires at a test point from pipeline A and pipeline B.

From data given in **Table 1**, we can determine that there is a stray current interference effect on pipeline B at terminal No.4. This is made evident by the negative value of coupling  $R_{4,1}$  (-0.1 volt per ampere). The negative value indicates that for every ampere of current applied at terminal No.1 (the rectifier) pipeline B becomes positive with respect to the ground reference (terminal No. 4) by 0.10 volt.

Assume that cathodic protection will be realized on pipeline A when the pipe to soil potential at terminal No.3 shifts +0.3 volt as a result of the current applied at the rectifier. Assume also that an interference mitigation bond is to be installed across terminal No.5 such that operation of the rectifier (terminal No.1) will not shift the potential at terminal No.4 on pipeline B. In this instance, assume that the electrical potential between the two pipelines at terminal No.5 is negligible when the cathodic protection system is not functioning.

The first step is to write mathematical equations based on the set requirements using the network constants from Table 1-7. The data indicate that current applied at terminals No. 1 and 5 affect all other terminals in the network.

For the first criterion (a potential shift at terminal No. 3 of +0.3 volts write equation 1:

$$1) \quad \Delta V_3 = I_1 \times R_{3,1} + I_5 \times R_{3,5} = 0.30 \text{ volt}$$

For the second criterion (no voltage change at terminal No. 4 for operation of the rectifier) write equation 2:

$$2) \quad \Delta V_4 = I_1 \times R_{4,1} + I_5 \times R_{4,5} = 0.00 \text{ volt}$$

Solving equation 2 for  $I_5$  in terms of  $I_1$ , and substituting the value in equation 1:

$$3) \quad I_5 = 0.2 \times I_1$$

Substituting in equation 1 yields:

$$4) \quad I_1 = 0.192 \text{ ampere}$$

$$5) \quad I_5 = 0.038 \text{ ampere}$$

Now calculate the resistance of a bond to be installed in terminal No.5 that will yield the desired current.

The voltage developed at terminal No.5, as the result of the operation of the rectifier, was determined to be -2.5 volts per ampere. There was no potential between the two pipelines without operation of the rectifier  $I_1$ . The voltage which will develop across terminal No.5 under operating conditions, will be:

$$6) \quad V_5 = I_1 \times R_{5,1}$$

$$V_5 = 0.192 \times -2.5 = -0.48 \text{ volt}$$

The circuit resistance to deliver a bond current of 0.038 ampere at -0.48 volt is calculated by Ohm's Law:

$$7) \quad R = 0.48/0.038 = 12.6 \text{ ohms}$$

## Appendix J

### Anode Stress Derivation

# Anode Stress Derivation

Maximum stress intensity in the rod occurs at the wall through which the anode is installed.

$$S = M/Z$$

Where:

$S$  = stress intensity at the wall ( $\text{kg/m}^2$ )

$M$  = bending moment at wall ( $\text{kg/m}$ )

$Z$  = section modules ( $\text{m}^3$ )

for a cylindrical rod anchored at one end

$$M = WE^2/2$$

$$Z = \pi d^3/32 = J_o/y$$

where

$$y = d/2 \quad J_o = \pi d^4/64$$

Where:

$W$  = water drag ( $\text{kg/m}$ )

$E$  = extension from wall (m)

$d$  = diameter of rod (m)

$$S = M/Z = 32WE^2/2d^3 = 16WE^2/d^3$$

The total drag force on the rod caused by water flow is given by the equation:

$$D = CA \frac{1}{2} \rho V^2 \quad ^1$$

Where:

$D$  = total drag force (kg)

$C$  = drag coefficient (1.0 to 1.5) (for Reynold's numbers

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<sup>1</sup> **Handbook of Engineering Fundamentals**, O.W. Eshbach Editor, 3rd Ed., pp. 741, John Wiley & Sons, NY

between 100 and 100,000 with flow around a circular rod or pipe. Assume  $C = 1.1$ )  
 $A$  = cross sectional area of the rod ( $E \times d$ )  $m^2$   
 $p$  = mass density of seawater  $kg/M^3/g$   
 $p = (109.6 \text{ kg sec}^2/m^4)$   
 $V$  = velocity (m/sec)

$$W = D/E \text{ (kg/m)}$$

Therefore:

$$W = CA (pV^2/2)/E$$

$$W = C Ed pV^2/(2E) = CdpV^2/2$$

$$W = 60.28 dV^2 \text{ kg/m}$$

Since:

$$S = (16 WE^2/\pi d^3) \times f$$

$$S = (16 \times 60.28 dV^2 E^2/\pi d^3)f$$

$$S = 307 fV^2 E^2/d^2$$

Where:

$S$  = maximum stress ( $kg/m^2$ )  
 $V$  = fluid velocity (m/sec)  
 $E$  = extension from wall (m)  
 $d$  = rod diameter (m)  
 $f$  = safety factor (see note)

The equation in English units is:

$$S = 0.0409 V^2 E^2/d^2$$

Where:

$S$  = maximum stress (psi)  
 $V$  = fluid velocity (ft/sec)  
 $E$  = extension from wall (in)  
 $d$  = rod diameter (in)  
 $f$  = safety factor

Note: The equation factor of 3 should be used where pump surges or other factors create cyclic loads. A safety factor of 5 should be used if there is sever vibration.

Substituting the tensile strength of the rod material ( $S_m$ ) for the maximum stress and taking the square root of both sides of the equation.

$$0.057(sm/f)^{0.5} = VE/d$$

Where:

$S_m$  = tensile strength of rod material (kg/m=2)

$V$  = fluid velocity (m/sec)

$E$  = extension from wall (m)

$d$  = rod diameter (m)

$f$  = safety factor

Note: Use  $2.81^2 \times 10^7$  kg/m<sup>2</sup> (40,000 psi) for tensile strength of titanium.



# APPENDIX K

NACE Standard  
RP0169

## **Standard Recommended Practice**

# **Control of External Corrosion on Underground or Submerged Metallic Piping Systems**

This NACE International standard represents a consensus of those individual members who have reviewed this document, its scope, and provisions. Its acceptance does not in any respect preclude anyone, whether he has adopted the standard or not, from manufacturing, marketing, purchasing, or using products, processes, or procedures not in conformance with this standard. Nothing contained in this NACE International standard is to be construed as granting any right, by implication or otherwise, to manufacture, sell, or use in connection with any method, apparatus, or product covered by Letters Patent, or as indemnifying or protecting anyone against liability for infringement of Letters Patent. This standard represents minimum requirements and should in no way be interpreted as a restriction on the use of better procedures or materials. Neither is this standard intended to apply in all cases relating to the subject. Unpredictable circumstances may negate the usefulness of this standard in specific instances. NACE International assumes no responsibility for the interpretation or use of this standard by other parties and accepts responsibility for only those official NACE International interpretations issued by NACE International in accordance with its governing procedures and policies which preclude the issuance of interpretations by individual volunteers.

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## Foreword

This standard recommended practice presents procedures and practices for achieving effective control of external corrosion on buried or submerged metallic piping systems. These recommendations are also applicable to many other buried or submerged metallic structures. It is intended for use by corrosion control personnel concerned with the corrosion of buried or submerged piping systems, including oil, gas, water, and similar structures. This standard describes the use of electrically insulating coatings, electrical isolation, and cathodic protection as external corrosion control methods. It contains specific provisions for the application of cathodic protection to existing bare, existing coated, and new piping systems. Also included are procedures for control of interference currents on pipelines.

This standard should be used in conjunction with the practices described in the following NACE standards and publications when appropriate (use latest revisions):

RP0572<sup>1</sup>

RP0177<sup>2</sup>

RP0285<sup>3</sup>

RP0186<sup>4</sup>

RP0286<sup>5</sup>

RP0387<sup>6</sup>

RP0188<sup>7</sup>

TPC 11<sup>8</sup>

TM0497<sup>9</sup>

For accurate and correct application of this standard, the standard must be used in its entirety. Using or citing only specific paragraphs or sections can lead to misinterpretation and misapplication of the recommendations and practices contained in this standard.

This standard does not designate practices for every specific situation because of the complexity of conditions to which buried or submerged piping systems are exposed.

This standard was originally published in 1969, and was revised by NACE Task Group T-10-1 in 1972, 1976, 1983, and 1992. It was reaffirmed in 1996 by NACE Unit Committee T-10A on Cathodic Protection, and in 2002 by Specific Technology Group (STG) 35 on Pipelines, Tanks, and Well Casings. This standard is issued by NACE International under the auspices of STG 35, which is composed of corrosion control personnel from oil and gas transmission companies, gas distribution companies, power companies, corrosion consultants, and others concerned with external corrosion control of buried or submerged metallic piping systems.

In NACE standards, the terms *shall*, *must*, *should*, and *may* are used in accordance with the definitions of these terms in the *NACE Publications Style Manual*, 4th ed., Paragraph 7.4.1.9. *Shall* and *must* are used to state mandatory requirements. The term *should* is used to state something considered good and is recommended but is not mandatory. The term *may* is used to state something considered optional.

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**NACE International  
Standard  
Recommended Practice**

**Control of External Corrosion on Underground  
or Submerged Metallic Piping Systems**

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## Section 1: General

1.1 This standard presents acknowledged practices for the control of external corrosion on buried or submerged steel, cast iron, ductile iron, copper, and aluminum piping systems.

1.2 This standard is intended to serve as a guide for establishing minimum requirements for control of external corrosion on the following systems:

1.2.1 New piping systems: Corrosion control by a coating supplemented with cathodic protection, or by some other proven method, should be provided in the initial design and maintained during the service life of the piping system, unless investigations indicate that corrosion control is not required. Consideration should be given to the construction of pipelines in a manner that facilitates the use of in-line inspection tools.

1.2.2 Existing coated piping systems: Cathodic protection should be provided and maintained, unless investigations indicate that cathodic protection is not required.

1.2.3 Existing bare piping systems: Studies should be made to determine the extent and rate of corrosion on existing bare piping systems. When these studies indicate that corrosion will affect the safe or economic operation of the system, adequate corrosion control measures shall be taken.

1.3 The provisions of this standard should be applied under the direction of competent persons who, by reason of knowledge of the physical sciences and the principles of engineering and mathematics, acquired by education and related practical experience, are qualified to engage in the practice of corrosion control on buried or submerged metallic piping systems. Such persons may be registered professional engineers or persons recognized as corrosion specialists or cathodic protection specialists by NACE if their professional activities include suitable experience in external corrosion control of buried or submerged metallic piping systems.

1.4 Special conditions in which cathodic protection is ineffective or only partially effective sometimes exist. Such conditions may include elevated temperatures, disbonded coatings, thermal insulating coatings, shielding, bacterial attack, and unusual contaminants in the electrolyte. Deviation from this standard may be warranted in specific situations provided that corrosion control personnel in responsible charge are able to demonstrate that the objectives expressed in this standard have been achieved.

1.5 This standard does not include corrosion control methods based on chemical control of the environment, on the use of electrically conductive coatings, or on control of internal corrosion.

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## Section 2: Definitions<sup>(1)</sup>

**Amphoteric Metal:** A metal that is susceptible to corrosion in both acid and alkaline environments.

**Anode:** The electrode of an electrochemical cell at which oxidation occurs. Electrons flow away from the anode in the external circuit. Corrosion usually occurs and metal ions enter solution at the anode.

**Anodic Polarization:** The change of the electrode potential in the noble (positive) direction caused by current across the electrode/electrolyte interface.

**Beta Curve:** A plot of dynamic (fluctuating) interference current or related proportional voltage (ordinate) versus values of corresponding structure-to-soil potentials at a selected location on the affected structure (abscissa) (see Appendix A).

**Cable:** One conductor or multiple conductors insulated from one another.

**Cathode:** The electrode of an electrochemical cell at which reduction is the principal reaction. Electrons flow toward the cathode in the external circuit.

**Cathodic Disbondment:** The destruction of adhesion between a coating and the coated surface caused by products of a cathodic reaction.

**Cathodic Polarization:** The change of electrode potential in the active (negative) direction caused by current across the electrode/electrolyte interface.

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<sup>(1)</sup> Definitions in this section reflect common usage among practicing corrosion control personnel and apply specifically to how the terms are used in this standard. In many cases, in the interests of brevity and practical usefulness, the scientific definitions are abbreviated or paraphrased.

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

**Coating:** A liquid, liquefiable, or mastic composition that, after application to a surface, is converted into a solid protective, decorative, or functional adherent film.

**Coating Disbondment:** The loss of adhesion between a coating and the pipe surface.

**Conductor:** A material suitable for carrying an electric current. It may be bare or insulated.

**Continuity Bond:** A connection, usually metallic, that provides electrical continuity between structures that can conduct electricity.

**Corrosion:** The deterioration of a material, usually a metal, that results from a reaction with its environment.

**Corrosion Potential ( $E_{\text{corr}}$ ):** The potential of a corroding surface in an electrolyte relative to a reference electrode under open-circuit conditions (also known as *rest potential*, *open-circuit potential*, or *freely corroding potential*).

