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Appalachian Underground Corrosion Short Course

Advanced Course

Appalachian Underground Corrosion Short Course
West Virginia University
Morgantown, West Virginia

APPALACHIAN UNDERGROUND CORROSION SHORT COURSE ADVANCED COURSE

CHAPTER 7 - MIC INSPECTION AND TESTING

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Chapter 1 - Pipe-to-Soil Potential Surveys and Analysis

INTRODUCTION

The objective of this chapter is to discuss the most important corrosion control measurement, the pipe-to-soil potential measurement, and the various methods that can be used to make this measurement.

This chapter will also show how pipe-to-soil potential data can be used to identify and evaluate corrosion problems as well as assist in determining the effectiveness of a cathodic protection system.

Also included in this chapter will be a review of the criteria for cathodic protection and the applications for each.

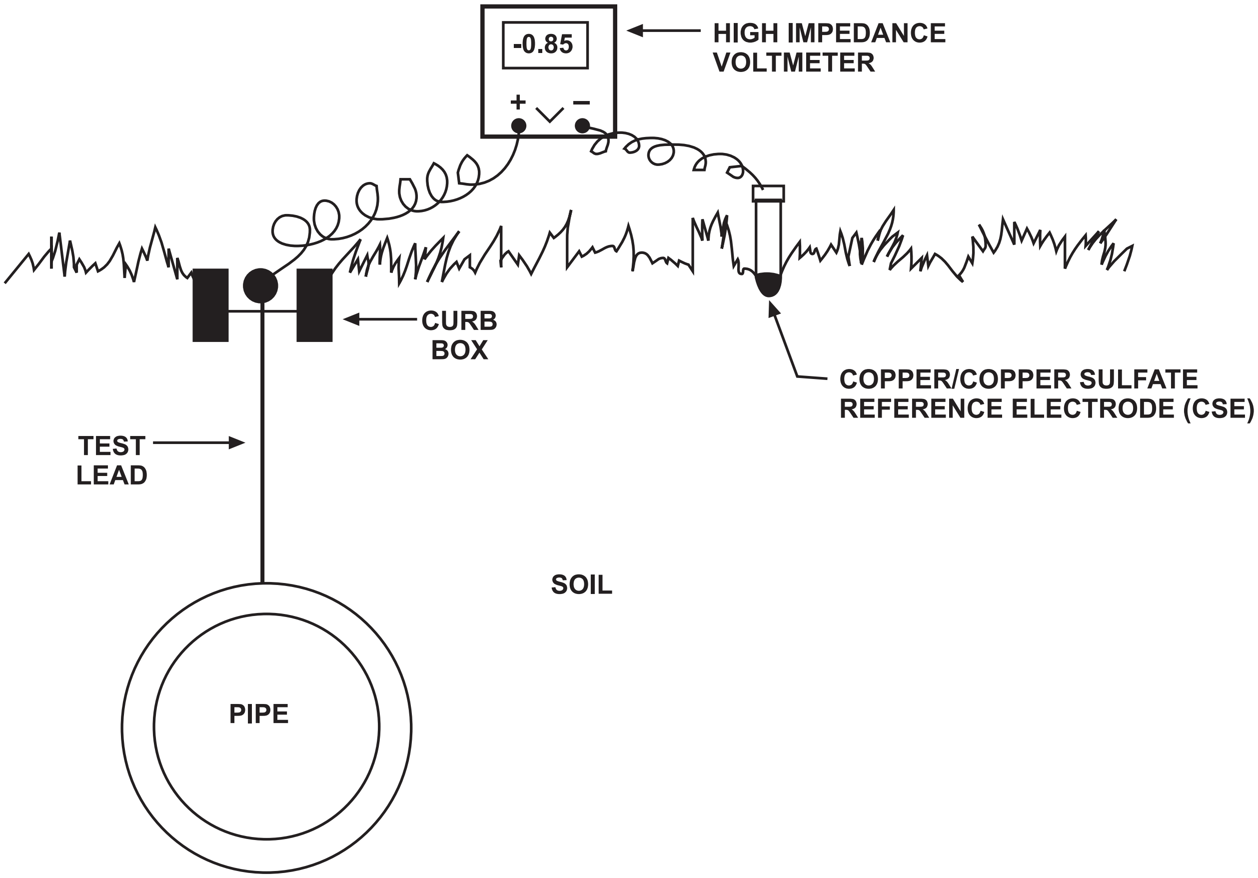
All pipe-to-soil potential values given in this chapter will be with respect to a saturated copper/copper sulfate reference electrode (CSE). Unless otherwise noted, or in an example where lateral measurements are being taken, all potential values given will be with the reference electrode placed at grade directly over the structure being tested. Keep in mind that the pipeline potential is referenced to the electrode location not to the structure connection point. See Figure 1-1 for a typical pipe-to-soil potential measurement test setup.

Because the normal pipe-to-soil potential of steel measured with respect to a CSE is almost always negative, this chapter will present examples using potentials with negative values. Therefore, negative potentials with greater absolute values are "more negative". For example, a potential measurement of -600 mV is "more negative" than a measurement of -400 mV.

CORROSION MECHANISMS

The corrosion of an underground or submerged metallic structure is electrochemical in nature. There are two different mechanisms that cause corrosion: electrolytic corrosion and galvanic/natural corrosion.

Electrolytic corrosion, often called stray current corrosion, results from currents which are introduced into the ground from neighboring sources of direct current (DC) such as electric railways, DC powered machinery, and foreign cathodic protection systems.



PIPE-TO-SOIL POTENTIAL MEASUREMENT

FIGURE 1-1

Galvanic and natural corrosion is the result of the natural electrochemical process that takes place on a buried metallic structure due to potential differences which exist between points on the same structure due to different surfaces, dissimilar electrolytes, differential aeration or the coupling of dissimilar metals. This type of corrosion can be classified into categories such as local action, long line activity, and bimetallic activity. Both of these corrosion mechanisms can be detected and evaluated using the pipe-to-soil potential measurement.

Pipe-to-soil potential measurements can indicate whether a structure is subject to stray current corrosion. Stray currents can be static or dynamic in nature. Dynamic stray current is stray current that has a varying magnitude and/or path. DC powered railways, welding machines, HVDC power systems and telluric activity are examples of dynamic stray current sources. Because its magnitude and/or path varies, dynamic stray currents will cause pipe-to-soil potentials to fluctuate. To determine the degree of potential fluctuation and the amount of time that the structure is affected, DC voltage recording instruments can be employed.

Static stray current is not as obvious as dynamic stray current since the pipe-to-soil potentials do not fluctuate. The interference effect from a foreign cathodic protection system will usually remain constant and unless there is existing historical potential data, or one participates in cooperative interference testing, this type of stray current interference may not be immediately detected. However, there are potential measurement techniques that can detect this type of stray current interference such as lateral potential surveys, which will be discussed later in this chapter.

PIPE-TO-SOIL POTENTIAL MEASUREMENT

Before the various test methods and evaluation processes are discussed, a review of the pipe-to-soil potential measurement is required. This measurement must be obtained using a high impedance voltmeter, a calibrated reference electrode, an electrolyte present over the pipe where the reference electrode can be placed, and a method by which to contact the structure under test. A high impedance voltmeter is required in order to obtain an accurate potential reading. The electrolyte for the placement of the reference electrode should be soil or water. Concrete and asphalt should be avoided. The connection to the structure under test can be a valve, riser pipe, test station, etc., any point electrically continuous with that portion of pipe being evaluated.

The preferred polarity convention has the reference electrode connected to the negative terminal of the voltmeter and the structure connected to the positive terminal.

This polarity connection will normally result in a negative value. It is important to note that consistency is critical when recording these potential values whether it be as a negative value or a positive value. The methods and instrumentation employed for this testing are critical in order to provide meaningful data that can be properly evaluated.

TYPES OF POTENTIAL SURVEYS

A normal survey of a pipeline system in order to obtain either static or native potential values or to ascertain the effectiveness of an existing cathodic protection system might consist of measuring pipe-to-soil potentials at all available test locations such as those described previously. However, there are occasions when it is necessary to obtain additional potential measurements between test points. This is accomplished by placing the reference electrode at regular intervals over the pipeline and measuring potentials at each reference location. The spacing of the intervals will depend on the type of survey being performed and the type of detail required. This type of survey will indicate the anodic locations along an unprotected structure which will be those areas with the most negative potentials. However, these more negative potentials may also correspond to a stray current "pickup" area. In the case of a pipeline under cathodic protection, this type of survey will reveal those locations where protection might not be achieved based on an evaluation of the potential values.

In order to insure the accuracy of an over-the-line potential survey, the pipeline should be first electronically located and staked out by the survey crew. This will help to ensure that the potential measurements are taken directly over the pipeline. Just as it is important to use the proper equipment as explained earlier, it is equally important that the reference electrode be placed in clean soil devoid of rocks, weeds, or grass which could affect the electrode contact resistance and thereby effect the accuracy of the measurement. In other words, make sure to establish good cell contact with the electrolyte.

It is also important to insure that the pipeline you are testing is electrically continuous for the length of pipe to be surveyed.

Detailed over-the-line potential surveys can be conducted using various methods and test equipment which will yield a variety of useful information. The following is a description of some commonly used survey methods.

SINGLE ELECTRODE CLOSE INTERVAL SURVEY METHOD

The first method to be discussed is the single electrode survey, see Figure 1-2. This survey utilizes one CSE, a high impedance voltmeter, and a reel of test wire. There must also be a point of electrical contact to the structure being tested.

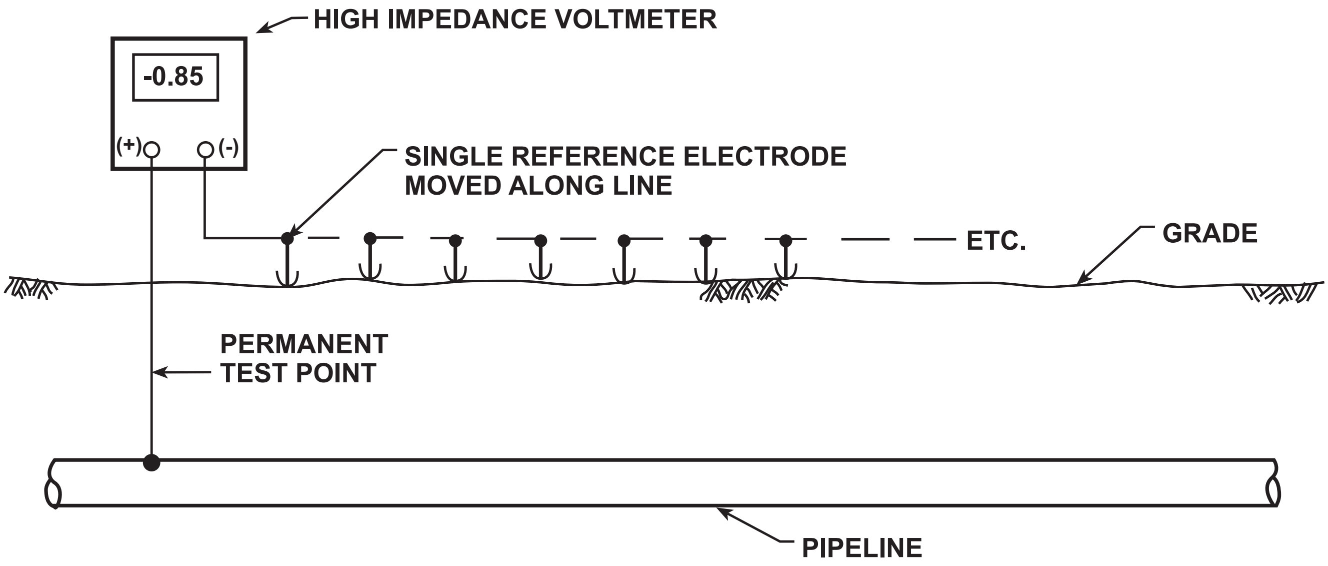
There are two ways to perform this type of survey. In the first procedure, the pipeline is contacted through a test lead or other suitable connection point which is connected to a test reel. The test reel is connected to the positive terminal of a voltmeter and the testing personnel measure potentials along the pipeline at prescribed intervals, carrying and moving both the voltmeter and the reference electrode together. Once again, the reference electrode is connected to the negative terminal of the voltmeter. This polarity convention can be altered if the convention is consistent and the test personnel are aware of the polarity of the measured pipe-to-soil potential.

In the second procedure, the test reel is connected to the reference electrode and the voltmeter is left at the point of connection to the pipeline. This method requires two testing personnel with one at the voltmeter recording the data and the other individual moving the reference electrode along the pipeline and contacting the soil at set intervals. In cases where a long section of pipeline is to be tested or where the terrain is such that visual contact cannot be maintained, some type of communication is needed to coordinate the timing of the readings.

It should be noted that potential readings taken using the one electrode method may be affected by the metallic voltage drop in the pipeline and measuring circuit or by stray current interference.

The data can be recorded manually on field data sheets or electronically using a recording voltmeter or datalogger.

Figure 1-3 shows the basic components and connections for recording the data electronically using a computerized system. In this case, the voltage measuring and datalogging equipment can be carried in a compact backpack arrangement by the operator. The operator carries one or two reference electrodes, which may be affixed to the bottom of extension rod(s), which are then "walked" forward at some specific interval, usually 2½ to 3 feet. Potential measurements are recorded electronically and stored by the instrument. The long test lead back to the connection to the pipeline at the survey starting point can be a single-use disposable light gauge wire. During the potential survey the operator can electronically note distances, terrain features and



SINGLE ELECTRODE POTENTIAL SURVEY

FIGURE 1-2

landmarks as well as other pertinent information. Modern equipment will record GPS coordinates as well.

The electronically collected data can then be processed by a personal computer in the field or at the office. The computers can be programmed to produce a potential profile complete with identifying notes for the pipeline section surveyed. Some programs will allow for the plotting of previous survey data for comparison.

Single electrode close interval surveys are also discussed in Chapter 2.

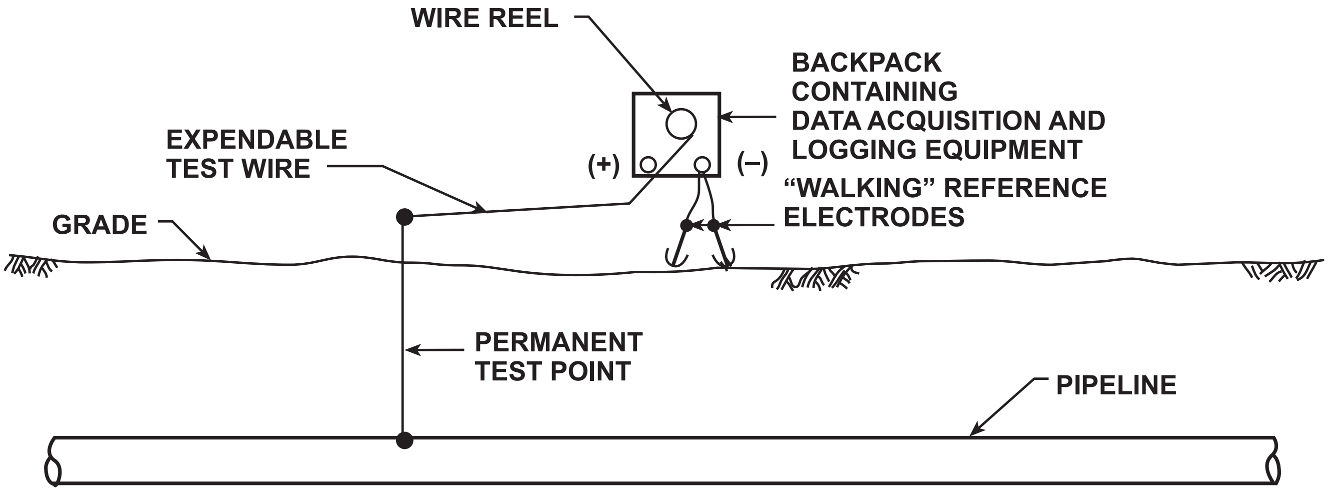
TWO-ELECTRODE SURVEY METHOD

Another potential survey method to be discussed is the two-electrode survey as illustrated in Figure 1-4. This survey uses two CSEs, a high impedance voltmeter, and a pair of test leads. These leads can be cut equal to the span of the preselected survey distance. The survey is conducted by first measuring and recording the pipe-to-soil potential with respect to reference electrode "A" as shown in Figure 1-4. Reference electrode "B" is then placed along and directly over the pipeline at some preselected survey interval from reference electrode "A". The potential difference between the two electrodes is then measured and numerically added or subtracted from the previous reading in accordance with the measured polarity of the forward electrode ("B" in this case). This "leap frogging" of the two electrodes is continued until the next permanent test station is reached or any other location where the pipeline can be electrically contacted.

At this juncture, the cumulative potential up to this point is compared to the actual potential measured to a CSE at this second permanent test station and adjusted as necessary. The survey then continues following the above described procedure to the next contact point.

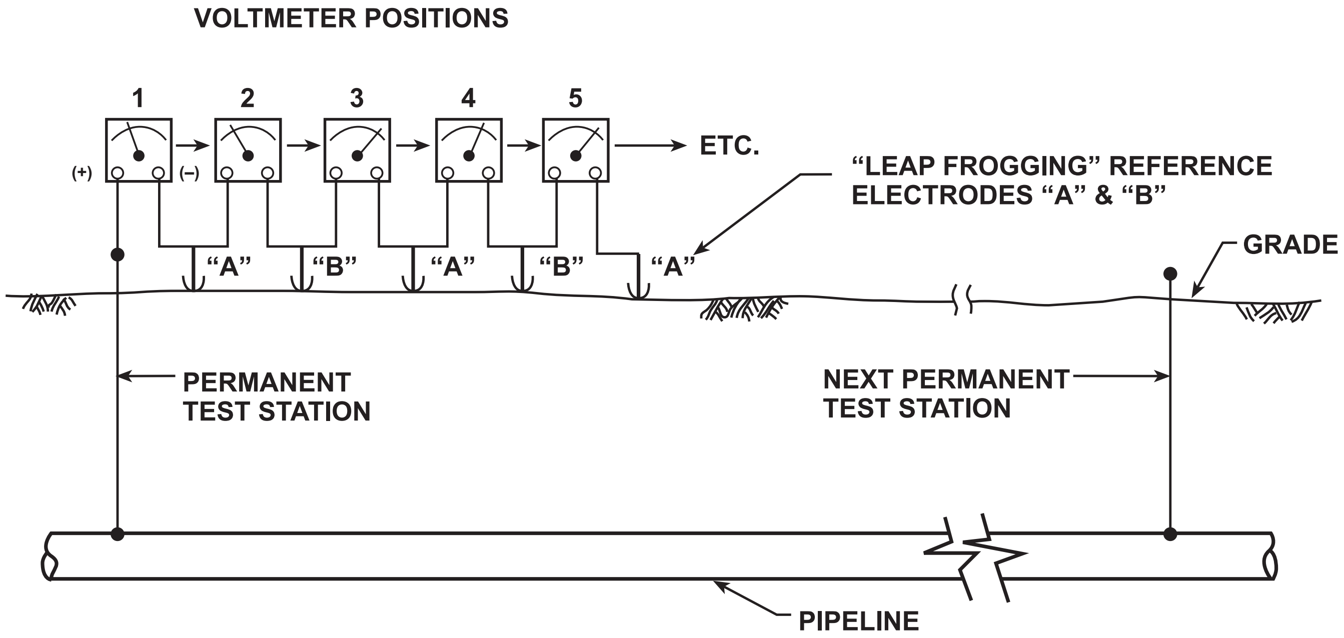
The data should be recorded in a permanent log. See Table 1-1 for a typical recording format.

The two-electrode method works well. However, it requires that a great deal of care be taken in recording the data. An error made in the calculating of potentials or the noting of polarity at any given point will cause all subsequent calculated potentials to be erroneous. In the case of an error, the calculated pipe-to- electrode potential will not correspond to the potential measured at the next contact point.



TYPICAL COMPUTERIZED POTENTIAL SURVEY

FIGURE 1-3



TWO ELECTRODE POTENTIAL SURVEY

FIGURE 1-4

TABLE 1-1

Typical Data Record For Two Electrode Potential Survey Conducted on a Cathodically Protected Pipeline

A	B	C	D	Comments
1	--	-	-0.860[(1)]	--
2	0.035	+	-0.895	--
3	0.021	+	-0.916	--
4	0.065	-	-0.851	--
5	0.092	-	-0.759	Unprotected Area
6	0.045	+	-0.804	Unprotected Area
7	0.063	+	-0.867	--
8	0.011	+	-0.878	--
9	0.020	-	-0.858	--
10	0.032	+	-0.890	--

Where: A = position or pipeline section
B = potential drop from electrode at last position (volts)
C = polarity of forward electrode
D = pipe to CSE (volts)

Note: (1) Initial value measured via direct pipeline contact at Position 1

Note however, that even if there are no data errors, a discrepancy could still exist between the last calculated pipe-to-soil potential and the actual measured potential at the contact point. One possible reason is that any current flowing on the pipe will cause a voltage drop across the pipeline between the two test points which could account for the difference. Another reason for a difference could be the effect of stray current activity on the pipeline potential.

This survey method is seldom used anymore and is presented to illustrate legacy survey techniques.

SIDE-DRAIN MEASUREMENTS

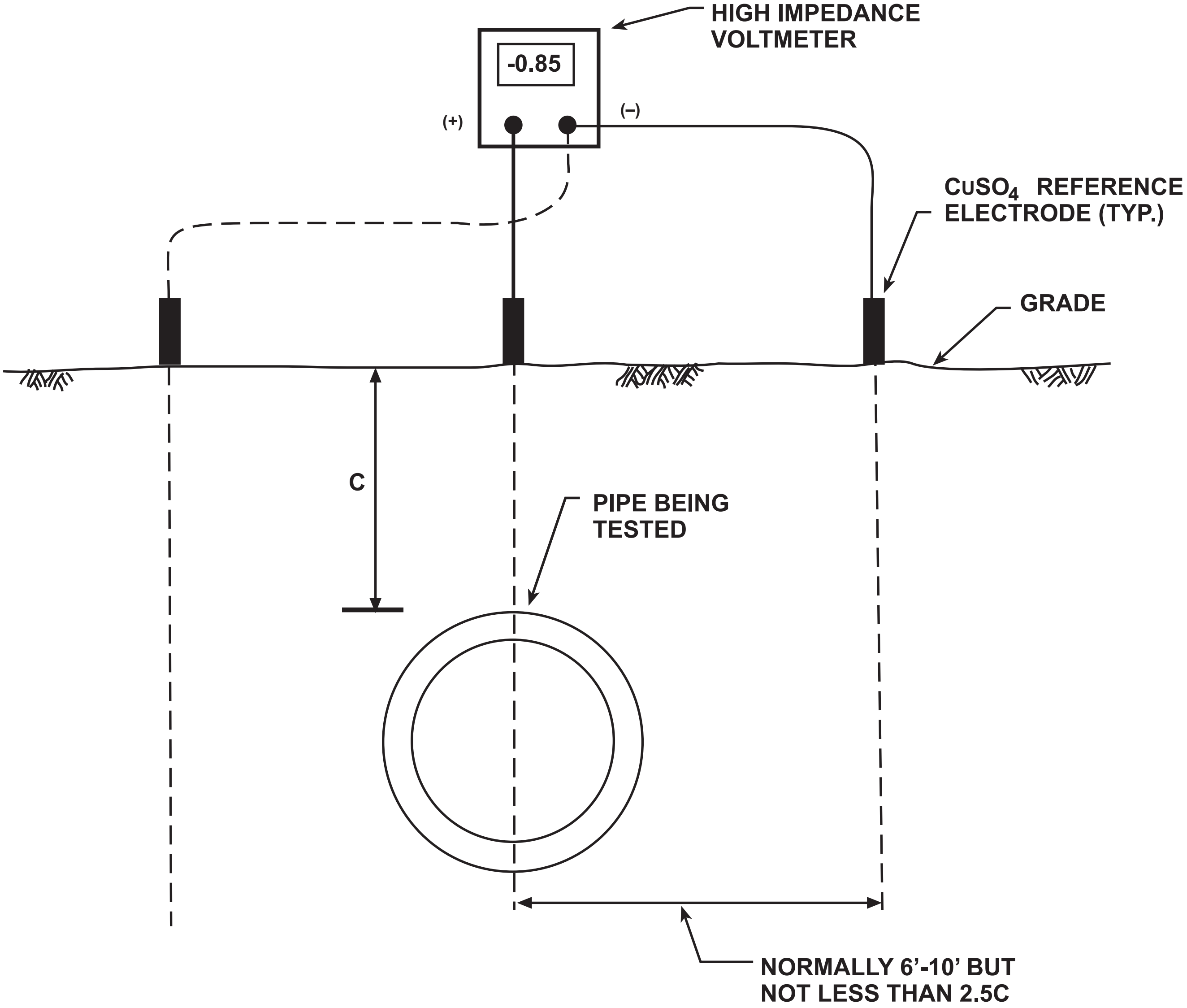
If more detailed information is desired, another method known as side-drain measurements can often be used to troubleshoot problem areas. Side-drain measurements are conducted utilizing two CSEs and a high impedance voltmeter, as shown in Figure 1-5. The first electrode is placed directly above the pipe, in contact with the soil. The second electrode is placed in contact with the soil at a 90° angle to the pipe at a distance approximately equal to 2½ times the pipe depth. During testing, the electrode placed directly above the pipe should be connected to the positive terminal of the voltmeter and the other electrode to the negative terminal. Positive side-drain readings indicate that current is being discharged from the pipe at this point, making it an anodic area. Negative side-drain readings normally indicate that current is flowing towards or onto the pipe at this point, making it a cathodic area. The side-drain measurements should be taken typically at no more than 5-foot intervals. Tests must be made on both sides of the pipe, until the extent of the problem section has been determined.

This technique should be used with caution. Under certain conditions, a relatively strong localized anodic cell could exist on the bottom of the pipe with the top of the pipe serving as a cathode and negative side-drain readings could be measured while severe corrosion is occurring on the bottom of the pipe at this location.

ANALYZING PIPE-TO-SOIL POTENTIAL DATA

Upon completion of the pipe-to-soil potential survey, the compiled data is normally plotted on a graph to facilitate interpretation. Potential (V or mV to CSE) is plotted versus distance (ft.).

On cathodically protected pipelines, the pipe-to-soil potential survey is used to



TYPICAL TEST SET UP FOR SIDE DRAIN MEASUREMENTS

FIGURE 1-5

determine if adequate levels of protection are being provided to all areas of the pipeline. Adequate levels of protection are often based on the -850 mV ("instant off," or "on corrected for voltage drops") versus a CSE. However, the 100 mV criterion could be used if a static potential profile of the line is available.

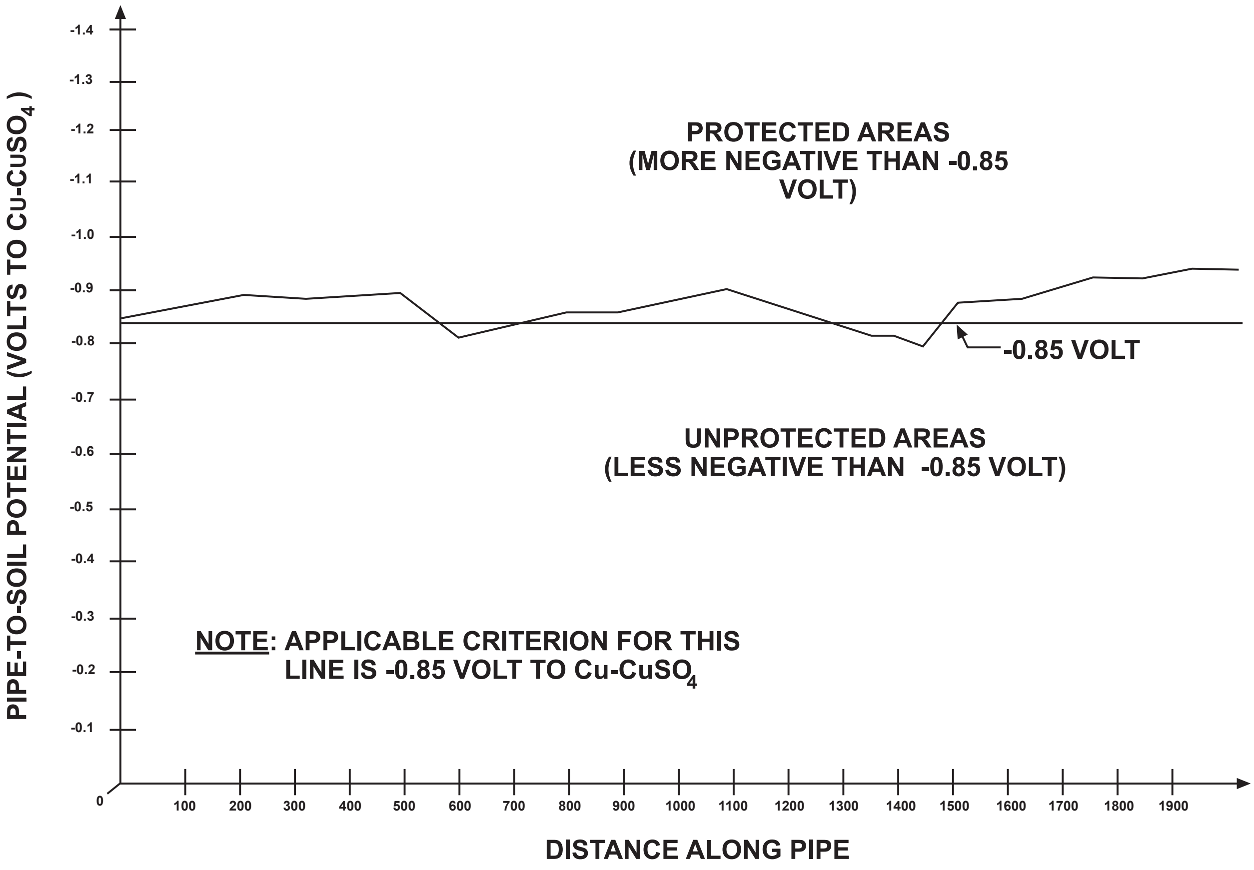
Normally, after the survey data is plotted, the -850 mV value is shown on the plot. All areas below this line are considered to be inadequately protected and in need of remedial measures. Figure 1-6 shows a typical pipe-to-soil potential profile of a cathodically protected pipeline.

On pipelines which are not cathodically protected, the pipe-to-soil potential profile and surface potential surveys can be used to locate corroding areas or "hot spots" along the pipeline. Experience has shown that when a difference in pipe-to-soil potential values exist along a pipeline, corrosion occurs at, and for a given distance on either side of, the most negative or anodic points along the pipeline.

Figure 1-7 shows some typical potential and polarity changes which may be recorded at corroding or anodic areas on the pipe. The exact point of "current discharge" can be determined by resurveying the affected area and successively reducing the electrode spacing by one-half. When the exact point of maximum "current discharge" (most negative potential) has been determined, the point should be staked, and all pertinent data recorded.

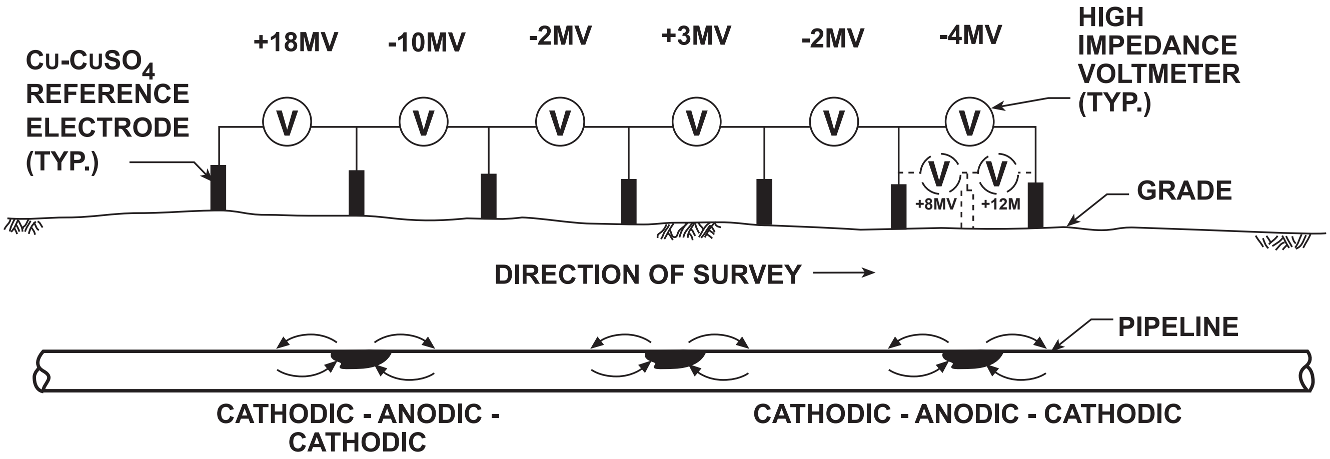
Pipe-to-soil potential measurements taken over the line can be used to indicate if a pipeline is being affected by dynamic stray current corrosion. This is possible however, only if the potentials are fluctuating at the time of the survey. The two-potential profile method is sometimes used to detect the effects of static stray currents on a section of pipe. The first profile is developed with the reference electrode placed directly above the pipe and the second by placing the electrode some distance laterally away from the pipe.

Dual potential profiles, over the pipe and laterally away from the pipe, are used to interpret various types of corrosion activity on unprotected pipes. It should be noted, however, that such profiles should be utilized to evaluate the effects of "long line" corrosion cells. Such profiles can sometimes miss very small localized corrosion cells where the anode and the cathode are located very close to each other.