**Corrosion Rate:** The rate at which corrosion proceeds.

**Criterion:** Standard for assessment of the effectiveness of a cathodic protection system.

**Current Density:** The current to or from a unit area of an electrode surface.

**Diode:** A bipolar semiconducting device having a low resistance in one direction and a high resistance in the other.

**Distributed-Anode Impressed Current System:** An impressed current anode configuration in which the anodes are “distributed” along the structure at relatively close intervals such that the structure is within each anode’s voltage gradient. This anode configuration causes the electrolyte around the structure to become positive with respect to remote earth.

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

**Electrical Survey:** Any technique that involves coordinated electrical measurements taken to provide a basis for deduction concerning a particular electrochemical condition relating to corrosion or corrosion control.

**Electrode:** A conductor used to establish contact with an electrolyte and through which current is transferred to or from an electrolyte.

**Electroosmotic Effect:** Passage of a charged particle through a membrane under the influence of a voltage. Soil or coatings may act as the membrane.

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

**Foreign Structure:** Any metallic structure that is not intended as a part of a system under cathodic protection.

**Galvanic Anode:** A metal that provides sacrificial protection to another metal that is more noble when electrically coupled in an electrolyte. This type of anode is the electron source in one type of cathodic protection.

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

**Holiday:** A discontinuity in a protective coating that exposes unprotected surface to the environment.

**Impressed Current:** An electric current supplied by a device employing a power source that is external to the electrode system. (An example is direct current for cathodic protection.)

**In-Line Inspection:** The inspection of a steel pipeline using an electronic instrument or tool that travels along the interior of the pipeline.

**Insulating Coating System:** All components of the protective coating, the sum of which provides effective electrical isolation of the coated structure.

**Interference:** Any electrical disturbance on a metallic structure as a result of stray current.

**Interference Bond:** A metallic connection designed to control electrical current interchange between metallic systems.

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

**Isolation:** See *Electrical Isolation*.

**Line Current:** The direct current flowing on a pipeline.

**Long-Line Corrosion Activity:** Current through the earth between an anodic and a cathodic area that returns along an underground metallic structure.

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

**Pipe-to-Electrolyte Potential:** The potential difference between the pipe metallic surface and electrolyte that is measured with reference to an electrode in contact with the electrolyte.

**Polarization:** The change from the open-circuit potential as a result of current across the electrode/electrolyte interface.

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

**Reference Electrode:** An electrode whose open-circuit potential is constant under similar conditions of measurement, which is used for measuring the relative potentials of other electrodes.

**Reverse-Current Switch:** A device that prevents the reversal of direct current through a metallic conductor.

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

**Shorted Pipeline Casing:** A casing that is in direct metallic contact with the carrier pipe.

**Sound Engineering Practices:** Reasoning exhibited or based on thorough knowledge and experience, logically valid and having technically correct premises that demonstrate good judgment or sense in the application of science.

**Stray Current:** Current through paths other than the intended circuit.

**Stray-Current Corrosion:** Corrosion resulting from current through paths other than the intended circuit, e.g., by any extraneous current in the earth.

**Telluric Current:** Current in the earth as a result of geomagnetic fluctuations.

**Voltage:** An electromotive force or a difference in electrode potentials expressed in volts.

**Wire:** A slender rod or filament of drawn metal. In practice, the term is also used for smaller-gauge conductors (6 mm<sup>2</sup> [No. 10 AWG<sup>(2)</sup>] or smaller).

### Section 3: Determination of Need for External Corrosion Control

#### 3.1 Introduction

3.1.1 This section recommends practices for determining when an underground or submerged metallic piping system requires external corrosion control.

3.1.2 Metallic structures, buried or submerged, are subject to corrosion. Adequate corrosion control procedures should be adopted to ensure metal integrity for safe and economical operation.

3.2 The need for external corrosion control should be based on data obtained from one or more of the following: corrosion surveys, operating records, visual observations, test results from similar systems in similar environments, in-line inspections, engineering and design specifications, and operating, safety, and economic requirements. The absence of leaks alone is insufficient evidence that corrosion control is not required.

3.2.1 Environmental and physical factors include the following:

3.2.1.1 Corrosion rate of the particular metallic piping system in a specific environment (see Appendix B);

3.2.1.2 Nature of the product being transported, the working temperature, temperature differentials within the pipeline causing thermal expansion and contraction, tendency of backfill to produce soil stress, and working pressure of the piping system as related to design specification;

3.2.1.3 Location of the piping system as related to population density and frequency of visits by personnel;

3.2.1.4 Location of the piping system as related to other facilities; and

3.2.1.5 Stray current sources foreign to the system.

3.2.2 Economic factors include the following:

3.2.2.1 Costs of maintaining the piping system in service for its expected life (see Appendix B);

3.2.2.2 Contingent costs of corrosion (see Appendix C); and

3.2.2.3 Costs of corrosion control (see Appendix D).

<sup>(2)</sup> American Wire Gauge.

## Section 4: Piping System Design

### 4.1 Introduction

4.1.1 This section provides accepted corrosion control practices in the design of an underground or submerged piping system. A person qualified to engage in the practice of corrosion control should be consulted during all phases of pipeline design and construction (see Paragraph 1.3). These recommendations should not be construed as taking precedence over recognized electrical safety practices.

### 4.2 External Corrosion Control

4.2.1 External corrosion control must be a primary consideration during the design of a piping system. Materials selection and coatings are the first line of defense against external corrosion. Because perfect coatings are not feasible, cathodic protection must be used in conjunction with coatings. For additional information, see Sections 5 and 6.

4.2.2 New piping systems should be externally coated unless thorough investigation indicates that coatings are not required (see Section 5).

4.2.3 Materials and construction practices that create electrical shielding should not be used on the pipeline. Pipelines should be installed at locations where proximity to other structures and subsurface formations do not cause shielding.

### 4.3 Electrical Isolation

4.3.1 Isolation devices such as flange assemblies, prefabricated joint unions, or couplings should be installed within piping systems where electrical isolation of portions of the system is required to facilitate the application of external corrosion control. These devices should be properly selected for temperature, pressure, chemical resistance, dielectric resistance, and mechanical strength. Installation of isolation devices should be avoided or safeguarded in areas in which combustible atmospheres are likely to be present. Locations at which electrical isolating devices should be considered include, but are not limited to, the following:

4.3.1.1 Points at which facilities change ownership, such as meter stations and well heads;

4.3.1.2 Connections to main-line piping systems, such as gathering or distribution system laterals;

4.3.1.3 Inlet and outlet piping of in-line measuring and/or pressure-regulating stations;

4.3.1.4 Compressor or pumping stations, either in the suction and discharge piping or in the main line immediately upstream and downstream from the station;

4.3.1.5 Stray current areas;

4.3.1.6 The junction of dissimilar metals;

4.3.1.7 The termination of service line connections and entrance piping;

4.3.1.8 The junction of a coated pipe and a bare pipe; and

4.3.1.9 Locations at which electrical grounding is used, such as motorized valves and instrumentation.

4.3.2 The need for lightning and fault current protection at isolating devices should be considered. Cable connections from isolating devices to arresters should be short, direct, and of a size suitable for short-term high-current loading.

4.3.3 When metallic casings are required as part of the underground piping system, the pipeline should be electrically isolated from such casings. Casing insulators must be properly sized and spaced and be tightened securely on the pipeline to withstand insertion stresses without sliding on the pipe. Inspection should be made to verify that the leading insulator has remained in position. Concrete coatings on the carrier pipe could preclude the use of casing insulators. Consideration should be given to the use of support under the pipeline at each end of the casing to minimize settlement. The type of support selected should not cause damage to the pipe coating or act as a shield to cathodic protection current.

4.3.4 Casing seals should be installed to resist the entry of foreign matter into the casing.

4.3.5 When electrical contact would adversely affect cathodic protection, piping systems should be electrically isolated from supporting pipe stanchions, bridge structures, tunnel enclosures, pilings, offshore structures, or reinforcing steel in concrete. However, piping can be attached directly to a bridge without isolation if isolating devices are installed in the pipe system on each side of the bridge to electrically isolate the bridge piping from adjacent underground piping.

4.3.6 When an isolating joint is required, a device manufactured to perform this function should be used, or, if permissible, a section of nonconductive pipe, such as plastic pipe, may be installed. In either case, these



should be properly rated and installed in accordance with the manufacturer's instructions.

4.3.7 River weights, pipeline anchors, and metallic reinforcement in weight coatings should be electrically isolated from the carrier pipe and designed and installed so that coating damage does not occur and the carrier pipe is not electrically shielded.

4.3.8 Metallic curb boxes and valve enclosures should be designed, fabricated, and installed in such a manner that electrical isolation from the piping system is maintained.

4.3.9 Insulating spacing materials should be used when it is intended to maintain electrical isolation between a metallic wall sleeve and the pipe.

4.3.10 Underground piping systems should be installed so that they are physically separated from all foreign underground metallic structures at crossings and parallel installations and in such a way that electrical isolation could be maintained if desired.

4.3.11 Based on voltage rating of alternating current (AC) transmission lines, adequate separation should be maintained between pipelines and electric transmission tower footings, ground cables, and counterpoise. Regardless of separation, consideration should always be given to lightning and fault current protection of pipeline(s) and personnel safety (see NACE Standard RP0177<sup>2</sup>).

#### 4.4 Electrical Continuity

4.4.1 Nonwelded pipe joints may not be electrically continuous. Electrical continuity can be ensured by the use of fittings manufactured for this purpose or by bonding across and to the mechanical joints in an effective manner.

#### 4.5 Corrosion Control Test Stations

4.5.1 Test stations for potential, current, or resistance measurements should be provided at sufficient locations to facilitate cathodic protection testing. Such locations may include, but not be limited to, the following:

- 4.5.1.1 Pipe casing installations,
- 4.5.1.2 Metallic structure crossings,
- 4.5.1.3 Isolating joints,
- 4.5.1.4 Waterway crossings,
- 4.5.1.5 Bridge crossings,
- 4.5.1.6 Valve stations,
- 4.5.1.7 Galvanic anode installations,

4.5.1.8 Road crossings,

4.5.1.9 Stray-current areas, and

4.5.1.10 Rectifier installations.

4.5.2 The span of pipe used for line current test stations should exclude:

4.5.2.1 Foreign metallic structure crossings;

4.5.2.2 Lateral connections;

4.5.2.3 Mechanical couplings or connections such as screwed joints, transition pieces, valves, flanges, anode or rectifier attachments, or metallic bonds; and

4.5.2.4 Changes in pipe wall thickness and diameter.

#### 4.5.3 Attachment of Copper Test Lead Wires to Steel and Other Ferrous Pipes

4.5.3.1 Test lead wires may be used both for periodic testing and for current-carrying purposes. As such, the wire/pipe attachment should be mechanically strong and electrically conductive.

4.5.3.2 Methods of attaching wires to the pipe include (a) thermit welding process, (b) soldering, and (c) mechanical means.

4.5.3.3 Particular attention must be given to the attachment method to avoid (a) damaging or penetrating the pipe, (b) sensitizing or altering of pipe properties, (c) weakening the test lead wire, (d) damaging internal or external pipe coatings, and (e) creating hazardous conditions in explosive environments.

4.5.3.4 Attachment by mechanical means is the least desirable method. Such a connection may loosen, become highly resistant, or lose electrical continuity.

4.5.3.5 The connection should be tested for mechanical strength and electrical continuity. All exposed portions of the connection should be thoroughly cleaned of all welding slag, dirt, oils, etc.; primed, if needed; and coated with materials compatible with the cable insulation, pipe coating, and environment.

#### 4.5.4 Attachment of Aluminum Test Lead Wire to Aluminum Pipes

4.5.4.1 Aluminum test lead wire, or aluminum tabs attached to aluminum wire, may be welded to aluminum pipe using the tungsten inert-gas shielded arc (TIG) or metal inert-gas shielded arc (MIG) process. Welded attachments should be

made to flanges or at butt weld joints. Attachment at other sites may adversely affect the mechanical properties of the pipe because of the heat of welding.

4.5.4.2 Test lead wire may be attached to aluminum pipe by soldering. If low-melting-point soft solders are used, a flux is required. Flux residues may cause corrosion unless removed.

NOTE: The use of copper test lead wire may cause preferential galvanic attack on the aluminum pipe. When copper wire or flux is used, care must be taken to seal the attachment areas against moisture. In the presence of moisture, the connection may disbond and be damaged by corrosion.

4.5.4.3 Aluminum tabs to which test lead wires have been TIG welded can be attached by an explosive bonding technique called high-energy joining.

4.5.4.4 Mechanical connections that remain secure and electrically conductive may be used.

#### 4.5.5 Attachment of Copper Test Lead Wire to Copper Pipe

4.5.5.1 Copper test lead wire, or copper tabs attached to copper wire, may be attached to copper pipe by one of the following methods. The relative thickness of the wire and the pipe wall dictates, in part, which of the methods can be used.