TYPICAL POTENTIAL PLOT OF A CATHODICALLY PROTECTED PIPELINE

FIGURE 1-6



SCHEMATIC SURFACE POTENTIAL SURVEY

FIGURE 1-7

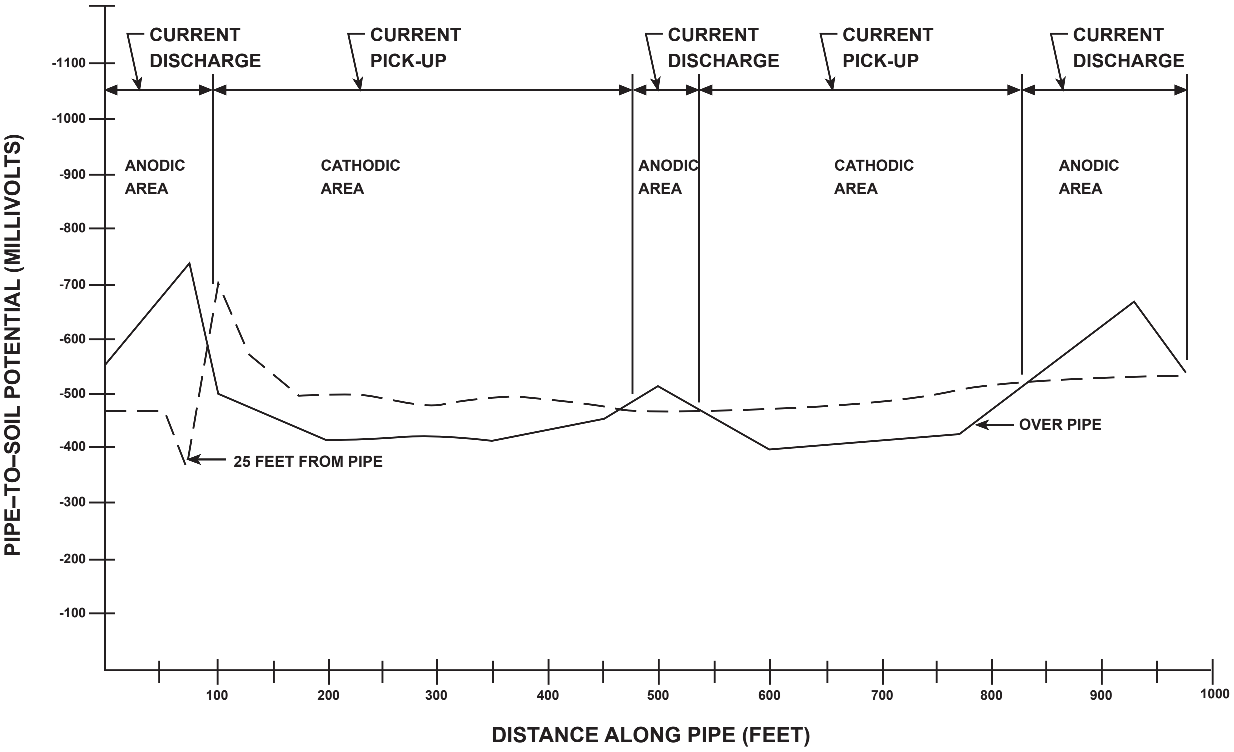
PIPE-TO-SOIL POTENTIAL SURVEYS AND ANALYSIS OF UNPROTECTED PIPELINES

Figure 1-8 shows a typical potential profile on an unprotected pipe on which the corrosion activity is one of straight forward galvanic action and is not being influenced by interference currents or bimetallic corrosion. Figure 1-9 shows a typical potential profile on an unprotected pipe which is exposed to damage as the result of a rectifier unit on a crossing pipeline. In comparing these two potential profiles, it should be noted that irrespective of the condition which exists, anodic areas always exist at the locations where the "over the pipe" potentials are more negative than the "off the pipe" potentials. However, in a straightforward galvanic situation such as shown in Figure 1-8, the anodic areas occur at locations where the "over the pipe" potentials are of higher negative values than those measured in the cathodic areas. In an interference situation, such as shown in Figure 1-9, the anodic areas are at those locations where the potentials (both "over" and "off" the pipe) are of lower negative values than those at the cathodic areas.

It should be noted that although a potential profile like that shown in Figure 1-8 almost always indicates a galvanic corrosion pattern and almost always rules out a stray current or interference situation, a profile like that shown in Figure 1-9 does not necessarily indicate a stray current situation. It is possible that a bimetallic corrosion condition will yield a potential profile like that which is encountered in an interference situation. Figure 1-10 shows a potential profile on a pipeline, a portion of which is influenced by a neighboring copper grounding system to which the pipe is connected. This potential profile is like that shown in Figure 1-9 in that the anodic areas occur at locations of low negative potential. In some situations, it may be difficult to distinguish between an interference situation and a bimetallic one merely by analyzing the potential profiles. In that type of situation, a complete investigation of the conditions which exist in each area will usually yield the information necessary to establish whether the potentials are attributable to interference or bimetallic activity.

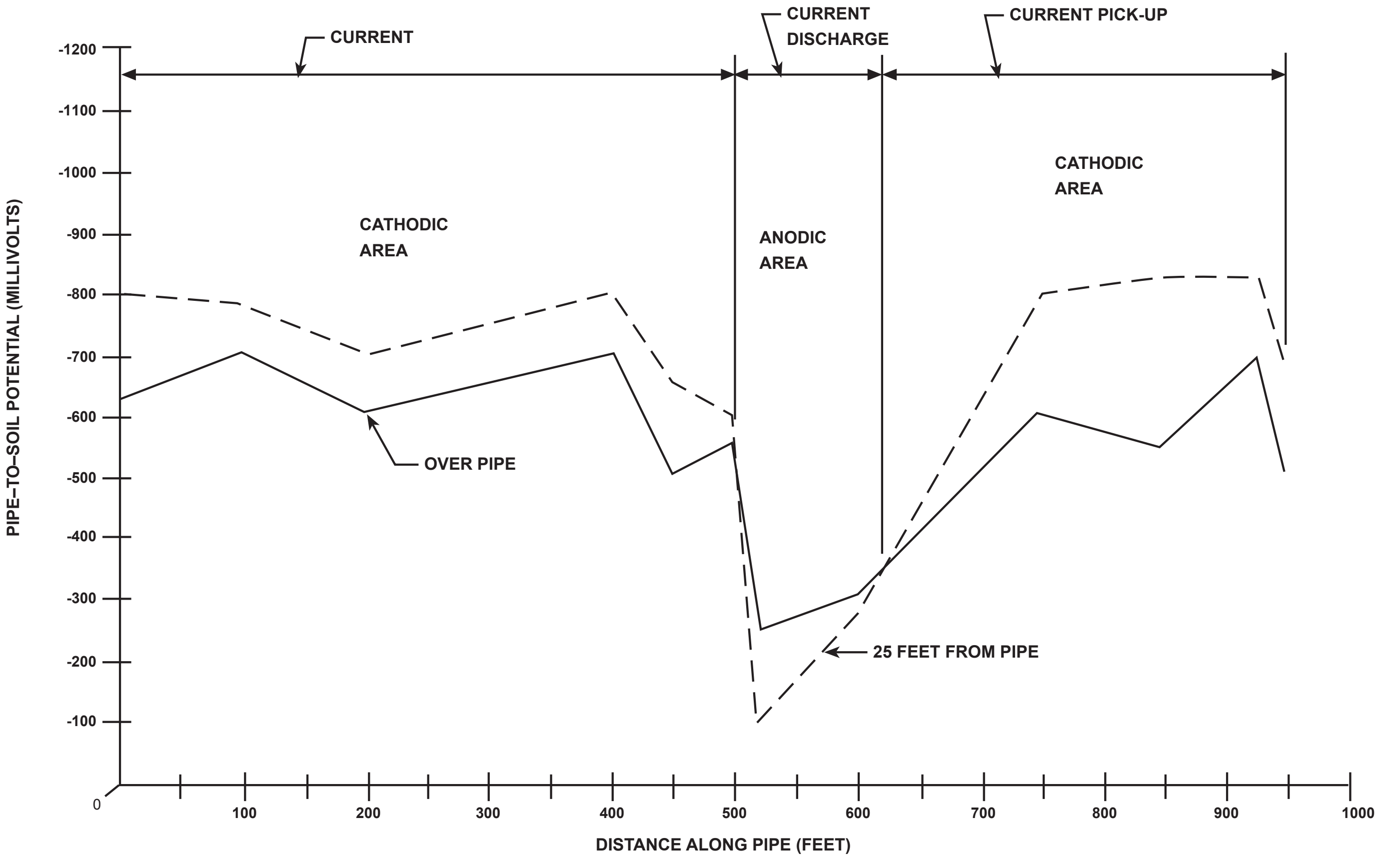
Even without knowledge of the surrounding conditions, there are usually sufficient differences between the two profiles to distinguish them. Thus, in an interference situation, the portions of the pipe immediately adjacent to the anodic area are almost always entirely cathodic. In a bimetallic situation, the profile of the pipe outside the area of bimetallic influence is one which is like the normal galvanic profile shown in Figure 1-8.

For distinguishing the type of corrosion activity that is present, in the absence of a cathodic protection system, the following general rules can be given.



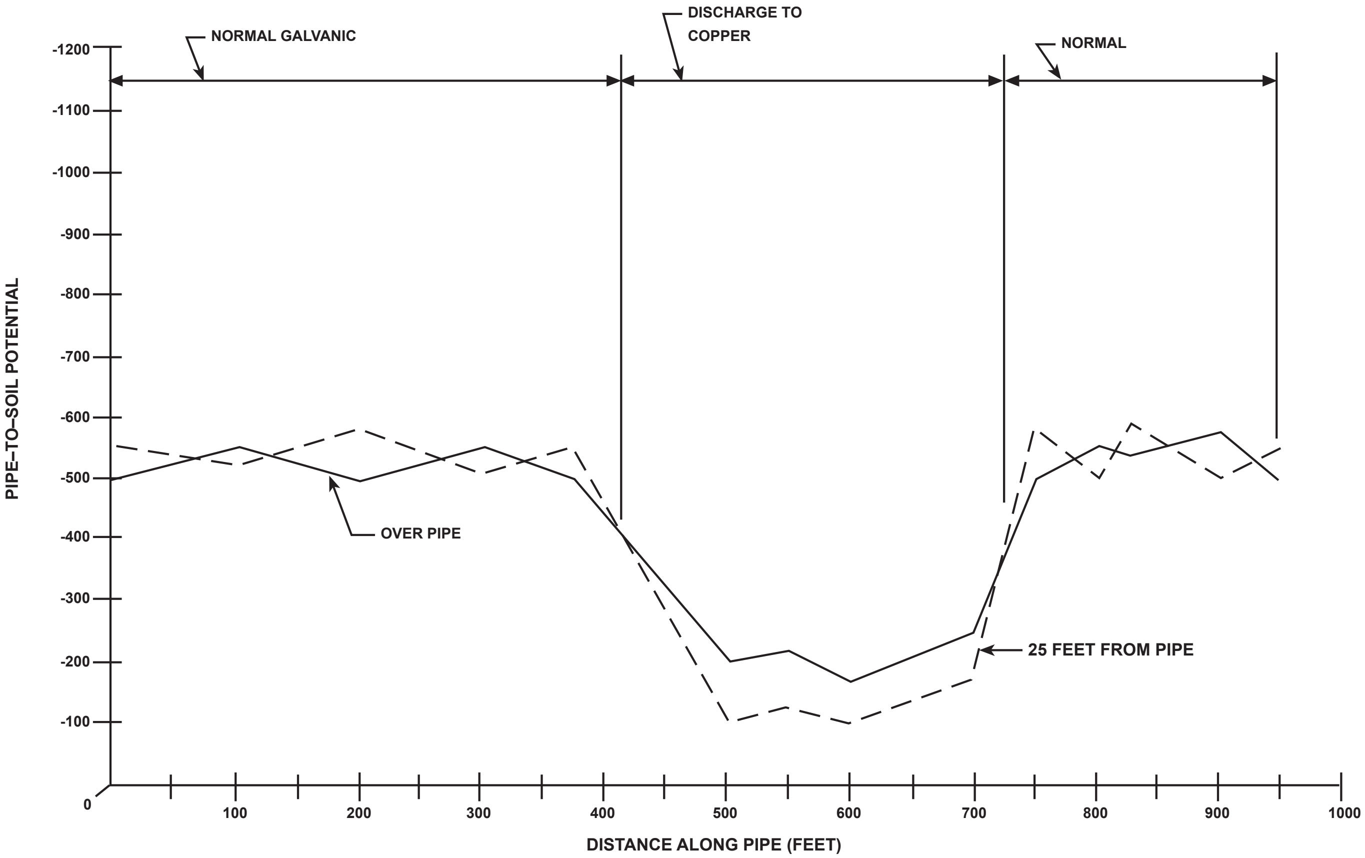
POTENTIAL PROFILE SHOWING GALVANIC CORROSION ACTIVITY

FIGURE 1-8



POTENTIAL PROFILE OF PIPE EFFECTED BY STRAY CURRENT INTERFERENCE

FIGURE 1-9



POTENTIAL PROFILE SHOWING BIMETALLIC EFFECT

FIGURE 1-10

1. Anodic areas exist at locations where the lateral (off the pipe) measurements are less negative than the "over the pipe" measurements. Conversely, cathodic areas exist at locations where the lateral measurements are more negative than the "over the pipe" measurement. This condition always holds, irrespective of whether the corrosion activity is a result of an electrolytic or galvanic action.

2. When anodic areas coincide with areas of high negative potential, the corrosion activity is one of "straightforward" galvanic action (this does not include bimetallic activity). In a straightforward galvanic situation, the more negative the potential, the more anodic the condition will be.

3. When anodic areas coincide with areas of low negative potentials (or in severe cases, positive potentials), the corrosion activity is one of either electrolytic action or bimetallic coupling. In an electrolytic or bimetallic situation, the less negative (or more positive) the potential, the more anodic the area.

INTERPRETATION OF POTENTIALS UNDER NON-STRAY CURRENT CONDITIONS

After it has been determined that stray currents are not present, potential measurements can be used in analyzing the galvanic corrosion pattern which may exist. Surface condition of the pipe, chemical composition of the soil, and other local conditions can greatly influence static potentials along the length of a pipeline. Therefore, the more readings taken, the better the evaluation. A more comprehensive interpretation of potential measurements can be derived from the following statements.

1. The potentials of newer pipes are more negative than those of older pipes.

2. The potentials of coated pipes (organic coating such a coal tar, asphalt, plastic tape, etc.) are more negative than those of bare pipes.

3. The variation in potential with respect to distance is generally greater along a bare pipe than along a coated pipe.

4. The normal potentials taken along a bare pipe fall in the range of -500 to -600 mV. A newly installed bare pipe will have higher negative potentials, and very old bare pipe can have much lower negative potentials.

5. The normal potentials taken along a coated line fall in the range of -650 to -750 mV. A newly installed coated pipe can have higher negative potentials, and older

pipe or poorly coated pipe will have less negative potentials.

6. In highly alkaline soils, the normal potentials will be less negative than those taken in neutral or acidic soils.

7. On bare pipe, there is usually a correlation between potential measurements and resistivity measurements, i.e., locations of higher resistivity soil correspond with locations of lower negative potentials.

All the above statements apply primarily to steel pipelines that are in non-stray current areas and are not subject to bimetallic influences or cathodic protection. Also, where comparisons are made, such as between coated and bare pipe or between old and new pipe, it is assumed that other conditions are equal.

These statements are intended as a generalized guide for interpretation of potential measurements. They are not to be considered as scientific principles and they do not necessarily hold true under all circumstances. They are merely a summation of field experience. They are not derived from controlled experiments or rigid reasoning. Despite the apparently severe qualifications that have been applied to these statements, if they are used with care and with complete appreciation of the theory of galvanic corrosion, most corrosion problems can be evaluated successfully.

COATED CROSS-COUNTRY PIPELINE WITHOUT CATHODIC PROTECTION

The potential measurements shown in Table 1-2 were recorded during a pipe-to-soil potential survey along a portion of a well-coated, cross-country pipeline. Examining the data in the table we see that about one-half of the readings/locations fall in the range as indicated in statement 5, measurements at five of the metering and regulator stations were less negative than those given in statement 5. (The potential of -780 mV at location 31 is slightly more negative than the range given in statement 5, but as indicated in that statement, higher negative potentials are possible on newly installed, well-coated pipes.)

The low negative potentials at the metering and regulator stations prompted a more detailed investigation.

This investigation found that the isolators that had been installed at those stations were shorted, and thus, the coated line was directly coupled to older uncoated distribution piping at those locations.

TABLE 1-2

Potential Measurements

Test Station Location No.	Description of Location	Pipe-to-Soil Potential (mV to CSE)
21	Crestdale Regulator Station	-703
22	North side of Blue River on Rt. 95	-700
24	South side of Blue River	-735
26	Linden Metering Station	-542
26	Valve box approximately 7.8 miles South of Blue River	-730
28	Creek, 10.2 miles south of Blue River	-674
30	Atlantic Regulator Station	-563
31	Glendale Metering Station	-780
32	Crossing of railroad near Glendale	-506
33	Forest Park Regulator No. 1	-480
35	Forest Park Regulator No. 2	-537

Statements 1 and 2 indicate that older, bare lines are of lower negative potentials than newer, coated lines. The coupling of the coated line to the bare line makes the potentials on the coated line less negative at the shorted meter and regulator stations than along the balance of the pipeline. This situation shows the importance of placing isolating flanges between new coated pipe and older bare pipe. This isolation is needed whether or not cathodic protection is provided for the coated line. If cathodic protection is not provided, the new coated pipe will be anodic with respect to the older, bare pipe. Thus, if there were no isolating flange installed between the two sections, or if the flange were shorted, the newer coated section of pipe would be subjected to accelerated galvanic corrosion attack. When using isolating flanges or devices, safety precautions must be followed to prevent a spark or arc across the isolator during a fault or power surge or static discharge. Devices exist that will maintain DC isolation while acting as a shunt under the above conditions.

GAS SERVICE LINE

The previous example shows the need for a thorough investigation of a situation where there is an apparent contradiction between the measurements taken and the statements listed. The next example illustrates this need in a slightly more complicated situation. In this example, we have gas service lines in a housing development. The original service lines had been installed without coating, and failures began to appear after five years. The lines which failed were replaced with coated steel pipes, and some of the replacement pipe developed leaks within only two years of service. A potential survey conducted on the system found a range of potentials from -250 to -350 mV on the new coated replacement lines and potentials ranging from -500 to -600 mV on the older bare lines.

Examination of these data tends to indicate a contradiction to statements 1, 2, and 5. Upon closer inspection however, it was discovered that the water service lines in the development were electrically continuous with the gas service lines. Copper, being cathodic with respect to steel, will when connected to a steel pipe, cause the potential of the steel pipe to become less negative than its natural potential. Because of area relationships (the ratio of areas of copper to steel is greater when the steel is coated than when it is bare), the effect of copper on the potential of coated steel pipe will be far greater than that on the potential of bare pipes.

GROUNDING SYSTEM

The next example involves a somewhat similar situation as the previous example, but an extensive copper electrical grounding system is involved rather than copper pipes. A potential profile was conducted on a newly installed, underground, coated steel pipe. The over-the-line potentials were in the range of -600 to -700 mV, which seems to be in accordance with the previous statements. An off-the-line potential profile was also conducted on the line. Interestingly, the two profiles were nearly identical.

Potential profiles were also conducted along another newly installed, well coated pipeline in a similar environment. In this case, however, there was an extensive grounding system installed along the pipeline and electrically connected to it. The grounding system consisted of copper mats installed at 50 foot intervals. The potentials measured along the pipeline were considerably less negative than expected along a coated pipe. All the potentials were less negative than -500 mV, and at some locations the potentials were less negative than -300 mV. In addition, the off-the- line potentials were considerably less negative than the over-the-pipe potentials.

These low negative potential levels and the lateral potential gradients are directly attributable to the copper grounding system and indicate that severe bimetallic (galvanic) corrosion activity exists. In fact, the condition at this plant was so severe that leaks developed within the first year of operation even though the pipeline was extremely well-coated and had been backfilled with sand. The very good coating no doubt contributed to the rapid development of leaks on the pipeline due to the concentration of current discharge at holidays in the coating. The corrosion current was generated by the bimetallic coupling.

STEEL GAS AND WATER LINES

In the examples given thus far, it is possible that the bimetallic effect of copper could have been anticipated without having a complete knowledge of the potential pattern. The next example, however, describes a situation which is like a bimetallic corrosion pattern but where there is no copper present. This example involves a group of school buildings. Leaks occurred on these pipes within the first year, and these leaks were attributed to the very corrosive soil in which resistivity was less than 100 ohm-centimeters. However, potential measurements taken on the gas and water lines were all in the range of -350 to -450 mV. If the corrosion activity was one of straightforward galvanic action resulting from the corrosiveness of the soil, these potentials would be considered as very cathodic and, therefore, not indicative of a very corrosive condition. Therefore, it was difficult to reconcile the very severe corrosion history with the apparent cathodic potentials.

Because the soil at this location was very alkaline, somewhat lower potentials than normal would be expected. However, the very low negative potentials at this site could not be entirely attributed to the alkaline soil. More detailed investigation found that the low potentials on the gas and water lines were caused by the radiant heat piping under each of the buildings. Although the radiant heat lines were also steel, they were installed in concrete, and the normal potential of steel in concrete is approximately -200 mV, versus the normal -500 to -600 mV potential of steel in earth. The electrical coupling of the gas and water lines in the soil to the radiant heat lines in the concrete (there were common structural connections in the boiler room) made the potential on the gas and water lines less negative than normal. These gas and water lines thus behaved as the anode in a mechanism which is similar to a bimetallic couple. The conditions which made this couple particularly severe were the low resistivity soil, the proximity of the gas and water lines to the radiant heat lines, and the fact that the area of the gas and water lines was small compared to the area of the radiant heat lines. This area relationship was made still worse by the fact that the gas and water lines were coated.

The examples given show how the pipe-to-soil potential measurement can be used in analyzing a corrosion problem. These examples further show the need for learning as much about the structure under investigation as possible and about any other structures in the area. The remaining part of this chapter deals with the current NACE criteria for cathodic protection of steel and cast iron structures and some of their applications.

CRITERIA FOR CATHODIC PROTECTION

Although cathodic protection criteria were discussed in the Intermediate Course it is such an important topic that a review is in order.

Criteria for adequate cathodic protection of buried metallic piping systems can be found in several sources including:

- NACE Standard Practice SP0169-2013 "Control of External Corrosion on Underground or Submerged Metallic Piping Systems"
- ISO 15589-1:2015 “Petroleum, petrochemical and natural gas industries -- Cathodic protection of pipeline systems -- Part 1: On-land Pipelines”
- Part 192 “ Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards” Appendix D

- Part 195 “Transportation of Hazardous Liquids by Pipeline” §195.571

We are going to review the criteria as listed in NACE Standard Practice SP0169-2013.

Paragraph 6.1.1 of SP0169-2013 states "This section lists criteria for CP that indicate whether adequate CP of a metallic piping system has been achieved." SP0169-2013 lists three (3) main criteria for the cathodic protection of steel and cast iron structures. These criteria are as follows:

6.2.1.1 Criteria that have been documented through empirical evidence to indicate corrosion control effectiveness on specific piping systems may be used on those piping systems or others with the same characteristics.

6.2.1.2 A minimum of 100 mV of cathodic polarization. Either the formation or the decay of polarization can be measured to satisfy this criterion.

6.2.1.3 A structure-to-electrolyte potential of -850 mV or more negative as measured with respect to a saturated copper/copper sulfate (CSE) reference electrode. This potential may be a direct measurement of the polarized potential or a current-applied potential. Interpretation of a current-applied measurement requires consideration of the significance of voltage drops in the earth and metallic paths.

The criteria listed for steel and cast iron, as well as the criteria given for other metals, require pipe-to-soil potential measurements. When these criteria are to be applied in a particular situation and potential measurements are taken, a number of questions that are not always precisely answerable arise:

- Which criterion or criteria are applicable to the particular corrosion mechanism?
- Where should the reference electrode be placed to obtain valid readings?
- How many readings are required to obtain an accurate representation of the entire pipeline or piping network?

Which Criterion?

The selection of the criterion to use should be governed not merely by what is most convenient for the user. It should be recognized as a function of the particular corrosion mechanism being considered.

Let's look at the 3 criteria in the opposite order of how they appear in the standard.

Structure-to-Electrolyte Potential of -850 mV or More Negative

6.2.1.3 A structure-to-electrolyte potential of -850 mV or more negative as measured with respect to a saturated copper/copper sulfate (CSE) reference electrode. This potential may be a direct measurement of the polarized potential or a current-applied potential. Interpretation of a current-applied measurement requires consideration of the significance of voltage drops in the earth and metallic paths.

This section can be looked at as 2 separate criteria: "a direct measurement of the polarized potential" or "a current-applied potential" with "consideration of the significance of voltage drops in the earth and metallic paths."

Current-Applied Measurement of -850 mV or More Negative

A current-applied measurement of -850 mV has historically been the most widely used criterion for determining if an acceptable degree of cathodic protection has been achieved.

Some sources indicate that this criterion was developed from the fact that the most negative native potential found for coated steel was -800 mV. Therefore, the assumption was made that if sufficient current is applied to change the potential of the entire structure to a value more negative than the open circuit potential, then the effects of corrosion will be mitigated. A potential of -850 mV to CSE was therefore adopted.

As stated in the criterion "Interpretation of a current-applied measurement requires consideration of the significance of voltage drops in the earth and metallic paths".

SP0169-2013 lists several methods for consideration of voltage drops including:

- Measuring or calculating the voltage drop(s)
- Reviewing the historical performance of the cathodic protection system
- Determining whether there is physical evidence of corrosion
- Evaluating the physical and electrical characteristics of the pipe and its

environment

- Evaluation of indirect inspection data, such as above-grade electrical surveys, in-line inspections and direct assessment

- The use of coupons

Voltage drops in the earth can be reduced by placing the reference electrode as close to the pipe surface as possible. It should be noted that this means "electrically" close, not just "physically" close. A reference electrode placed physically close to a well-coated pipeline is not electrically close to it and voltage drops are not reduced.

Voltage drops are more prevalent near an anode bed or in areas where dynamic stray currents are present. Unusually high resistivity soil will also cause high voltage drops. In areas where dynamic stray currents are present, an instantaneous reading may be impossible to accurately record and therefore meaningless. The use of voltage recording instruments is recommended so as to obtain potential values over a 24-hour period, or at least during the known period of highest stray current activity. Often it is possible to obtain fairly stable potentials of the piping system once the DC transit system stops operating in the early morning hours if recording instruments are left in place overnight. These potentials can provide a base-line from which to evaluate other measurements.

The -850 mV current-applied criterion is the one which is almost always used in areas with significant dynamic stray current activity. It is generally accepted that if the potential of the structure to a CSE remains more negative than -850 mV at all times, even if there are substantial fluctuations in potential with time, then the pipe can be considered protected at that particular test point. It is possible that the amount of test points surveyed and the frequency at which those surveys are performed may have to increase in heavy stray current areas due to ever-changing conditions.

Limitations of the -850 mV Current-Applied Potential

The primary limitation of using a current-applied potential is that the voltage drop component in the potential measurement has to be considered.

Direct Measurement of the Polarized Potential of -850 mV

The criterion also allows for "a direct measurement of the polarized potential".

This can be done by interrupting all sources of cathodic protection current and measuring the "off" potential. The instantaneous "off" potential should be free of voltage drop error.

A polarized potential is defined in Section 2 of SP0169-2013 as "The potential across the electrode/electrolyte interface that is the sum of the corrosion potential and the applied polarization". The difference in potential between the static or native potential and this polarized (instant off) potential would be the amount of polarization that has occurred due to the operation of the cathodic protection system. In the same section of SP0169-2013 polarization is defined as, "The change from the open-circuit potential as a result of current across the electrode/electrolyte interface."

Limitations of a Direct Measurement of the Polarized Potential

The primary limitation of a direct measurement of the polarized potential is that it may be impractical to interrupt all sources of cathodic protection current. This is especially true of systems protected by multiple galvanic anodes.

Polarized potentials well in excess of -850 mV should be avoided for coated structures in order to minimize the possibility of cathodic disbondment of the coating. SP0169-2013 also warns that, "Polarized potentials that result in excessive generation of atomic hydrogen should be avoided on all metals susceptible to hydrogen embrittlement."

100 mV of Cathodic Polarization

6.2.1.2 A minimum of 100 mV of cathodic polarization. Either the formation or the decay of polarization can be measured to satisfy this criterion

The 100 mV polarization criterion, like the -850 mV polarized potential, is based on the development of polarization. This causes the structure to exhibit a more negative potential than in its native state.

Measurement of the polarization shift can be determined by either measuring its formation or decay. Determination of the amount of polarization is normally made during the polarization decay (positive shift) period subsequent to de-energizing the cathodic system, or in the case of galvanic anodes, when they are disconnected. When the cathodic protection system is de-energized, there is an immediate rapid drop of potential. The polarization decay does not include this drop. The potential of the structure after this initial rapid drop is recorded and used as a basis for determining the polarization shift. To obtain the total polarization shift, the final potential after polarization decay has taken place is measured and subtracted from the potential read immediately after the cathodic system has been turned off or disconnected. If this total shift is 100 mV or more, the structure is considered to be cathodically protected.

One drawback of this method is that the time required for full depolarization could take from hours to days for a coated structure to several weeks for a bare structure. This could make this method very time consuming and might also leave the structure unprotected for an extended period of time. Normally however, the bulk of the depolarization will take place in the initial phase of the polarization decay. Therefore, it may not be necessary to wait the full decay period except in those cases in which the total actual polarization shift of the structure is relatively close to 100 mV. If, during the early phase of the polarization decay measurement the potential drops 100 mV or more, there is no need to wait for further de-polarization unless the actual value is desired. If, on the other hand, the potential drop in the initial phase of the decay period is only on the order of 50 to 60 mV, it may be doubtful that the 100 mV shift will occur. In this case, a determination should be made as to whether a longer wait for total depolarization is required and justifiable.

In order to determine the formation of polarization, it is first necessary to obtain static or native potentials (before the application of cathodic protection current) on the structure at a sufficient number of test locations. Once the protection system is energized and the structure has had time to polarize, these potential measurements are repeated with the current source interrupted. The amount of polarization formation can then be determined by comparing the static potentials with the "instant off" potentials.

Applications of the 100 mV Polarization Criterion

In many cases, the cost of the power required to achieve the 100 mV polarization criterion may be less than that required to obtain either a current-applied potential of -850 mV or a polarized potential of -850 mV. Further, the polarized potential corresponding to 100 mV of polarization may be less negative than -850 mV. This criterion takes into account only the polarization film on the pipe surface and is independent of any voltage (IR) drops in the soil or at the structure electrolyte interface. This criterion should not be used in areas subject to stray currents because any outside interference would tend to break down the polarization at the point of discharge. The results obtained under these conditions could be misleading. Corrosion personnel must determine the effectiveness of this criterion in areas of stray current activity.

The 100 mV polarization criterion is mostly used on poorly coated or bare structures and in some instances could be useful in large pipe networks as in compressor and regulating stations where the cost of a cathodic protection system to achieve either a -850 mV current-applied or polarized potential may be prohibitive. However, in an economic analysis, the additional cost of conducting future periodic surveys has to be taken into account; as the use of the 100 mV criterion is somewhat more complicated and costly than the use of the -850 mV current-applied criteria.

This criterion can be used on metals other than steel where there could be some question as to what specific potential to use as an indication of protection. This criterion is often used for those installations where it is impractical to meet either of the -850 mV criterion.

In piping networks, where new pipe is coupled to old pipe, it may be good practice to use the -850 mV polarized potential criterion for the new pipes and the 100 mV polarization criterion for the older pipes.

Limitations of the 100 mV Polarization Criterion

The limitations for the 100 mV polarization criterion are as follows:

- Interrupting all DC current sources is not always possible.
- Stray current potential variations can make this criterion difficult to measure.
- If dissimilar metals are coupled in the system, protection may not be complete on the anodic metal.
- Another limitation is related to the time required for the pipe to depolarize. In some cases, adequate time may not be available to monitor the polarization decay of the pipe to the point where the criterion could have been met.

Cathodic Protection Coupons

A cathodic protection coupon is metal sample that is intended to represent a structure at a coating holiday. The coupon has a lead wire attached to it which is normally bonded to the structure through a test station so that it receives cathodic protection current just as the structure does at a coating holiday. Cathodic protection coupons are used to help determine the level of cathodic protection of a buried or submerged metallic structure.

Tests that can be made with cathodic protection coupons include:

- measuring the coupon-to-soil potential with the coupon connected to the structure,
- measuring the coupon-to-soil potential after disconnecting the coupon from the structure (coupon instant-disconnect potential),
- measuring the current flow between the coupon and the structure.

The coupon-to-soil potential is typically measured with the reference electrode in close proximity to the coupon. This is accomplished by the use of a permanently installed reference electrode near the coupon or by placing a portable reference electrode in a soil-access tube.

Measurements made with coupons can help determine if a criterion has been met:

- Since the coupon-to-soil potential is measured with the reference electrode in close proximity to the coupon, the voltage drop is minimized for a current-applied potential.
- Measuring the coupon-to-soil potential after disconnecting the coupon from the structure is a way of interrupting all sources of cathodic protection current in order to obtain a direct measurement of the polarized potential.
- Measuring the coupon-to-soil potential after disconnecting the coupon from the structure is a way of interrupting all sources of cathodic protection current in order to obtain an “off” reading to be used in determining the level of polarization.

These measurements are especially useful in the situations where interrupting all sources of cathodic protection current is impractical.

Other Criteria

6.2.1.1 Criteria that have been documented through empirical evidence to indicate corrosion control effectiveness on specific piping systems may be used on those piping systems or others with the same characteristics.

This section allows a practitioner to continue using criteria that have been applied successfully in the past but are no longer specifically listed in SP0169. Some examples of criteria that have been used in the past are:

- Net Protective Current
- E-log-I Method
- 300 mV Potential Shift

Net Protective Current Criterion

This criterion had been listed in SP0169-2007 under a special conditions section to cover those situations for bare or ineffectively coated pipelines where it appears that long line corrosion activity is the primary concern.

This protection criterion is based on the premise that if the net current at any point on a structure is flowing from the electrolyte to the structure, there cannot be any corrosion current discharging from the structure to the electrolyte at that point. The principle is based on first locating points of active corrosion and then measuring current flow to or from the structure.

Some pipeline companies use the side drain method for application of this criterion on the basis that if the polarity of the voltage readings on each side of the structure indicates current flow towards the structure, then the structure is receiving protective current. If the electrode located over the pipe is positive with respect to the other two electrodes, then current is discharging from the pipe to the electrolyte and corrosion is taking place.

The above statement is considered correct as long as there are no outside sources of influence such as other pipelines or other gradient sources such as stray currents. In cases where other gradient sources exist, the results could be misleading. The results might also be questionable in areas with high resistivity surface soil, for deeply buried pipelines, or where local corrosion cell exists.

Applications of the Net Protective Current Criterion

This criterion is normally used on uncoated structures. The "side drain' surface method is normally used in cases of single isolated pipelines to obtain an indication of whether the pipeline was receiving cathodic protection. If the electrodes that are placed perpendicular to the pipeline (remote) are positive in relation to the electrode over the pipeline, it was assumed that current is flowing toward the pipe.

In cases where there are sources of outside gradients, it may be difficult to evaluate the results of these tests properly.

Limitations of the Net Protective Current Criterion

The use of this criterion is to be avoided in areas of stray current activity because potential variations could interfere with its use. Also, extreme care must be taken in common pipeline corridors because other gradient sources may exist that could result in erroneous or misleading measurements.

Even though the results indicate a net current flow towards the pipe/structure, that net current flow is indicative only of what is happening at the specific point of test and does not represent what may be happening at other points on the pipeline/structure. Pipeline companies that use the side drain method for application of this criterion, normally require that tests be conducted at close intervals (2 to 20 feet along the pipeline).

E-log-I Method

The E-log-I method is not so much a criterion of protection as it is a means of determining the correct amount of cathodic protection current required for a structure. Being complicated in application, the E-log-I method is limited to specialized applications where other methods may be inadequate.

Applications of the E-log-I Method

The E-log-I method is not generally used by itself to evaluate existing cathodic protection systems. Its primary use is to determine the potential value, measured with respect to a reference electrode, which will give a specific minimum current value required for protection. This potential value is to be at least as negative (cathodic) as that originally measured at the beginning of the Tafel segment of the E-log-I curve.

Once the current value and the potential to a remote electrode have been established, future surveys consist of checking the current output of the cathodic protection system and the potential of the structure to a remote electrode. It is important that the reference electrode be in the same place where it was located during the E-log-I tests. Because the test method involved is rather elaborate, the use of this method is generally limited to structures where conventional means of determining current requirements would be difficult. Examples of such structures are pipeline river crossings, well casings, piping networks in a concentrated area, and in industrial parks.

Limitations of the E-log-I Method

The main limitation of this technique is that testing is elaborate, thus making it relatively slow in comparison to that required for other criteria. Future tests are relatively simple, however. The remote reference electrode must be located exactly at the same locations where it was placed during the E-log-I tests. Because the E-log-I method is time dependent, there is no guarantee that a repeat E-log I test will yield the same minimum potential or current for protection as an earlier curve.

Using this criterion in areas where stray currents are present could result in erroneous results as the stray currents may affect the readings and make obtaining a good polarization curve impossible due to the fluctuations in the structure potential.

For information on how to perform an E-log-I test refer to SP0186-2007 "Application of Cathodic Protection for External Surfaces of Steel Well Casings".

300 mV Potential Shift Criterion

As opposed to working toward a certain minimum potential value to a reference electrode as discussed in some of the previous sections, the 300 mV potential shift criterion is based on changing the potential of the structure in the negative direction by a specified minimum amount. The minimum potential shift for steel, as used in the past is 300 mV. Any stable reference electrode may be used with this criterion because the method consists of measuring a potential shift and is independent of the actual potential of the electrode. Determination of the voltage shift is made with the protective current applied.

The development of this criterion appears to have been largely empirical or experimental in nature. Although 300 mV is the figure commonly used now, other values such as 200 or 250 mV have also been used in the past. There were, however, two considerations that supported this criterion, recognizing that corrosion prevention still may not be 100% complete.

The first consideration was that 300 mV may be greater than the driving potential of most of the galvanic cells on a structure to be protected. By shifting the structure in the negative direction by 300 mV, the majority of the cells should be overcome.

The second consideration was based on tests conducted by Marcel Pourbaix. His work showed that if a protective potential applied to a structure is made more negative by equal increments starting from the natural or static potential, the first increment would yield the greatest reduction in corrosion rate and subsequent increments would result in progressively smaller reductions in the corrosion rate per increment. Experience indicated that the 300 mV shift encompassed sufficient reduction in the rate of corrosion to make it a somewhat effective criterion for practical applications.

Later evaluation of this criterion by a NACE committee concluded that the actual measurements or shift was not representative of what was occurring on the surface of the structure. This is because when a cathodic protection system is energized, an immediate shift of potential, due to a voltage (IR) drop, will be seen. In this particular application, this voltage drop value is included in the measured shift.

Applications of the 300 mV Potential Shift Criterion

This criterion has been used for entire structures and for hot-spot protection. It is mainly used for bare steel structures which have undergone a slow uniform corrosion rate due to their age. These structures/pipelines normally have a natural potential range from about -200 mV to -500 mV as a result of oxidation products developing on the external surfaces. This criterion has also been used on some coated pipelines where soil conditions alter the natural or static potential of the steel to -500 mV or lower. In this case, the 300 mV shift may also be easier to attain than achieving a potential reading of -850 mV, and could be expected to stop the majority of corrosion.

The 300 mV potential shift criterion is almost always more applicable to impressed current systems than galvanic anode systems. The reason is that the native state potential may be such that a limited number of galvanic anodes will not produce the required change of potential on the structure to be protected.

Limitations of the 300 mV Potential Shift Criterion

The 300 mV potential shift in some instances is impractical to use and in other cases, may not correctly indicate the level of cathodic protection achieved. Some galvanic cells may still be active even after the 300 mV shift is obtained and there could be areas between adjacent structure to electrolyte readings where the 300 mV shift is not being attained. Furthermore, a pipeline subject to stray currents could have positive potentials with respect to a CSE even after the pipe potential is shifted in the negative direction by 300 mV. If the potential of the structure is fluctuating more than the shift required, this criterion cannot be valid.

If the steel structure is coupled to a more noble metal, a 300 mV shift might indicate that much of the adverse effect produced by the dissimilar metal union has been overcome, but it would not necessarily indicate that complete cathodic protection is being provided to the steel structure/pipeline itself.

USE OF CRITERIA

It must be noted that there will be situations or conditions where a single criterion cannot be used to evaluate the effectiveness of a cathodic protection system and it is necessary to employ a combination of criteria.

REFERENCES

1. NACE Standard Practice SP0169-2013 "Control of External Corrosion on Underground or Submerged Metallic Piping Systems", NACE International, Houston, Texas

Chapter 2 - Evaluation of Underground Coatings Using Aboveground Techniques

INTRODUCTION

This chapter describes the indirect inspection methods intended for use as part of the External Corrosion Direct Assessment (ECDA) process for detecting coating flaws and determining cathodic protection levels on buried pipelines. These methods are often more laborious than surveys completed as part of normal daily operating practices as a result of the requirement for precise data set alignment. Standard pipeline surveys generally investigate data trends over time or pipeline distance, while ECDA surveys look for small data variations over short distances.

This chapter describes the methods of conducting the following surveys for above grade indirect inspections. Other inspection methods can and should be used as required by the unique situations along a pipeline. The techniques described herein are not intended to illustrate the only methods by which these tools can be applied.

- *Pipeline Locating* is used to establish the location and centerline of the pipeline.

- *Direct Current Voltage Gradient (DCVG) Surveys* are used to locate and size coating holidays.

- *Alternating Current Voltage Gradient (ACVG) Surveys* are used to locate and size coating holidays.

- *Close-Interval Surveys (CIS)* are used to determine cathodic protection (CP) levels, electrical shorts to other structures, static stray current conditions, and large coating holidays.

- *Alternating Current (AC) Attenuation Surveys* are used to assess coating quality and to detect and compare coating anomalies.

SURVEY SEQUENCE

The sequence in which the surveys are conducted is crucial to optimizing the survey techniques and data analysis. Coating holiday surveys (DCVG and ACVG) and AC attenuation surveys should be completed prior to a CIS survey. With surveys completed in this manner, pipe to electrolyte potentials can be measured directly above the coating holiday indications found using the DCVG or ACVG method.

Some ECDA surveys require existing CP systems to be turned off, the rectifier outputs increased, or systems disconnected. Structure potentials should be measured and recorded at sufficient locations to demonstrate that the pipeline has returned to the original level of polarization prior to completion of additional surveys that may be influenced by these actions. The structure potentials should be measured before and after these activities have taken place.

REFERENCED PROCEDURES

Additional information regarding the techniques cited in this chapter can be found in the latest revisions of the following documents:

- NACE/CEA 54277, Specialized Surveys for Buried Pipelines 1988
- NACE Standard TM0497, Measurement Techniques Related to Criteria for Cathodic Protection on Underground or Submerged Metallic Piping Systems
- NACE Standard SP0169, Control of External Corrosion on Underground or Submerged Metallic Piping Systems
- NACE Standard SP0177, Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems

DEFINITIONS

a) Anomaly: Any deviation from nominal conditions in the external wall of a pipe, its coating, or the electromagnetic condition around the pipe.

b) Cathodic Protection (CP): A technique to reduce the corrosion of a metal surface by making the surface the cathode of an electrochemical cell.

c) Close-Interval Survey (CIS): A method of measuring the potential between the pipe and earth at regular intervals along the pipeline.

d) Corrosion: The deterioration of a material, usually a metal that results from a reaction with its environment.

e) Disbonded Coating: Any loss of adhesion between the protective coating and a pipe surface as a result of adhesive failure, chemical attack, mechanical damage, hydrogen concentrations, surface preparation and application problems, etc. Disbonded coating may or may not be associated with a coating holiday.

f) ECDA Region: A section or sections of pipeline that have similar physical characteristics and operating history and in which the same indirect inspection tools are used.

g) Electrolyte: A chemical substance containing ions that migrate in an electric field. For the purposes of this chapter, 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.

h) Electromagnetic Inspection Technique: An aboveground survey technique used to locate coating defects on buried pipelines by measuring changes in the magnetic field that are caused by the defects.

i) External Corrosion Direct Assessment (ECDA): A four-step process that combines pre-assessment, indirect inspections, direct examinations, and post assessment to evaluate the impact of external corrosion on the integrity of a pipeline.

j) Fault: Any anomaly in the coating, including disbonded areas and holidays.

k) Holiday: A discontinuity (hole) in a protective coating that exposes the structure surface to the environment.

l) Indication: Any deviation from the norm as measured by an indirect inspection tool.

m) Indirect Inspection: Equipment and practices used to take measurements at ground surface above or near a pipeline to locate or characterize corrosion activity, coating holidays, or other anomalies.

n) IR Drop: The voltage difference between the On and Off pipe to soil potential.

o) Microbiologically Influenced Corrosion (MIC): Localized corrosion resulting from the presence and activities of microorganisms, including bacteria and fungi.

p) Pipe-to-Electrolyte Potential: See Structure-to-Electrolyte Potential.

q) Pipe-to-Soil Potential: See Structure-to-Electrolyte Potential.

r) Region: See ECDA Region.

s) Structure-to-Electrolyte Potential: The potential difference between the surface of a buried or submerged metallic structure and the electrolyte that is measured with reference to an electrode in contact with the electrolyte.

SAFETY CONSIDERATIONS

Appropriate safety precautions, including the following, should be observed when making electrical measurements.

- Be knowledgeable and qualified in electrical safety precautions before installing, adjusting, repairing, removing, or testing impressed current cathodic protection equipment.

- Use properly insulated test lead clips and terminals to avoid contact with an unanticipated high voltage (HV). Attach test clips one at a time using the single-hand technique for each connection.

- Use caution when long test leads are extended near overhead high-voltage alternating current (HVAC) power lines, which can induce hazardous voltages onto the test leads. Refer to NACE Standard SP0177 for additional information about electrical safety.

- Use caution when performing tests at electrical isolation devices. Before proceeding with further tests, use appropriate voltage-detection instruments or voltmeters with insulated test leads to determine whether hazardous voltages, both AC and DC, may exist.

- Avoid testing when thunderstorms are in the area. Remote lightning strikes can create hazardous voltage surges that travel along the pipeline.

- Use caution when stringing test leads across streets, roads, and other locations subject to vehicular and pedestrian traffic. When conditions warrant, use appropriate barricades, flagging, and/or flag persons.

- Observe appropriate Company safety procedures, electrical codes, and applicable safety regulations.

PIPELINE LOCATING

The pipeline must be located and marked to ensure that subsequent measurements are made directly above the pipeline. An inductive or conductive pipe locating device can be used. The pipe should be located within six (6) inches perpendicular of the pipe centerline and survey flags or paint marks placed directly above the pipeline every 100 feet using a slack chain distance technique or a measuring wheel. Slack chain stationing error shall be no more than 2% +/-.

The locating flags/paint marks can be numbered using a permanent marker by writing the flag number directly on the flag or painting the flag number on the ground. Numbering of the 100 foot stations will ensure that the different indirect survey techniques will be perfectly aligned by using the flag locations as the point of alignment.

The pipeline should be stationed beginning with 0+00 at the initial ECDA region and should progress in increasing station numbers in the direction of gas/product flow. The pipeline stationing should be reset to 0+00 at each following ECDA region start. As an alternative, actual pipeline as-built stationing can be used. With this method, the actual pipeline stationing is used for the initial start of the ECDA region and stationing continued until the end of the ECDA region.

DIRECT CURRENT VOLTAGE GRADIENT SURVEYS (DCVG)

Direct current voltage gradient (DCVG) surveys are used to evaluate the coating condition on buried pipelines. Voltage gradients arise as a result of current pickup or discharge at coating holidays. In a DCVG survey, the DC signal is created by interrupting the pipeline’s CP current or a temporary CP current, and the voltage gradient in the soil above the pipeline is measured. Voltage gradients are located by a change in the interrupted signal strength at grade.

DCVG is the only method that can be used to approximate the size of a coating holiday. DCVG signal strength is not always proportional to holiday size, as the orientation of the holiday and other factors affect the measured signal.

DCVG surveys are capable of distinguishing between isolated and continuous coating damage. The shape of the gradient field surrounding a holiday provides this information.

PIPELINE LOCATING CREW CLEARING PATH AND MARKING PIPELINE CENTERLINE

FIGURE 2-1

PIPELINE LOCATION STATIONING FLAGS NUMBERED FOR PRECISE DATA ALIGNMENT

FIGURE 2-2

Isolated holidays, such as rock damage, produce fairly concentric gradient patterns in the soil. Continuous coating damage, such as disbonded coatings or cracking, produces elongated patterns.

The DCVG system consists of a current interrupter, an analog or digital voltmeter, connection cables, and two probes with electrodes filled with water. The interrupter is used to interrupt current from an existing rectifier unit, galvanic anode system, or a temporary CP system installed for the purpose of the DCVG survey.

An analog voltmeter must have a needle with the ability to deflect in both the positive and negative directions from the zero point, which assists in determining the direction the current is flowing in the soil. Digital voltmeters must be sufficiently sensitive to measure 1 mV changes between the two reference probes and have the ability to indicate the direction of current flow in the soil. The voltmeter should have the ability to adjust the input impedance for use in high resistance contact situations.

The current interrupter is installed in series with the current source and set to cycle at a fast rate with the "on" period less than the "off" period. A common interruption cycle is 0.3 seconds on and 0.7 seconds off. This short cycle allows for a quick deflection by the analog voltmeter needle.

DCVG surveys can be performed with impressed current CP systems energized. Sacrificial anodes and bonds that are not disconnected show up as anomalies. Sacrificial anodes and bonds to other structures are usually disconnected to prevent signal loss and enhance current flow down the pipeline under investigation.

The IR drop is measured at the test stations in the proximity of the DCVG survey. It is desirable to have a minimum of 100 to 400 mV of IR drop in soil environments and more IR drop when surveying on asphalt/concrete, in the section of pipeline to be surveyed. If at the estimated daily survey section limits there is not a 100 to 400 mV IR drop, then the current output of the CP current source should be increased to achieve the desired result. If the output cannot be increased, then the section of pipe with the 100 to 400 mV IR drop is the only section that can be surveyed using that CP current source. Alternative CP current sources may need to be temporarily installed in order to achieve the desired IR drop. It is desirable to have as large an IR drop value as can be achieved. This will enable the surveyor to detect small holidays distant from the CP current source.

A surveyor walks along the pipeline such that the probes can be used in a walking stick fashion. One probe is always kept near the pipeline center line while the other is held approximately five (5) feet away perpendicular to the pipe. The voltmeter is read when both probes are in contact with the soil.

If possible, the pipeline under investigation should be electrically isolated from other parallel metallic structures by disconnecting electrical bonds, negative drains to rectifiers, etc. In pipeline right of ways with multiple electrically continuous pipelines or metallic conduits/structures, variations in the survey technique must be considered. For example, if parallel pipelines (metallic structures) are less than ten (10) feet from the pipeline under investigation, then the perpendicular probe should be placed at half the distance between the two pipelines, however, difficulties may be encountered with current flow to the parallel metallic structure. The perpendicular probe must be placed on the side of the investigated pipeline without a parallel pipeline (metallic structure). If the pipeline under investigation has pipelines (metallic structures) on either side, then the probe should be placed perpendicular, but not above or in close proximity to the parallel pipeline (metallic structures).

If the voltmeter indicates a coating holiday, additional measurements should be made to confirm the coating holiday is on the pipeline under investigation and not the parallel pipeline. These tests include gradient measurements on both sides of the pipeline and parallel with the pipeline under investigation to confirm the coating holiday location.

When parallel metallic structures or right of way conditions do not allow sufficient room for placement of the probe to the side of the pipeline, an alternate method of DCVG can be conducted. Place both probes directly above the pipe centerline approximately five to ten feet apart from one another and measure the voltage gradient in this manner. Leap frog the rear probe to the forward position and repeat the process continuing along the right of way directly above the pipe. Care must be taken to pinpoint the maximum deflection or indication when completing the survey in this manner. The exact location of the indication requires moving the probes at closer spacings once the coating holiday is detected.

When a coating holiday is approached, a noticeable signal swing can be observed on the voltmeter at the same rate as the interrupter switching cycle. The amplitude of the swing increases as the coating holiday is approached and decreases after it has been passed. Current flow from the interrupted current source to the pipeline indicates a possible coating holiday while current flow away from the pipeline indicates current flow past the pipeline.

When a coating holiday is found, additional gradient measurements can be beneficial to confirm its location and that the indication is not current traveling past the pipeline. These gradient measurements can be made on both sides of the pipe and parallel with the pipe on each side of the assumed coating holiday.

A straight-line attenuation effect is assumed between test station locations to calculate the signal strength at intermediate coating holiday locations. In order to calculate the coating holiday size (%IR), the difference between the on and off potentials at each test station, valve, or other above grade appurtenance must be measured and recorded.

One reference electrode is placed at the base of the test station or other electrical contact point, in contact with the soil while the second electrode porous tip contacts the test station wire or other properly cleaned electrical contact point. The maximum analog needle deflection is the test station IR drop or difference between the on and off potentials when using a digital voltmeter.

The distance between test stations or points of electrical contact must be determined from the pipeline stationing and used in the calculations for the signal attenuation.

An example of the attenuation calculations can be seen below:

$$\begin{aligned}\text{On potential} &= -1.45\text{ V}\\ \text{Off potential} &= -0.95\text{ V}\\ \text{Signal Strength} &= 1.45 - 0.95\text{ V}\\ &= 0.5\text{ V or }500\text{ mV}\end{aligned}$$

The estimated signal strength can be exemplified by using the data presented in Figure 2-6.

Estimated signal strength at defect:

$$= 200\text{ mV} + \left[\frac{1500}{500 + 1500}(300 - 200)\right]\text{ mV}$$

$$= 200\text{ mV} + 75\text{ mV}$$

$$= 275\text{ mV}$$

ANALOG DCVG METER

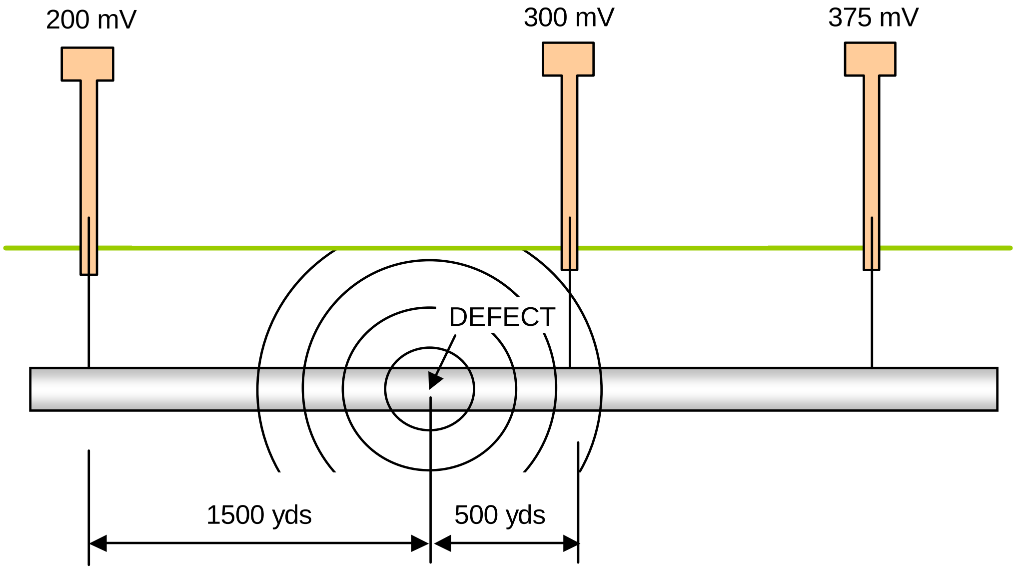
FIGURE 2-3

DCVG SURVEYOR MEASURING VOLTAGE GRADIENT
ABOVE PIPELINE

FIGURE 2-4

DCVG SURVEY COMPLETED ON WET ASPHALT IN MAJOR CITY

FIGURE 2-5



DCVG SIGNAL STRENGTH

FIGURE 2-6

Precisely locating a coating holiday is achieved by marking the approximate location of the holiday at the area where the maximum amplitude is indicated. Near the approximate coating holiday location and offset from the line by approximately 10 ft, the probes are placed along the voltage gradient to obtain a null (zero) on the meter. A right-angle line through the center of the probe locations passes over the coating holiday epicenter, as shown in point A in Figure 2-7. This geometrical procedure repeated on opposite sides of the pipeline locates the exact point above the holiday.

A survey flag, wooden stake, paint mark, or lathe is often placed at the indication epicenter and identified by a unique indication number using a permanent marker or paint.

After the epicenter of the coating holiday has been detected, a series of continuous lateral (perpendicular) readings are measured moving toward remote earth. Lateral readings near the holiday yield maximum voltage differences where gradients are at a maximum. Readings at remote earth are considered to be achieved when one has a 1 mV deflection. The summation of these readings is commonly referred to as the over-the-line-to-remote-earth voltage. The expression “percentage IR” has been adopted to give a relative indication size.

For instance, if a series of lateral millivolt readings to remote earth are as follows, 25, 15, 6, 4, 3, 1, 1, 0, the percentage IR can be calculated as follows:

$$\begin{aligned}\text{Over the line to remote earth voltages} &= 25+15+6+4+3+1+1 \text{ mV}\\ &= 55 \text{ mv}\end{aligned}$$

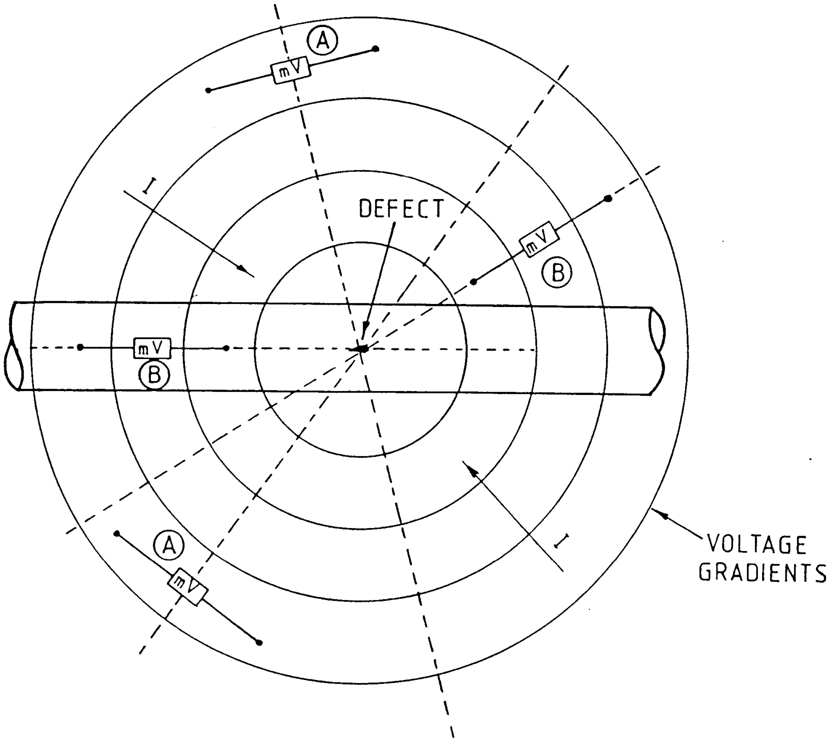
$$\text{Percentage IR} = \frac{\text{Over the line to remote earth voltage } * \ 100\%}{\text{Signal Strength}}$$

$$= \frac{55 * 100}{275}$$

$$= 20\%$$

The percentage IR is used to develop a coating condition classification system to prioritize coating damage.

Once an indication is located, its size or severity is estimated by measuring the potential lost from the holiday epicenter to remote earth. This potential difference is expressed



DCVG VOLTAGE GRADIENTS

FIGURE 2-7

as a fraction of the total potential shift on the pipeline (the difference between the “on” and “off” potential, also known as the IR drop) resulting in a value termed % IR. DCVG survey readings can be broken into four groups based on approximate size as follows:

Category 1: 1% to 15% IR - Indications in this category are often considered of low importance. A properly maintained CP system generally provides effective long-term protection to these areas of exposed steel.

Category 2: 16% to 35% IR - These indications are generally considered of no serious threat and are likely to be adequately protected by a properly maintained CP system. This type of indication may be slated for additional monitoring. Fluctuations in the levels of protection could alter the status at these points as the coating further degrades.

Category 3: 36% to 60% IR - The amount of exposed steel in such an indication indicates it may be a major consumer of protective CP current and that serious coating damage may be present. As in Category 2 indications, this type of possible coating holiday may be slated for monitoring as fluctuations in the levels of CP could alter the status as the coating further degrades.

Category 4: 61% to 100% IR - The amount of exposed steel indicates that this indication is a major consumer of protective CP current and that massive coating damage may be present. Category 4 indications typically indicate the potential for serious problems with the coating.

These example categories are empirical in nature and are based on the results of prior exploratory excavations at holiday locations determined by DCVG surveys.

ALTERNATING CURRENT VOLTAGE GRADIENT SURVEYS (ACVG)

Alternating current voltage gradient (ACVG) surveys are used to evaluate the coating condition on buried pipelines. Voltage gradients arise as a result of current pickup or discharge at coating holidays. In an ACVG survey, the AC signal is created by a low frequency transmitter connected to the pipeline and the voltage gradient in the soil above the pipeline is measured. Voltage gradients are located by a change in the signal strength at grade.

ACVG signal strength is not always proportional to holiday size, as the orientation of the holiday and other factors affect the measured signal.

ACVG SURVEY ABOVE PIPELINE LOCATING COATING HOLIDAYS

FIGURE 2-8

AC CURRENT ATTENUATION RECEIVER FACE

FIGURE 2-9

ACVG surveys are capable of distinguishing between isolated and continuous coating damage. The shape of the gradient field surrounding a holiday provides this information. Isolated holidays, such as rock damage, produce fairly concentric gradient patterns in the soil. Continuous coating damage, such as disbonded coatings or cracking, produces elongated patterns.

The ACVG system consists of a commonly employed, commercially available battery/AC powered signal-generating unit that provides a 937.5-Hz AC signal with a maximum output of 750 mA or a 4-Hz AC signal with a maximum output of three amperes. A handheld receiver unit is tuned to detect the signal frequency from the transmitter and block other signals. There are two probes which connect to the receiver and are in contact with the soil.

An AC current attenuation survey may be performed with impressed current CP systems energized, however by turning off the rectifier and using the positive and negative leads at the rectifier station, the signal-generation capabilities of the equipment can be maximized. Sacrificial anodes and bonds that are not disconnected show up as anomalies. Sacrificial anodes and bonds to other structures are usually disconnected to prevent signal loss and enhance current flow down the pipeline.

The signal generator (transmitter) is connected to the pipeline and appropriately grounded to earth. A constant AC signal is produced and transmitted along the pipe. The transmitter is energized and adjusted to an appropriate output. Typically, the largest attainable current output is chosen to maximize the length of pipe that can be surveyed. An impressed current anode bed or magnesium anode can be used to establish an electrical ground.

The receiver consists of a handheld, symmetrical, multi-axis antenna array. The electromagnetic field radiating from the pipeline is measured by the detector.

The detector is used to measure the attenuation of the signal current that has been applied to the pipe. An electrical current, when applied to a well coated buried pipeline, gradually decreases as distance increases from the point of current application. The electrical resistivity of the coating under test and the surface area in contact with the soil per unit length of pipe are the primary factors affecting the rate of decline and the frequency of the signal.

The two probes must be connected to the receiver unit and plugged in. Survey intervals should be no greater than ten (10) feet in those areas deemed to have coating holidays.

The operator walks above the pipeline centerline placing the contact probes into the soil above the pipe and measuring the voltage gradient and direction. Probes are placed parallel to the pipe. The receiver unit will “point” in the direction of a coating holiday. The magnitude will increase as the holiday is approached.

The survey continues until the receiver indicates that the coating holiday has been passed (signal magnitude decreases and direction arrow reverses direction) at which point the operator reverses direction and shortens the interval between readings.

When the holiday is centered between the two probes, the magnitude will be zero and the direction arrows will not indicate a consistent current direction.

The probe assembly can be used to the side of the pipe (perpendicular to the pipe) to confirm the coating indication location. The holiday location is indicated by the maximum signal magnitude with the probes placed perpendicular to the pipe.

Either store the data in the receiver unit or record the information in the project field book.

CLOSE-INTERVAL SURVEYS (CIS)

CIS is used to measure the potential difference between the pipe and the electrolyte. Data from close interval surveys are used to assess the performance and operation of the CP system. CIS can also be used to detect coating holidays.

While other indirect inspection tools may be better suited to detect coating holidays, CIS also aid in identifying:

1. Interference,
2. Shorted casings,
3. Areas of electrical or geologic current shielding,
4. Contact with other metallic structures, and
5. Defective electrical isolation joints.

On and off potential surveys are used to evaluate CP system performance in accordance with the NACE pipeline CP criteria as found in SP0169. On and Off surveys measure the potential difference between the pipe and the electrolyte as the CP current source(s) is switched on and off.

On and Off surveys rely on electronically synchronized current interrupters at each CP current source, bond, and other current drain point that influences the pipeline potential in the survey area. The ratio of the On-to-Off interruption cycle should be long enough for readings to be made but short enough to avoid significant depolarization. A three second On, one second Off cycle period or similar can be used to maintain pipeline polarization over time and allow accurate Off potentials to be recorded.

The copper sulfate reference electrodes (CSE) are placed directly over the pipeline, typically at 2.5 to 5 foot intervals such that both On and Off potentials can be measured and recorded at each reference cell location.

The accuracy of the on and off data can be verified by recording a continuous datalog (waveprint) at test stations or points of electrical contact such as valves or risers. This data log will illustrate proper interrupter synchronization and the effects of pipeline depolarization during the survey should it take place. The continuous data log should measure and store the potentials at a minimum time period as the total current interruption cycle. Waveprints can also be reviewed to confirm the point at which the Off potential should be recorded by the CIS datalogger. In addition, the waveprints can be analyzed to determine the affects of:

Inductive potential spiking,

Interrupter synchronization drift,

Stray DC and AC earth currents.

CIS equipment includes, at a minimum, several high input impedance data loggers/voltmeters, sufficient current interrupters for the project, copper sulfate reference electrodes, small gauge CIS wire (30 AWG), wire dispenser, and pipe/cable locating equipment (See above section on pipe locating).

Standard current interrupter units include 30, 60, or 100 ampere AC and DC interruption capacity, AC or battery-powered units, with electronic synchronization and Global Position Satellite (GPS) timing.

Prior to the CIS, a rectifier influence survey may be completed to determine the CP current sources which must be interrupted for the accurate measuring of Off potentials. These include company rectifiers, galvanic anode systems, foreign company rectifiers, and electrical bonds to foreign company structures. Individually, each CP current source should be tested. A current interrupter is used to interrupt the CP current source suspected of influencing the CIS pipeline segment. Typically, a slow interruption cycle is used such as a ten second On, five second Off period. Pipe-to-electrolyte potentials are measured at the furthest test points suspected of influence from the suspect CP current source.

Test points are monitored moving away from the suspect CP current source. Once a 10 mV or less difference between On and Off pipe to electrolyte potential is observed, the influence of the CP current source is deemed no longer significant for analysis of the pipe CP levels.

Several test points beyond the location where the influence of the CP current source is deemed to terminate should be tested to confirm the end of the influence from the suspect CP current source.

To start the CIS, a current interrupter is installed in series in either the AC or DC circuits of all of the current sources in the CP current sources identified. Current interrupters maintain interruption synchronization. All interrupters must be synchronized together. Interrupters should be programmed such that they are interrupting no longer than the anticipated survey duration each day. When no field surveying is taking place, the interrupters should be programmed to turn off in order to minimize the affects of depolarization.

A 30, 32, or 34 AWG gauge insulated wire is electrically connected to a test station test wire, valve, or other electrically continuous pipeline appurtenance and one terminal of the voltmeter. The other terminal of the voltmeter is attached to the reference electrode.

The pipeline is located with a pipe locator prior to collecting data to ensure that the reference electrode is placed directly over the pipeline (See Pipe Locating Section).

Industry standard copper sulfate reference electrodes (CSE) should be used for potential measurements. See NACE Standard TM0497. Reference electrodes should be calibrated with an unused control reference electrode daily, the results of which should be recorded in the project field book. The control reference electrode should be a recently

CLOSE-INTERVAL SURVEY TECHNICIAN WITH DATALOGGER, REFERENCE ELECTRODE, AND WIRE DISPENSERS

FIGURE 2-10

charged electrode not used to gather data in the field. To calibrate the CSE, the ceramic porous electrode tips are placed tip to tip to measure the voltage difference between the two electrodes or both tips are immersed in a container of potable water. A digital voltmeter on the millivolt scale is used to measure the voltage difference. If the voltage difference between the two electrodes exceeds 5 mV, the field electrode should be emptied, cleaned properly, and recharged with unused distilled water and copper sulfate crystals. If the voltage difference remains greater than 5 mV, the field electrode should be disposed of properly and not used to collect data.

A datalogger can be placed at the suspected midpoint of each day’s CIS progress for later analysis of the CIS data. The datalogger should measure and record the pipe-to-electrolyte potential continuously during each day’s survey. The datalogger should be programmed to record the pipe potential at a rate of one reading per second or greater. The datalogger should be installed and turned on prior to the start of CIS each day and should run until after the completion of CIS each day. The data can be retrieved from the datalogger each day and analyzed for the existence of dynamic stray currents, de-energizing of a CP source, or improper current interrupter operation.

On and Off pipe-to-electrolyte potentials are then measured and recorded typically at 2.5 to 5 foot intervals using a high-input impedance voltmeter/datalogger. The datalogger should have the ability to adjust the time during the Off cycle at which the handheld datalogger stores the Off potential value due to the possibility of inductive/capacitive spiking. The datalogger should be programmed such that the On and Off pipe to electrolyte potentials are measured and stored from a time period beyond the spiking as determined by the waveprints discussed above.

Pipe-to-electrolyte potential measurements should be measured and recorded at each test station and foreign pipeline crossing from each test wire within accessible test stations. Near ground (NG), metallic IR Drop (IR), and far ground (FG) On and Off pipe-to-electrolyte potential measurements should be made at each point of pipeline connection.

If the Off metallic IR drop exceeds 5 mV, the survey should be halted and an investigation made to determine the source of the error. Possible sources for this error include interrupter malfunction, stray currents, and unknown foreign rectifiers or electrical bonds.

AC pipe to electrolyte potentials can be measured at each point of pipeline connection and recorded in the project field book or within the CIS data stream.

On and Off casing to electrolyte potentials should be measured at each casing, either by monitoring the test wire attached directly to the casing pipe or by temporary electrical connection to the casing vent.

When a stationing flag is encountered, a flag comment or code is entered into the data logger for later computer graphing and stationing purposes. When a numbered flag is encountered, the flag number can also be entered into the data stream.

All permanent landmarks should be identified and entered into the data logger during the survey. These include pipeline markers, test points, fences, casing vents, creeks, and road names.

Upon completion of the survey, all CIS wire should be retrieved. Flags can be left in place until the final ECDA process/surveys are completed and deemed appropriate for final removal.

AC CURRENT ATTENUATION SURVEYS (ELECTROMAGNETIC)

AC current attenuation surveys are used to provide an assessment of the overall quality of the pipe coating within a section or as a comparison of several sections. A current is applied to the pipeline, and coating damage is located and prioritized according to the magnitude and change of current attenuation.

AC current attenuation surveys may be performed with impressed current CP systems energized, however by turning off the rectifier and using the positive and negative leads at the rectifier station, signal-generation capabilities of the equipment can be maximized. Sacrificial anodes and bonds that are not disconnected show up as anomalies. Sacrificial anodes and bonds to other structures are usually disconnected to prevent signal loss and enhance current flow down the pipeline.

Commonly employed, commercially available battery-powered signal-generating units include units that provide a 937.5-Hz AC signal with a maximum output of 750 mA or a 4-Hz AC signal with a maximum output of three amperes. A handheld receiver unit tuned to detect the signal from the transmitter and block other signals is used to pick up the signal.

The signal generator is connected to the pipeline and appropriately grounded to earth. A constant AC signal is produced and transmitted along the pipe. The transmitter is energized and adjusted to an appropriate output. Typically, the largest attainable current output is chosen to maximize the length of pipe that can be surveyed. An impressed current anode bed or magnesium anode can be used to establish an electrical ground. If operating rectifiers are interfering with the signal, then turn the units off.

Signals are measured using the receiver unit. The receiver consists of a handheld, symmetrical, multi-axis antenna array. The electromagnetic field radiating from the pipeline is measured by the detector. The detector is used to measure the attenuation of a signal current that has been applied to the pipe. An electrical current, when applied to a well-coated buried pipeline, gradually decreases as distance increases from the point of current application. The electrical resistivity of the coating under test and the surface area in contact with the soil per unit length of pipe are the primary factors affecting the rate of decline and the frequency of the signal.