4.5.5.1.1 Arc welding (TIG, MIG, or shielded metal);

4.5.5.1.2 Electrical resistance (spot) welding;

4.5.5.1.3 Brazing;

4.5.5.1.4 Soldering; or

4.5.5.1.5 Mechanical connection.

4.5.5.2 Attention should be given to proper joining procedures to avoid possible embrittlement or loss of mechanical properties of the metals from the heat of welding or brazing.

4.5.5.3 A flux may be required, or self-produced, when brazing with some filler metals or soldering with some low-melting-point soft solders. Because flux residues may cause corrosion, they should be removed.

## Section 5: External Coatings

### 5.1 Introduction

5.1.1 This section recommends practices for selecting, testing and evaluating, handling, storing, inspecting, and installing external coating systems for external corrosion control on piping systems.

The function of external coatings is to control corrosion by isolating the external surface of the underground or submerged piping from the environment, to reduce cathodic protection current requirements, and to improve current distribution.

5.1.3 External coatings must be properly selected and applied and the coated piping carefully handled and installed to fulfill these functions. Various types of external coatings can accomplish the desired functions.

5.1.2.1 Desirable characteristics of external coatings include the following:

5.1.2.1.1 Effective electrical insulator;

5.1.2.1.2 Effective moisture barrier;

5.1.2.1.3 Application to pipe by a method that does not adversely affect the properties of the pipe;

5.1.2.1.4 Application to pipe with a minimum of defects;

5.1.2.1.5 Good adhesion to pipe surface;

5.1.2.1.6 Ability to resist development of holidays with time;

5.1.2.1.7 Ability to resist damage during handling, storage, and installation;

5.1.2.1.8 Ability to maintain substantially constant electrical resistivity with time;

5.1.2.1.9 Resistance to disbonding;

5.1.2.1.10 Resistance to chemical degradation;

5.1.2.1.11 Ease of repair;

5.1.2.1.12 Retention of physical characteristics;

5.1.2.1.13 Nontoxic to the environment; and

5.1.2.1.14 Resistance to changes and deterioration during aboveground storage and long-distance transportation.

5.1.2.2 Typical factors to consider when selecting an external pipe coating include:

5.1.2.2.1 Type of environment;

5.1.2.2.2 Accessibility of piping system;

5.1.2.2.3 Operating temperature of piping system;

5.1.2.2.4 Ambient temperatures during application, shipping, storage, construction, installation, and pressure testing;

5.1.2.2.5 Geographical and physical location;

5.1.2.2.6 Type of external coating on existing pipe in the system;

5.1.2.2.7 Handling and storage;

5.1.2.2.8 Pipeline installation methods;

5.1.2.2.9 Costs; and

5.1.2.2.10 Pipe surface preparation requirements.

5.1.2.3 Pipeline external coating systems shall be properly selected and applied to ensure that adequate bonding is obtained. Unbonded coatings can create electrical shielding of the pipeline that could jeopardize the effectiveness of the cathodic protection system.

5.1.3 Information in this section is primarily by reference to other documents. It is important that the latest revision of the pertinent reference be used.

5.1.3.1 Table 1 is a listing of types of external coating systems, showing the appropriate references for material specifications and recommended practices for application.

5.1.3.2 Table 2 is a grouping of references for general use during installation and inspection, regardless of coating type.

5.1.3.3 Table 3 is a list of external coating system characteristics related to environmental conditions containing suggested laboratory test references for various properties.

5.1.3.4 Table 4 is a list of external coating system characteristics related to design and construction, with recommended laboratory tests for evaluating these properties.

5.1.3.5 Table 5 lists the references that are useful in field evaluation of external coating systems after the pipeline has been installed.

## 5.2 Storage, Handling, Inspection, and Installation

### 5.2.1 Storage and Handling

5.2.1.1 Coated pipe to be stored should be protected internally and externally from atmospheric corrosion and coating deterioration.

5.2.1.2 Damage to coating can be minimized by careful handling and by using proper pads and slings.

**TABLE 1**  
**Generic External Coating Systems with Material Requirements**  
**and Recommended Practices for Application<sup>(A)</sup>**

| Generic External Coating System | Reference                                                                                                                                                                                                                   |
|---------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Coal Tar                        | ANSI <sup>(B)</sup> /AWWA <sup>(C)</sup> C 203 <sup>10</sup>                                                                                                                                                                |
| Wax                             | NACE Standard RP0375 <sup>11</sup>                                                                                                                                                                                          |
| Prefabricated Films             | NACE Standard MR0274 <sup>12</sup><br>ANSI/AWWA C 214 <sup>13</sup><br>ANSI/AWWA C 209 <sup>14</sup>                                                                                                                        |
| Fusion-Bonded Epoxy Coatings    | <i>Peabody's Control of Pipeline Corrosion</i> <sup>15</sup><br>ANSI/AWWA C 213 <sup>16</sup><br>API <sup>(D)</sup> RP 5L7 <sup>17</sup><br>CSA <sup>(E)</sup> Z245.20M <sup>18</sup><br>NACE Standard RP0190 <sup>19</sup> |
| Polyolefin Coatings             | NACE Standard RP0185 <sup>20</sup><br>DIN <sup>(F)</sup> 30 670 <sup>21</sup><br>ANSI/AWWA C215 <sup>22</sup>                                                                                                               |

<sup>(A)</sup> NOTE: Many other references are available and this table is not comprehensive. Listing does not constitute endorsement of any external coating system in preference to another. Omission of a system may be due to unavailability of reference standards or lack of data.

<sup>(B)</sup> American National Standards Institute (ANSI), 1819 L Street, NW, Washington, DC 20036.

<sup>(C)</sup> American Water Works Association (AWWA), 6666 West Quincy Ave., Denver, CO 80235.

<sup>(D)</sup> American Petroleum Institute (API), 1220 L St. NW, Washington, DC 20005.

<sup>(E)</sup> CSA International, 178 Rexdale Blvd., Toronto, Ontario, Canada M9W 1R3.

<sup>(F)</sup> Deutsches Institut für Normung (DIN), Burggrafenstrasse 6, D-10787 Berlin, Germany.

**TABLE 2**  
**References for General Use in the Installation and Inspection of External Coating Systems**  
**for Underground Piping**

| Subject                                  | Reference                                                                                                                                                                                                                                                            |
|------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Application of Organic Pipeline Coatings | ANSI/AWWA C 203 <sup>10</sup><br>NACE Standard RP0375 <sup>11</sup><br><i>Peabody's Control of Pipeline Corrosion</i> <sup>15</sup><br>ANSI/AWWA C 213 <sup>16</sup><br>API RP 5L7 <sup>17</sup><br>CSA Z245.20M <sup>18</sup><br>NACE Standard RP0190 <sup>19</sup> |
| Film Thickness of Pipeline Coatings      | ASTM <sup>(A)</sup> G 128 <sup>23</sup>                                                                                                                                                                                                                              |
| Inspection of Pipeline Coatings          | NACE Standard RP0274 <sup>24</sup>                                                                                                                                                                                                                                   |

<sup>(A)</sup> ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959.

**TABLE 3**  
**External Coating System Characteristics Relative to Environmental Conditions<sup>(A)</sup>**

| <b>Environmental Factor</b>                                                   | <b>Recommended Test Methods<sup>(B)</sup></b>                                                                                                                                                                                                                                                            |
|-------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| General underground exposure with or without cathodic protection              | <i>Peabody's Control of Pipeline Corrosion</i> <sup>15</sup><br>ANSI/AWWA C 213 <sup>16</sup><br>API RP 5L7 <sup>17</sup><br>CSA Z245.20M <sup>18</sup><br>NACE Standard RP0190 <sup>19</sup><br>ASTM G 8 <sup>25</sup><br>ASTM G 19 <sup>26</sup><br>ASTM G 42 <sup>27</sup><br>ASTM G 95 <sup>28</sup> |
| Resistance to water penetration and its effect on choice of coating thickness | ASTM G 9 <sup>29</sup>                                                                                                                                                                                                                                                                                   |
| Resistance to penetration by stones in backfill                               | ASTM G 17 <sup>30</sup><br>ASTM D 2240 <sup>31</sup><br>ASTM G 13 <sup>32</sup><br>ASTM G 14 <sup>33</sup>                                                                                                                                                                                               |
| Soil stress                                                                   | <i>Underground Corrosion</i> <sup>34</sup><br>ASTM D 427 <sup>35</sup>                                                                                                                                                                                                                                   |
| Resistance to specific liquid not normally encountered in virgin soil         | ASTM D 543 <sup>36</sup><br>Federal Test Standard <sup>(C)</sup> No. 406A, Method 7011 <sup>37</sup><br>ASTM G 20 <sup>38</sup>                                                                                                                                                                          |
| Resistance to thermal effects                                                 | ASTM D 2304 <sup>39</sup><br>ASTM D 2454 <sup>40</sup><br>ASTM D 2485 <sup>41</sup>                                                                                                                                                                                                                      |
| Suitability of supplementary materials for joint coating and field repairs    | ASTM G 8 <sup>25</sup><br>ASTM G 19 <sup>26</sup><br>ASTM G 42 <sup>27</sup><br>ASTM G 95 <sup>28</sup><br>ASTM G 9 <sup>29</sup><br>ASTM G 18 <sup>42</sup><br>ASTM G 55 <sup>43</sup>                                                                                                                  |
| Resistance to microorganisms                                                  | ASTM G 21 <sup>44</sup><br>Federal Test Standard No. 406A, Method 6091 <sup>45</sup>                                                                                                                                                                                                                     |

<sup>(A)</sup> NOTE: Apply only those factors pertinent to the installation.

<sup>(B)</sup> No specific criteria are available. Comparative tests are recommended for use and evaluation as supplementary information only.

<sup>(C)</sup> Available from General Services Administration, Business Service Center, Washington, DC 20025.

**TABLE 4**  
**External Coating System Characteristics Related to Design and Construction**

| <b>Design and Construction Factor</b>                          | <b>Recommended Test Methods<sup>(A)</sup></b>                                                                                                                                                                                                                                                                                                                                                                                                                                  |
|----------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Yard Storage, Weathering                                       | ASTM G 11 <sup>46</sup>                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| Yard Storage, Penetration Under Load                           | ASTM G 17 <sup>30</sup><br>ASTM D 2240 <sup>31</sup>                                                                                                                                                                                                                                                                                                                                                                                                                           |
| Handling Resistance, Abrasion                                  | ASTM G 6 <sup>47</sup>                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
| Handling Resistance, Impact                                    | ASTM G 13 <sup>32</sup><br>ASTM G 14 <sup>33</sup>                                                                                                                                                                                                                                                                                                                                                                                                                             |
| Field Bending Ability                                          | ASTM G 10 <sup>48</sup>                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| Driving Ability (Resistance to Sliding Abrasion)               | ASTM G 6 <sup>47</sup><br>ASTM D 2197 <sup>49</sup>                                                                                                                                                                                                                                                                                                                                                                                                                            |
| Special Requirements for Mill-Applied Coating                  | ANSI/AWWA C 20 <sup>40</sup><br>NACE Standard RP0375 <sup>11</sup><br>NACE Standard MR0274 <sup>12</sup><br>ANSI/AWWA C 214 <sup>13</sup><br>ANSI/AWWA C 209 <sup>14</sup><br><i>Peabody's Control of Pipeline Corrosion</i> <sup>15</sup><br>ANSI/AWWA C 213 <sup>16</sup><br>API RP 5L7 <sup>17</sup><br>CSA Z245.20M <sup>18</sup><br>NACE Standard RP0190 <sup>19</sup><br>NACE Standard RP0185 <sup>20</sup><br>DIN 30 670 <sup>21</sup><br>ANSI/AWWA C 215 <sup>22</sup> |
| Special Requirements for Application of Coating Over the Ditch | ANSI/AWWA C 20 <sup>40</sup><br>NACE Standard RP0375 <sup>11</sup><br>NACE Standard MR0274 <sup>12</sup><br>ANSI/AWWA C 214 <sup>13</sup><br>ANSI/AWWA C 209 <sup>14</sup><br><i>Peabody's Control of Pipeline Corrosion</i> <sup>15</sup><br>ANSI/AWWA C 213 <sup>16</sup><br>API RP 5L7 <sup>17</sup><br>CSA Z245.20M <sup>18</sup><br>NACE Standard RP0190 <sup>19</sup>                                                                                                    |
| Backfill Resistance                                            | ASTM G 13 <sup>32</sup><br>ASTM G 14 <sup>33</sup>                                                                                                                                                                                                                                                                                                                                                                                                                             |
| Resistance to Thermal Effects                                  | ASTM G 8 <sup>25</sup><br>ASTM G 19 <sup>26</sup><br>ASTM G 42 <sup>27</sup><br>ASTM G 95 <sup>28</sup><br>ASTM D 2304 <sup>39</sup><br>ASTM D 2454 <sup>40</sup><br>ASTM D 2485 <sup>41</sup>                                                                                                                                                                                                                                                                                 |

Table 4 Continued

| Design and Construction Factor                  | Recommended Test Methods <sup>(A)</sup>                                                                                                                                                                                                                                                                                                                                                  |
|-------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Suitability of Joint Coatings and Field Repairs | <i>Peabody's Control of Pipeline Corrosion</i> <sup>15</sup><br>ANSI/AWWA C 213 <sup>16</sup><br>API RP 5L7 <sup>17</sup><br>CSA Z245.20M <sup>18</sup><br>NACE Standard RP0190 <sup>19</sup><br>ASTM G 8 <sup>25</sup><br>ASTM G 19 <sup>26</sup><br>ASTM G 42 <sup>27</sup><br>ASTM G 95 <sup>28</sup><br>ASTM G 9 <sup>29</sup><br>ASTM G 18 <sup>42</sup><br>ASTM G 55 <sup>43</sup> |

<sup>(A)</sup> No specific criteria are available. Comparative tests are recommended for use and evaluation as supplementary information only.