The logarithmic rate of decline of the current (attenuation), which is effectively independent of the applied current and marginally affected by seasonal changes in soil resistivity, provides an indication of the average condition of the pipe coating between two given points on the date of the survey. Changes in attenuation provide a comparative change in coating condition between survey sections. Such comparative changes can indicate “better” coating (i.e., fewer anomalies or a small single anomaly) or “worse” coating (i.e., more anomalies or a larger single anomaly).

Survey intervals are typically 100 feet at the pipeline locating flags. The measured current value is recorded in the project field book or the transmitter for later analysis. The receiving unit must remain upright and perpendicular to the pipe when taking the measurements. When readings are suspect, stay on peak mode and check both the peak and null readings and verify pipe depth. Take multiple readings in one location if data accuracy is questionable. The accuracy of the readings may be affected by distortions in the AC signal caused by other underground piping and conduits, traffic control signaling, or vibrations due to passing vehicles.

Survey data are analyzed after the survey to determine which survey intervals exhibit reduced coating quality.

SUMMARY

The indirect above ground inspection techniques discussed in this chapter are used to identify and define coating faults and in turn those areas where corrosion activity may have occurred or may be occurring. Two or more of these inspection techniques should be used when conducting this indirect inspection testing so that different types of data can be compared and analyzed to determine whether there is any correlation. The

AC CURRENT ATTENUATION TRANSMITTER

FIGURE 2-11

TECHNICIAN MEASURING AC CURRENT ATTENUATION
WITH RECEIVER

FIGURE 2-12

effectiveness of the testing techniques employed will depend on factors such as operator experience, pipeline/coating/CP circuit conditions, depth of pipe, and type of cover at grade.

Should significant coating damage be indicated from these tests, the pipeline should be excavated and examined for possible corrosion damage and the appropriate remedial actions should be taken.

ACKNOWLEDGMENT

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Chapter 3 - Materials for Cathodic Protection

INTRODUCTION

This chapter will discuss common materials used for underground cathodic protection installations. Some of the materials have established track records and some are new with very little known about the long term life effects in a particular environment. For our purposes, we will define "long term" as any material with a successful application record in underground use of more than 20 years.

People who specify cathodic protection materials must understand the advantages and limitations of a product and how the product relates to any given application. Furthermore, they must be able to convey in writing, the specifics of how the product is to be manufactured or supplied to assure that it will conform to predetermined design life criteria. The object of this chapter is to fit the right type of materials with the structure to be protected at the lowest possible cost per year of predetermined service life.

CONSIDERATIONS FOR ALL MATERIALS

Material must be selected for each application with the following interrelated items considered:

1. Design criteria

2. Life required

3. Capacity or rating of material selected

4. Economics

5. Environment - both underground and above grade

When specifying materials, either requisitioning or purchasing, the following should be checked:

1. Specify materials completely.

2. Make sure that complete specifications are on the purchase order.

3. Check material received to ensure that it conforms to the original specifications.

Usage:

1. Follow the manufacturer's recommendations and instructions.

2. Use compatible components.

3. Use the proper tools.

4. When a problem or question arises, ask the manufacturer or distributor for assistance.

GALVANIC ANODES

Magnesium, zinc, and aluminum can be used as galvanic anodes for cathodic protection. Galvanic anodes are not supplied in the purest form of the metal but rather as an alloy that contains impurities at various concentrations. These impurities can have a profound effect on the long term operational characteristics of the anode.

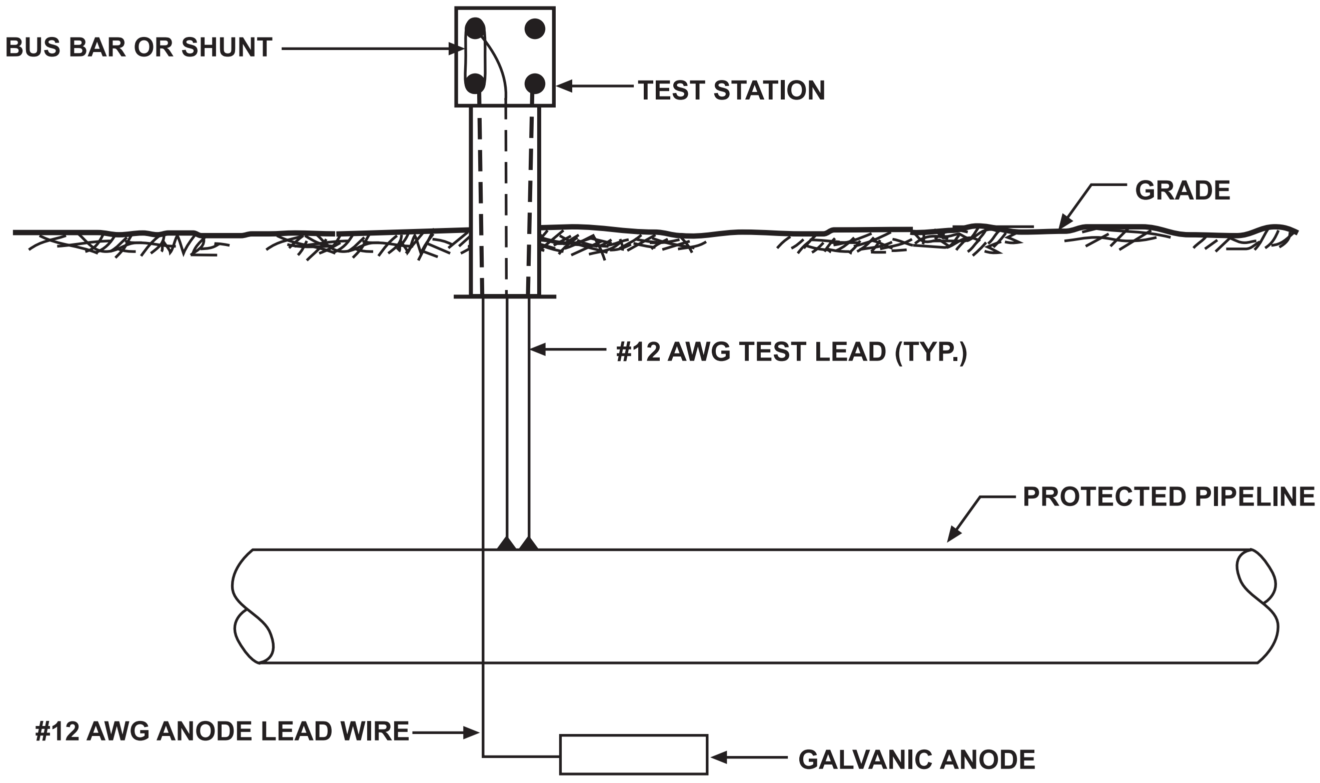
A galvanic anode must have a more negative potential than the structure it is designed to protect. The difference in potential between the anode and the structure is referred to as the "driving potential" or "driving voltage".

The amount of current produced by a galvanic anode is a function of the driving potential and the circuit resistance in accordance with Ohm's Law.

Figure 3-1 shows a schematic diagram of a typical galvanic anode installation.

Table 3-1 lists metals that are used as galvanic anodes and their alloys. For each alloy the table shows its open circuit potential, current capacity and consumption rate. Impurities and grain size will cause wide ranges in these theoretical values.

These are representative values taken from literature provided by various manufacturers. In general, magnesium is preferred for use in soils and fresh water. Zinc is generally limited to use in sea water, brackish water, sea mud, and soils with resistivities below 1500 ohm-cm. Aluminum is generally limited to sea water, brackish water, and sea mud environments.



TYPICAL GALVANIC ANODE INSTALLATION

FIGURE 3-1

TABLE 3-1
Capabilities and Consumption Rates of Galvanic Anodes

Type	Potential* (volts to CSE)	Current Capacity (A-hrs/lb)	Consumption Rate (lb/A-yr)
Magnesium			
H-1C AZ-63D Alloy	-1.4 to -1.5	250 to 470	19 to 36
High Potential Alloy	-1.7 to -1.8	450 to 540	16 to 19
Zinc			
ASTM B418-01			
Type I (saltwater)	-1.1	354	24.8
Type II (soil)	-1.1	335	26.2
Aluminum			
Mercury Alloys	-1.10	1250 to 1290	6.8 to 7.0
Indium Alloys	-1.15	1040 to 1180	7.4 to 8.4

* Copper/Copper Sulfate Reference Electrode - Open circuit practical values as shown

An important point to consider for maximum service life is the cost per ampere hour of current capacity, once it has been established that the driving potential is sufficient for the cathode metal and the resistivity of the electrolyte in the circuit. When working in the higher resistivity soils, long slender anodes have a lower resistance to earth than the shorter anodes which are available. This means that the circuit resistance for the limited driving voltage available from a galvanic anode will be less, and as a result, more current output will be obtained. To say it in another way, the same amount of anode material (such as a 20 lb. magnesium anode) in a given soil resistivity environment will produce more current if it has been cast in a long, slender shape than it will if cast in a short and more stocky shape. This will result in the longer shaped anode having a shorter life expectancy - although this "shorter" life expectancy may be fully adequate for applications in higher resistivity soils. The anode installation design for a particular situation will take the resistivity of the environment into account and will balance current requirements against desired life to determine the size, number, and weight of anodes needed. Design of galvanic anode cathodic protection systems is covered in detail in Chapter 6 of the Advanced Course.

Prepared Backfill and Packaging

Magnesium and zinc anodes for use in soils are typically supplied with a prepared backfill around the anode.

The most commonly used backfill for magnesium and zinc anodes consists of:

75% Hydrated Gypsum ($CaSO_4 \cdot 2H_20$)
20% Bentonite Clay
5% Sodium Sulfate

The purpose of the prepared backfill is:

It increases the effective surface area of the anode which lowers the anode-to-earth contact resistance.

The bentonite clay absorbs and retains moisture.

The gypsum provides a uniform, low resistance environment.

The sodium sulfate (a depolarizing agent) minimizes pitting attack and oxide film formation on the anode.

It provides a uniform environment directly in contact with the anode to assure even consumption.

When properly combined, the elements used to make the backfill will provide a uniform resistivity of 50 ohm-cm when measured by the ASTM G-58 Soil Box Test Method and corrected for temperature variations. Most reputable anode fabricators will test and document the resistivity values for each batch of backfill.

As an historical side note, zinc was formerly thought to perform better in a backfill of 50% gypsum and 50% bentonite. Over the years it was determined that zinc may passivate if sodium sulfate is not used in the backfill.

To keep the backfill uniformly around the anode, the anodes with their lead wire attached are placed in cloth bags or cardboard boxes and the prepared backfill is then added. Cloth bagged anodes are usually placed within a layered paper bag for resistance to short periods of inclement weather and handling damage. Prior to installation, the paper bag is removed and discarded, permitting the cloth bag containing the backfill to absorb moisture, allowing the anode to start putting out current soon after installation. During transportation and/or handling the anodes may shift in the prepared backfill. This may result in uneven consumption of the anode, reduction of current output and premature failure of the anode. This condition can be avoided by careful specification of transportation packaging and field handling precautions. Anodes packaged in cardboard boxes or bags with centralizing devices may tend to reduce anode shifting.

Wire and Cable Attachment

Galvanic anodes for use in soil are typically supplied with a lead wire that is used to connect the anode to the structure. The most common type of lead wire for a galvanic anode is an AWG #12 solid copper wire with TW insulation. Other wire sizes and insulations can be specified if desired.

Proper attachment of the lead wire to the anode core is critical for two reasons. First, the connection must be electrically sound to minimize internal resistance. Second, it must be strong enough to support the weight of the packaged anode if it is lifted by the lead wire. The lead wire is usually silver soldered to the core. Next, the connection is primed and covered with an inert thermoplastic electrical potting compound to prevent water migration to the connection.

Zinc anodes do not have a recessed core, so the cable is crimped and silver soldered to the extended rod core and coated with a piece of heat shrinkable polyethylene tubing or several laps of electrical tape to protect the connection.

Magnesium Alloys

Magnesium anodes are produced in a wide variety of sizes and shapes to fit design parameters. They may be cast in molds or extruded into ribbon or rod shapes, with steel spring, perforated strap or wire cores as shown in Figure 3-2. The core is important because it should extend 85 percent or more through the anode to reduce the internal circuit resistance. Table 3-2 shows the weights and dimensions of some common magnesium anodes. The chemical composition of the different alloys is shown in Table 3-3.

Four (4) magnesium alloys are available. Their respective potential values and consumption rates will be an important part of the calculations used to design a cathodic protection system using magnesium anodes. The potential values and consumption rates of the 4 magnesium alloys are shown in Table 3-3.

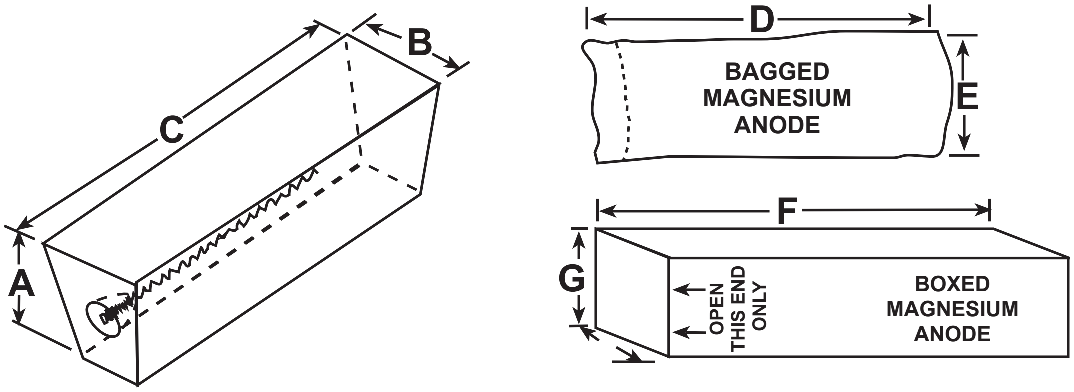
The purchaser should request a verifiable spectrographic analysis of any anode purchase to assure that the alloy falls within the predetermined range of acceptable impurities. The anodes should be identified by heat number and date of manufacture. The chemical analysis should detail the heat number, the date of manufacture, a listing of the impurities with the percentages of each, and be signed by a technically qualified person.

Anode current capacity and oxidation potential may be measured using ASTM Standard G97-97 "Standard Test Method for Laboratory Evaluation of Magnesium Sacrificial Anode Test Specimens for Underground Applications".

Zinc Alloys

Zinc anodes can be used in low resistivity electrolytes where driving potential is not a major factor. They are available in a variety of sizes and shapes including bracelet anodes for marine pipelines, docks and piers, hull anodes for marine vessels, and in ribbon form for use in utility ducts and for AC mitigation. Zinc is not recommended in environments where carbonates or bicarbonates are found, or where the temperature of the electrolyte is over 120º F. Under these situations zinc becomes cathodic to steel, rather than anodic, and its use should be avoided.

Table 3-4 shows the weights and dimensions of some common zinc anodes.



BARE AND PACKAGED MAGNESIUM ANODES

FIGURE 3-2

TABLE 3-2
Magnesium Anode Dimensions and Weights

	Nominal Dimensions (Inches) - See Figure 3-2							
Alloy	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Packaged Weight (lbs)**
1 AZ63	3.2	Rd	2	6	6	-	-	3.6
3 H.P./AZ63	3	3	6	8	6	-	-	9
5 H.P./AZ63	3	3	10	12	5	-	-	12
6 H.P./AZ63	3	3	10	-	-	12.5	5	14
9 H.P./AZ63	3	3	13.5	17	6	-	-	27
12 AZ63	4	4	12	18	7.5	-	-	32
17 H.P.	3.5	3.5	25.5	30	6	-	-	42
17 AZ63	3.5	3.5	28	-	-	32	5.5	45
20 H.P.	2	2	60	-	-	71	4.5	65
32	5.5	5.5	21	25	8	-	-	72
32	5.5	5.5	21	-	-	24	7.5	70
40 H.P.	3.5	3.5	60	64	6	-	-	105
48 H.P.	5.5	5.5	32	36	8	-	-	106
50 AZ63	7	7	15	24	10	-	-	110
60 H.P.	4	4	60	64	5.75	-	-	130

Magnesium Extruded Ribbon and Rods

Size (Inches)	Weight (lb/ft)	Core (Inches)
⅜ x ¾	0.24	0.125
0.750	0.36	0.125
0.840	0.45	0.125
1.050	0.68	0.125
1.315	1.06	0.125
1.561	1.50	0.125
2.024	2.50	0.125

* Data compiled from literature provided by various vendors and may vary slightly.

TABLE 3-3
Composition of Magnesium Alloy

Element	AZ63B (H1A)	AZ63C (H1B)	AZ63D (H1C)	M1C (High Potential)
Aluminum (Al)	5.3 - 6.7%	5.3 - 6.7%	5.0 - 7.0%	< 0.01%
Zinc (Zn)	2.5 - 3.5%	2.5 - 3.5%	2.0 - 4.0%	-
Manganese	0.15 - 0.7%	0.15 - 0.7%	0.15 - 0.7%	0.5 - 1.3%
Silicon (Si)	< 0.10%	< 0.30%	< 0.30%	< 0.05%
Copper (Cu)	< 0.02%	< 0.05%	< 0.10%	< 0.02%
Nickel (Ni)	< 0.002%	< 0.003%	< 0.003%	< 0.001%
Iron (Fe)	< 0.003%	< 0.003%	< 0.003%	< 0.03%
Others (each)	-	-	-	< 0.05%
Others (total)	< 0.30%	< 0.30%	< 0.30%	< 0.30%
Magnesium	Balance	Balance	Balance	Balance

Performance Characteristics*

	AZ63B (H1A)	AZ63C (H1B)	AZ63D (H1C)	M1C (HP)
Potential (Volts to CSE)	-1.60	-1.55	> -1.40	-1.75
Theoretical Current Capacity (A-hrs/lb)	1000	1000	1000	1000
Actual Current Capacity (A-hrs/lb)	450 - 580	300 - 470	250 - 470	400 - 540
Current Efficiency (%)	45 - 58	30 - 47	25 - 47	40 - 54
Actual Consumption Rate (lb/A-yr)	18 - 15	33 - 19	35 - 19	19 - 16

* Using ASTM Standard G97-97 “Standard Test Method for Laboratory Evaluation of Magnesium Sacrificial Anode Test Specimens for Underground Applications”.

TABLE 3-4
Zinc Anode Dimensions and Weights

Weight (lbs)	Height	Width	Length	Core (dia.")
Bare Zinc Anodes				
5	1.4	1.4	9	0.250
12	1.4	1.4	24	0.250
18	1.4	1.4	36	0.250
30	1.4	1.4	60	0.250
30-A	2.0	2.0	30	0.250
45	2.0	2.0	45	0.250
60	2.0	2.0	60	0.250
Zinc Ribbons				
2.4	1.0	1.250	--	0.185
1.2	0.625	0.875	--	0.135
0.6	0.500	0.563	--	0.130
0.25	0.344	0.469	--	0.115

The chemical composition of the different alloys is shown in Table 3-5.

When used strictly as an anode, zinc is well suited for low resistivity environments such as sea water, salt marshes, and brackish water. Zinc normally becomes impractical for protecting large bare areas when the resistivity of the electrolyte exceeds 1500 ohm-cm.

Zinc anodes are also used as grounding cells for electrical protection of isolators. Zinc grounding cells are usually made from 2 or 4 zinc anodes separated by a 1" isolating spacer and packaged in a cloth bag with backfill. Each anode has a lead wire (typically AWG #6) which is connected across an isolation device. Fault current and lightning will pass between the anodes without causing damage to the pipeline or the isolation device. Figure 3-3 shows two zinc anodes used in a grounding cell installed across an isolating flange.

Zinc can also be used as a permanently installed reference electrode.

Aluminum Alloys

Aluminum has been generally limited to applications of sea water and chloride rich environments such as offshore petroleum platforms, marine pipelines and onshore oil production separation equipment using a saltwater tank. There are two common alloy families. One uses mercury, the other uses indium, to reduce the passivating effect of the oxide film that forms on aluminum. The composition of each alloy is shown in Table 3-6.

The mercury alloys are effective in high chloride environments where chloride levels are consistently greater than 10,000 ppm. Sea water has an average chloride level of 19,000 ppm.

Indium alloys are effective in waters containing 1000 ppm or more of chlorides.

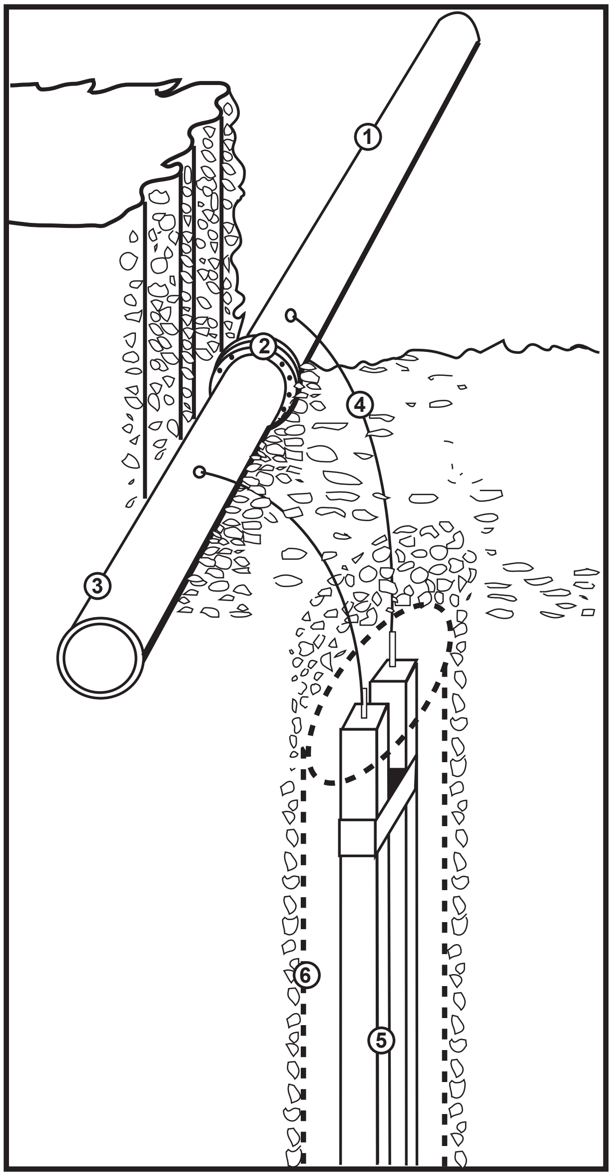
The mercury alloy is used in free flowing sea water and its principle advantage is its high current capacity. The current capacity of each alloy is shown in Table 3-6. Its primary disadvantages are that it cannot be used in brackish water, in silt/mud zones, or at elevated temperatures. Under high humidity atmospheric storage conditions some grades have been known to degrade and become totally unusable prior to installation. There is some controversy also concerning the long term environmental effects of this alloy in sea water since it contains mercury.

TABLE 3-5
Zinc Alloy Compositions

Element	ASTM B418-01 Type I (sea water)	ASTM B418-01 Type II (soil)
Aluminum	0.1 - 0.5%	< 0.005%
Cadmium	0.025 - 0.07%	< 0.003%
Iron	< 0.005%	< 0.0014%
Lead	< 0.006%	< 0.003%
Copper	< 0.005%	< 0.002%
Others	—	0.1%
Zinc	Balance	Balance

TABLE 3-6
Aluminum Alloy Composition and Performance

Element	Mercury Family Al/Hg/Zn	Indium Family Al/In/Zn
Zinc (Zn)	0.35 - 0.60%	2.8 - 6.5%
Silicon (Si)	0.14 - 0.21%	0.08 - 0.2%
Mercury (Hg)	0.035 - 0.060%	---
Indium (In)	---	0.01 - 0.02%
Copper (Cu)	0.004% max	0.006% max
Iron (Fe)	0.10% max	0.12% max
Aluminum (Al)	Balance	Balance
Consumption Rate (lb/A-y)	6.8 - 7.0	7.4 - 8.4
Current Capacity (A-hrs/lb)	1250 - 1290	1040 - 1180
Potential to Ag/AgCl	-1.05	-1.10
to $Cu/CuSO_4$	-1.10	-1.15



TWO UNIT ZINC GROUNDING CELLS

FIGURE 3-3

The indium alloy is used in free flowing sea water, brackish water, silt/mud zones, and at elevated temperatures. Its basic limitation is a lower current capacity than the mercury alloy.

Aluminum anodes have a variety of standard cores such as pipe, strap, bar, end type, side type, etc. The type of core must be specified. Cores should never be galvanized prior to pouring the anode.

On major projects it is advisable to monitor the quality control process and inspect the finished materials prior to shipment.

Just as with the magnesium, it is important that a certified analysis accompany each anode heat.

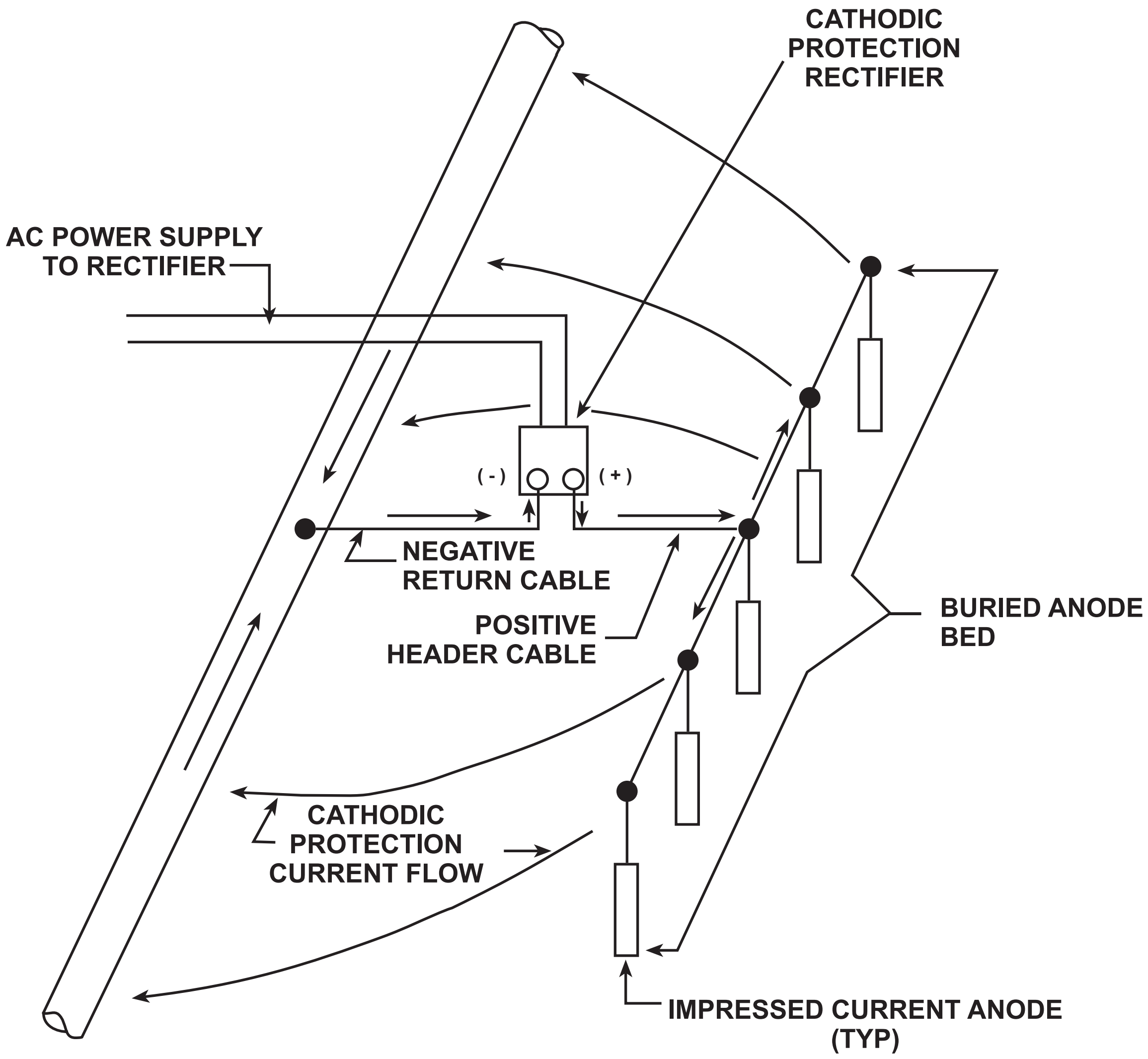
The purchaser should request a verifiable spectrographic analysis of any anode purchase to assure that the alloy falls within the predetermined range of acceptable impurities. The anodes should be identified by heat number and date of manufacture. The chemical analysis should detail the heat number, the date of manufacture, a listing of the impurities with the percentages of each, and be signed by a technically qualified person. Some manufacturers identify each anode with a stamp or tag; others may label each pallet of bare anodes with an identity number painted on the side.

IMPRESSED CURRENT CATHODIC PROTECTION SYSTEMS

Unlike galvanic systems, impressed current systems utilize an external power source such as a rectifier, electrically connected to anodes with a low consumption rate. The anodes are connected to the positive terminal of the rectifier and the circuit is completed by attaching the negative terminal to the structure to be protected. Figure 3-4 shows the components in an impressed current system.

An impressed current system is used to protect large bare and coated structures and structures in high resistivity electrolytes. Care must be taken when employing this type of system so that cathodic coating damage and the potential for the development of stray currents, adversely affecting other foreign structures, are minimized.

Prior to the 1970's there were only three types of anodes primarily used for impressed current anode beds: high silicon cast iron, graphite and scrap steel. As technology progressed, so did the materials used for impressed current anodes. When installation and operating costs are assessed, very few anodes can be used universally for any type



TYPICAL IMPRESSED CURRENT CATHODIC PROTECTION SYSTEM

FIGURE 3-4

of application and still achieve a desirable design life.

In most soils, anodes evolve oxygen and the anode oxidizes as the current is discharged. In chloride containing soils or water, anodes evolve chlorine gas which can form hydrochloric acid, and the anodes can breakdown chemically. Some anodes perform well in the presence of oxygen and others in the presence of acids.

It goes without saying that if corrosion personnel do not effectively detail the type of anode construction they expect, they will probably get less than they expected. The following are minimum details to address in an anode specification.

1. Anode Type, Size and Shape - composition, dimensions and weight, within 2%.

2. Lead Wire - size, type, insulation/thickness, length.

3. Type of Lead Wire Connection - end, center, <0.02 ohms resistance.

4. Lead Wire Termination - epoxy cap, full encapsulation, shrink cap.

5. Packaging - bare, canister size/gauge, backfill type, weight.

6. Palletizing - size, padding, number per pallet.

7. Options - lifting rings, centering devices.

The sections of the specification covering the various types of impressed current anodes should include additional information on construction methods.

TYPES OF IMPRESSED CURRENT ANODES

The three (3) most common anode materials for use in soil are high silicon cast iron, graphite and mixed-metal oxide.

Other impressed current anode materials include platinum, aluminum, lead silver, magnetite, and polymer conductive.

High Silicon Cast Iron

The typical alloy for cast iron anodes is ASTM A518 Grade 3. Table 3-7 shows the

TABLE 3-7
Cast Iron Composition
ASTM A518 Grade 3

ELEMENT	COMPOSITION
Silicon	14.2 - 14.75%
Carbon	0.70 - 1.10%
Manganese	1.50% max
Molybdenum	0.20%
Chromium	3.25 - 5.00%
Copper	0.50% max
Iron	Balance

TABLE 3-8
Typical Cast Iron Rod Anode Dimensions

NOMINAL WEIGHT lbs (kgs)	NOMINAL DIAMETER in (mm)	NOMINAL LENGTH in (mm)	NOMINAL AREA ft^2 (m^2)
1.0 (.5)	1.1 (28)	9 (230)	.22 (.02)
5.0 (2.3)	2.0 (51)	9 (230)	.39 (.04)
9.0 (4.1)	2.5 (64)	9 (230)	.50 (.05)
26 (12)	1.5 (38)	60 (1520)	2.0 (.19)
43 (20)	2.0 (51)	60 (1520)	2.6 (.24)
44 (20)	2.0 (51)	60 (1520)	2.6 (.24)
60 (27)	2.0 (51)	60 (1520)	2.7 (.25)
110 (50)	4.0 (102)	60 (1520)	4.0 (.37)
220 (100)	4.5 (114)	60 (1520)	5.5 (.51)

metallurgical composition of this alloy.

The principal reason for the good performance of cast iron anodes is the formation of a silicon oxide (SiO_2) film on the anode surface, reducing the rate of oxidation, and retarding the consumption rate. Chromium is added to produce a chlorine resistant alloy and improve its life in chloride containing soils and water.

Cast iron anodes have good electrical properties and the resistivity of the alloy is 72 micro ohm-cm at 20º C. In soils, the anodes are usually backfilled with metallurgical or calcined petroleum coke breeze to increase the effective anode surface area and provide uniform consumption. By increasing the diameter or length of a cylindrical anode, the anode to electrolyte resistance is lowered. Increasing the length has a greater effect than increasing the diameter.

The high tensile strength of the anode is an asset in some circumstances, but it is brittle and subject to fracture from severe mechanical and thermal shock.

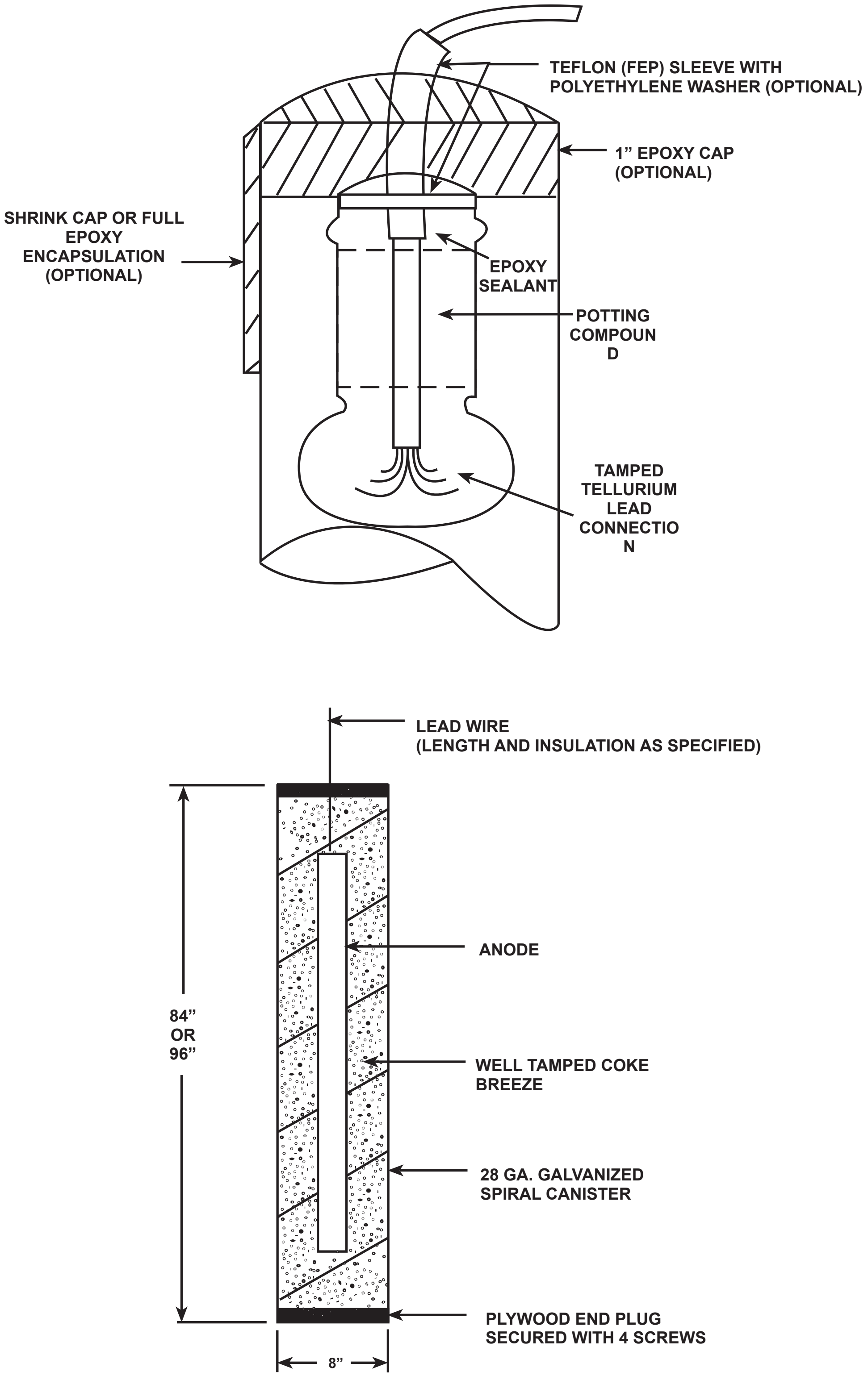
Cast iron anodes are manufactured in a wide variety of dimensions, shapes and weights. Table 3-8 shows the weights and dimensions of some common high silicon cast iron anodes,

Solid cast iron anodes have the lead wires attached at the end as shown in Figure 3-5. The connection is encapsulated with epoxy or a heat shrinkable cap to protect it from electrical discharge.

Current typically discharges from conventional end connected anodes at a greater rate (3:1) from the area of the cable connection than from the body of the anode. This causes an exaggerated attack, called "end effect". A connection in the center of a tubular anode, suitably sealed at each end, has been demonstrated to be effective against this rapid loss of the anode at the cable connection. A drawing of a center connected tubular anode is shown in Figure 3-6.

Testing of chromium bearing tubular anodes in artificial sea water has shown the consumption rate to be about 0.7 pounds per ampere year at a discharge rate of 3.5 amps per square foot of anode surface area. No data has been provided for soil or mud conditions but consumption in these environments could double or triple the consumption rate.

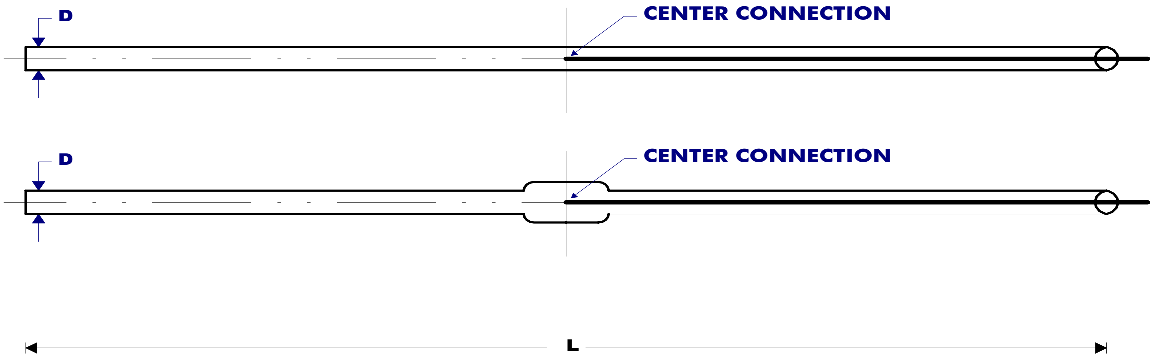
Tubular anodes range in size from 2.187" to 4.750" in diameter, and from 46 pounds to



TYPICAL CAST IRON ANODE LEAD WIRE CONNECTION AND PACKAGING

FIGURE 3-5

NOMINAL WEIGHT lbs (kgs)	NOMINAL DIAMETER in (mm)	NOMINAL LENGTH in (mm)	NOMINAL AREA ft² (m²)
31 (14)	2.6 (66)	41 (1067)	2.4 (.22)
50 (23)	2.6 (66)	60 (1520)	3.5 (.33)
46-50 (21-23)	2.2 (56)	84 (2130)	4.2 (.39)
63-70 (29-32)	2.6 (66)	84 (2130)	4.9 (.46)
85-95 (39-43)	3.8 (97)	84 (2130)	7.0 (.65)
110-122 (50-55)	4.8 (122)	84 (2130)	8.8 (.82)
175-177 (79-80)	4.8 (122)	84 (2130)	8.8 (.82)
230 (104)	4.8 (122)	84 (2130)	8.8 (.82)
260 (118)	6.7 (170)	76 (1981)	11.4 (1.06)
270 (122)	6.7 (170)	84 (2130)	12.3 (1.14)



TYPICAL TUBULAR ANODE DIMENSIONS

FIGURE 3-6

175 pounds in weight, with surface area ranging from 50 percent - 170 percent greater than conventional rod type anodes. The anode cable connection strength should be tested to be equal to the breaking strength of the cable without any change in the 0.004 ohms or less connection resistance.

Thus, for the following cable sizes, connection pull test values should be:

Connection Strength	Cable Break Strength
No. 8 - 799 pounds	525 pounds
No. 6 - 1258 pounds	832 pounds
No. 4 - 1980 pounds	1320 pounds

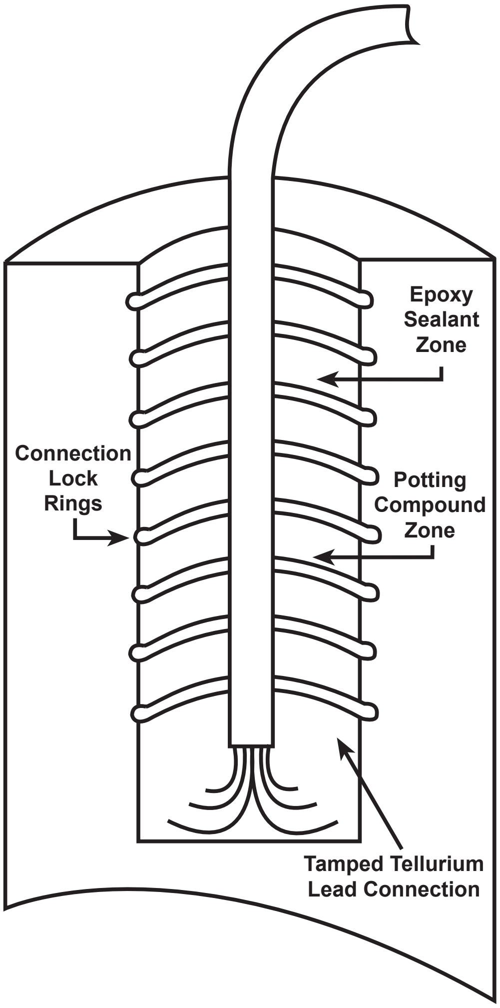
Graphite Anodes

Graphite rods have been used as an impressed current material for many years. The basic configurations consist of round or square rods, manufactured from a slurry of powdered petroleum, coke and coal tar resin. The coal tar is used as a bonding agent to hold the graphite particles together and then baked at high temperatures to fuse the mixture. This process increases the resistance to oxidation and subsequent breakdown.

There are many types of graphite compositions and the type used for cathodic protection anode beds is one of the most porous. Graphite cathodic protection anodes should have a specific gravity of 1-6 grams/cc minimum. The porosity allows moisture penetration to migrate to the connection, causing failure at the cable connection. The porosity is reduced by impregnating the rods with filler of linseed oil, micro-crystalline wax, or phenolic based resin.

There is controversy concerning the best type of filler and even whether a filler really reduces moisture penetration over long periods of time. Whatever filler is used, it should be applied by a method that assures complete penetration of the cross-section of the graphite anode. In soils, graphite anodes must be backfilled with metallurgical or calcined petroleum coke breeze to increase the effective anode surface area and provide a uniform low consumption rate.

The anode to lead wire connection is just as critical as with a cast iron anode. Figure 3-7 shows a typical graphite anode to lead wire connection. Both end and center connections are available. Additional specification details should include:



TYPICAL GRAPHITE ANODE
LEAD WIRE CONNECTION

FIGURE 3-7

1. Type of connector - lead, brass, molten, compression, centered.
2. Connection sealant - thermoplastic, thermosetting (epoxy).
3. Cable sealant - TFE tubing, shrink cap, encapsulation.
4. Impregnation - wax, linseed oil, resin.
5. Sizes - 3" x 30" - 2 sq. ft., 3" x 60" - 4 sq. ft., 4" x 40" - 3.5 sq. ft., 4" x 80" - 7 sq. ft.

Graphite should not be operated at current densities exceeding one ampere per square foot in soil with coke breeze backfill. For optimum life in soils, most engineers design graphite anodes for a maximum density of 0.20 amperes per square foot, or one ampere per 3" x 60" rod. If current densities are within these ranges, the consumption rate will be approximately 2 pounds per ampere-year (lb/A-yr). Exceeding these limits causes the material to become mushy and less conductive, due to chemical breakdown of the crystal boundary.

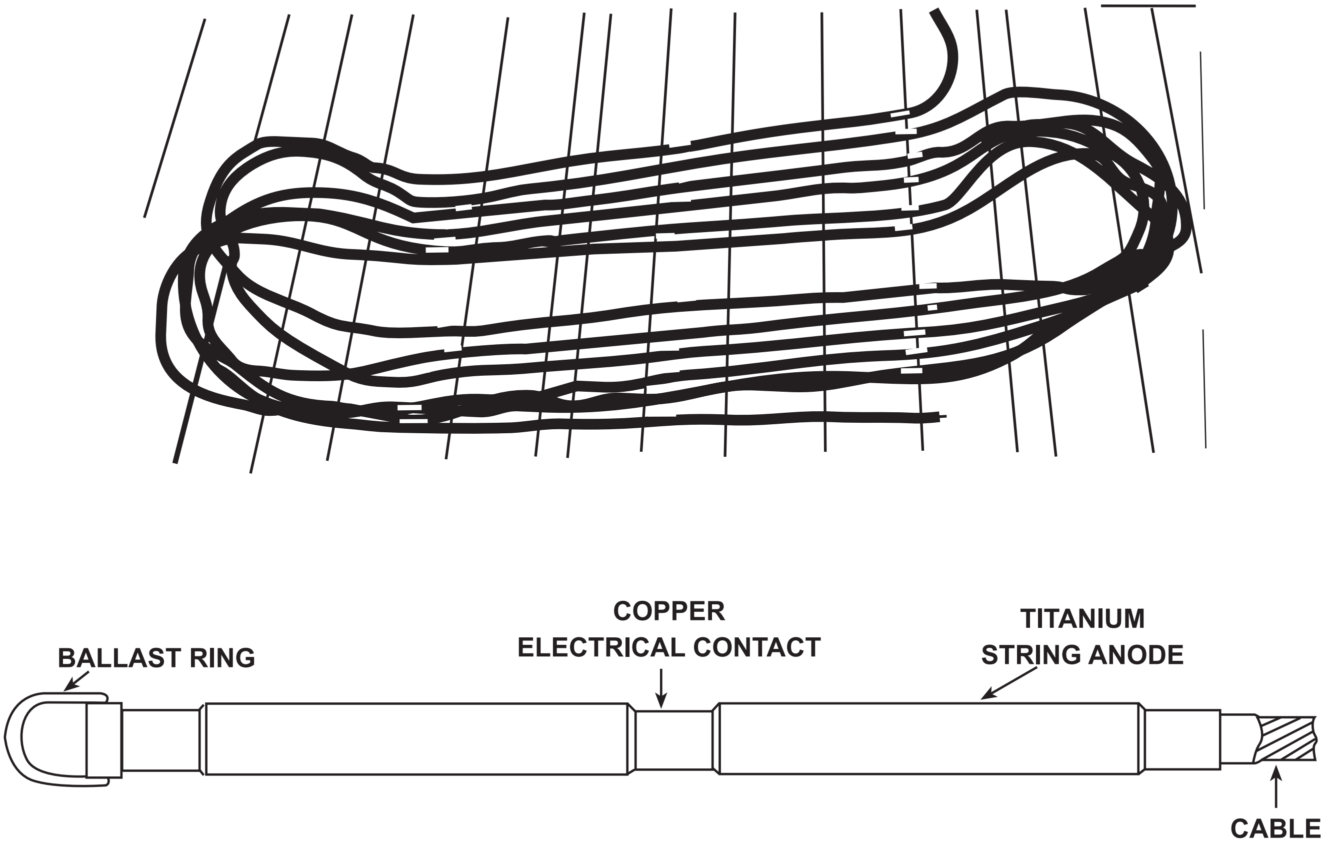
As with cast iron, graphite is brittle and may be easily damaged during transportation, either bare or packaged. Special handling and padding is necessary to prevent cracking and breaking.

Mixed Metal Oxide Anodes

Mixed metal oxide anodes were developed in Europe during the early 1960's for use in the industrial production of chlorine and caustic soda. The first known use of the technology for cathodic protection use occurred in Italy to protect a sea water jetty in 1971. These anodes exhibit favorable design life characteristics while providing current at very high density levels. The oxide film is not susceptible to rapid deterioration due to anode acid generation, rippled direct current, or half wave rectification, as is common with other precious metal anodes.

The composition of the anode consists of a titanium rod, wire, tube or expanded mesh (refer to Figure 3-8) with the oxide film baked on the base metal. Sometimes these anodes are referred to as dimensionally stable or ceramic anodes.

For oxygen evolution environments such as soils, the anode oxide consists of ruthenium crystals and titanium halide salts in an aqueous solution that is applied like a paint on the base metal and baked at 400 to 800º C forming a rutile metal oxide. After baking,



MIXED METAL ANODE

FIGURE 3-8

the rutile develops a matte black appearance and is highly resistant to abrasion.

For chlorine evolving environments such as sea water, the oxide consists of an aqueous solution of iridium and platinum powder that is also baked at high temperatures to achieve a desirable film.

Some manufacturers produce variations of the oxide films specifically for chloride or non- chloride electrolytes and they are not interchangeable.

Normally, titanium will experience physical breakdown around 10 volts, but the oxide film is so highly conductive (0.00001 ohm-cm resistivity) that the current is discharged from the oxide rather than the base metal even with a rectifier voltage of 90 volts in soils. This is in contrast to the insulating titanium dioxide film that naturally forms on the surface of bare titanium. When the mixed metal oxide film has been consumed, the insulating titanium dioxide film will cover the anode and not allow current to discharge unless the applied voltage is greater than 10 volts in sea water or 50 to 70 volts in fresh water.

The maximum recommended current densities for various electrolytes are:

Soil, Mud, Fresh Water:	9.0 amps/ft^2 (20 years)
Sea water:	55.7 amps/ft^2 (15 years)

Anodes in soil or mud must be backfilled with fine, low resistance, calcined petroleum coke breeze for maximum life and performance. Even when the anode is pre-packaged with petroleum coke, conservative engineering judgment would dictate that the anode package be surrounded with metallurgical coke, prior to finishing the backfilling with native soil. Consumption rates at these densities range from 0.5 mg/Ay in sea water to 5 mg/Ay in coke breeze, fresh water and sea mud.

As with any anode, the connection must be constructed so as to be moisture proof, water tight and have no more than 0.001 ohm resistance.

Advantages of mixed metal oxide anodes:

- Lightweight and Unbreakable
- Dimensionally Stable
- Negligible Consumption Rate

- High Current Density Output
- Inert to Acid Generation
- Cost Effective

Mixed metal oxide anodes are available in a variety of shapes including wire, rods, tubes and mesh.

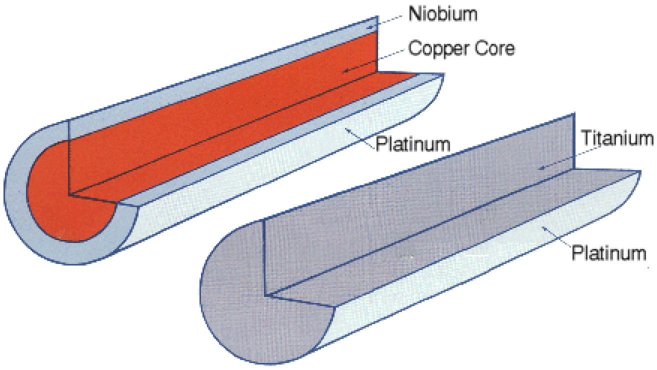
Platinum Anodes

Platinum can be used as an anode coating for many types of cathodic protection installations. Structures in a vast array of environments such as underground, offshore, concrete, power plants, and the internal surfaces of piping, tanks and machinery have utilized platinum for cathodic protection systems. In sea water, platinum has a low consumption rate, 0.00018 pounds per ampere year, so only a small amount is needed for a twenty-year anode life. In soil and fresh water, the consumption may range up to 0.005 pounds per ampere year depending on the resistivity of the electrolyte and the amount of coke breeze surrounding the anode in soil applications. Pure platinum, by itself, would be too expensive. Therefore, it is normally coated over noble base metals such as titanium and niobium. When anodes are in the form of wire and rods, there may be a copper core to increase the conductivity for lengths in excess of 25 feet since titanium and niobium are relatively poor electrical conductors compared to copper. Wire anodes for use in deep anode beds, and packaged anodes for surface anode beds are manufactured. Figure 3-9 shows different types and sizes of platinum anodes.

The passive film on titanium starts to break down at 10 volts, anode to cathode potential, therefore, these anodes are limited to low resistance environments such as sea water. Niobium has a break down voltage of 120 volts, anode to cathode potential, and is used in higher resistivity electrolytes.

Current densities range from 50 amps per square foot in soils to 500 amps per square foot in sea water, with a platinum thickness of 300 micro inches, depending on the anode surface area and the method of coating application. Platinum has been coated on base metals using many techniques including sputtered electrode position, cladding, and metallurgically bonded.

In metallurgically bonded anodes, the metals are compressed together in an oxygen free vacuum. This provides an oxide free, low resistance bond between the metals.



20% Niobium

Diameter Inches	Nb Thickness Inches	Resistance microhm/ft	Pt Thickness µ-in (2X)*
.750	.038	22	300 (600)
.500	.025	50	200 (400)
.375	.019	89	150 (300)
.250	.013	201	100 (200)
.188	.009	356	75 (150)
.125	.006	806	50 (100)

40% Niobium

Diameter Inches	Nb Thickness Inches	Resistance microhm/ft	Pt Thickness µ-in (2X)*
.375	.038	113	150 (300)
.250	.025	256	100 (200)
.188	.019	453	75 (150)
.125	.013	1025	50 (100)
.093	.010	1822	38 (75)
.063	.007	4102	25 (50)
.031	.0035	16,408	12.5 (25)

100% Titanium

Diameter Inches	Ti Thickness Inches	Resistance microhm/ft	Pt Thickness µ-in
.750	Solid	468	300
.500	Solid	1054	200
.375	Solid	1874	150
.250	Solid	4215	100
.188	Solid	7454	75
.125	Solid	16,862	50

* Double Platinum Thickness

PLATINUM ANODES

FIGURE 3-9

Cladding involves wrapping a thin sheet of platinum around a rod and spot welding the platinum to the base metal at the overlap area.

Electrodeposition techniques plate a film of platinum on the base metal.

Thermal decomposition and welded techniques exhibit the same problems as cladding, and as of the late 1980's are rarely used.

Each process has its advantages and disadvantages and the corrosion worker should evaluate them for each application.

The anode to cable connection is critical and improper connections will result in very early premature failure. Users should assure that the anodes are manufactured in compliance with their specifications by skilled personnel under the guidance of established quality control methods.

The major disadvantage to platinum is poor resistance to anode acid evolution in static electrolytes, rippled direct current, and half wave rectifiers. Use of a 3-phase transformer rectifier in sea water systems has been known to double the life of platinum anodes by reducing the ripple in the DC output.

Very rapid deterioration will occur if the anode is driven at current discharges exceeding the manufacturer's limitations. In underground applications, platinum anodes have had only limited.

Aluminum Anodes

Aluminum anodes have been used in the past as an impressed current anode for protecting the interior of water tanks, particularly where ice destroys the anodes annually. The consumption rate of 9 pounds per ampere year limits the cost effectiveness of aluminum anodes compared to other anode systems. There are several proprietary systems for water tank cathodic protection using other anode materials that will withstand icing.

Lead Silver Anodes

Lead alloy anodes are only used in free flowing sea water applications and may employ various metals such as antimony, lead, tin, and 1 or 2% silver. Commonly supplied in rod or strip form of 1.5" diameter by 10" long, they have been used extensively in Europe with a 2% silver alloy, which doubles its life.

Upon initial startup, the consumption rate is about three pounds per ampere year and eventually a black, passive film of lead peroxide forms to extend the life of the anode, resulting in consumption of about 0.2 pounds per ampere year. Normal current density ranges from 3 to 25 amps per square foot. In silting or low chloride conditions, this oxide film does not form and the anode is consumed rapidly.

Cable connections are made by drilling a hole and silver soldering the lead wire at the base of the hole. The connection cavity is then filled with epoxy to prevent moisture penetration.

Installation is accomplished by hanging the anodes from a structure, dock or pier in a perforated fiberglass pipe or by a support device to maintain its position. This support is important to prevent ice damage and keep the anodes from coming in contact with mud or silt.

Magnetite Anodes

Magnetite (Fe_3O_4), a European inspired anode, is itself an iron based corrosion product. Therefore, there is little or no corrosion involved during current discharge.

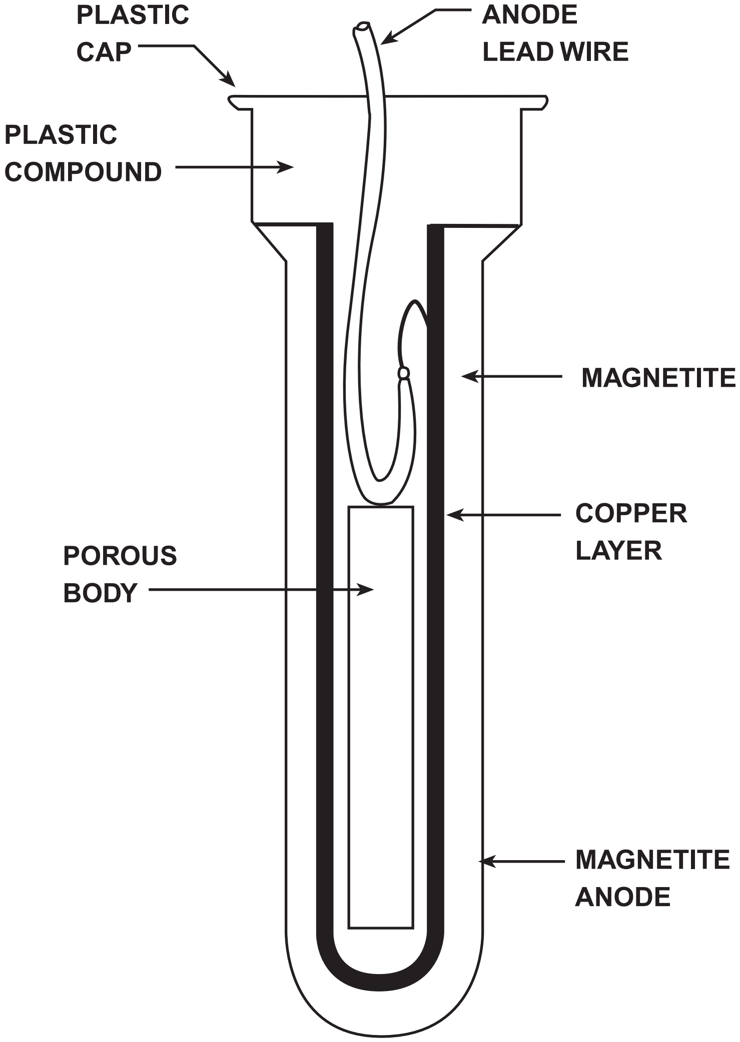
The anodes are manufactured and shipped direct from the factory with the lead wire attached and distributors splice extra wire to meet user requirements. The material is brittle and a factory installed lead wire attachment to the internal wall of the anode is critical. Figure 3-10 shows the anode construction.

Magnetite anodes installed in free flowing sea-water (25 ohm-cm) is a normal application.

Polymer Conductive Anodes

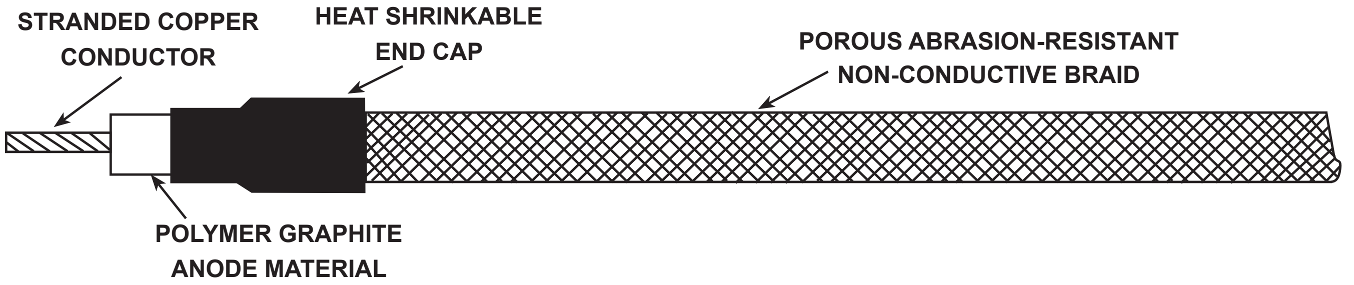
In 1982, an anode material was test marketed to provide a small amount of current in restricted spaces such as internal pipe surfaces, heat exchangers, utility ducts, and areas shielded from conventional anode bed current.

The material resembles electrical cable but actually consists of a stranded copper conductor with an extruded, conductive polyethylene (see Figure 3-11). This concept is used in underground concentric power cables as a conductive shield around the ground



TYPICAL MAGNETITE ANODE

FIGURE 3-10



POLYMER ANODE

FIGURE 3-11

wires. The polymer contains carbon granules which discharge the current. The anode should be backfilled in carbonaceous coke breeze for maximum life.

An optional plastic mesh is available, to separate the anode from the cathode in restricted spaces, preventing electrical shorting between the anode and cathode. Currently the material is available in four different diameters and the current output ranges from 3 to 9 milliamperes per linear foot.

Scrap Steel Anodes

For companies who have access to scrap pipe or old rails, this type of anode may be economical if properly installed. If scrap pipe is used, multiple lead wire connections are made at close intervals and carefully coated at each location to prevent premature connection failure. The major cost of the system is in labor, welders and heavy construction equipment necessary to install the components.

An abandoned pipeline can also be used as an impressed current anode.

A major disadvantage in the use of scrap steel anodes is the high consumption rate of 20 lb/A-yr.

Backfill for Impressed Current Anodes

Special carbonaceous backfill is used to surround most impressed current anodes installed in soil in order to reduce the anode bed resistance and extend the anode life. The only exception applies to anodes used in photovoltaic power supply systems, where magnesium anode backfill is used due to the high back voltage encountered with carbonaceous backfill.

Coke breeze is conductive and transfers current from the anode to the interface of native soil. Some types pass the current more efficiently by more electronic conductance and others are less efficient and current passes electrolytically. The first type is metallurgical coke breeze, derived as a waste by-product of coking (heating) coal, associated with steel production. The composition and particle size of coke may greatly enhance the life of an anode and should be considered at the design stage. Most often the particle size is about 0.375" (d") and smaller for surface anode bed backfill. The smaller the particle size, the greater the compaction and conductivity is. Metallurgical coke should not exceed 50 ohm-cm when measured using ASTM G-58 Soil Box Test Method, temperature corrected. The carbon, iron, copper, sulfur content and weight per cubic foot are important values to analyze prior to installation. Refer to Table 3-9. Metallurgical coke breeze is available bagged or bulk and is often used in prepackaged impressed current anodes.

Calcined petroleum coke consists of finely screened particles of coke that are typically derived as a waste by-product of crude oil refining. It consists predominately of round carbon granules and is much more conductive than metallurgical grades of coke. The resistance should be less than 2 ohm-cm using ASTM G-58 Soil Box Test Method, temperature corrected. Since resistance values are low, high current density is less prone to gas generation and the incidence of gas blocking in deep anode beds using a 92 percent carbon content coke is rare. Some grades incorporate a surfactant, similar to detergent, to reduce water tension and promote pumping and compaction in deep anode beds.

WIRE AND CABLE

Conductors typically used for underground service are made of solid or stranded copper, with a variety of insulation materials designed for the type of electrical and chemical exposure to be encountered (see Table 3-10).

Conductors are rated on their ampacity under certain temperature and service conditions (see Table 3-11). Insulation values also vary depending on wet or dry conditions. The following data are general in nature, covering the most common types, and specification data should be obtained directly from manufacturer pertaining to their product.

CABLE TO STRUCTURE CONNECTIONS

The most common method of connecting cables to structures is the exothermic welding process.

Exothermic welding uses a graphite mold to contain a mixture of copper alloy and magnesium starter powder. After igniting the powder with a flint gun, the powder becomes molten and drops on the cable and structure. The slag on the connection is removed by lightly striking the weld with a chipping hammer after cooling. Figure 3-12 shows a typical set-up for an exothermic weld.

Newer systems utilize a ceramic mold with an electronic ignition.

TABLE 3-9
Coke Breeze Composition

Type	Bulk Density (lb/cu ft)	Porosity (%)	Carbon (lb/cu ft)
Metallurgical	45	48.0	32.51
Petroleum, calcined			
Delayed	48	59.5	47.76
Fluid	54	56.7	49.93
	70	44.0	64.73
	74	40.8	68.53

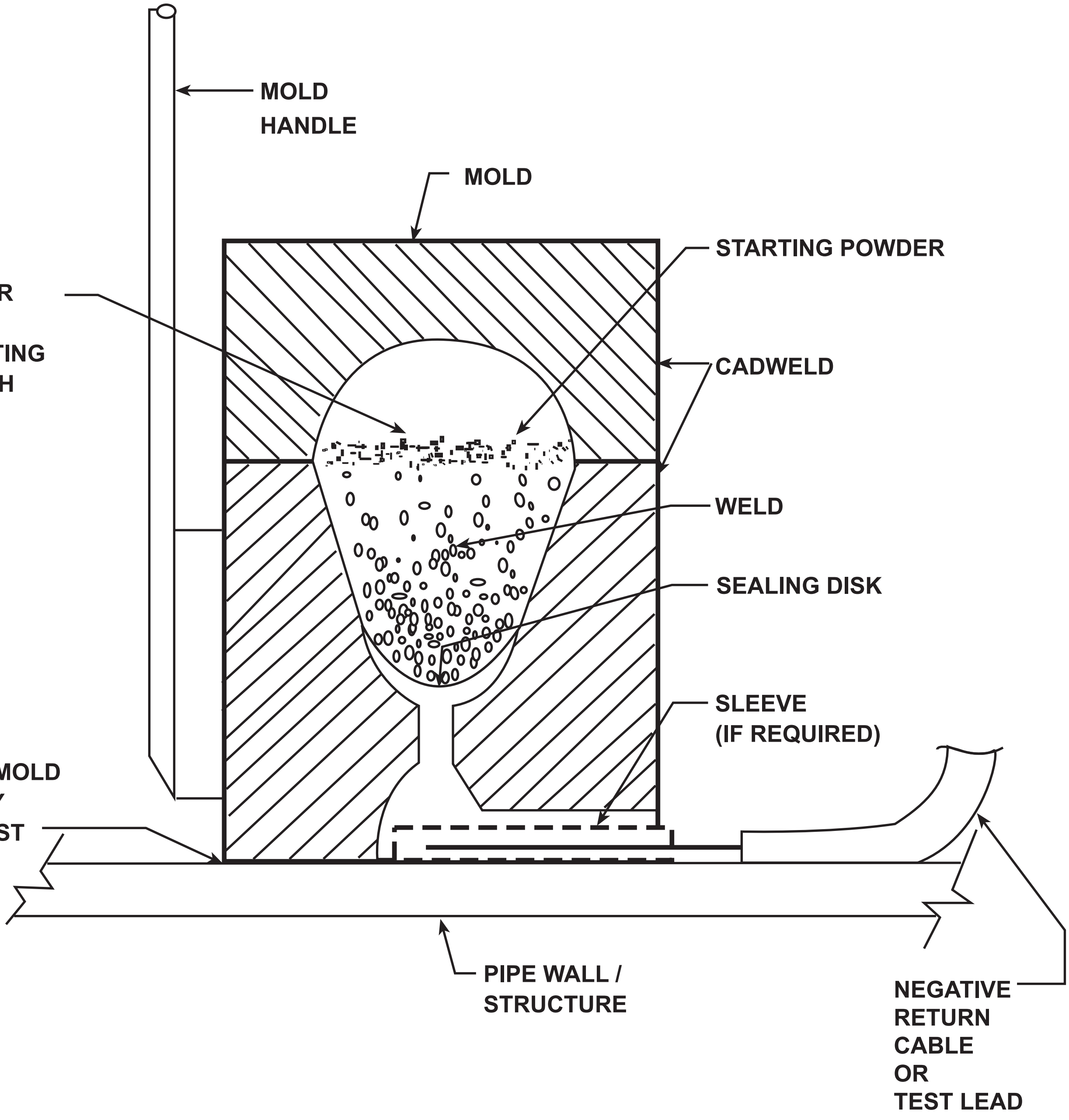
TABLE 3-10
Wire And Cable Insulation Designations

Designation	Insulation	Thick (in)	Cable Size	Specification
HMWPE	High Molecular Weight Polyethylene	.110 .125	No 8 - No 2 No 1 - 4/0	D-1248, Type 1 Class C, Cat. 5
TW	Polyvinyl Chloride (PVC)	.030 .034 .060	No 14 - No 10 No 8 No 6-No 2	U.L. Standard 83 (60º C wet/dry)
THW	Polyvinyl Chloride (PVC)	.045 .060	No 14 - No 10 No 8 - No 2	U.L. Standard 83 (75º C wet/dry)
THHN	PVC/Nylon Jacket (.0004" Nylon)	.015 .020	No 14 - No 12 No 10	U.L. Standard 83 (90º C dry)
THWN	PVC/Nylon Jacket (.004" Nylon)	.015 .020	No 14 - No 12 No 10	U.L. Standard 83 (75º C wet)
PVF/HMWPE	Polyvinylidene (.020") HMWPE jacket (.065")	.085	No 8 - No 2	Kynar™ ASTM D-257
ECTFE/HMWPE	Ethylene Chlorotriflora-ethylene (.020") HMWPE jacket (.065")	.085	No 8 - No 2	Halar™

TABLE 3-11
Conductor Ampacities And Resistances
NACE Corrosion Engineer's Reference Book

Size AWG	Ampacity* (Copper)	Resistance (Ohms/1000 ft @ 25º C)
No. 16	6	4.18
No. 14	15	2.62
No. 12	20	1.65
No. 10	30	1.04
No. 8	50	0.652
No. 6	65	0.411
No. 4	85	0.258
No.2	115	0.162
No. 1	130	0.129
No. 1/0	150	0.102
No. 2/0	175	0.0811
No. 3/0	200	0.0642
No. 4/0	230	0.0509
250 MCM	255	0.0423
300 MCM	285	0.0353
350 MCM	310	0.0302
400 MCM	335	0.0264
500 MCM	380	0.0212

* Ampacity based on THW and HMWPE insulation



TYPICAL EXOTHERMIC WELD PROCESS

FIGURE 3-12

In order to prevent damage to the pipe, weld metal charges are limited to 15 grams for steel pipe and 32 grams for cast iron and ductile iron pipe.