**TABLE 5**  
**Methods for Evaluating In-Service Field Performance of External Coatings**

| Title or Subject of Method                                     | Reference                                                                                               | Basis for Rating                                                                                                                     |
|----------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|
| (1) Rate of Change in Current Required for Cathodic Protection | <i>Underground Corrosion</i> <sup>34</sup>                                                              | Comparison of initial current requirement with subsequent periodic determination of current requirement                              |
| (2) Inspection of Pipeline Coating                             | NACE Standard RP0274 <sup>12</sup>                                                                      | (a) With cathodic protection: no active corrosion found<br>(b) Without cathodic protection: no new holidays showing active corrosion |
| (3) Cathodic Disbondment                                       | ASTM G 8 <sup>25</sup><br>ASTM G 19 <sup>26</sup><br>ASTM G 42 <sup>27</sup><br>ASTM G 95 <sup>28</sup> | Purpose is to obtain data relative to specific conditions for comparison with laboratory data                                        |

## 5.2.2 Inspection

5.2.2.1 Qualified personnel should keep every phase of the coating operation and piping installation under surveillance.

5.2.2.2 Surface preparation, primer application, coating thickness, temperature, bonding, and other specific requirements should be checked periodically, using suitable test procedures, for conformance to specifications.

5.2.2.3 The use of holiday detectors is recommended to detect coating flaws that would not be observed visually. The holiday detector should be operated in accordance with the manufacturer's instructions and at a voltage level appropriate to the electrical characteristics of the coating system.

## 5.2.3 Installation

5.2.3.1 Joints, fittings, and tie-ins must be coated with a material compatible with the existing coating.

5.2.3.2 Coating defects should be repaired.

5.2.3.3 Materials used to repair coatings must be compatible with the existing pipe coating.

5.2.3.4 The ditch bottom should be graded and free of rock or other foreign matter that could damage the external coating or cause electrical shielding. Under difficult conditions, consideration should be given to padding the pipe or the ditch bottom.

5.2.3.5 Pipe should be lowered carefully into the ditch to avoid external coating damage.

5.2.3.6 Care should be taken during backfilling so that rocks and debris do not strike and damage the pipe coating.

5.2.3.7 Care shall be exercised when using materials such as loose wrappers, nonconducting urethane foam, and rock shield around pipelines as protection against physical damage or for other purposes, because these materials may create an electrical shielding effect that would be detrimental to the effectiveness of cathodic protection.

5.2.3.8 When a pipeline comes above ground, it must be cleaned and externally coated, or jacketed with a suitable material, for the prevention of atmospheric corrosion.

### 5.3 Methods for Evaluating External Coating Systems

#### 5.3.1 Established Systems Proven by Successful Use

5.3.1.1 Visual and electrical inspection of in-service pipeline coatings should be used to evaluate the performance of an external coating system. These inspections can be conducted wherever the pipeline is excavated or at bell holes made for inspection purposes.

#### 5.3.2 Established or Modified Systems for New Environments

5.3.2.1 This method is intended for use when external coating systems will continue to be used and are qualified under Paragraph 5.3.1, but when application will be extended to new environments or when it is desired to revise a system to make use of new developments.

5.3.2.1.1 The use of applicable material requirements, material specifications, standards, and recommended practices for application, as given in Table 1, is recommended.

5.3.2.1.2 The use of applicable references in Table 2 is recommended unless previously covered in applicable references in Table 1.

#### 5.3.3 New External Coating System Qualification

5.3.3.1 The purpose of this method is to qualify a new external coating material by subjecting it to laboratory tests appropriate for the intended service. After laboratory tests have been conducted and indicate that the external coating system appears to be suitable, application and installation are conducted in accordance with recommended practices. In-service field performance tests are made to confirm the success of the previous steps. The steps of the method are (1) laboratory tests, (2) application under recommended practices, (3) installation under recommended practices, and (4) in-service field performance tests. If good results are obtained after five years, only Steps 2 and 3 are required thereafter.

5.3.3.1.1 Applicable sections of Tables 3 and 4 are recommended for the initial laboratory test methods.

5.3.3.1.2 Applicable sections of Tables 1 and 2 are recommended for conditional use during Steps 2 and 3.

5.3.3.1.3 During a period of five years or more, the use of the evaluation methods given in Table 5, Item 1 or 2 are recommended. The test method in Item 3 may be used as a supplementary means for obtaining data for correlation with laboratory tests.

#### 5.3.4 Method for Evaluating an External Coating System by In-Service Field Performance Only

5.3.4.1 The purpose of this method is to qualify an external coating system when none of the first three methods given in Paragraph 5.3 has been or will be used. It is intended that this method should be limited to minor pilot installations.

5.3.4.1.1 The use of at least one of the first two methods given in Table 5 is recommended on the basis of at least one investigation per year for five consecutive years.

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## Section 6: Criteria and Other Considerations for Cathodic Protection

### 6.1 Introduction

6.1.1 This section lists criteria and other considerations for cathodic protection that indicate, when used either separately or in combination, whether adequate cathodic protection of a metallic piping system has been achieved (see also Section 1, Paragraphs 1.2 and 1.4).

6.1.2 The effectiveness of cathodic protection or other external corrosion control measures can be confirmed by visual observation, by measurements of pipe wall thickness, or by use of internal inspection devices. Because such methods sometimes are not practical, meeting any criterion or combination of criteria in this section is evidence that adequate cathodic protection has been achieved. When excavations are made for



any purpose, the pipe should be inspected for evidence of corrosion and/or coating condition.

6.1.3 The criteria in this section have been developed through laboratory experiments and/or verified by evaluating data obtained from successfully operated cathodic protection systems. Situations in which a single criterion for evaluating the effectiveness of cathodic protection may not be satisfactory for all conditions may exist. Often a combination of criteria is needed for a single structure.

6.1.4 Sound engineering practices shall be used to determine the methods and frequency of testing required to satisfy these criteria.

6.1.5 Corrosion leak history is valuable in assessing the effectiveness of cathodic protection. Corrosion leak history by itself, however, shall not be used to determine whether adequate levels of cathodic protection have been achieved unless it is impractical to make electrical surveys.

## 6.2 Criteria

6.2.1 It is not intended that persons responsible for external corrosion control be limited to the criteria listed below. Criteria that have been successfully applied on existing piping systems can continue to be used on those piping systems. Any other criteria used must achieve corrosion control comparable to that attained with the criteria herein.

### 6.2.2 Steel and Cast Iron Piping

6.2.2.1 External corrosion control can be achieved at various levels of cathodic polarization depending on the environmental conditions. However, in the absence of specific data that demonstrate that adequate cathodic protection has been achieved, one or more of the following shall apply:

6.2.2.1.1 A negative (cathodic) potential of at least 850 mV with the cathodic protection applied. This potential is measured with respect to a saturated copper/copper sulfate reference electrode contacting the electrolyte. Voltage drops other than those across the structure-to-electrolyte boundary must be considered for valid interpretation of this voltage measurement.

NOTE: Consideration is understood to mean the application of sound engineering practice in determining the significance of voltage drops by methods such as:

6.2.2.1.1.1 Measuring or calculating the voltage drop(s);

6.2.2.1.1.2 Reviewing the historical performance of the cathodic protection system;

6.2.2.1.1.3 Evaluating the physical and electrical characteristics of the pipe and its environment; and

6.2.2.1.1.4 Determining whether or not there is physical evidence of corrosion.

6.2.2.1.2 A negative polarized potential (see definition in Section 2) of at least 850 mV relative to a saturated copper/copper sulfate reference electrode.

6.2.2.1.3 A minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte. The formation or decay of polarization can be measured to satisfy this criterion.

### 6.2.2.2 Special Conditions

6.2.2.2.1 On bare or ineffectively coated pipelines when long-line corrosion activity is of primary concern, the measurement of a net protective current at predetermined current discharge points from the electrolyte to the pipe surface, as measured by an earth current technique, may be sufficient.

6.2.2.2.2 In some situations, such as the presence of sulfides, bacteria, elevated temperatures, acid environments, and dissimilar metals, the criteria in Paragraph 6.2.2.1 may not be sufficient.

6.2.2.2.3 When a pipeline is encased in concrete or buried in dry or aerated high-resistivity soil, values less negative than the criteria listed in Paragraph 6.2.2.1 may be sufficient.

### 6.2.2.3 PRECAUTIONARY NOTES

6.2.2.3.1 The earth current technique is often meaningless in multiple pipe rights-of-way, in high-resistivity surface soil, for deeply buried pipe, in stray-current areas, or where local corrosion cell action predominates.

6.2.2.3.2 Caution is advised against using polarized potentials less negative than -850 mV for cathodic protection of pipelines when operating pressures and conditions are conducive to stress corrosion cracking (see references on stress corrosion cracking at the end of this section).

6.2.2.3.3 The use of excessive polarized potentials on externally coated pipelines should be avoided to minimize cathodic disbondment of the coating.

6.2.2.3.4 Polarized potentials that result in excessive generation of hydrogen should be avoided on all metals, particularly higher-strength steel, certain grades of stainless steel, titanium, aluminum alloys, and prestressed concrete pipe.

### 6.2.3 Aluminum Piping

6.2.3.1 The following criterion shall apply: a minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte. The formation or decay of this polarization can be used in this criterion.

#### 6.2.3.2 PRECAUTIONARY NOTES

6.2.3.2.1 Excessive Voltages: Notwithstanding the minimum criterion in Paragraph 6.2.3.1, if aluminum is cathodically protected at voltages more negative than -1,200 mV measured between the pipe surface and a saturated copper/copper sulfate reference electrode contacting the electrolyte and compensation is made for the voltage drops other than those across the pipe-electrolyte boundary, it may suffer corrosion as the result of the buildup of alkali on the metal surface. A polarized potential more negative than -1,200 mV should not be used unless previous test results indicate that no appreciable corrosion will occur in the particular environment.

6.2.3.2.2 Alkaline Conditions: Aluminum may suffer from corrosion under high-pH conditions and application of cathodic protection tends to increase the pH at the metal surface. Therefore, careful investigation or testing should be done before applying cathodic protection to stop pitting attack on aluminum in environments with a natural pH in excess of 8.0.

### 6.2.4 Copper Piping

6.2.4.1 The following criterion shall apply: a minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte. The formation or decay of this polarization can be used in this criterion.

### 6.2.5 Dissimilar Metal Piping

6.2.5.1 A negative voltage between all pipe surfaces and a stable reference electrode contacting the electrolyte equal to that required for the protection of the most anodic metal should be maintained.

#### 6.2.5.2 PRECAUTIONARY NOTE

6.2.5.2.1 Amphoteric materials that could be damaged by high alkalinity created by cathodic protection should be electrically isolated and separately protected.

## 6.3 Other Considerations

6.3.1 Methods for determining voltage drop(s) shall be selected and applied using sound engineering practices. Once determined, the voltage drop(s) may be used for correcting future measurements at the same location, providing conditions such as pipe and cathodic protection system operating conditions, soil characteristics, and external coating quality remain similar. (Note: Placing the reference electrode next to the pipe surface may not be at the pipe-electrolyte interface. A reference electrode placed at an externally coated pipe surface may not significantly reduce soil voltage drop in the measurement if the nearest coating holiday is remote from the reference electrode location.)

6.3.2 When it is impractical or considered unnecessary to disconnect all current sources to correct for voltage drop(s) in the structure-to-electrolyte potential measurements, sound engineering practices should be used to ensure that adequate cathodic protection has been achieved.

6.3.3 When feasible and practicable, in-line inspection of pipelines may be helpful in determining the presence or absence of pitting corrosion damage. Absence of external corrosion damage or the halting of its growth may indicate adequate external corrosion control. The in-line inspection technique, however, may not be capable of detecting all types of external corrosion damage, has limitations in its accuracy, and may report as anomalies items that are not external corrosion. For example, longitudinal seam corrosion and general corrosion may not be readily detected by in-line inspection. Also, possible thickness variations, dents, gouges, and external ferrous objects may be detected as corrosion. The appropriate use of in-line inspection must be carefully considered.

6.3.4 Situations involving stray currents and stray electrical gradients that require special analysis may exist. For additional information, see Section 9, "Control of Interference Currents."