Connecting large cables may require separating the cable strands and using multiple exothermic welds.

Another method of connecting cables to structures is pin brazing.

The technique of pin brazing is based mainly upon electric-arc silver soldering using a pin brazing unit, a hollow brazing pin containing silver solder and flux.

A thin layer of silver is transferred from the brazing pin to between the pipe and the cable. It creates a metallurgical bond between the materials.

The pin brazing process uses a lower temperature than the exothermic welding process.

Structures that contain certain types of flammable substances may require the use of grounding clamps to make the cable attachment.

Special attention should be given to coating any attachment or cable splice to prevent bi-metallic corrosion attack. The coating should be solvent free to prevent deterioration of the insulation.

CABLE SPLICES

Cables can be spliced together using exothermic welding, high compression crimps, or split-bolts as shown in Figure 3-13.

SPLICE ENCAPSULATION

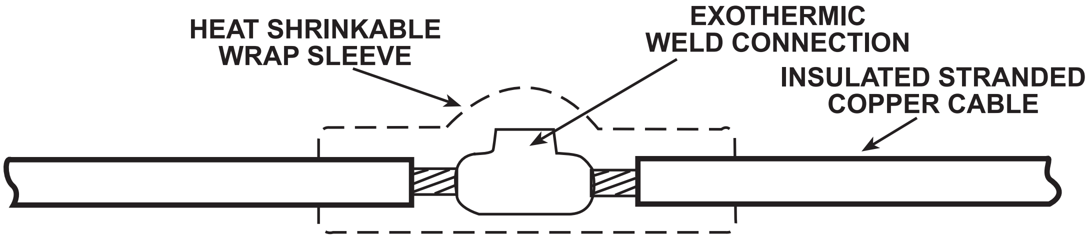
There are many methods available for moisture proofing cable splices:

1. Hand wrapping

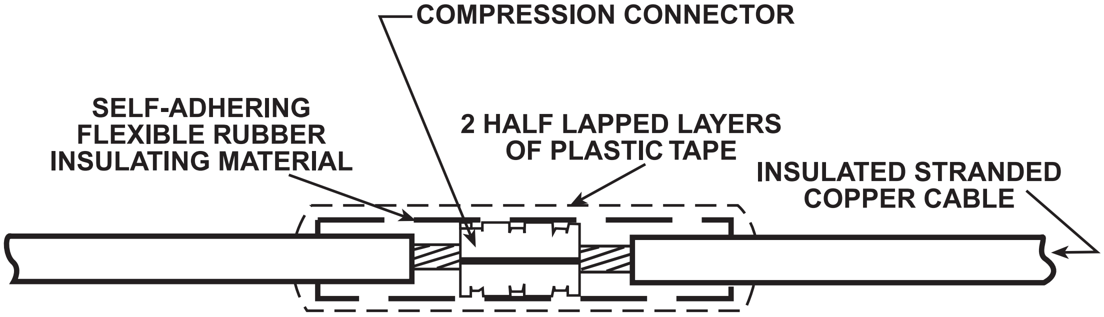
2. Epoxy mold encapsulation

3. Shrink tubing and sleeves

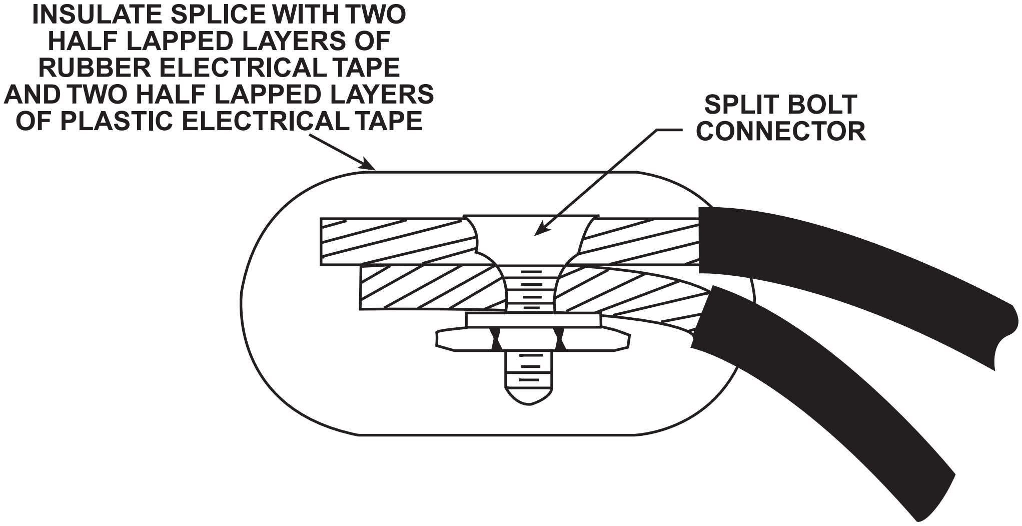
4. Elastomer/urethane impregnated wrap



EXOTHERMICALLY WELDED SPLICE



COMPRESSION CONNECTION



SPLIT BOLT SPLICE CONNECTION

CABLE SPLICE CONNECTIONS

FIGURE 3-13

Hand wrapping has historically been the most reliable method if done properly, although it is also the most expensive since more labor time is required. The exposed splice area is cleaned with a clean rag, dampened with solvent to remove release oil and human oil on the strands. The area is wrapped with 3 laps of electrical rubber insulating tape extending 2 inches on adjacent insulation, paying special attention to the crease area if wrapping a "Y" connection, as in an anode header cable splice. The entire area is then wrapped with 3 laps of PVC electrical tape and coated with an electrical sealant to complete the splice.

Epoxy molds (Figure 3-14) have been used extensively over the years with some mixed results. Epoxy does not bond to the release oils used on wire, permitting moisture to travel eventually into the connection. Since there is no chemical bond to polyethylene, the mold must extend far enough over the adjacent insulation to prevent hygroscopic moisture migration.

Epoxy molds should not be disturbed or backfilled for 30 minutes at 70º F so that the mixture begins to cross link and bonds to the surfaces. Any movement will distort the material and reduce the adhesion. During cold weather, this time will be extended to approximately 3 hours at 32º F.

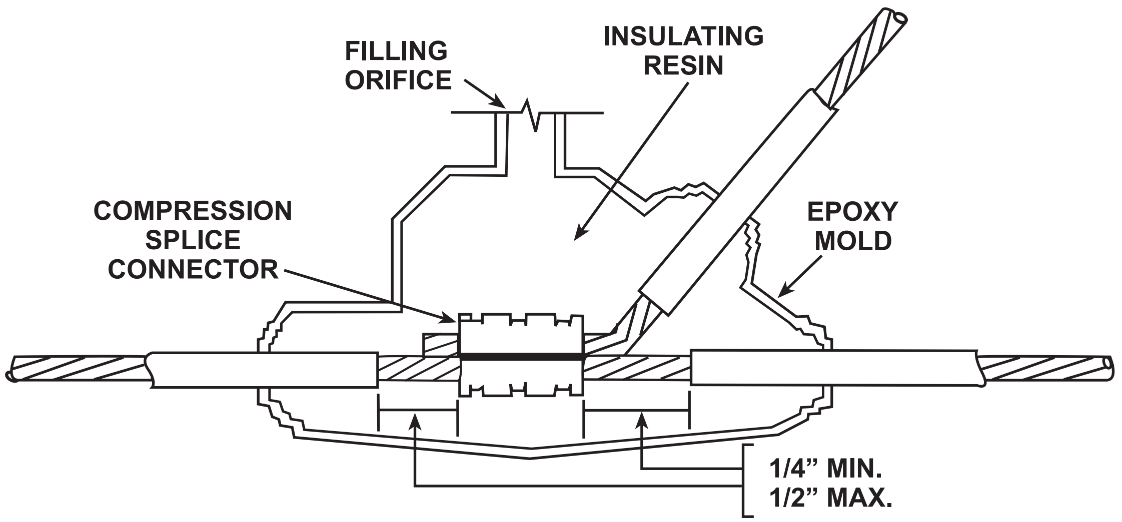
Heat shrinkage tubing of irradiated polyethylene with an effective electrical sealant is used to insulate in-line cable splices. This method has proven to be very effective and inexpensive. Care must be taken when using a propane torch so as not to melt or distort the cable insulation while shrinking the sleeve.

Elastomer sealant kits are a recent development that involves wrapping a pliable strip of sealant around the splice area to moisture-proof the connection. An outer wrap of elastic fabric impregnated with a quick setting, moisture cured urethane is wrapped around the sealant and sprayed with water to harden the fabric. This forms a hard shell to eliminate cold flow of the sealant and prevent rocks or soil stress from damaging the encapsulation.

POWER SUPPLIES

Many sources of direct current (DC) power are available, as discussed in detail in Chapter 7 of the Intermediate Course, for use with impressed current systems as follows:

1. Transformer-Rectifier



EPOXY ENCAPSULATED SPLICE

FIGURE 3-14

2. Solar Photovoltaic Cells

3. Thermoelectric Generators

4. Turbine Generator Units

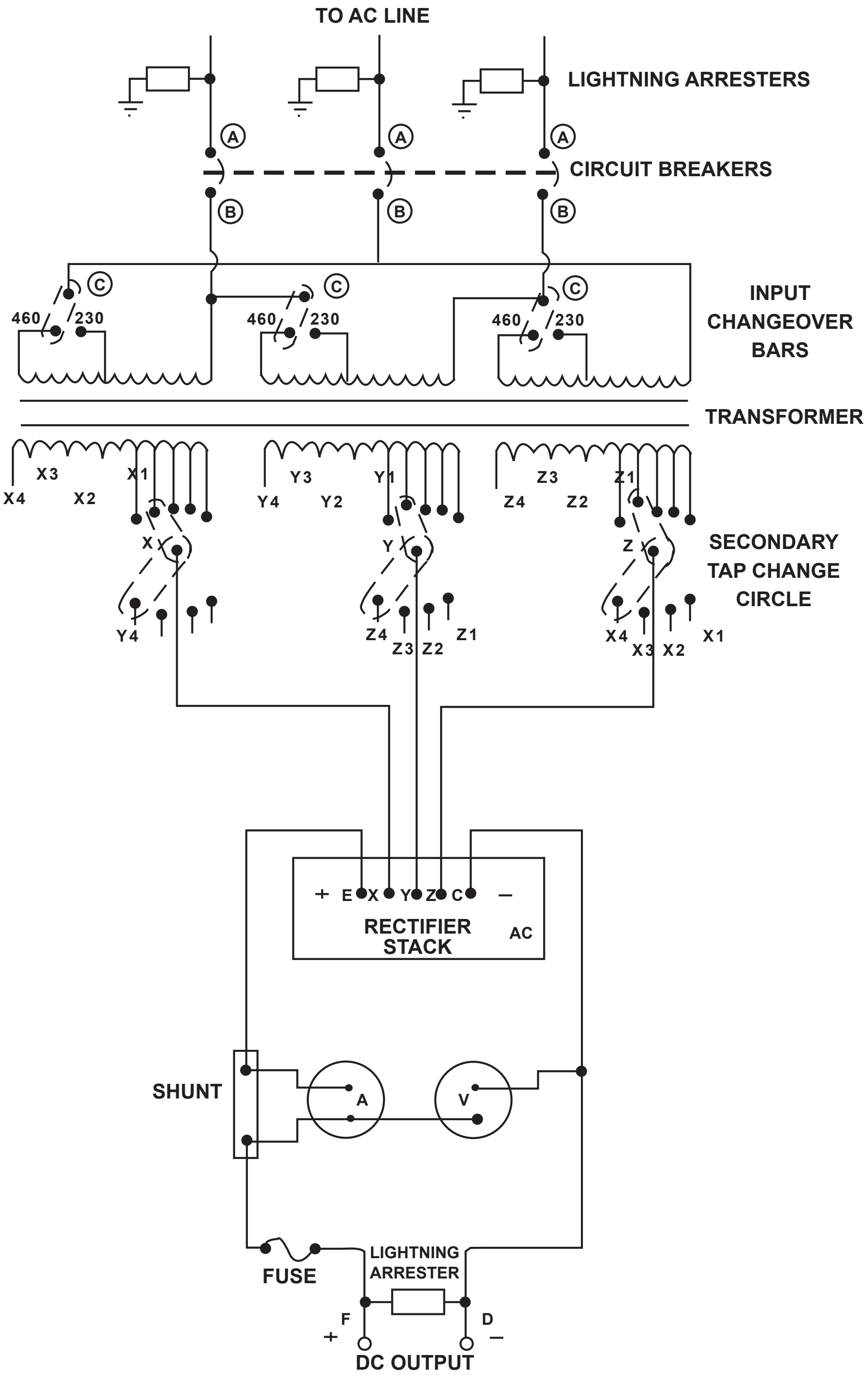
5. Engine Generator Units

6. Wind Powered Generators

Transformer-rectifiers, commonly referred to as simply "rectifiers", are the most frequently used power source for impressed current anode systems. The unit consists of a step down transformer to reduce alternating current to an acceptable level, and a rectifying element to convert the alternating current (AC) to direct current (DC). Output terminals and a host of options and accessories complete the final assembly of the unit. Figure 3-15 shows a typical rectifier circuit.

Specifying the various options is easily accomplished using the following options menu. Selecting them properly requires knowledge.

	Options
1. Enclosure Type	Utility
	Swing Out
	Cabinets
	Slide Out Racks
	Custom
	Small Arms Proof
	Pole Mount
	Wall Mount
	Pad Mount
	Photovoltaic (solar panel)
2. Cooling Type	Air Cooled
	Oil Cooled
	Explosion Proof
	Submersible
	Fan Cooled
	Forced Oil Cooling



TYPICAL RECTIFIER CIRCUIT

FIGURE 3-15

3. Control Type	Standard Control Current Regulated Voltage Regulated Automatic Potential Control Solid State Control - no taps IR Drop Free
4. Rectifying Element	Selenium Bridge Selenium Center Tap Silicon Bridge Silicon Center Tap
5. Circuit Type	Center Tap, Single Phase Bridge, Single Phase Three Phase Wye Three Phase Bridge Multiple Output Circuit
6. AC Input	115 volts 230 volts, single or 3 phase 460 volts, single or 3 phase 115/230 volts 230/460 volts, 3 phase 115/460 volts
7. DC Volts	Specify maximum DC output in volts
8. DC Amperes	Specify maximum DC output in amperes
9. Options	AC and DC Lighting Arresters AC Arresters only DC Arresters only Communications Filter Efficiency Filter (choke) Meter Switches Pilot Light DC Failure Light DC Fuse Painted Cabinet

Hot Dipped Galvanized Cabinet
Anodized Aluminum Cabinet
Stainless Steel Cabinet
Cabinet Gauge - 16,14,12,11
Cabinet Legs
Cabinet Side Door
Slide Out Racks
High Ambient Operation
Special Taps
Coolant - Oil cooled units
Non-Standard Access Knockouts
AC Frequency - other than 60 hz
Elapsed Time Meter
Convenience Outlet - 115 volts

JUNCTION BOXES

Junction boxes are an enclosure for terminating multiple cables to a common electrical bus bar.

An anode junction box can be used to connect multiple anode cables to a common electrical bus bar. The rectifier positive cable is fed through a conduit to the main anode bus and a perpendicular bus terminates the lead wires at individual terminals. Leads may be attached to fixed value current limiting resistors and the current output can be measured by connecting a DC voltmeter across each respective shunt. A typical anode junction box is shown in Figure 3-16.

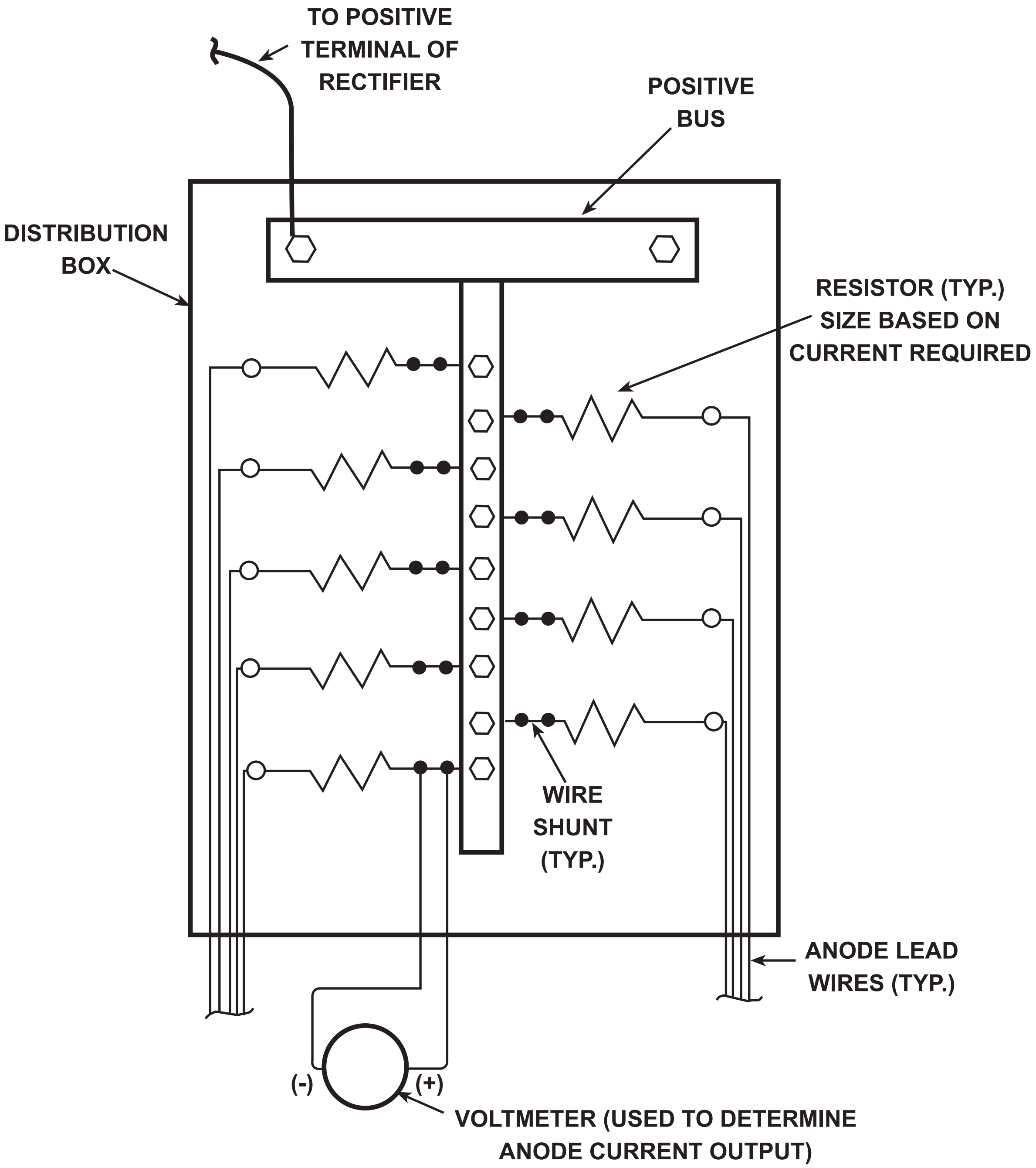
Where several anode circuits are supplied from one power supply, it may be desirable to control the current to each anode using variable resistors connected in series with the output cable. Many of these control options can now be built into the rectifier circuitry.

A junction box can also be used to connect multiple structures together.

A junction box can be installed at a rectifier where multiple structure cables are connected to a bus bar which is in turn connected to the rectifier negative terminal.

PERMANENTLY INSTALLED REFERENCE ELECTRODES

There are 3 types of permanently installed reference electrodes that are used for



TYPICAL JUNCTION BOX WITH SHUNTS

FIGURE 3-16

monitoring the potential of a structure or as a sensor in conjunction with potentially controlled rectifiers. They are:

High Purity Zinc
Copper/Copper Sulfate Electrode
Silver/Silver Chloride Electrode

If the electrode is to be buried, it must be surrounded with special backfill to increase the ion trap area. Zinc is particularly subject to the effects of polarization and should be surrounded with a 75%/20%/5% mixture of prepared backfill to prevent this passivation effect.

Copper bearing electrodes with a saturated sulfate solution will become contaminated in the presence of chlorides and are limited to fresh water and chloride free environments for maximum life.

Silver bearing electrodes with a saturated chloride solution are used in sea water and brackish waters where chlorides are found. Other types utilize a perforated plastic tube containing a chloridized silver rod and depend on the natural chlorides in sea water to provide meaningful readings. This second type will give erroneous readings in brackish waters due to the constant changes in chloride levels.

TEST STATIONS

As simple as a test station is, it seems to cause a great deal of confusion, particularly to those people who are unfamiliar with the concept of cathodic protection. The variables are many and here is a partial listing of the variations.

	Choices
1. Box Type	Post Mount
	Flush Mount
	Flange Mount
	Round
	Square
	Explosion Proof - Specify Type, Class
	Condulet
2. Construction	Polycarbonate
	Flake Filled Polyester

	Cast Iron Cast aluminum ABS Polymer Thermosetting Composite
3. Terminals	Specify Number Plated Brass Copper Brass Banana Plugs Stainless Steel Lock Washers
4. Hub Type	Slip Fit, size Threaded, size Double Hub Single Hub
5. Hub Size	Specify size and quantity
6. Post Type	Treated wood, size PVC Conduit, size Steel Conduit, size With or without anchors
7. Post Length	Specify Length
8. Flush Type	Cast Aluminum Top Cast Iron Top Plastic Top, magnetic
9. Wiring	None Pre-wired, specify size, length, insulation Shunts - specify quantity, size, type
10. Covers	Name cast on top “O" Ring Seal, round only Weather Proof Seal

Waterproof Seal
Slip Fit
Exposed Terminals
Locking Type

11. **Terminal Blocks** Polyester Laminate - 0.125"
Polycarbonate

12. **Options** Shorting Bars - specify quantity, material
Lightning Arresters - specify type
Fixed Current Limiting Resistors - specify amperage
Variable Slide Wire Resistor - specify amperage
Rotary Rheostat - specify amperage
Meters - specify type, range
Locking Devices
Shunts - specify amperage

Figure 3-17 shows some typical test stations.

FLANGE ISOLATORS AND DIELECTRIC UNIONS

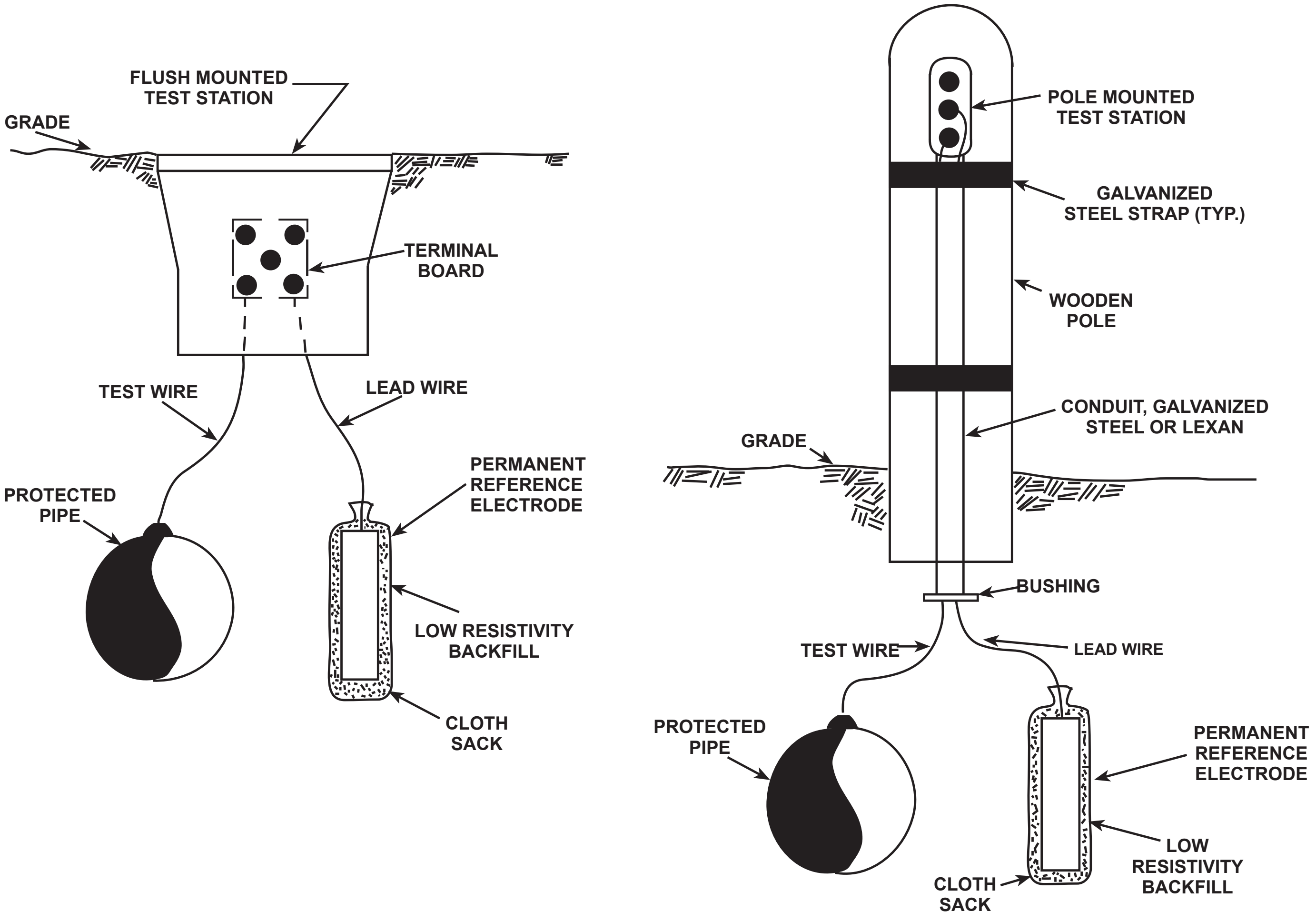
To isolate cathodically protected structures requires the mechanical insertion of nonconductive materials between the metal components. The isolation material should not deform or deteriorate due to the operational conditions of the external or internal environment or the structure itself. Once again, there are a wide variety of materials to choose from depending on the particular application.

Flange gaskets (Figure 3-18) are selected on the basis of pipe size, ANSI pressure rating, full face or raised face, and material composition to suit the pipeline product. The components of a flange isolation kit consist of a gasket, sleeves, isolating washers, and steel washers.

Components

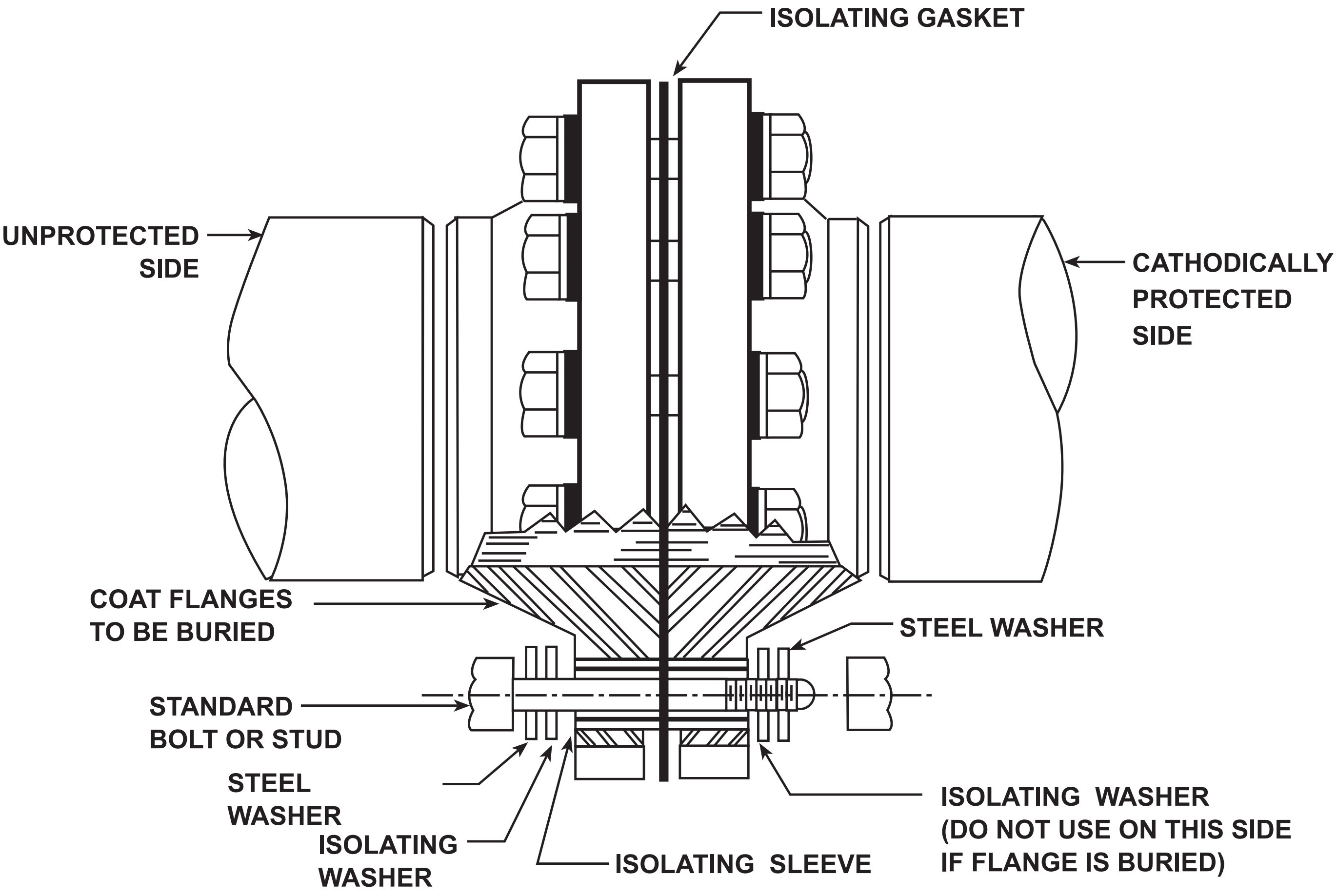
1. Size Specify

2. Gasket Type Full Face “E” (with bolt holes)
Ring “F” (without bolt holes)
“D” for RTJ flanges



TYPICAL CATHODIC PROTECTION SYSTEM TEST STATION INSTALLATIONS

FIGURE 3-17



TYPICAL ISOLATING FLANGE
ASSEMBLY

FIGURE 3-18

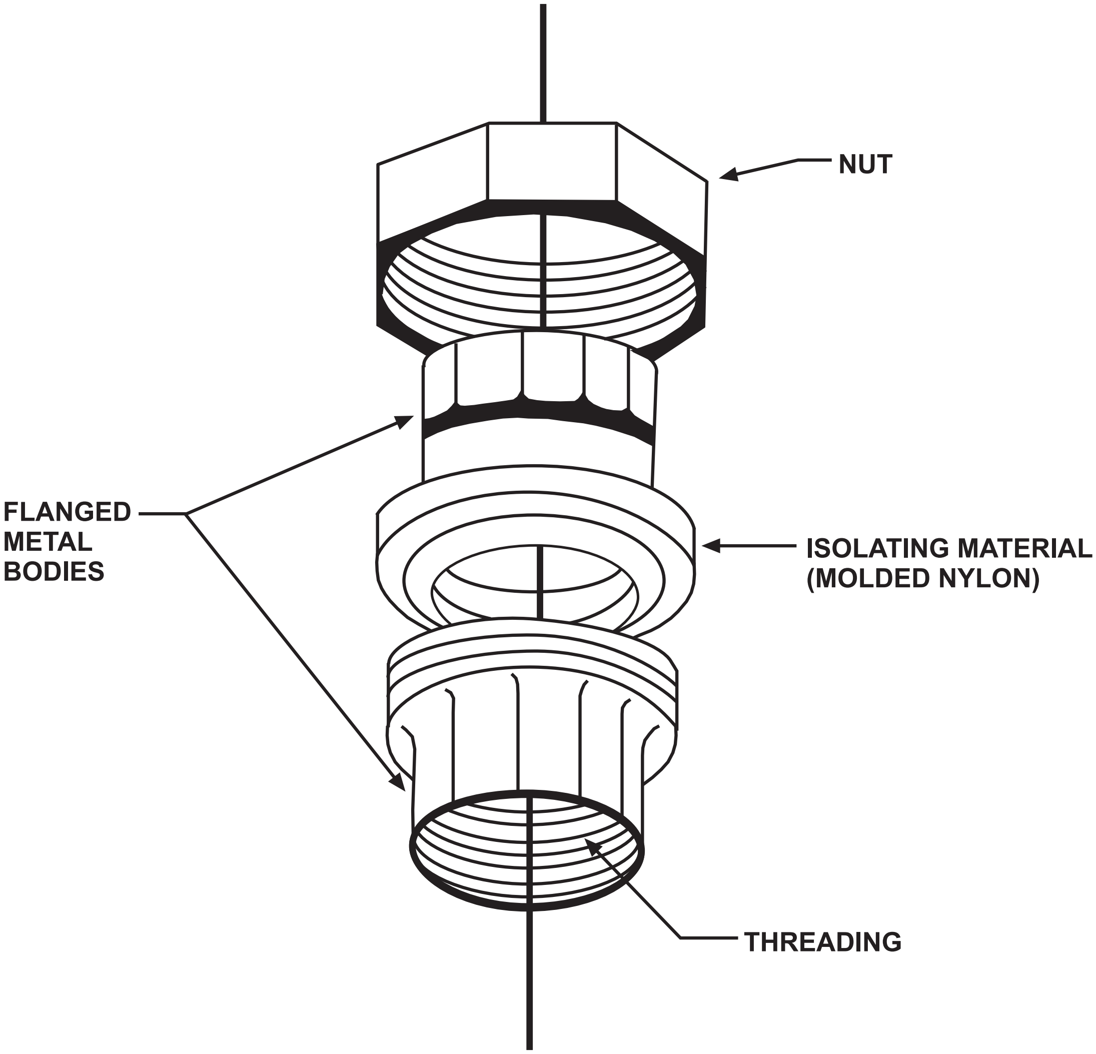
3. Materials	Plain Phenolic - 225º F, max.
	Neoprene Faced Phenolic - 175º F, max.
	Glass/Phenolic - 350º F, max.
	Aramid Fiber - 450º F, max.
	Epoxy/Glass - 350º F
4. Sealing Element	Nitrile Sealing Element - 250º F, max.
	Viton - 350º F, max.
	Teflon - 450º F, max.
5. Pressure Rating	ANSI Class - 150 lbs to 2500 lbs
6. Isolating Sleeves	Polyethylene - 180º F, max.
	Phenolic - 225º F, max.
	Mylar - 300º F, max.
	Acetal - 180º F, max.
	Nomex - 450º F
7. Isolating Washers	Glass/Phenolic - 300º F
	High Temp. Phenolic - 350º F
	Silicon/Glass - 350º F
	Epoxy/Glass - 280º F to 350º F
8. Steel Washers	Cadmium Plated, 1/8" thick

Check with the manufacturer for more specific and absolute data. Flange isolation kits are best suited for above ground electrical isolation on new installations.

Dielectric isolating unions (Figure 3-19) perform the same basic function as flange gaskets by inserting a high resistance plastic between the union faces. They are normally available as “O” Ring Type or Ground Joint Type in pressure ratings of 150 to 3,000 psi working pressure. Common installations include hot water heaters, service station pumps, natural gas distribution service lines, and hydraulic lines.

MONOLITHIC WELD IN ISOLATORS

Monolithic weld in isolators are factory assembled, one piece, isolating devices designed to eliminate underground isolating flanges. They eliminate bolts and washers therefore providing a uniform surface to easily apply an exterior dielectric coating.