## 6.4 Alternative Reference Electrodes

6.4.1 Other standard reference electrodes may be substituted for the saturated copper/copper sulfate

reference electrode. Two commonly used reference electrodes are listed below along with their voltage equivalent (at 25°C [77°F]) to -850 mV referred to a saturated copper/copper sulfate reference electrode:

6.4.1.1 Saturated KCl calomel reference electrode: -780 mV; and

6.4.1.2 Saturated silver/silver chloride reference electrode used in 25 ohm-cm seawater: -800 mV.

6.4.2 In addition to these standard reference electrodes, an alternative metallic material or structure may be used in place of the saturated copper/copper sulfate reference electrode if the stability of its electrode potential is ensured and if its voltage equivalent referred to a saturated copper/copper sulfate reference electrode is established.

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## Section 7: Design of Cathodic Protection Systems

### 7.1 Introduction

7.1.1 This section recommends procedures for designing cathodic protection systems that will provide effective external corrosion control by satisfying one or more of the criteria listed in Section 6 and exhibiting maximum reliability over the intended operating life of the systems.

7.1.2 In the design of a cathodic protection system, the following should be considered:

7.1.2.1 Recognition of hazardous conditions prevailing at the proposed installation site(s) and the selection and specification of materials and installation practices that ensure safe installation and operation.

7.1.2.2 Specification of materials and installation practices to conform to the latest editions of applicable codes, National Electrical Manufacturers Association (NEMA)<sup>(7)</sup> standards, National

<sup>(7)</sup> National Electrical Manufacturers Association (NEMA), 2101 L St., NW, Washington, DC 20037.

Electrical Code (NEC),<sup>(8)</sup> appropriate international standards, and NACE standards.

7.1.2.3 Selection and specification of materials and installation practices that ensure dependable and economical operation throughout the intended operating life.

7.1.2.4 Selection of locations for proposed installations to minimize currents or earth potential gradients, which can cause detrimental effects on foreign buried or submerged metallic structures.

7.1.2.5 Cooperative investigations to determine mutually satisfactory solution(s) of interference problems (see Section 9).

7.1.2.6 Special consideration should be given to the presence of sulfides, bacteria, disbonded coatings, thermal insulating coatings, elevated temperatures, shielding, acid environments, and dissimilar metals.

7.1.2.7 Excessive levels of cathodic protection that can cause external coating disbondment and possible damage to high-strength steels as a result of hydrogen evolution should be avoided.

7.1.2.8 When amphoteric metals are involved, care should be taken so that high-pH conditions that could cause cathodic corrosion of the metal are not established.

7.2 Major objectives of cathodic protection system design include the following:

7.2.1 To provide sufficient current to the structure to be protected and distribute this current so that the selected criteria for cathodic protection are effectively attained;

7.2.2 To minimize the interference currents on neighboring underground structures (see Section 9);

7.2.3 To provide a design life of the anode system commensurate with the required life of the protected structure, or to provide for periodic rehabilitation of the anode system;

7.2.4 To provide adequate allowance for anticipated changes in current requirements with time;

7.2.5 To install anodes where the possibility of disturbance or damage is minimal; and

7.2.6 To provide adequate monitoring facilities to test and evaluate the system performance.

### 7.3 Information Useful for Design

7.3.1 Useful piping system specifications and information include the following:

7.3.1.1 Route maps and atlas sheets;

7.3.1.2 Construction dates;

7.3.1.3 Pipe, fittings, and other appurtenances;

7.3.1.4 External coatings;

7.3.1.5 Casings;

7.3.1.6 Corrosion control test stations;

7.3.1.7 Electrically isolating devices;

7.3.1.8 Electrical bonds; and

7.3.1.9 Aerial, bridge, and underwater crossings.

7.3.2 Useful information on piping system site conditions includes the following:

7.3.2.1 Existing and proposed cathodic protection systems;

7.3.2.2 Possible interference sources (see Section 9);

7.3.2.3 Special environmental conditions;

7.3.2.4 Neighboring buried metallic structures (including location, ownership, and corrosion control practices);

7.3.2.5 Structure accessibility;

7.3.2.6 Power availability; and

7.3.2.7 Feasibility of electrical isolation from foreign structures.

7.3.3 Useful information from field surveys, corrosion test data, and operating experience includes the following:

7.3.3.1 Protective current requirements to meet applicable criteria;

7.3.3.2 Electrical resistivity of the electrolyte;

7.3.3.3 Electrical continuity;

7.3.3.4 Electrical isolation;

7.3.3.5 External coating integrity;

7.3.3.6 Cumulative leak history;

<sup>(8)</sup> National Fire Protection Association, Batterymarch Park, Quincy, MA 02269.

7.3.3.7 Interference currents;

7.3.3.8 Deviation from construction specifications; and

7.3.3.9 Other maintenance and operating data.

7.3.4 Field survey work prior to actual application of cathodic protection is not always required if prior experience or test data are available to estimate current requirements, electrical resistivities of the electrolyte, and other design factors.

## 7.4 Types of Cathodic Protection Systems

### 7.4.1 Galvanic Anode Systems

7.4.1.1 Galvanic anodes can be made of materials such as alloys of magnesium, zinc, or aluminum. The anodes are connected to the pipe, either individually or in groups. Galvanic anodes are limited in current output by the anode-to-pipe driving voltage and the electrolyte resistivity.

### 7.4.2 Impressed Current Anode Systems

7.4.2.1 Impressed current anodes can be of materials such as graphite, high-silicon cast iron, lead-silver alloy, precious metals, or steel. They are connected with an insulated cable, either individually or in groups, to the positive terminal of a direct-current (DC) source, such as a rectifier or generator. The pipeline is connected to the negative terminal of the DC source.

7.5 Considerations influencing selection of the type of cathodic protection system include the following:

7.5.1 Magnitude of protective current required;

7.5.2 Stray currents causing significant potential fluctuations between the pipeline and earth that may preclude the use of galvanic anodes;

7.5.3 Effects of cathodic protection interference currents on adjacent structures that may limit the use of impressed current cathodic protection systems;

7.5.4 Availability of electrical power;

7.5.5 Physical space available, proximity of foreign structures, easement procurement, surface conditions, presence of streets and buildings, river crossings, and other construction and maintenance concerns.

7.5.6 Future development of the right-of-way area and future extensions to the pipeline system;

7.5.7 Costs of installation, operation, and maintenance; and

7.5.8 Electrical resistivity of the environment.

## 7.6 Factors Influencing Design of Cathodic Protection Systems

7.6.1 Various anode materials have different rates of deterioration when discharging a given current density from the anode surface in a specific environment. Therefore, for a given current output, the anode life depends on the environment and anode material, as well as the anode weight and the number of anodes in the cathodic protection system. Established anode performance data may be used to calculate the probable deterioration rate.

7.6.2 Data on the dimensions, depth, and configuration of the anodes and the electrolyte resistivity may be used to calculate the resultant resistance to electrolyte of the anode system. Formulas and graphs relating to these factors are available in the literature and from manufacturers.

7.6.3 Design of galvanic anode systems should consider anode-to-pipe potential, electrolyte resistivity, current output, and in special cases, anode lead-wire resistance. A separate design for each anode or anode system may not be necessary.

7.6.4 Galvanic anode performance in most soils can be improved by using special backfill material. Mixtures of gypsum, bentonite, and anhydrous sodium sulfate are most commonly used.

7.6.5 The number of impressed current anodes required can be reduced and their useful life lengthened by the use of special backfill around the anodes. The most common materials are coal coke, calcined petroleum coke, and natural or manufactured graphite.

7.6.6 In the design of an extensive distributed-anode impressed current system, the voltage and current attenuation along the anode-connecting (header) cable should be considered. In such cases, the design objective is to optimize anode system length, anode spacing and size, and cable size in order to achieve efficient external corrosion control at the extremities of the protected structure.

7.6.7 When it is anticipated that entrapment of gas generated by anodic reactions could impair the ability of the impressed current groundbed to deliver the required current, suitable provisions should be made for venting the anodes. For the same current output of the system, an increase in the surface area of the special backfill material or an increase in the number of anodes may reduce gas blockage.

7.6.8 When it is anticipated that electroosmotic effects could impair the ability of the impressed current groundbed to deliver the required current output, suitable provisions should be made to ensure adequate soil moisture around the anodes. Increasing the number of impressed current anodes or increasing the

surface area of the special backfill materials may further reduce the electroosmotic effect.

## 7.7 Design Drawings and Specifications

7.7.1 Suitable drawings should be prepared to designate the overall layout of the piping to be protected and the location of significant items of structure hardware, corrosion control test stations, electrical bonds, electrical isolation devices, and neighboring buried or submerged metallic structures.

7.7.2 Layout drawings should be prepared for each impressed current cathodic protection installation, showing the details and location of the components of

the cathodic protection system with respect to the protected structure(s) and to major physical landmarks. These drawings should include right-of-way information.

7.7.3 The locations of galvanic anode installations should be recorded on drawings or in tabular form, with appropriate notes on anode type, weight, spacing, depth, and backfill.

7.7.4 Specifications should be prepared for all materials and installation practices that are to be incorporated in construction of the cathodic protection system.

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## Section 8: Installation of Cathodic Protection Systems

### 8.1 Introduction

8.1.1 This section recommends procedures that will result in the installation of cathodic protection systems that achieve protection of the structure. The design considerations recommended in Sections 4 and 7 should be followed.

### 8.2 Construction Specifications

8.2.1 All construction work on cathodic protection systems should be performed in accordance with construction drawings and specifications. The construction specifications should be in accordance with recommended practices in Sections 4 and 7.

### 8.3 Construction Supervision

8.3.1 All construction work on cathodic protection systems should be performed under the surveillance of trained and qualified personnel to verify that the installation is in strict accordance with the drawings and specifications. Exceptions may be made only with the approval of qualified personnel responsible for external corrosion control.

8.3.2 All deviations from construction specifications should be noted on as-built drawings.

### 8.4 Galvanic Anodes

#### 8.4.1 Inspection, Handling, and Storage

8.4.1.1 Packaged anodes should be inspected and steps taken to ensure that backfill material completely surrounds the anode. The individual container for the backfill material and anode should be intact. If individually packaged anodes are supplied in waterproof containers, the containers must be removed before installation. Packaged anodes should be kept dry during storage.

8.4.1.2 Lead wire must be securely connected to the anode. Lead wire should be inspected for assurance that it is not damaged.

8.4.1.3 Other galvanic anodes, such as the unpackaged "bracelet" or ribbon type, should be inspected to ensure that dimensions conform to design specifications and that any damage during handling does not affect application. If a coating is used on bands and the inner side of bracelet anode segments, it should be inspected and, if damaged, repaired before the anodes are installed.

### 8.4.2 Installing Anodes

8.4.2.1 Anodes should be installed according to construction specifications.

8.4.2.2 Packaged galvanic anodes should be backfilled with appropriately compacted material. When anodes and special chemical backfill are provided separately, anodes should be centered in special backfill, which should be compacted prior to backfilling. Care should be exercised during all operations so that lead wires and connections are not damaged. Sufficient slack should exist in lead wires to avoid strain.

8.4.2.3 When anodes in bracelet form are used, external pipe coating beneath the anode should be free of holidays. Care should be taken to prevent damage to the external coating when bracelet anodes are installed. After application of concrete (if used) to pipe, all coating and concrete should be removed from the anode surface. If reinforced concrete is used, there must be no metallic contact between the anode and the reinforcing mesh or between the reinforcing mesh and the pipe.

8.4.2.4 When a ribbon-type anode is used, it can be trenched or plowed in, with or without special chemical backfill as required, generally parallel to the section of pipeline to be protected.

### 8.5 Impressed Current Systems

#### 8.5.1 Inspection and Handling

8.5.1.1 The rectifier or other power source should be inspected to ensure that internal connections are mechanically secure and that the unit is free of damage. Rating of the DC power source should comply with the construction specification. Care should be exercised in handling and installing the power source.

8.5.1.2 Impressed current anodes should be inspected for conformance to specifications concerning anode material, size, length of lead cable, anode lead connection, and integrity of seal. Care should be exercised to avoid cracking or damaging anodes during handling and installation.

8.5.1.3 All cables should be carefully inspected to detect defects in insulation. Care should be taken to avoid damage to cable insulation. Defects in the cable insulation must be repaired.

8.5.1.4 Anode backfill material should conform to specifications.

#### **8.5.2 Installation Provisions**

8.5.2.1 A rectifier or other power source should be installed so that the possibility of damage or vandalism is minimized.

8.5.2.2 Wiring to rectifiers shall comply with local and national electrical codes and requirements of the utility supplying power. An external disconnect switch should be provided in the AC circuit. A rectifier case shall be properly grounded.

8.5.2.3 On thermoelectric generators, a reverse-current device should be installed to prevent galvanic action between the anode bed and the pipe if the flame is extinguished.

8.5.2.4 Impressed current anodes can be buried vertically, horizontally, or in deep holes (see NACE Standard RP0572<sup>1</sup>) as indicated in construction specifications. Backfill material should be installed to ensure that there are no voids around anodes. Care should be exercised during backfilling to avoid damage to the anode and cable.

8.5.2.5 The cable from the rectifier negative terminal to the pipe should be connected to the pipe as described in Paragraph 8.6. Cable connections to the rectifier must be mechanically secure and electrically conductive. Before the power source is energized, it must be verified that the negative cable is connected to the structure to be protected and that the positive cable is connected to the anodes. After the DC power source has been energized, suitable measurements should be made to verify that these connections are correct.

8.5.2.6 Underground splices on the header (positive) cable to the groundbed should be kept to a minimum. Connections between the header and anode cables should be mechanically secure and electrically conductive. If buried or submerged, these connections must be sealed to prevent moisture penetration so that electrical isolation from the environment is ensured.

8.5.2.7 Care must be taken during installation of direct-burial cable to the anodes (positive cable) to avoid damage to insulation. Sufficient slack should be left to avoid strain on all cables. Backfill material around the cable should be free of rocks and foreign matter that might cause damage to the insulation when the cable is installed in a trench. Cable can be installed by plowing if proper precautions are taken.

8.5.2.8 If insulation integrity on the buried or submerged header cable, including splices, is not maintained, this cable may fail because of corrosion.

#### **8.6 Corrosion Control Test Stations, Connections, and Bonds (see Paragraph 4.5)**

8.6.1 Pipe and test lead wires should be clean, dry, and free of foreign materials at points of connection when the connections are made. Connections of test lead wires to the pipe must be installed so they will remain mechanically secure and electrically conductive.

8.6.2 All buried or submerged lead-wire attachments should be coated with an electrically insulating material, compatible with the external pipe coating and wire insulation.

8.6.3 Test lead wires should be color coded or otherwise permanently identified. Wires should be installed with slack. Damage to insulation should be avoided and repairs made if damage occurs. Test leads should not be exposed to excessive heat and sunlight. Aboveground test stations are preferred. If test stations are flush with the ground, adequate slack should be provided within the test station to facilitate test connections.

8.6.4 Cable connections at bonds to other structures or across isolating joints should be mechanically secure, electrically conductive, and suitably coated. Bond connections should be accessible for testing.

#### **8.7 Electrical Isolation**

8.7.1 Inspection and electrical measurements should ensure that electrical isolation is adequate (see NACE Standard RP0286<sup>5</sup>).

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### **Section 9: Control of Interference Currents**

#### **9.1 Introduction**

9.1.1 This section recommends practices for the detection and control of interference currents. The mechanism and its detrimental effects are described.

#### **9.2 Mechanism of Interference-Current Corrosion (Stray-Current Corrosion)**

9.2.1 Interference-current corrosion on buried or submerged metallic structures differs from other causes of corrosion damage in that the direct current,

which causes the corrosion, has a source foreign to the affected structure. Usually the interfering current is collected from the electrolyte by the affected structure from a DC source not metallically bonded to the affected structure.

9.2.1.1 Detrimental effects of interference currents usually occur at locations where the currents transfer between the affected structures and the electrolyte.

9.2.1.2 Structures made of amphoteric metals such as aluminum and lead may be subject to corrosion damage from a buildup of alkalinity at or near the metal surface collecting interference currents.

9.2.1.3 Coatings may become disbonded at areas where voltage gradients in the electrolyte force current onto the affected structure. However, as the external coating becomes disbonded, a larger area of metal may be exposed, which would increase the demand for a cathodic protection current. This disbondment may create shielding problems.

9.2.2 The severity of external corrosion resulting from interference currents depends on several factors:

9.2.2.1 Separation and routing of the interfering and affected structures and location of the interfering current source;

9.2.2.2 Magnitude and density of the current;

9.2.2.3 Quality of the external coating or absence of an external coating on the structures involved; and

9.2.2.4 Presence and location of mechanical joints having high electrical resistance.

9.2.3 Typical sources of interference currents include the following:

9.2.3.1 Direct current: cathodic protection rectifiers, thermoelectric generators, DC electrified railway and transit systems, coal mine haulage systems and pumps, welding machines, and other direct current power systems;

9.2.3.2 Alternating current: AC power systems and AC electrified railway systems; and

9.2.3.3 Telluric current.

### 9.3 Detection of Interference Currents

9.3.1 During external corrosion control surveys, personnel should be alert for electrical or physical observations that could indicate interference from a foreign source such as the following:

9.3.1.1 Pipe-electrolyte potential changes on the affected structure caused by the foreign DC source;

9.3.1.2 Changes in the line current magnitude or direction caused by the foreign DC source;

9.3.1.3 Localized pitting in areas near or immediately adjacent to a foreign structure; and

9.3.1.4 Damage to external coatings in a localized area near an anode bed or near any other source of stray direct current.

9.3.2 In areas in which interference currents are suspected, appropriate tests should be conducted. All affected parties shall be notified before tests are conducted. Notification should be channeled through corrosion control coordinating committees, when they exist (see NACE Publication TPC 11<sup>8</sup>). Any one or a combination of the following test methods can be used.

9.3.2.1 Measurement of structure-electrolyte potentials with recording or indicating instruments;

9.3.2.2 Measurement of current flowing on the structure with recording or indicating instruments;

9.3.2.3 Development of beta curves to locate the area of maximum current discharge from the affected structure (see Appendix A); and

9.3.2.4 Measurement of the variations in current output of the suspected source of interference current and correlations with measurements obtained in Paragraphs 9.3.2.1 and 9.3.2.2.

### 9.4 Methods for Mitigating Interference Corrosion Problems

9.4.1 Interference problems are individual in nature and the solution should be mutually satisfactory to the parties involved. These methods may be used individually or in combination.

9.4.2 Design and installation of electrical bonds of proper resistance between the affected structures is a technique for interference control. The bond electrically conducts interference current from an affected structure to the interfering structure and/or current source.

9.4.2.1 Unidirectional control devices, such as diodes or reverse-current switches, may be required in conjunction with electrical bonds if fluctuating currents are present. These devices prevent reversal of current flow.

9.4.2.2 A resistor may be necessary in the bond circuit to control the flow of electrical current from the affected structure to the interfering structure.

9.4.2.3 The attachment of electrical bonds can reduce the level of cathodic protection on the interfering structure. Supplementary cathodic protection may then be required on the interfering structure to compensate for this effect.

9.4.2.4 A bond may not effectively mitigate the interference problem in the case of a cathodically protected bare or poorly externally coated pipeline that is causing interference on an externally coated pipeline.

9.4.3 Cathodic protection current can be applied to the affected structure at those locations at which the interfering current is being discharged. The source of cathodic protection current may be galvanic or impressed current anodes.

9.4.4 Adjustment of the current output from interfering cathodic protection rectifiers may resolve interference problems.

9.4.5 Relocation of the groundbeds of cathodic protection rectifiers can reduce or eliminate the pickup of interference currents on nearby structures.

9.4.6 Rerouting of proposed pipelines may avoid sources of interference current.

9.4.7 Properly located isolating fittings in the affected structure may reduce or resolve interference problems.

9.4.8 Application of external coating to current pick-up area(s) may reduce or resolve interference problems.

## 9.5 Indications of Resolved Interference Problems

9.5.1 Restoration of the structure-electrolyte potentials on the affected structure to those values that existed prior to the interference.

9.5.2 Measured line currents on the affected structure that show that the interference current is not being discharged to the electrolyte.

9.5.3 Adjustment of the slope of the beta curve to show that current discharge has been eliminated at the location of maximum exposure (see Appendix A).

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## Section 10: Operation and Maintenance of Cathodic Protection Systems

### 10.1 Introduction

10.1.1 This section recommends procedures and practices for energizing and maintaining continuous, effective, and efficient operation of cathodic protection systems.

10.1.1.1 Electrical measurements and inspection are necessary to determine that protection has been established according to applicable criteria and that each part of the cathodic protection system is operating properly. Conditions that affect protection are subject to change. Correspondingly, changes may be required in the cathodic protection system to maintain protection. Periodic measurements and inspections are necessary to detect changes in the cathodic protection system. Conditions in which operating experience indicates that testing and inspections need to be made more frequently than recommended herein may exist.

10.1.1.2 Care should be exercised in selecting the location, number, and type of electrical measurements used to determine the adequacy of cathodic protection.

10.1.1.3 When practicable and determined necessary by sound engineering practice, a detailed (close-interval) potential survey should be conducted to (a) assess the effectiveness of the

cathodic protection system; (b) provide base line operating data; (c) locate areas of inadequate protection levels; (d) identify locations likely to be adversely affected by construction, stray currents, or other unusual environmental conditions; or (e) select areas to be monitored periodically.

10.1.1.4 Adjustments to a cathodic protection system should be accompanied by sufficient testing to assure the criteria remain satisfied and to reassess interference to other structures or isolation points.

10.2 A survey should be conducted after each cathodic protection system is energized and/or adjusted to determine whether the applicable criterion or criteria from Section 6 have been satisfied.

10.3 The effectiveness of the cathodic protection system should be monitored annually. Longer or shorter intervals for monitoring may be appropriate, depending on the variability of cathodic protection factors, safety considerations, and economics of monitoring.

10.4 Inspection and tests of cathodic protection facilities should be made to ensure their proper operation and maintenance as follows:

10.4.1 All sources of impressed current should be checked at intervals of two months. Longer or shorter intervals for monitoring may be appropriate. Evidence

of proper functioning may be current output, normal power consumption, a signal indicating normal operation, or satisfactory cathodic protection levels on the pipe.

10.4.2 All impressed current protective facilities should be inspected annually as part of a preventive maintenance program to minimize in-service failure. Longer or shorter intervals for monitoring may be appropriate. Inspections may include a check for electrical malfunctions, safety ground connections, meter accuracy, efficiency, and circuit resistance.

10.4.3 Reverse-current switches, diodes, interference bonds, and other protective devices, whose failures would jeopardize structure protection, should be inspected for proper functioning at intervals of two months. Longer or shorter intervals for monitoring may be appropriate.

10.4.4 The effectiveness of isolating fittings, continuity bonds, and casing isolation should be evaluated during the periodic surveys. This may be accomplished by electrical measurements.

10.5 When pipe has been uncovered, it should be examined for evidence of external corrosion and, if externally coated, for condition of the external coating.

10.6 The test equipment used for obtaining each electrical value should be of an appropriate type. Instruments and related equipment should be maintained in good operating condition and checked for accuracy.

10.7 Remedial measures should be taken when periodic tests and inspections indicate that cathodic protection is no longer adequate. These measures may include the following:

10.7.1 Repair, replace, or adjust components of cathodic protection systems;

10.7.2 Provide supplementary facilities where additional cathodic protection is necessary;

10.7.3 Thoroughly clean and properly coat bare structures if required to attain cathodic protection;

10.7.4 Repair, replace, or adjust continuity and interference bonds;

10.7.5 Remove accidental metallic contacts; and

10.7.6 Repair defective isolating devices.

10.8 An electrical short circuit between a casing and carrier pipe can result in inadequate cathodic protection of the pipeline outside the casing due to reduction of protective current to the pipeline.

10.8.1 When a short results in inadequate cathodic protection of the pipeline outside the casing, steps must be taken to restore cathodic protection to a level required to meet the cathodic protection criterion. These steps may include eliminating the short between the casing and carrier pipe, supplementing cathodic protection, or improving the quality of the external coating on the pipeline outside the casing. None of these steps will ensure that external corrosion will not occur on the carrier pipe inside the casing; however, a shorted casing does not necessarily result in external corrosion of the carrier pipe inside the casing.

10.9 When the effects of electrical shielding of cathodic protection current are detected, the situation should be evaluated and appropriate action taken.

## Section 11: External Corrosion Control Records

### 11.1 Introduction

11.1.1 This section describes external corrosion control records that will document in a clear, concise, workable manner, data that are pertinent to the design, installation, operation, maintenance, and effectiveness of external corrosion control measures.

11.2 Relative to the determination of the need for external corrosion control, the following should be recorded:

11.2.1 Corrosion leaks, breaks, and pipe replacements; and

11.2.2 Pipe and external coating condition observed when a buried structure is exposed.

11.3 Relative to structure design, the following should be recorded:

11.3.1 External coating material and application specifications; and

11.3.2 Design and location of isolating devices, test leads and other test facilities, and details of other special external corrosion control measures taken.

11.4 Relative to the design of external corrosion control facilities, the following should be recorded:

11.4.1 Results of current requirement tests;

11.4.2 Results of soil resistivity surveys;

11.4.3 Location of foreign structures; and

11.4.4 Interference tests and design of interference bonds and reverse-current switch installations.

11.4.4.1 Scheduling of interference tests, correspondence with corrosion control coordinating committees, and direct communication with the concerned companies.