TYPICAL ISOLATING UNION DETAIL

FIGURE 3-19

They are available in pipe sizes up to 120 inches diameter in all ANSI pressure ratings. Factory pretested, they assure high dielectric qualities and are available with an internal coating to reduce bridging of the insulating gap when the product carried in a conductive liquid.

CASING ISOLATORS AND END SEALS

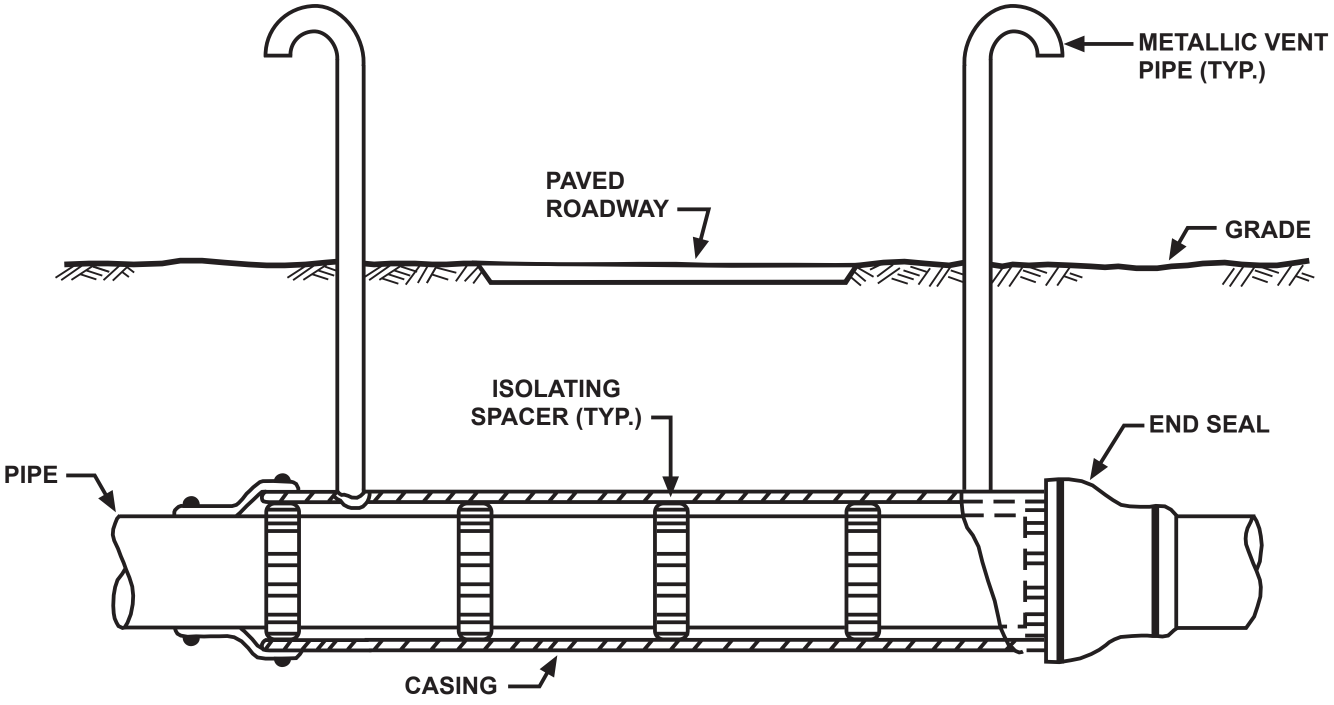
Since the mid-1980's, the effects of electrically shorted casings has received enhanced scrutiny from regulatory agencies. The cause and effect relationship of electrically shorted casings should be well known to the reader by now, and the purpose of this section is to acquaint the reader with the types of materials that are currently available. Careful selection and installation of the components during construction, either new or rehabilitative, will reduce the possibility of a shorted casing.

Casing isolators (Figure 3-20) generally consist of molded polyethylene segments, joined together to form rings at frequent intervals on the pipe, to support the weight of the pipe with product and keep the carrier (product line) centered in the casing. On occasion these segments become damaged during installation or during operation due to soil shifting and pipe movement, resulting in a shorted condition.

Other types are made of steel, shaped like a saddle, and are lined with a thick rubber or PVC sheeting to isolate the carrier pipe from the saddles. These too may become damaged and ineffective as mentioned previously if not properly specified. To order, specify a high compressive strength runner suitable for the pipe and product weight and the length of the casing or crossing. The isolator should have a quality coating and be properly designed for the particular project.

Another form of casing isolation is a nonconductive wax filler, used in conjunction with isolating rings, to fill the annular space between the carrier and the casing. If done properly, the filler will prevent ground water penetration and condensation from filling the annular space with electrolyte, thus preventing ion flow. It will also prevent atmospheric corrosion from occurring within the casing.

If the casing has been in service, it should be flushed with water to remove debris. The end seals are usually replaced with new seals that can accommodate the weight and installation pressures encountered during the filling procedure. For new and rehabilitated casings, the vents are temporarily sealed off and the casing is pressurized to determine if the filler will be contained.



TYPICAL ISOLATED CASING DETAIL

FIGURE 3-20

Complications that may arise are, stitch welded casing, perforated casing, out of round casing, improper seals and constricted vent openings.

Casing end seals (Figure 3-20) have traditionally consisted of rubber boots held in place with hose clamps, shrink sleeves with support skirting, and a proprietary rubber link system. Only careful selection and supervision during installation can prevent the end seals from being the weakest link in the system.

CONCLUSIONS

It is important for corrosion control personnel to understand the characteristics of the various materials and equipment associated with cathodic protection systems.

Before designing a system, the corrosion worker should acquire catalogs from various cathodic protection equipment suppliers to determine what materials and equipment are available and to determine their characteristics.

Chapter 4 - Dynamic Stray Current Analysis

INTRODUCTION

This chapter will review the causes and common means of detecting and mitigating dynamic stray current effects. Steady state, or static, stray current has been covered in Chapter 5 in the Intermediate Course text.

This chapter presents detailed information on dynamic stray currents emanating from direct current (DC) sources. While alternating current (AC) may create a potential safety hazard, its effect on corrosion of ferrous structures is not fully understood. A brief discussion on stray AC appears at the end of this chapter.

STRAY CURRENTS

Stray currents are defined as electrical currents flowing through electrical paths other than the intended paths. Stray, or interference currents can be classified as being either static or dynamic.

Static interference currents (Chapter 5, Intermediate Course text) are defined as those, which maintain constant amplitude and geographical path. Examples of typical sources are railroad signal batteries, HVDC ground electrodes and cathodic protection system rectifiers.

Dynamic interference currents, on the other hand, are defined as those which are continually varying in amplitude, direction or electrolytic path. These currents can be manmade or caused by natural phenomena. Typical examples of man-made sources are DC welding equipment, electrical railway systems, chlorine and smelter plants. Telluric, or natural sources of dynamic stray currents, are caused by disturbances in the earth's magnetic field due to sun spot activity. Telluric effects have not been shown to contribute to corrosion, but they do, however, create measurement difficulties and can interfere with one's ability to assess cathodic protection system performance.

THE EARTH AS A CONDUCTOR

In order to understand the control of stray current, one must first understand what these stray currents are. In underground corrosion, we are dealing with the earth as a huge electrolytic medium in which various metallic structures are buried and often interconnected. The earth is an electrolyte because of the water contained in the soils.

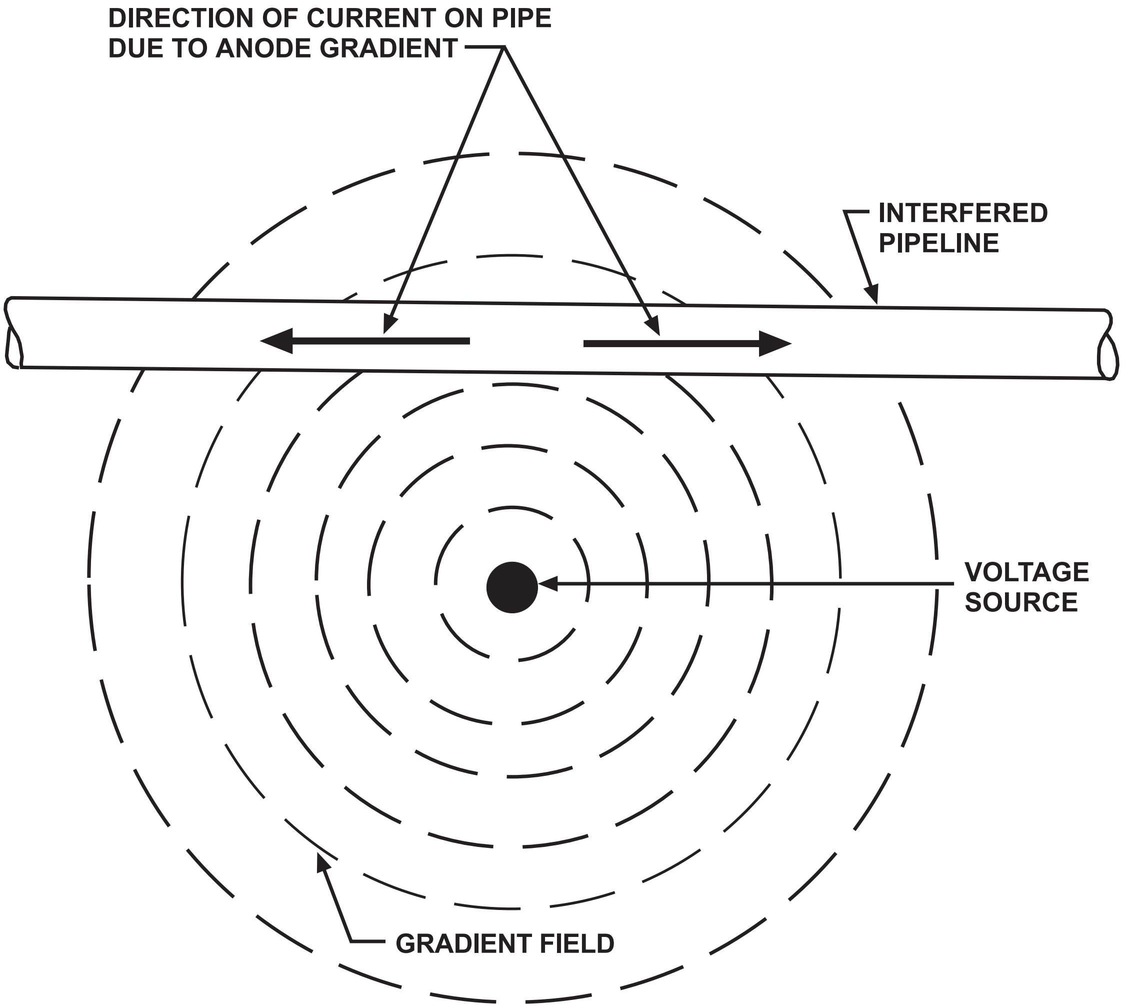
This water causes ionization of various soluble salts and makes the earth an electrolytic conductor. Conductance is measured in electrical units known as Siemens, or mho centimeters. More commonly, the reciprocal of conductivity, resistivity, is measured and expressed as ohm centimeters. The more conductive the earth, the lower the resistivity. Seawater, for example, has a resistivity of 25 to 30 ohm centimeters. Natural soils, depending on the amount of ionizable material present and the moisture content, range in resistivity from near that of sea water up to the hundreds of thousands of ohm centimeters. When one considers stray currents, it should be borne in mind that the lower the resistivity of the soil, the more severe the effects of stray currents may be.

From the values of resistivity cited, it is quite evident that a metallic structure in the earth may be a far better conductor of electricity than the earth itself, even seawater. Resistivities for copper and iron are less than 10×10^{-6} ohm centimeters, while that for lead is approximately 22×10^{-6} ohm centimeters. It is readily understandable, therefore, that should current flowing in the earth produce a potential difference (voltage gradient) crossed by such a metallic conductor, the conductor will readily acquire a part of the current that is flowing. See Figure 4-1. Thus, pipelines and cables can become major conductors of stray currents in the earth environment.

POTENTIAL GRADIENTS IN THE EARTH

How do the stray currents that accumulate on metallic structures underground get into the earth? As in any electrical circuit, it is necessary to have potential differences between two points in order to have a current flow. One also must have an electrical circuit, that is, a source of the current and a return for that current. The magnitudes of current will be dependent upon the electrical potential and electrical resistance. The amount of current which will flow on any one structure will be inversely proportional to the resistance of the various parallel electrical paths that join the two points of different electrical potential in the circuit. This is true of any electrical circuit where parallel resistances are involved. A metallic electrode in earth that is positive with respect to the earth around it will discharge current into the earth and onto any other metallic structures that may be in the vicinity. Any element that is negative to earth will have the opposite effect of collecting current from the earth or from metallic structures in its vicinity.

Many companies feel that any positive pipe-to-soil voltage swing of less than 10 millivolts on a structure is tolerable and does not require mitigation, since interference is negligible. The British “Joint Committee for Coordination of Cathodic Protection of Buried Structures”, has suggested that the allowable limit of positive change be 20



CURRENT FLOW CAUSED ON STRUCTURE
WITHIN A VOLTAGE GRADIENT FIELD

FIGURE 4-1

millivolts. It is possible that positive voltage changes within these ranges may be indications of strong adverse electrolytic currents, but in the majority of cases where voltage swings are less than 10 millivolts negligible interference exists.

In practice, if the positive swing does not cause a potential less negative than -0.850 volts (IR drop free), then negligible corrosion can be expected.

DETECTION OF DYNAMIC STRAY CURRENTS

The easiest way to keep abreast of possible interference problems in an area is through contact with Corrosion or Electrolysis Coordinating Committees. These committees act as clearinghouses for information on underground plant locations and known interference sources.

Dynamic stray currents are present if the structure-to-soil potential is continually fluctuating while the reference electrode is kept in a stationary position in contact with the soil. See Figure 4-2. These potential changes are a direct result of current changes at the source of the interference due to loading variations. This would also be detected by constantly changing line current measurements (Figure 4-3).

In efforts to locate the source of man-made dynamic stray currents, the following steps should be taken:

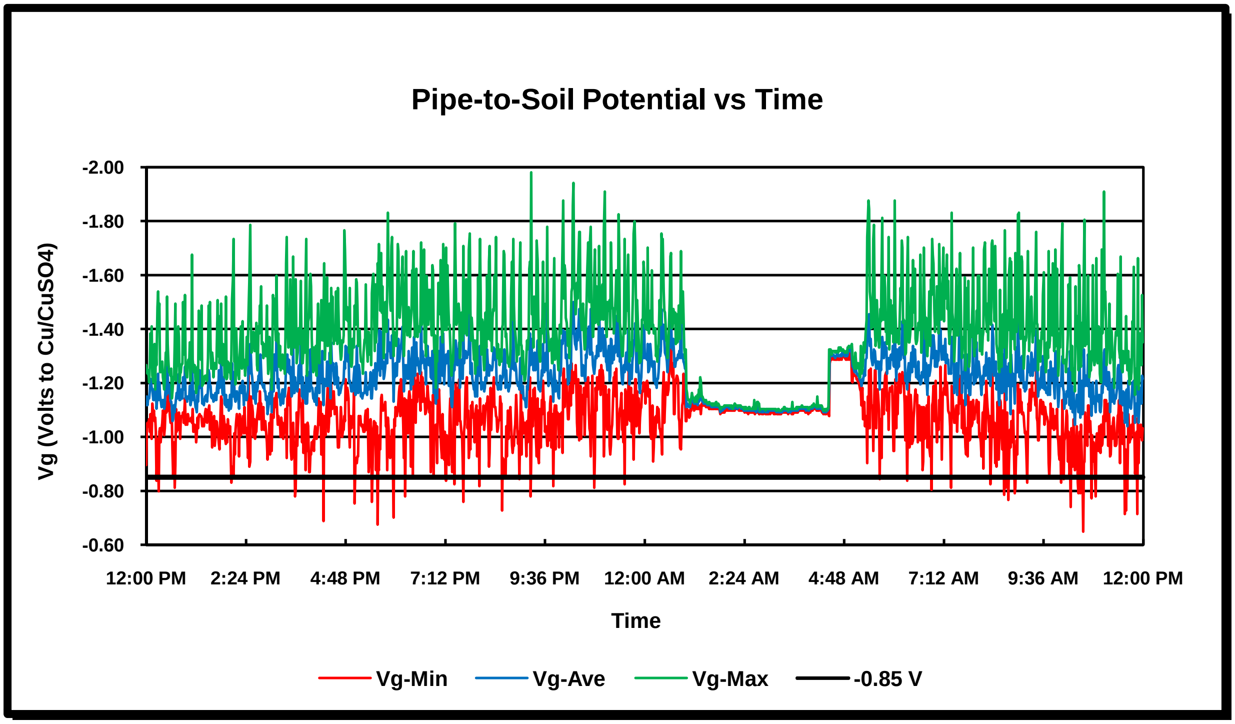
1. Determine if any DC electrical railway systems, mines or industrial plants (aluminum, chlorine, etc) exist in the area where the interference was detected.

2. Inquire of other pipeline operators, cable operators or corrosion committees in the area if any dynamic earth current sources in the area, such as rapid transit systems or electrical DC substations exist.

3. If there are mines or DC railways in the area, contact them to determine the location of their operations and current sources.

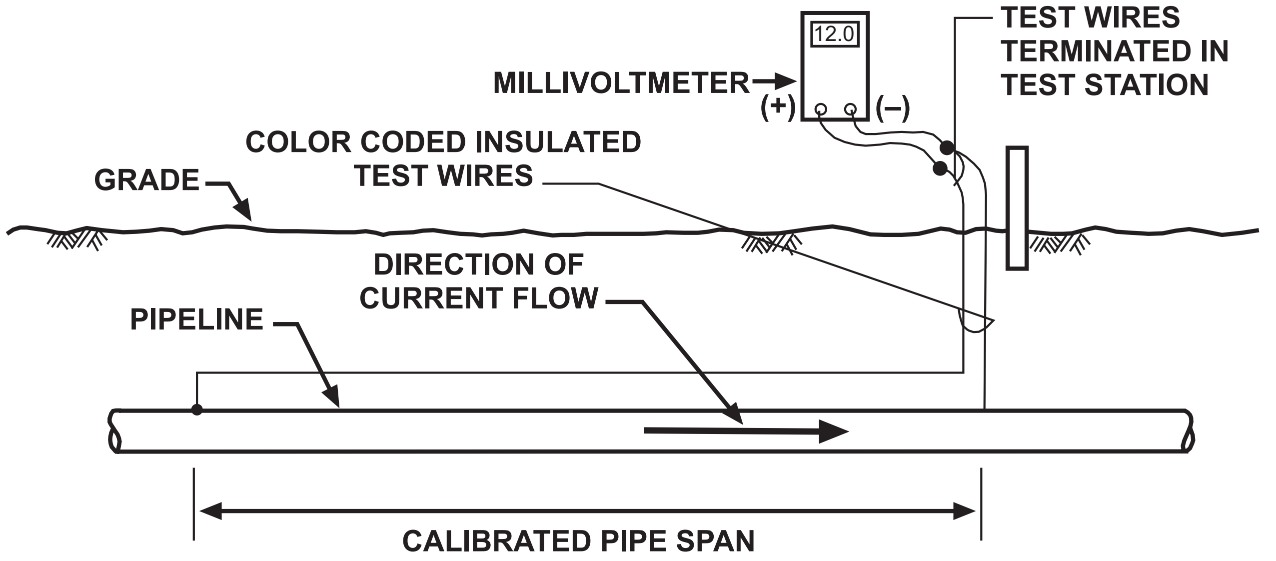
4. Trace the current flow along the structure back to its source. This can be done by observing the current flow at intervals along the interfered structure by utilizing millivolt drop test station lead wires, to determine the direction of the current flow. This technique is illustrated in Figure 4-3.

Let us assume that a situation exists where a single generating unit is causing



TYPICAL PIPE-TO-SOIL POTENTIAL (Vg) PROFILE INDICATING DYNAMIC STRAY CURRENT

FIGURE 4-2



NOTE: POSITIVE POTENTIALS MEASURED WITH METER HOOK-UP AS SHOWN INDICATES CURRENT FLOW IN DIRECTION SHOWN

DETERMINING DIRECTION OF LINE CURRENT FLOW

FIGURE 4-3

interference problems. A voltmeter connection, to be used for pipe-to-soil potential (V_{gsc}) measurements, is made between the pipeline and a reference electrode, somewhere within the earth current pattern of the generator and its load. Observing the fluctuating potential readings at this point alone would not enable one to determine if the readings are being taken at a point where the pipeline is picking up or discharging current. If measurements are being taken at a point of current pickup, a negative potential swing would occur. A positive swing would indicate a decrease of current flow and a condition of the pipe returning to its steady state condition. Readings observed at a discharge point, swinging in the positive direction would indicate an increase in current leaving the line and a negative swing would indicate a decrease in current discharge.

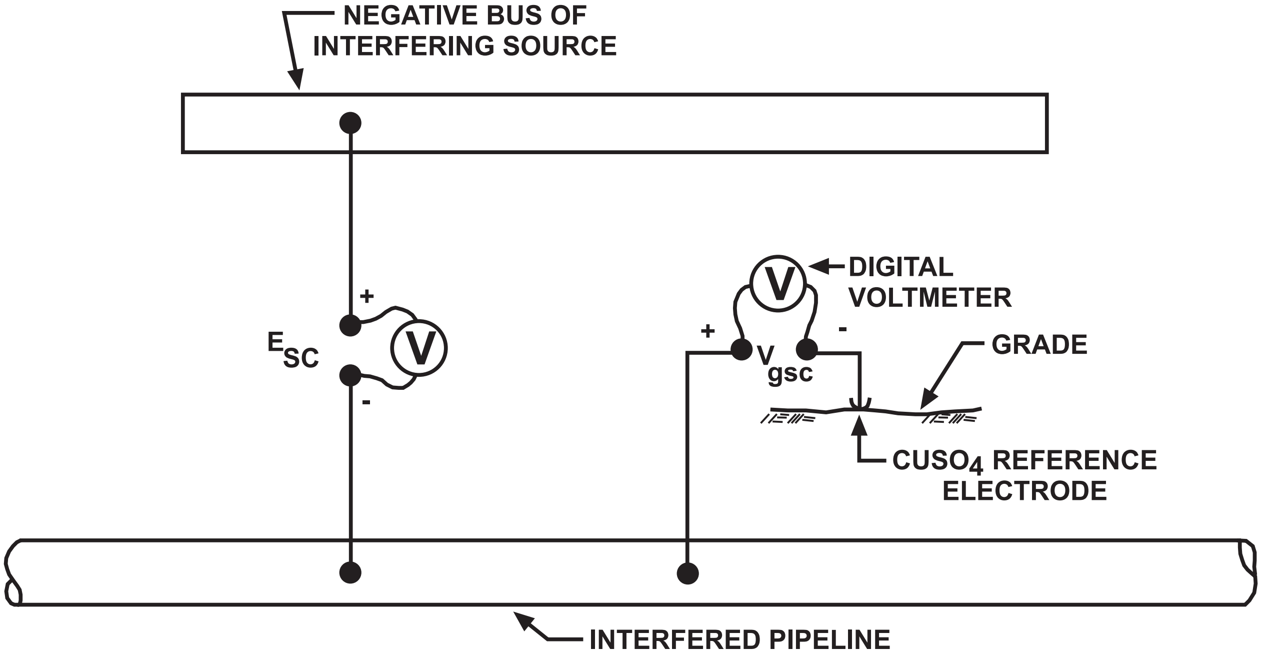
The determination of whether test locations are either pick-up or discharge points is done by obtaining correlations of the pipe-to-soil potential to the open circuit voltage between the interfered pipeline and the stray current source. This is known as a Beta Plot. Figure 4-4 illustrates a typical Beta plot measurement connections. The locations for the pipe-to-soil measurements may be remote from the open circuit measurements. Communication must be established between the locations, as both measurements must be made simultaneously. Sufficient data points must be obtained to indicate trends in the data. Figure 4-5 is an example of a Beta Plot of one location indicating a current pick up area and Figure 4-6 shows a current discharge area at another location.

As the connection shown in Figure 4-4 indicates, a positive value for E_{sc} occurs when current flows from the stray current source to the pipeline. Conversely, a negative value of E_{sc} indicates a flow from the pipeline to the stray current source. The slope of a straight line drawn through the data points is the value of Beta (β):

$$\beta = \frac{\Delta V_{gsc}}{\Delta E_{sc}}$$

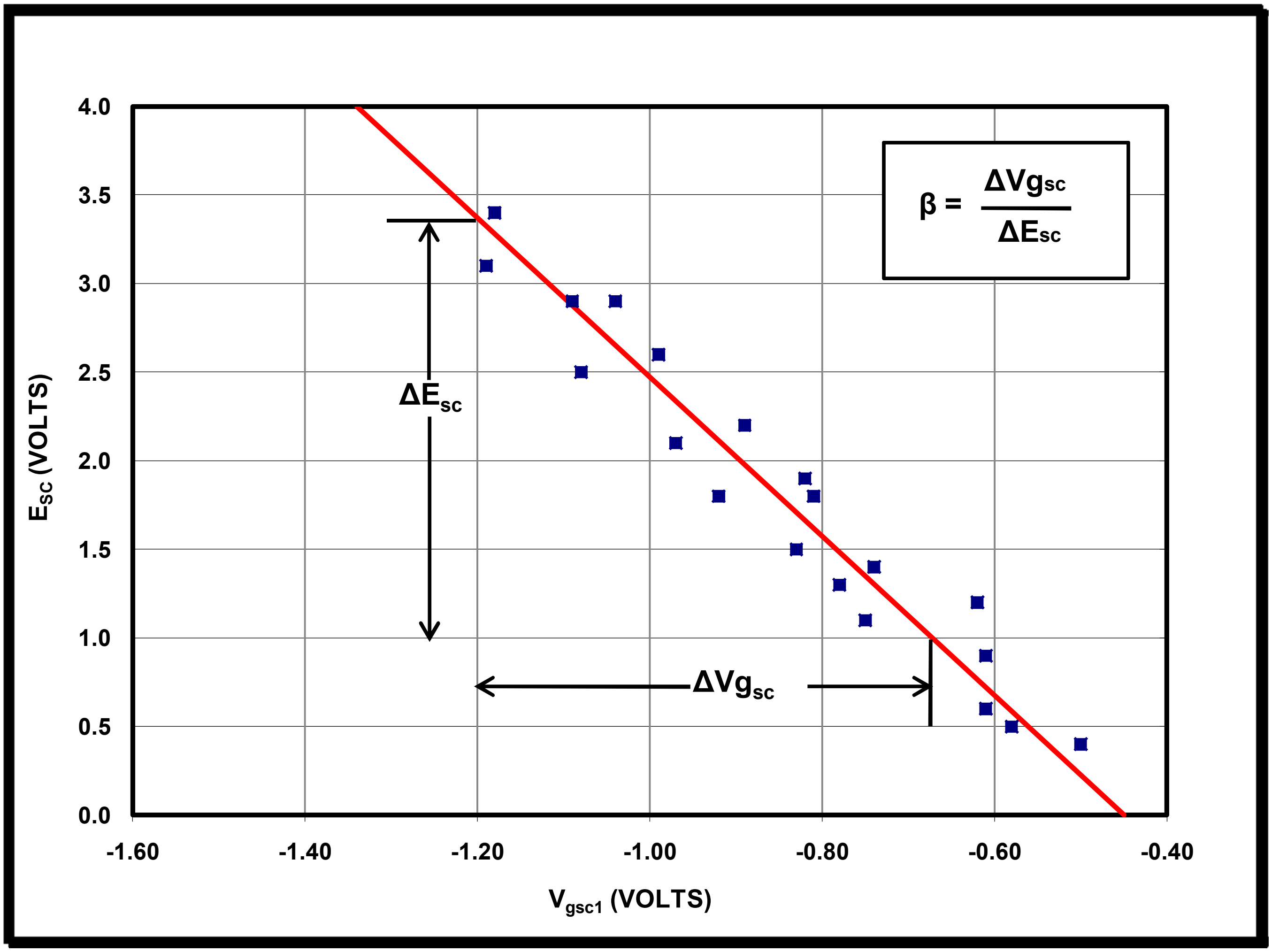
As indicated, this type of testing requires that voltage measurements be taken at two different locations. Many readings should be taken at the two locations simultaneously. The meters used at the two locations must be identical or else comparison of the two sets of readings will be difficult.

In most cases, a dual channel recorder such as an X-Y plotter is used or a multi-channel datalogger is used.



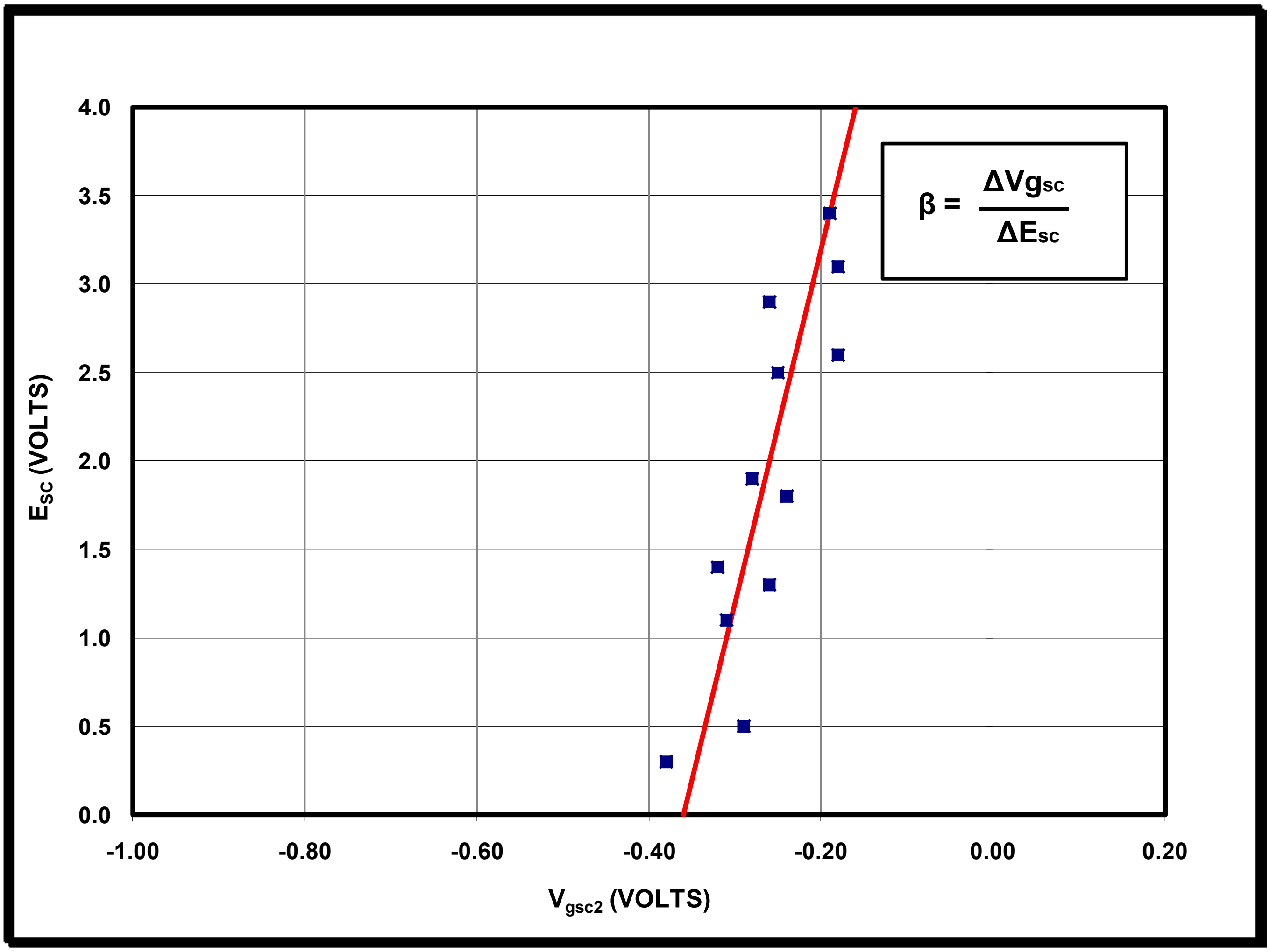
TYPICAL TEST SET-UP USED TO LOCATE
POINT OF MAXIMUM EXPOSURE

FIGURE 4-4



TYPICAL BETA CURVE - PICKUP AREA

FIGURE 4-5



TYPICAL BETA CURVE - DISCHARGE AREA

FIGURE 4-6

Interpreting Beta Curves

Beta curves, which are sloped from the bottom right hand side of the graph to the top left side, would indicate an area of current pick up. What this means is that as the current output of the source increases, the current pick up by the interfered structure also increases. An example of such a curve is shown in Figure 4-5.

An area of current discharge is indicated by a curve which slopes from the bottom left to the top right of the graph, indicating that the rate of current discharge increases as the current output of the source increases. An example of such a curve is shown in Figure 4-6.

If the plotted points describe a vertical line, this would indicate a neutral curve. This means that there is no influence on V_g by the output fluctuations of the current source. Such a curve is rare in practice and if one is plotted, the possibility of equipment malfunctions or errors during testing should be investigated.

If the plotted points do not describe a straight line, this may indicate that the interfered structure may be picking up stray currents from an additional source or that the suspected source is not causing the interference. Plots describing two or more distinct lines would indicate the presence of more than one interfering current sources. The slopes of these lines will indicate whether currents are discharging or being picked up according to their slopes and the polarity of the meter connections.

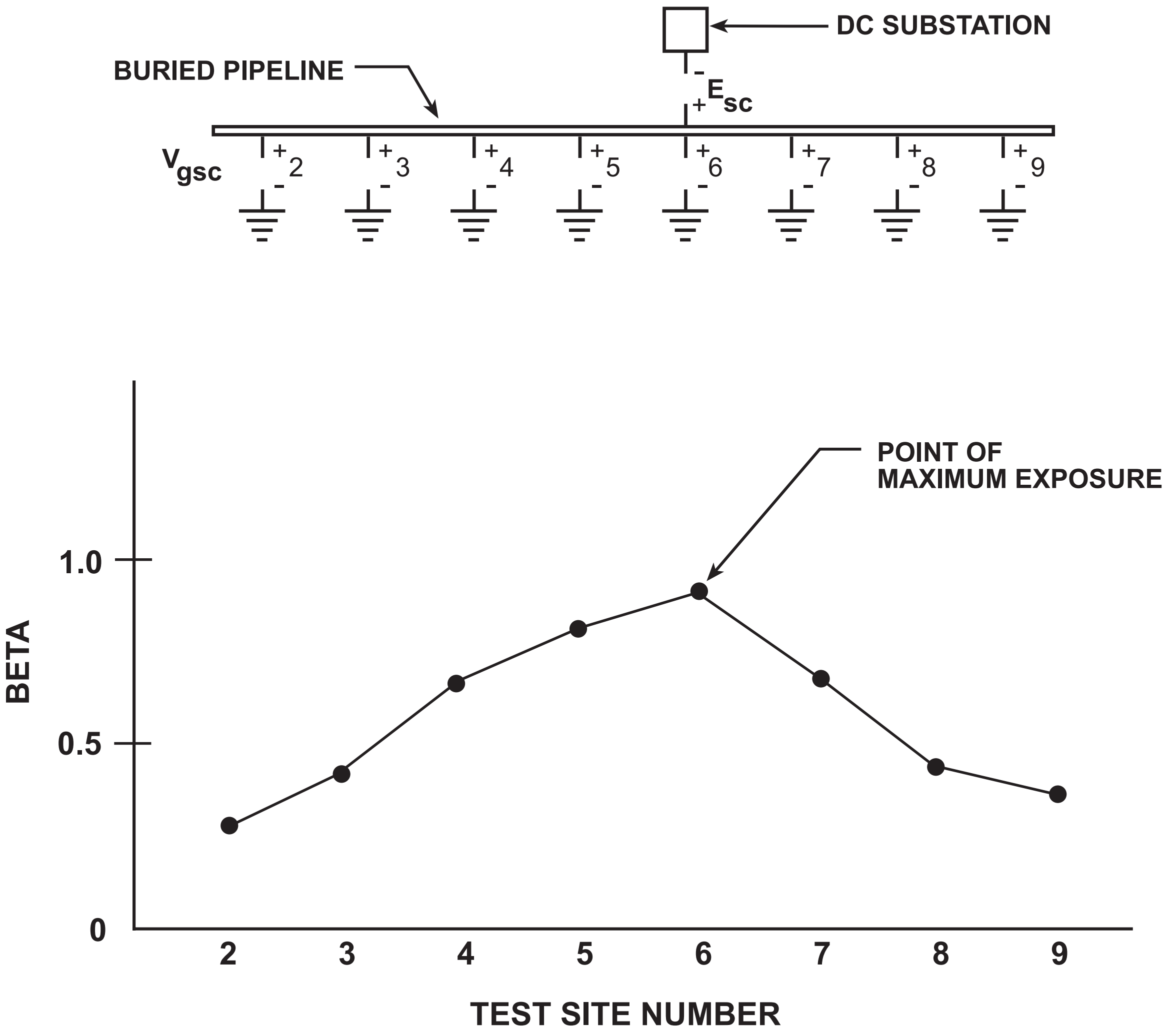
Determining the Point of Maximum Exposure

The point of maximum exposure can be determined based on the slopes of the plotted discharge beta curves. The beta curve which has the most horizontal (largest) slope indicates the location of maximum exposure. Figure 4-7 shows this graphically.