11.4.4.2 Record of interference tests conducted, including location of tests, name of company involved, and results.

11.5 Relative to the installation of external corrosion control facilities, the following should be recorded:

11.5.1 Installation of cathodic protection facilities:

11.5.1.1 Impressed current systems:

11.5.1.1.1 Location and date placed in service;

11.5.1.1.2 Number, type, size, depth, backfill, and spacing of anodes;

11.5.1.1.3 Specifications of rectifier or other energy source; and

11.5.1.1.4 Cable size and type of insulation.

11.5.1.2 Galvanic anode systems:

11.5.1.2.1 Location and date placed in service;

11.5.1.2.2 Number, type, size, backfill, and spacing of anodes; and

11.5.1.2.3 Wire size and type of insulation.

11.5.2 Installation of interference mitigation facilities:

11.5.2.1 Details of interference bond installation:

11.5.2.1.1 Location and name of company involved;

11.5.2.1.2 Resistance value or other pertinent information; and

11.5.2.1.3 Magnitude and polarity of drainage current.

11.5.2.2 Details of reverse-current switch:

11.5.2.2.1 Location and name of companies;

11.5.2.2.2 Type of switch or equivalent device; and

11.5.2.2.3 Data showing effective operating adjustment.

11.5.2.3 Details of other remedial measures.

11.6 Records of surveys, inspections, and tests should be maintained to demonstrate that applicable criteria for interference control and cathodic protection have been satisfied.

11.7 Relative to the maintenance of external corrosion control facilities, the following information should be recorded:

11.7.1 Maintenance of cathodic protection facilities:

11.7.1.1 Repair of rectifiers and other DC power sources; and

11.7.1.2 Repair or replacement of anodes, connections, wires, and cables.

11.7.2 Maintenance of interference bonds and reverse current switches:

11.7.2.1 Repair of interference bonds; and

11.7.2.2 Repair of reverse-current switches or equivalent devices.

11.7.3 Maintenance, repair, and replacement of external coating, isolating devices, test leads, and other test facilities.

11.8 Records sufficient to demonstrate the evaluation of the need for and the effectiveness of external corrosion control measures should be maintained as long as the facility involved remains in service. Other related external corrosion control records should be retained for such a period that satisfies individual company needs.

## References

1. NACE Standard RP0572 (latest revision), "Design, Installation, Operation, and Maintenance of Impressed Current Deep Groundbeds" (Houston, TX: NACE).
2. NACE Standard RP0177 (latest revision), "Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems" (Houston, TX: NACE).
3. NACE Standard RP0285 (latest revision), "Corrosion Control of Underground Storage Tank Systems by Cathodic Protection" (Houston, TX: NACE).
4. NACE Standard RP0186 (latest revision), "Application of Cathodic Protection for Well Casings" (Houston, TX: NACE).
5. NACE Standard RP0286 (latest revision), "The Electrical Isolation of Cathodically Protected Pipelines" (Houston, TX: NACE).
6. NACE Standard RP0387 (latest revision), "Metallurgical and Inspection Requirements for Cast Sacrificial Anodes for Offshore Applications" (Houston, TX: NACE).
7. NACE Standard RP0188 (latest revision), "Discontinuity (Holiday) Testing of Protective Coatings" (Houston, TX: NACE).
8. NACE Publication TPC 11 (latest revision), "A Guide to the Organization of Underground Corrosion Control Coordinating Committees" (Houston, TX: NACE).
9. NACE Standard TM0497 (latest revision), "Measurement Techniques Related to Criteria for Cathodic Protection on Underground or Submerged Metallic Piping Systems" (Houston, TX: NACE).
10. ANSI/AWWA C 203 (latest revision), "Standard for Coal-Tar Protective Coatings and Linings for Steel Water Pipelines—Enamel and Tape—Hot Applied" (Washington, DC: ANSI and Denver, CO: AWWA).
11. NACE Standard RP0375 (latest revision), "Wax Coating Systems for Underground Piping Systems" (Houston, TX: NACE).
12. NACE Standard MR0274 (latest revision), "Material Requirements for Polyolefin Cold-Applied Tapes for Underground Submerged Pipeline Coatings" (Houston, TX: NACE).
13. ANSI/AWWA C 214 (latest revision), "Tape Coating Systems for the Exterior of Steel Water Pipelines" (Washington, DC: ANSI and Denver, CO: AWWA).
14. ANSI/AWWA C 209 (latest revision), "Cold-Applied Tape Coatings for the Exterior of Special Sections, Connections, and Fittings for Steel Water Pipelines" (Washington, DC: ANSI and Denver, CO: AWWA).
15. Ronald Bianchetti, ed., Peabody's Control of Pipeline Corrosion, 2<sup>nd</sup> ed. (Houston, TX: NACE, 2000).
16. ANSI/AWWA C 213 (latest revision), "Fusion-Bonded Epoxy Coating for the Interior and Exterior of Steel Pipelines" (Washington, DC: ANSI and Denver, CO: AWWA).
17. API RP 5L7 (latest revision), "Recommended Practices for Unprimed Internal Fusion Bonded Epoxy Coating of Line Pipe" (Washington, DC: API).
18. CSA Z245.20M (latest revision), "External Fusion Bond Epoxy Coated Steel Pipe" (Toronto, ON: CSA).
19. NACE Standard RP0190 (latest revision), "External Protective Coatings for Joints, Fittings, and Valves on Metallic Underground or Submerged Pipelines and Piping Systems" (Houston, TX: NACE).
20. NACE Standard RP0185 (latest revision), "Extruded Polyolefin Resin Coating Systems with Soft Adhesives for Underground or Submerged Pipe" (Houston, TX: NACE).
21. DIN 30 670 (latest revision), "Polyethylene-Coatings for Steel Pipes and Fittings Requirements and Testing" (Berlin, Germany: DIN).
22. ANSI/AWWA C 215 (latest revision), "Extruded Polyolefin Coatings for the Exterior of Steel Water Pipe Lines" (Washington, DC: ANSI and Denver, CO: AWWA).
23. ASTM G 128 (latest revision), "Control Of Hazards And Risks In Oxygen Enriched Systems" (West Conshohocken, PA: ASTM).
24. NACE Standard RP0274 (latest revision), "High-Voltage Electrical Inspection of Pipeline Coatings Prior to Installation" (Houston, TX: NACE).
25. ASTM G 8 (latest revision), "Standard Test Method for Cathodic Disbonding of Pipeline Coatings" (West Conshohocken, PA: ASTM).
26. ASTM G 19 (latest revision), "Standard Test Method for Disbonding Characteristics of Pipeline Coatings by Direct Soil Burial" (West Conshohocken, PA: ASTM).
27. ASTM G 42 (latest revision), "Standard Test Method for Cathodic Disbonding of Pipeline Coatings Subjected to Elevated Temperatures" (West Conshohocken, PA: ASTM).

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28. ASTM G 95 (latest revision), "Test Method for Cathodic Disbondment Test of Pipeline Coatings (Attached Cell Method)" (West Conshohocken, PA: ASTM).
29. ASTM G 9 (latest revision), "Standard Test Method for Water Penetration into Pipeline Coatings" (West Conshohocken, PA: ASTM).
30. ASTM G 17 (latest revision), "Standard Test Method for Penetration Resistance of Pipeline Coatings (Blunt Rod)" (West Conshohocken, PA: ASTM).
31. ASTM D 2240 (latest revision), "Standard Test Method for Rubber Property—Durometer Hardness" (West Conshohocken, PA: ASTM).
32. ASTM G 13 (latest revision), "Standard Test Method for Impact Resistance of Pipeline Coatings (Limestone Drop Test)" (West Conshohocken, PA: ASTM).
33. ASTM G 14 (latest revision), "Standard Test Method for Impact Resistance of Pipeline Coatings (Falling Weight Test)" (West Conshohocken, PA: ASTM).
34. M. Romanoff, *Underground Corrosion* (Houston, TX: NACE, 1989).
35. ASTM D 427 (latest revision), "Test Method for Shrinkage Factors of Soils by the Mercury Method" (West Conshohocken, PA: ASTM).
36. ASTM D 543 (latest revision), "Resistance of Plastics to Chemical Reagents" (West Conshohocken, PA: ASTM).
37. Federal Test Standard No. 406A, Method 7011 (latest revision), "Test Method for Resistance of Plastics to Chemical Reagents" (Washington, DC: General Services Administration).
38. ASTM G 20 (latest revision), "Standard Test Method for Chemical Resistance of Pipeline Coatings" (West Conshohocken, PA: ASTM).
39. ASTM D 2304 (latest revision), "Standard Test Method for Thermal Endurance of Rigid Electrical Insulating Materials" (West Conshohocken, PA: ASTM).
40. ASTM D 2454 (latest revision), "Determining the Effect of Overbaking on Organic Coatings" (West Conshohocken, PA: ASTM).
41. ASTM D 2485 (latest revision), "Standard Test Methods for Evaluating Coatings for High-Temperature Service" (West Conshohocken, PA: ASTM).
42. ASTM G 18 (latest revision), "Standard Test Method for Joints, Fittings, and Patches in Coated Pipelines" (West Conshohocken, PA: ASTM).
43. ASTM G 55 (latest revision), "Standard Test Method for Evaluating Pipeline Coating Patch Materials" (West Conshohocken, PA: ASTM).
44. ASTM G 21 (latest revision), "Standard Practice for Determining Resistance of Synthetic Polymetric Materials To Fungi" (West Conshohocken, PA: ASTM).
45. Federal Test Standard No. 406A, Method 6091 (latest revision), "Test Method for Mildew Resistance of Plastics by Mixed Culture Method (Agar Medium)" (Washington, DC: General Services Administration).
46. ASTM G 11 (latest revision), "Standard Test Method for Effects of Outdoor Weathering on Pipeline Coatings" (West Conshohocken, PA: ASTM).
47. ASTM G 6 (latest revision), "Standard Test Method for Abrasion Resistance of Pipeline Coatings" (West Conshohocken, PA: ASTM).
48. ASTM G 10 (latest revision), "Standard Test Method for Specific Bendability of Pipeline Coatings" (West Conshohocken, PA: ASTM).
49. ASTM G 2197 (latest revision), "Test Method for Adhesion of Organic Coatings by Scrape Adhesion" (West Conshohocken, PA: ASTM).

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## Appendix A—Interference Testing

A beta curve is a plot of dynamic (fluctuating) interference current or related proportional voltage (ordinate) versus values of corresponding structure-to-soil potentials at a selected location on the affected structure (abscissa). If the correlation is reasonably linear, the plot will indicate whether the affected structure is receiving or discharging current at the location where the structure-to-soil potential was measured. Dynamic interference investigation involves

many beta curve plots to search for the point of maximum interference-current discharge. Interference is resolved when the correlation of maximum current discharge has been changed to a correlation that shows that current pickup is being achieved in the exposure area by the corrective measures taken. These corrective measures may be accomplished by metallic bonding or other interference control techniques.



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## Appendix B—Method for Determining Probable Corrosion Rate and Costs of Maintaining Service

Maintenance of a piping system may include repairing corrosion leaks and reconditioning or replacing all or portions of the system.

In order to make estimates of the costs involved, it is necessary to determine the probability of corrosion or the rate at which corrosion is proceeding. The usual methods of predicting the probability or rate of corrosion are as follows:

- (a) Study of corrosion history on the piping system in question or on other systems of the same material in the same general area or in similar environments. Cumulative leak-frequency curves are valuable in this respect.
- (b) Study of the environment surrounding a piping system: resistivity, pH, and composition. Redox potential tests may also be used to a limited extent. Once the nature of the environment has been determined, the probable corrosiveness is estimated by reference to actual corrosion experience on similar metallic structures where environmental conditions are similar. Consideration of

possible environmental changes such as might result from irrigation, spillage of corrosive substances, pollution, and seasonal changes in soil moisture content should be included in such a study.

- (c) Investigation for corrosion on a piping system by visual inspection of the pipe and/or by instruments that mechanically or electrically inspect the condition of the pipe. Condition of the piping system should be carefully determined and recorded each time a portion of the line is excavated for any reason.
  - (d) Maintenance records detailing leak locations, soil studies, structure-to-electrolyte potential surveys, surface potential surveys, line current studies, and wall thickness surveys used as a guide for locating areas of maximum corrosion.
  - (e) Statistical treatment of available data.
  - (f) Results of pressure testing. Under certain conditions, this may help to determine the existence of corrosion.
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## Appendix C—Contingent Costs of Corrosion

In addition to the direct costs that result from corrosion, contingent costs include:

- (a) Public liability claims;
  - (b) Property damage claims;
  - (c) Damage to natural facilities, such as municipal or irrigation water supplies, forests, parks, and scenic areas;
  - (d) Cleanup of product lost to surroundings;
  - (e) Plant shutdown and startup costs;
  - (f) Cost of lost product;
  - (g) Loss of revenue through interruption of service;
  - (h) Loss of contract or goodwill through interruption of service; and
  - (i) Loss of reclaim or salvage value of piping system.
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## Appendix D—Costs of Corrosion Control

The usual costs for protecting buried or submerged metallic structures are for complete or partial cathodic protection or for external coatings supplemented with cathodic protection. Other corrosion control costs include:

- (a) Relocation of piping to avoid known corrosive conditions (this may include installing lines above ground);
- (b) Reconditioning and externally coating the piping system;
- (c) Use of corrosion-resistant materials;
- (d) Use of selected or inhibited backfill;
- (e) Electrical isolation to limit possible galvanic action; and
- (f) Correction of conditions in or on the pipe that might accelerate corrosion.

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## CHAPTER 1 QUIZ

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1. Calculate the CP current required for each of the following situations.
  - a.) For a 1 km long, 6.625"  $\varnothing$  coated pipeline if the coating is 99.9% effective and the current density required for protection is 30 mA/m<sup>2</sup> of bare surface.
  - b.) For a 1 mile long, 30 cm OD, coated pipeline that requires 10  $\mu$ A/ft<sup>2</sup> of coated surface.
  - c.) For a pipeline that has an average coupling factor of 23 mV/A if a 300 mV shift is required for protection.

- d.) For a pipeline that polarizes 62 mV with an applied current of 372 mA to satisfy the 100 mV polarization shift criterion.
- 2 (a). Calculate the IR drop in a pipe-to-soil potential measurement using the step wise current reduction technique (Figure 1.20) if  
 $V_2 = 378 \text{ mV}$   $V_{2,1} = 270 \text{ mV}$  and  $\Delta V_{1,1} = 30 \text{ mV}$ .
- 2 (b). If the 'On' pipe-to-soil potential ( $V_1$ ) is  $-935 \text{ mV/CSE}$ , is the structure cathodically protected with regard to the  $-850 \text{ mV/CSE}$  polarized criterion in NACE RP0169?

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## CHAPTER 2 QUIZ

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1.(a) An underground storage tank, buried in 1000 ohm-cm soil, has a .4mm thick coating, a surface area of 700 m<sup>2</sup>, and a 2 cm diameter holiday. If the specific leakage resistance of the coating is 10<sup>4</sup> ohm-m<sup>2</sup>, does the coated tank surface have a higher resistance than the holiday?

1. (b) If the CP driving potential is 1 volt, what is the current density at the holiday? What is the current density through the coating?

1.(c) What is the resistivity of the coating?

2. The following data was measured on an 800 m length of a .6 m diameter pipeline during a coating conductance test.

@ TS #1       $V_{on} = -1070 \text{ mV/CSE}$      $V_{off} = -780 \text{ mV/CSE}$   
                     $I_{on} = 2.1 \text{ A}$                        $I_{off} = 1.7 \text{ A}$

@ TS #2       $V_{on} = -1125 \text{ mV/CSE,}$                $V_{off} = -805 \text{ mV/CSE}$   
                     $I_{on} = 2.0 \text{ A}$                        $I_{off} = 1.65 \text{ A}$

- a) What is the conductance of this section of pipe?
  - b) What is the specific conductance of the coating based on 1000  $\Omega$ -cm soil if the actual average soil resistivity is 6,100  $\Omega$ -cm?
  - c) Based on Table 2.5 what is the quality of the coating on this section of pipe?
3. If a pipeline has a short circuit resistance ( $R_{ss}$ ) of 0.7  $\Omega$  and an open circuit resistance ( $R_{so}$ ) of 1.9  $\Omega$ , what is the characteristic resistance ( $R_G$ ) of the pipeline?
4. What is the voltage rise in the earth 100 m from a 2 m long graphite anode in 8,200 ohm-cm soil at an output of 2A?

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## CHAPTER 3 QUIZ

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1. A structure requires 120 mA of cathodic protection current. What would be the weight loss per year for the following galvanic anode materials and efficiencies?

Magnesium @ 40 efficiency

Zinc @ 85% efficiency

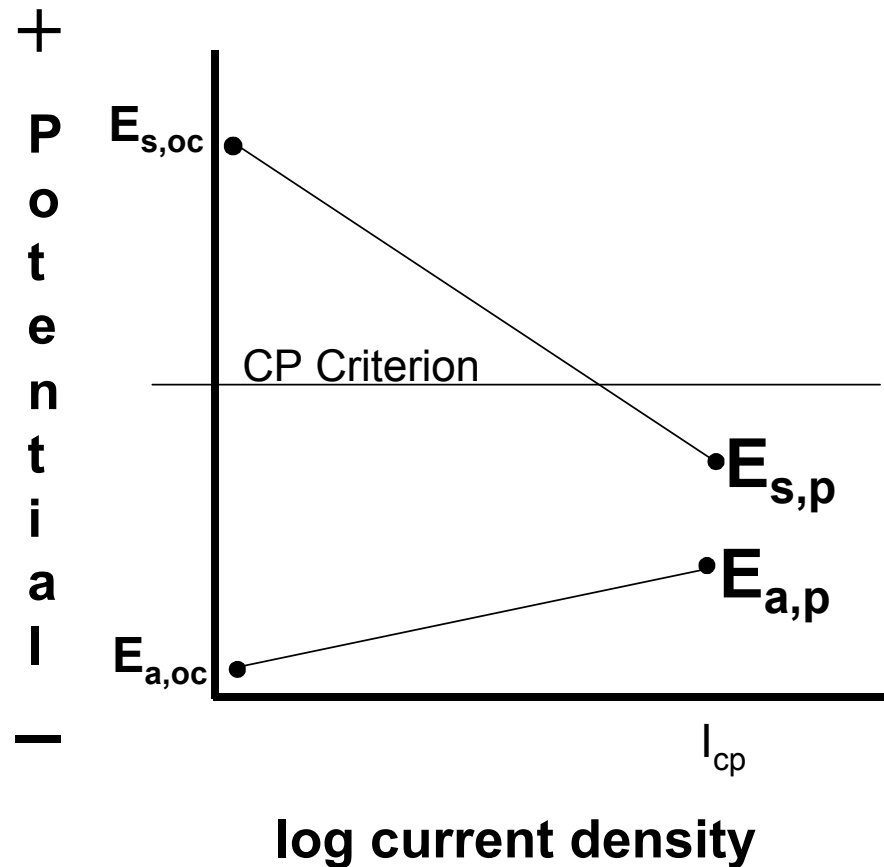
Aluminum @ 90% efficiency

2. (a) Using the polarization diagram for a Galvanic CP system show graphically what would happen for the following circumstances.
- (i) an increase in soil resistivity
  - (ii) an increase in anode polarization
  - (iii) depolarization of the structure

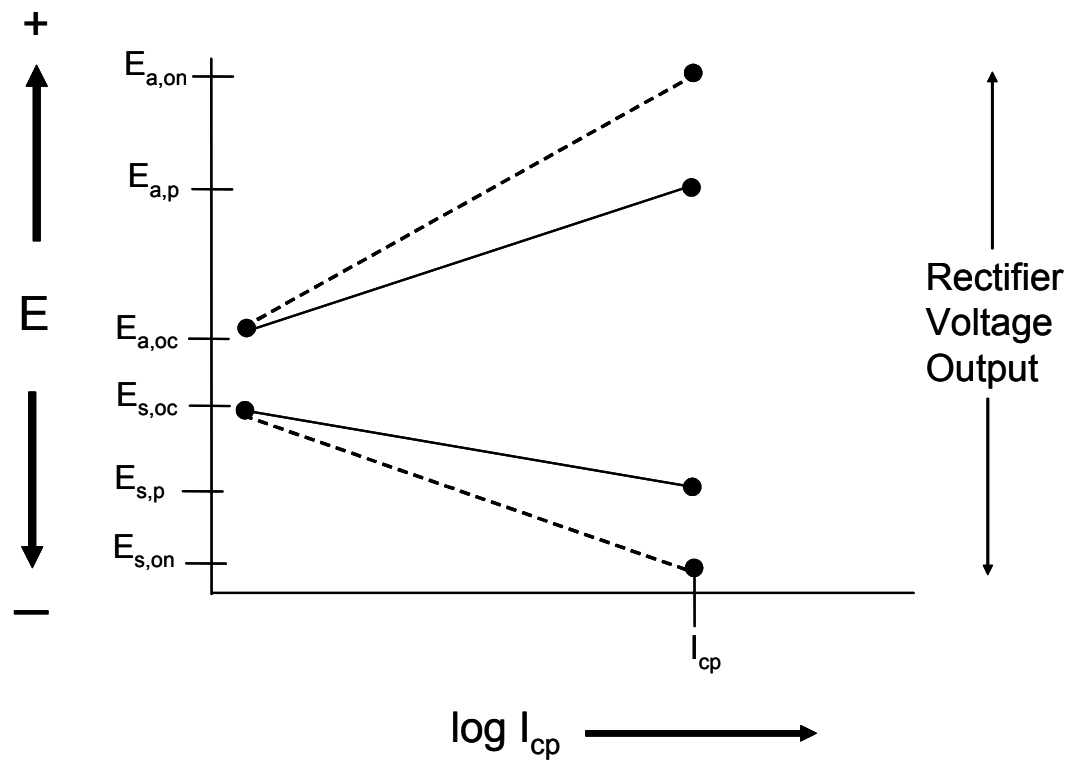
- 2.(b) What circumstances would cause each of the foregoing?
3. (a) Using the polarization diagram for an impressed current CP system show graphically what would happen for the following circumstances?
- (i) an increase in soil resistivity
  - (ii) an increase in anode polarization
  - (iii) depolarization of the structure
- 3.(b) What circumstances could cause each of the following?



# Polarization (Evans) Diagram



## Polarization diagram for an Impressed Current CP System



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## CHAPTER 4 QUIZ

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1. In Figure 4.3 change the resistance obtained at the 200 ft and 250 ft pin spacing to  $0.3 \, \Omega$  and  $0.28 \, \Omega$  respectively. Calculate the resulting 'd' and 'e' layer resistivities.
  
- 2.(a) For the parameters used to compute the data in Table 4.2 on 'Paralleling Effect', calculate ' $R_n$ ' and the average anode resistance, ' $R_{a, \text{avg}}$ ' for a 15 m spacing with 66 anodes.
  
- 2.(b) Using the new value of  $R_{a, \text{avg}}$  calculate the average conductance of each anode and recalculate the resistance  $R_{so}$  in Example 4.6 for a 66 anode groundbed.
  
- 3.(a) In example 4.9, assume that the magnesium anode being used is a #17D3 (in the appendix) and calculate the anode current density.

3. (b) Assuming the amp-hr capacity decreases linearly from 1100 A-hr/kg at an anode current density of 20mA/ft<sup>2</sup> zero A-hr/kg at zero current density, what is the new anode service life expectancy?

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## CHAPTER 5 QUIZ

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1. For the riveted water main example: If the anode run to location 2 (30 anodes) was fed by a AWG #4 cable connected into the middle of the run (i.e., 15 anodes in each direction), what would be the voltage applied to the last anode (furthest away) in this distributed groundbed if 1.0 V is applied at the midpoint (p 5:31)?
2. In the design example for the mobile home park, assume that the anode efficiency is only 35%. What is the new service life for the 21.8 kg anode in the 1,400  $\Omega$ -cm soil. What is the new service life for the 14.5 kg anode in the 3,400  $\Omega$ -cm soil? (p 5:53)?
3. In the design example for the coated steel gas transmission line the rectifier voltage to deliver 4 amps with an allowance for 2 volts of back voltage is 4.75 V. This ignores the pipe-to-earth resistance. What rectifier voltage is required if the structure-to-earth resistance is included (p 5:39 & 5:44)?

4. In the example of the coated steel gas distribution system in a subdivision the number of anodes estimated to achieve a minimum groundbed resistance of  $4.0 \Omega$  is 7. (p 5:65-5:68)

Does it? If not, how many anodes are required?

5. Calculate the leakage conductance of 5,000 feet of a 4.5 inch (11.4 cm) pipeline. The average soil resistivity in the area is 1,000 ohm-cm and the average specific leakage conductance has been determined to be  $0.00003 \text{ S/ft}^2$ .
6. Calculate the allowable DC circuit resistance of a high potential magnesium anode in 10,000 ohm-cm soil. A current output of 65 millampere is required to polarize the pipeline to -0.950 V.

## CHAPTER 6 QUIZ

1. What is the total resistance of a ribbon anode system as described in the AST example (Page 6:19) if the average anode length is 10 m and the resistivity is 7,800 ohm-cm? (Assume other variables as given in text.)
2. From Figure 6.9 what is the active column length required to provide a  $3\ \Omega$  groundbed in 6,000  $\Omega$ -cm soil if the anode diameter is 10 cm (p 6:29)?

3. An above ground storage tank has a diameter of 120 feet. An anode ribbon is placed 4 inches from the bottom of the tank in 10,000 ohm-cm soil. Calculate the width of coverage for each strip of anode ribbon.



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## CHAPTER 7 QUIZ

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1. What is the current output of a 45 cm radius Al-Ind. Alloy bracelet anode in 25  $\Omega$ -cm water when the pipe is polarized to  $-920$  mV? (Ignore pipe resistance)
2. Calculate the number of silicon iron anodes (46 kg each) needed for a ground bed which will have an output of 50 amps for 20 years. Assume a utilization factor of 0.75 and an anode consumption rate of 0.5 kg/amp-yr.?
3. If an aluminum anode has cross sectional dimensions of 0.26 m wide by 0.28 m high what is the de-rated radius,  $r$ , for this anode? (7:23)