In practice, the calculated slopes can be plotted versus distance to indicate clearly the location of the largest slope (indicative of the most horizontal line).

METHODS OF MITIGATING THE EFFECTS OF DYNAMIC STRAY CURRENT

There are several general methods used to reduce or mitigate the effects of dynamic stray current. These methods include: control at the source, installation of mitigation bonds and reverse current switches, use of sacrificial anodes, and use of impressed current cathodic protection to counter the stray current. Each of these methods is



LOCATING THE POINT OF MAXIMUM EXPOSURE
FROM A BETA PROFILE

FIGURE 4-7

discussed in the following sections.

Controlling Stray Currents at the Source

The most effective way to minimize dynamic stray current is to minimize the electrical current entering the earth in the first place. In the case of transit and any other systems involving rail returns, the best procedure is to ensure that the rails are installed with insulated fasteners on well-ballasted roadbeds or concrete inverts. The DC negative bus of the traction power substation should be ungrounded, and the substations should be spaced at a maximum of about one-mile apart. Modern rail transit systems use welded rail; this reduces the voltage drop in the rail, which in turn reduces the stray current induced in the earth.

Similarly, when dealing with equipment, if isolated electrical positive and negative circuits can be used, stray current problems will be avoided because the currents never reach the earth. When welding is done, care should be taken to assure that the welding electrode and the ground are relatively close together and the electrical path between them is of negligible resistance. Thus, no voltage drop of any significance will exist between them.

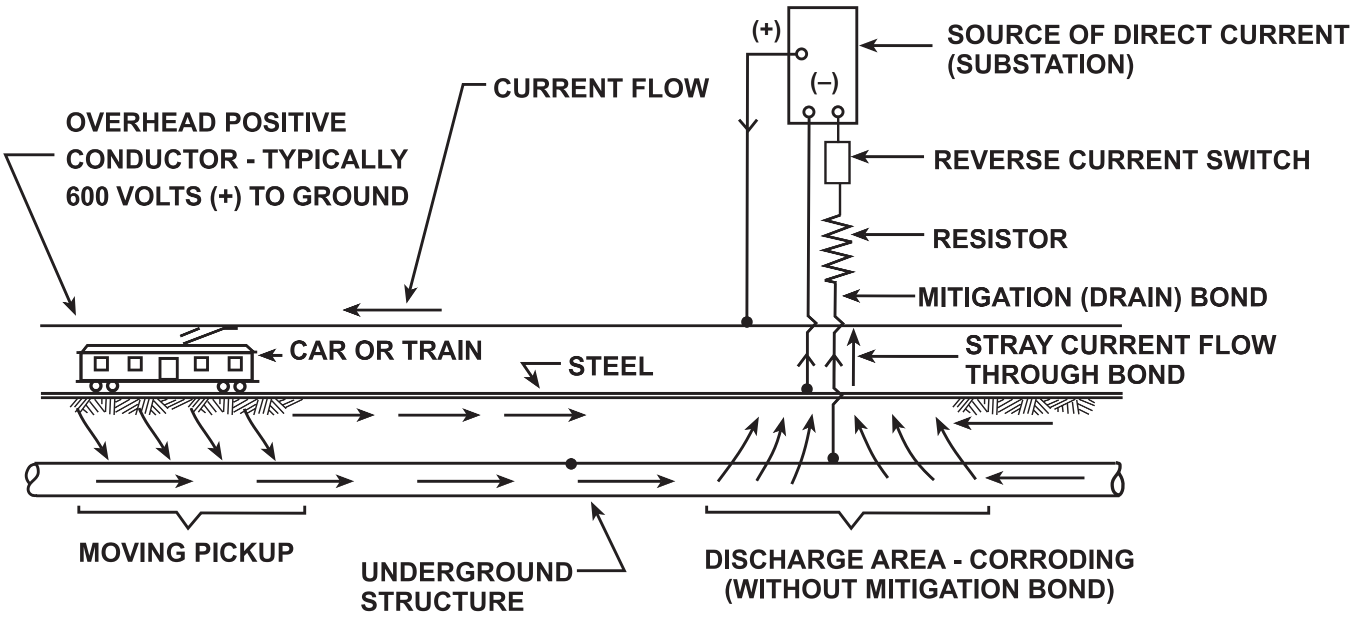
Mitigation (Drainage) Bonds and Reverse Current Switches

Mitigation bonds and reverse current switches are used to mitigate the effects of stray current corrosion on a structure.

The purpose of a mitigation, or drainage bond is to eliminate current flow from a metallic structure into the electrolyte by providing a metallic return path for such current. The drainage bond will allow the stray current to flow through the structure and back to the source, through the bond. Figure 4-8 shows the typical current flow when a drainage bond is installed. As a result, corrosion will not occur if the current is not allowed to flow from the metal surface into the electrolyte.

It is not good practice to install drainage bonds on modern rail transit systems that have been designed to minimize stray current at the source. The high resistance to ground of these systems minimizes stray current. Installation of a bond lowers this resistance and in turn increases stray current flow.

When designing a bond, the goal is to find the proper size resistance to be inserted between the affected structure and the source so that stray current discharge into the



INSTALLATION OF A MITIGATION BOND ON A
DC TRANSIT SYSTEM TO PREVENT
STRAY CURRENT CORROSION

FIGURE 4-8

electrolyte is eliminated at all points. The proper bond will cause the affected structure to return the pickup current to the interfering structure through the bond.

Before the mitigation bond can be sized, the point of maximum exposure must be located. This is done as described earlier under “Determining the Point of Maximum Exposure”.

As previously indicated, dynamic stray current testing requires potential measurements taken simultaneously at two different locations. These readings can be taken by two technicians who are in communication with each other by radio so that one can tell the other when to take a reading. Many readings should be taken at the two locations simultaneously. Meters used at the two locations must have identical characteristics or comparison of the two sets of readings will be difficult.

To facilitate the taking of these potential readings, strip chart recorders can be set up at the two locations. Recordings obtained over a 24-hour period will normally provide all the data required. The corresponding readings taken at the two locations can then be plotted on linear graph paper. This plot of points is known as a “beta curve”. Several locations should be tested longitudinally along the pipeline within the exposure area. The location of the recorder at the source remains constant. A separate set of simultaneous readings should be made at each test location. This type of survey is known as a beta profile.

State-of-the-art computerized multi-channel test equipment is available to facilitate obtaining a beta profile. These computerized recorders can be set to record the potentials at as many as 28 different locations simultaneously for any desired length of time. The recorder will store all readings in a permanent memory until it is down-loaded into a computer terminal. Computer programs are available which will then plot beta curves. Similarly X-Y recorders, which simultaneously record pipe-to-soil potential and pipe to source voltage are frequently used.

The points when plotted should describe a straight-line plot referred to as the beta curve. The slope of the plotted line will indicate whether the interfered structure in the area of the test is picking up current, discharging current or neither.

Once the location of maximum exposure is determined and its negative slope or beta curve plotted, the size of the resistance bond can be determined. The required size of the resistance bond is such that its installation will cause the beta curve at the point of maximum exposure to assume a neutral or pick-up slope. Figure 4-9 shows a beta curve at a point of maximum exposure as well as the required mitigation curve.

Sizing the Mitigation (Drain) Bond

Two methods are available to size the bond, trial and error and mathematical. Both are explained below.

Trial and Error Method

In relatively simple cases, such as where a single source of stray current is involved, a trial and error solution may be possible. The size of the resistance bond can be determined by installing temporary cables and variable resistors and determining when stray current corrosion has been mitigated. Since drain currents of up to 200 to 500 amperes can be involved, test cables must be sized accordingly. A mitigation curve such as that shown in Figure 4-9 must be obtained from the test bond.

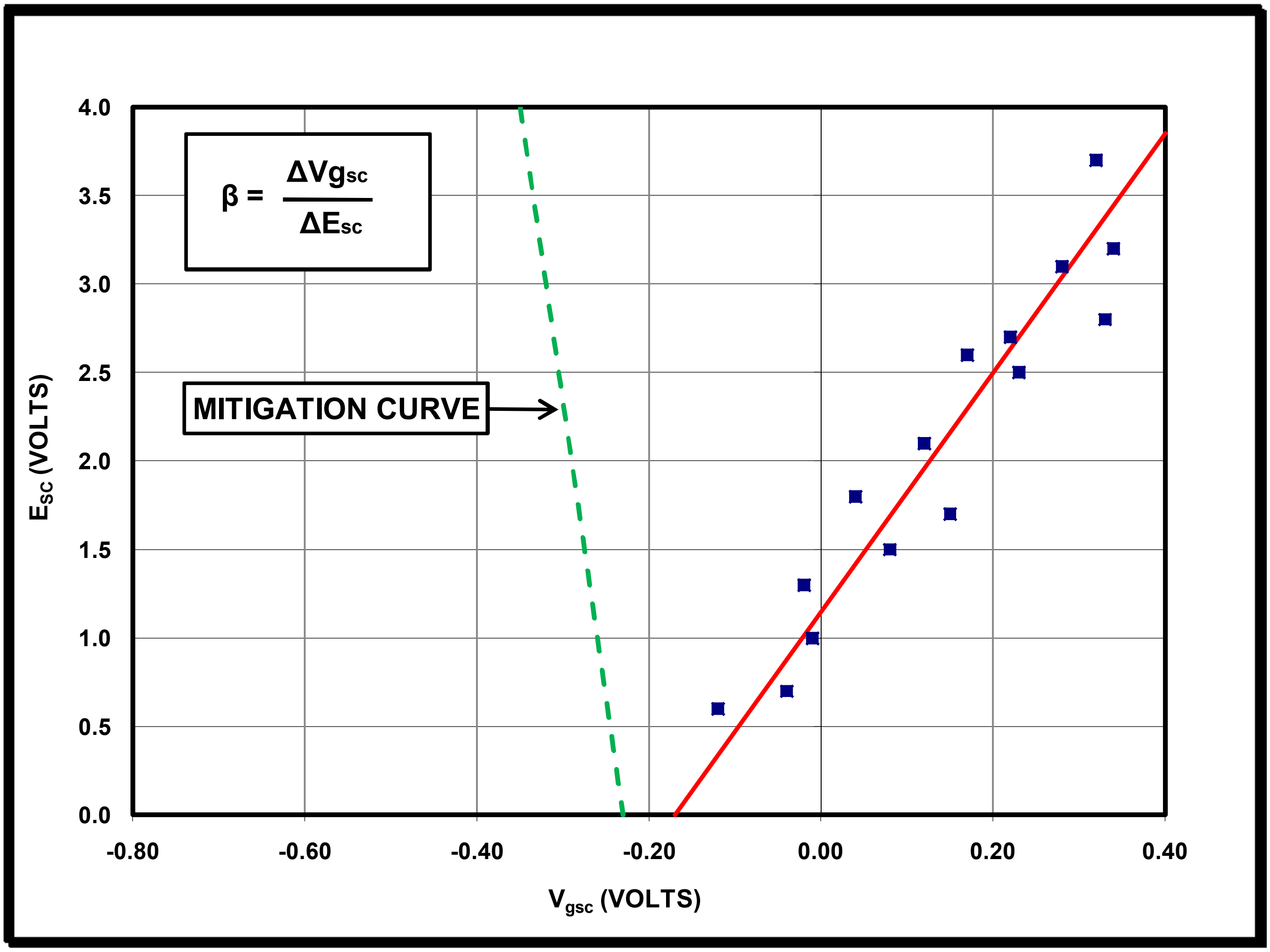
When using the trial and error method on stray current problems involving transit systems, care should be exercised to ensure that the temporary bond does not affect signaling.

Mathematical Method

Where a more complex interference problem exists that precludes the use of the trial and error method, the following mathematical method can be used to size the resistance bond. As noted earlier, dynamic stray currents may involve large values of current flow, so the anticipated currents must be known to size cable and associated electrical equipment properly. A mathematical solution can provide the designer with these anticipated values.

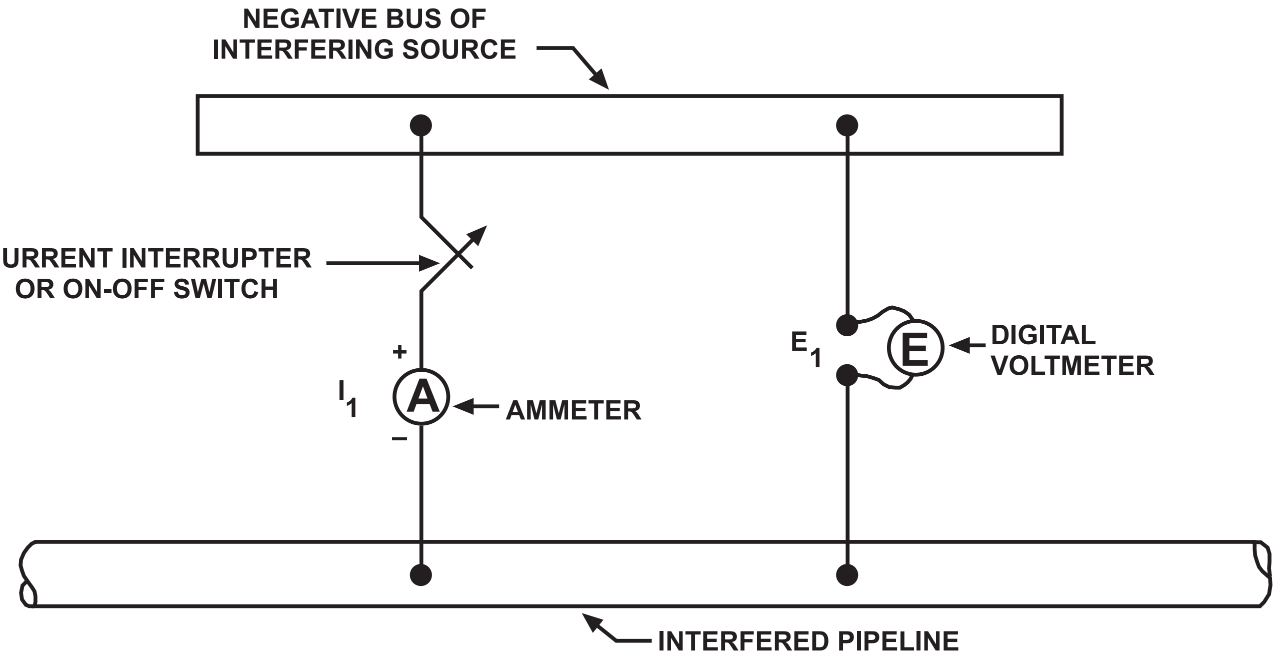
This method is based upon the electrical relationships between the source and the pipeline. The measured potential-to-earth of a pipeline is a combination of its natural potential-to-earth plus the sum of all potential changes caused by the DC sources influencing it.

The test set ups for the mathematical method are shown in Figures 4-10 and 4-11. Figure 4-10 explains the test procedure for determining the internal resistance (R_{int}) between the pipeline and the stray current source. Figure 4-11 shows the procedure to determine the change in pipe to soil potential per ampere of drain current.



TYPICAL BETA CURVE - DISCHARGE AREA
(MITIGATION CURVE)

FIGURE 4-9



Several sets of data are taken by interrupting the current circuit. Current and voltage are taken simultaneously with the switch closed (on) and open (off: $I_1 = 0$). The resistance between the two structures ($R_{1\text{-}1}$) is calculated from Ohm's Law:

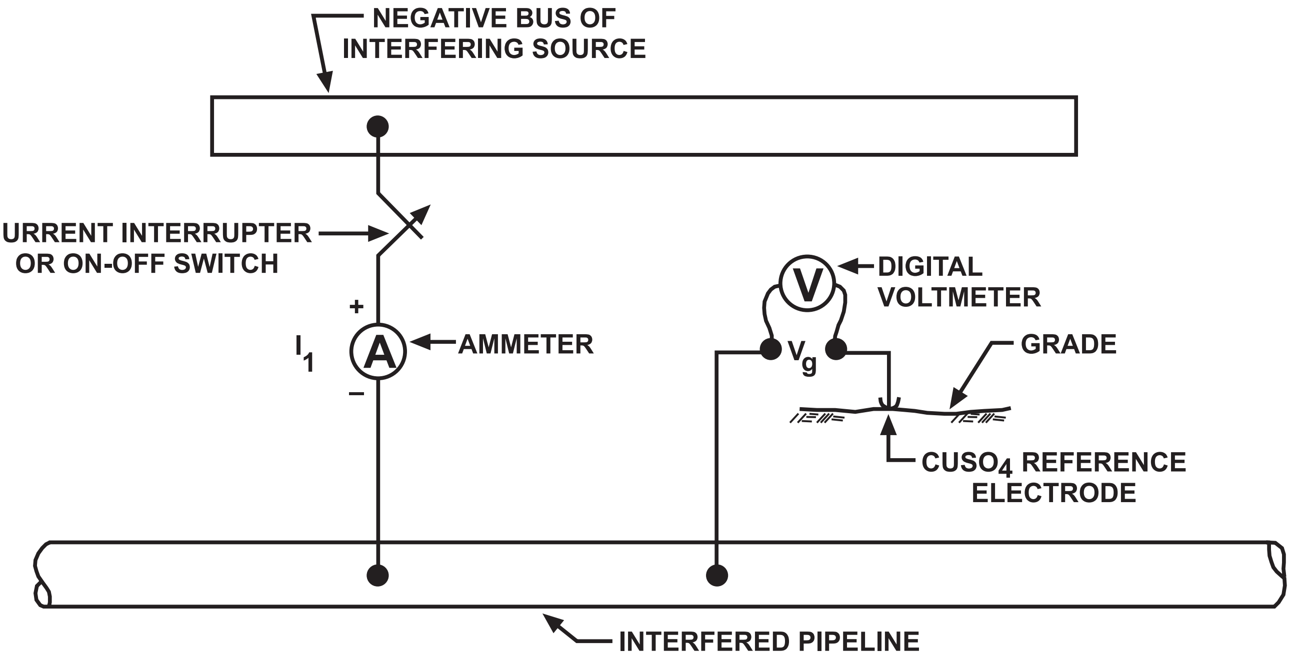
$$\Delta E_1 = E_{1ON} - E_{1OFF}$$

$$\Delta I_1 = I_{1ON} - I_{1OFF} \ (I_{1OFF} = 0)$$

$$R_{int} = \Delta E_1 / \Delta I_1$$

TYPICAL TEST SET-UP USED TO DETERMINE INTERNAL RESISTANCE (R_{int}) BETWEEN THE PIPE AND NEGATIVE BUS

FIGURE 4-10



Several sets of data are taken by interrupting the current circuit. Current and pipe to soil potential readings are taken simultaneously with the switch closed (on) and open (off: $I_1 = 0$). The change in pipe to soil potential per ampere of current flow ($\Delta V_g/I_1$) is calculated from Ohm's Law and is expressed as volts per ampere (V/A):

$$\Delta V_g = V_{gON} - V_{gOFF}$$

$$\Delta I_1 = I_{1ON} - I_{1OFF} \quad (I_{1OFF} = 0)$$

$$V/A = \Delta V_g / \Delta I_1$$

TYPICAL TEST SET-UP USED TO DETERMINE PIPE TO SOIL POTENTIAL CHANGE PER AMPERE OF DRAINAGE CURRENT

FIGURE 4-11

The beta curve at the point of maximum exposure, such as the one shown in Figure 4-12, is plotted. The equations used in reaching the solution are as follows:

Equation 1

$$V_g = \Delta V_{go} + \Delta V_{gcp} + \Delta V_{gsc} + \Delta V_{gb}$$

Where:

V_g = Pipe-to-soil potential with all current sources operating

ΔV_{go} = Natural pipe-to-soil potential of the pipeline

ΔV_{gcp} = Change in pipe-to-soil potential caused by cathodic protection of pipeline

ΔV_{gsc} = Change in pipe-to-soil potential caused by stray current sources

ΔV_{gb} = Change in pipe-to-soil potential caused by mitigation bond

In the case of a dynamic stray current:

Equation 2

$$\Delta V_{gsc} = \beta \times \Delta E_{sc} \text{ (See Figure 4-4)}$$

Where:

$$\beta = \Delta V_{gsc} / \Delta E_{sc}$$

If no cathodic protection is present, Equation 1 simplifies to Equation 3:

Equation 3

$$V_g = V_{go} + (\beta \times \Delta E_{sc}) + \Delta V_{gb}$$

For the dynamic stray currents to be mitigated:

Equation 4

$$\beta \text{ x } \Delta E_{sc} = \Delta V_{gb} \qquad (V_g - V_{go} \text{ must} = 0)$$

From Figure 4-12, the value for V_{go} = 0.570 volts and β (the slope of the plotted points) = 0.017.

ΔV_{gb} is the change in potential-to-soil of the interfered structure caused by a bond current. The value of ΔV_{gb} can be calculated for any given bond current from Equation 5:

Equation 5

$$\Delta V_{gb} = I_1 \text{ x } \left(\frac{\Delta V_g}{I_1} \right) \qquad \text{(See Figure 4-11)}$$

Combining Equation 4 with Equation 5 yields Equation 6:

Equation 6

$$\beta \text{ x } E_{sc} = I_1 \text{ x } \left(\frac{\Delta V_g}{I_1} \right)$$

The value of the bond current, I_b, is calculated from Equation 7:

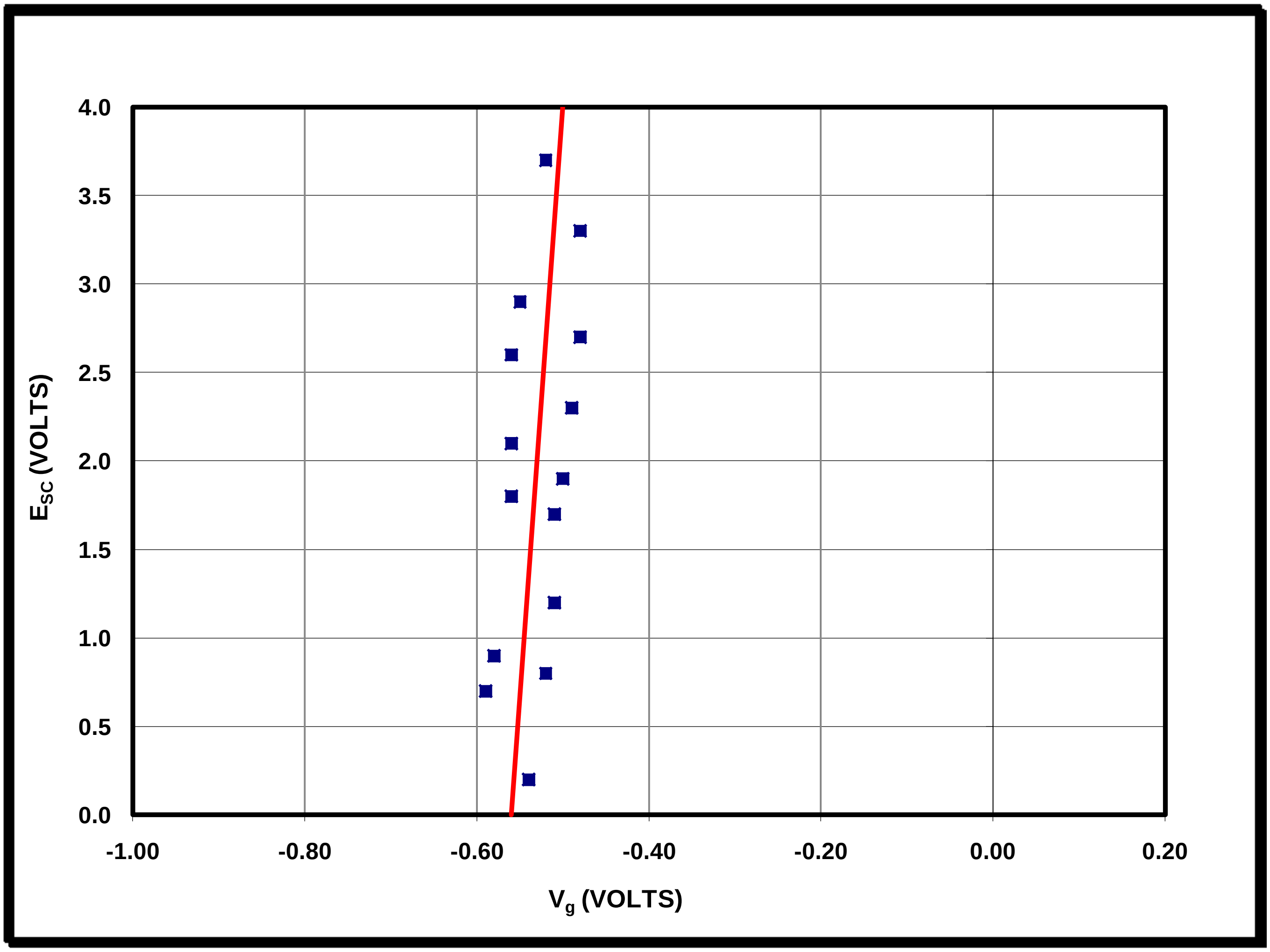
Equation 7

$$I_b = \beta \text{ x } E_{sc} \Big/ \left(\frac{\Delta V_g}{I_1} \right)$$

The resistance of the bond can be calculated from Ohm's Law:

Equation 8

$$E_{sc} = I_b \text{ x } (R_{int} + R_b)$$



BETA CURVE PLOTTED AT POINT OF MAXIMUM EXPOSURE

FIGURE 4-12

Or, rearranging:

Equation 9

$$R_b = \frac{E_{sc}}{I_b} - R_{int}$$

Substituting:

Equation 10

$$R_b = E_{sc} \times \frac{\Delta V_g / I_1}{\beta \times E_{sc}} - R_{int}$$

Or:

Equation 11

$$R_b = \frac{\Delta V_g / I_1}{\beta} - R_{int}$$

Tables 4-1 and 4-2 present sample data for a single bond stray current problem. From Table 4-1, the average resistance between structures is found to be 0.070 ohms. Table 4-2 shows the value of $\Delta V_g/I_1$ to be 0.00169 V/A. Using the β value from Figure 4-12 of 0.017 and substituting the values into Equation 11, the bond resistance, R_b, is calculated:

$$R_b = \frac{0.00169}{0.017} - 0.070 = 0.0294\ \Omega$$

The bond resistance value, 0.0294 ohm for this example, can be a simple cable or a combination of cable and variable or fixed resistors. The bond must also be sized to permit the maximum current flow and still remain in the ampacity range for the bond. In a dynamic stray current situation, the maximum current can be calculated once the maximum open circuit voltage between the structures is known. This value is usually obtained by using a recording voltage instrument over several operating cycles of the stray current source to measure the peak value. For most stray current sources the typical cycles is 24 hours.

TABLE 4-1

R_{int} Data - See Figure 4-10

	E_1 (Volts)	**I_1 (Amperes)**	**R_{int} (ohms)**
On	+1.30	36.0	
Off	-1.15	0	
Delta	+2.45	36.0	0.068
On	+0.80	39.0	
Off	-1.80	0	
Delta	+2.60	39.0	0.067
On	+0.50	41.0	
Off	-2.30	0	
Delta	+2.80	41.0	0 .068
On	+2.10	29.0	
Off	0.00	0	
Delta	+2.10	29.0	0.072
On	+2.00	29.5	
Off	-0.15	0	
Delta	+2.15	29.5	0.073
On	+1.30	35.0	
Off	-1.25	0	
Delta	+2.55	35.0	0.073
On	+0.35	43.0	
Off	-2.65	0	
Delta	+3.00	43.0	0.070
		Average R_{int} =	**0.070**

TABLE 4-2

$\Delta V_g/I_1$ Data - See Figure 4-11

	V_g (Volts)	I_1 (Amperes)	$\Delta V_g/I_1$ (V/A)
On	0.645	34.0	
Off	0.590	0	
Delta	0.055	34.0	0.00162
On	0.635	23.0	
Off	0.600	0	
Delta	0.035	23.0	0.00150
On	0.770	82.0	
Off	0.620	0	
Delta	0.150	82.0	0.00183
On	0.770	86.0	
Off	0.625	0	
Delta	0.145	86.0	0.00168
		Average $\Delta V_g/I_1$ =	**0.00169**

For example, if the maximum value of open circuit voltage, E_{sc}, is 12.0 volts, substitution of this value into Equation 8 and rearranging the equation gives the value of the maximum stray current through the bond 120.7 amperes as shown below:

$$E_{sc} = I_b \times (R_{int} + R_b)$$

$$I_b = \frac{E_{sc}}{R_{int} + R_b}$$

$$I_b = \frac{12.0}{0.070 + 0.0294} = \frac{12.0}{0.0994}$$

$$I_b = 120.7 \text{ amperes}$$

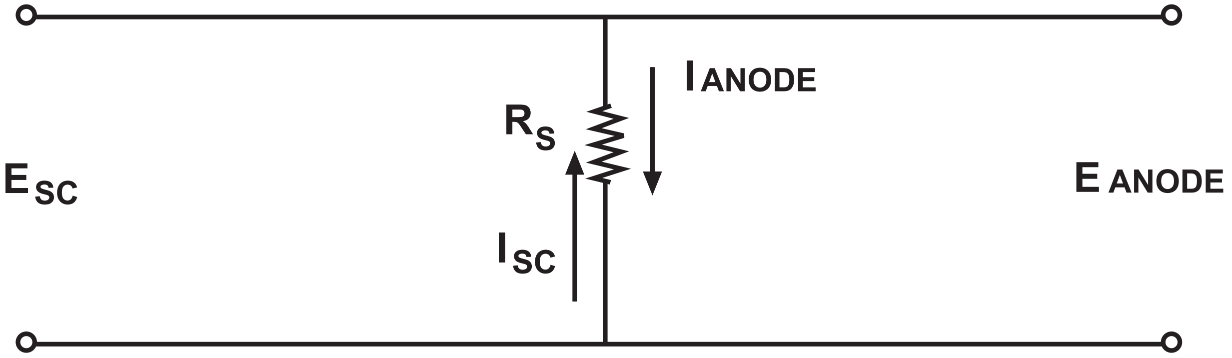
Table 4-1 also shows some typical measured values for E_1 and I_1, using the test setup shown in Figure 4-10, as well as the calculated internal resistance.

Table 4-2 also shows some typical measured values for V_g and I_1, using the test setup shown in Figure 4-11, and the corresponding calculated $\Delta V_g/I_1$.

In many instances of stray current work where traction systems are involved, there may be locations where drainage bonds are required in areas where electrical reversals of potential could occur. Therefore, it is often necessary to install an electrolysis switch or silicon diode into the circuit to prevent current flow from the railroad back onto the pipeline through the bond. The resistance to the forward flow of current created by these devices must be included in the sizing of the bond.

Use of Sacrificial Anodes

Sacrificial or galvanic anodes may be used to mitigate stray current effects in situations where small current flows or small voltage gradients exist. A misconception surrounding the use of galvanic anodes for stray current mitigation states that the anode draws the stray currents and prevents currents from entering into the electrolyte from the interfered structure. This over-simplification does not consider the entire electrical network involved. In effect, a potential gradient field produced by the galvanic anode(s) counteracts the interference current. The effect is a net current flow to the interfered with structure. A version of the electrical circuit is shown in Figure 4-13.



R_S — RESISTANCE OF STRUCTURE TO EARTH

I_{SC} — STRAY CURRENT

E_{SC} — VOLTAGE GRADIENT OF STRAY CURRENT

WHEN E-ANODE > E_{SC} — GALVANIC DRAINS FUNCTION TO PRODUCE A NET PROTECTIVE FLOW

WHEN E-ANODE < E_{SC} — GALVANIC DRAINS INEFFECTIVE

SIMPLE EQUIVALENT CIRCUIT FOR GALVANIC ANODE DRAIN

FIGURE 4-13

The potential gradients of the stray current source and of the anodes counteract each other. Galvanic anodes produce limited voltages, however, and as such are limited to the stray current voltages, which they can overcome.

Another consideration when using a galvanic anode system to overcome stray currents is the expected life of the anodes. As the anodes dissipate, their resistance to ground increases. The increased resistance reduces the current flow from the anode and decreases the resulting voltage gradients. Sacrificial anodes should be sized to provide a sufficient anticipated life span. As with any other stray current mitigation procedure, the anodes should be placed on an active monitoring schedule.

Galvanic anode drains are commonly used in lieu of bonds where small drain currents are involved. In areas of large current drains, the use of galvanic anode drains would be impractical due to the high consumption rate of the anode material; frequent anode replacement would be required. Galvanic anodes would also be impracticable where voltage gradients are encountered that are greater than those galvanic anodes can produce.

Use of Impressed Current Systems

When the magnitude of stray currents are beyond the ability of galvanic anodes to counteract, impressed current systems can sometimes be utilized. Impressed current systems have much higher voltage capacities than galvanic anodes and a greater life per pound of anode material. Built-in control and monitoring circuits in the impressed current rectifier can be used to adjust the protective current output based upon the voltage-to-earth fluctuations of the interfered pipeline.

The design of galvanic or impressed current mitigation systems is done by the trial and error method. Simulated systems are placed in the field and the results measured. Based upon the results, a full-scale system can be designed.

STRAY CURRENT FROM ALTERNATING CURRENT (AC) SOURCES

Stray current from AC sources can cause corrosion as well as be a safety hazard. Both steady state and dynamic stray AC current may be found.

Several laboratory and field studies have indicated that above a certain minimum AC current density, normal levels of cathodic protection will not control AC corrosion to acceptable levels and that AC mitigation is often required to prevent serious corrosion.[1]

Methods of mitigating AC corrosion are beyond the scope of this text.

Steady state stray AC is most commonly associated with pipelines laid in close proximity and paralleling high voltage AC electrical transmission lines. AC induction on such pipelines can create dangerous voltages. Mitigation of the voltage on the line as well as safety grounding of test stations and above ground appurtenances to buried equipotential mats are recommended if the AC pipe-to-soil potential exceeds 15 volts.

Dynamic AC stray currents may be generated by AC welding operations, bad grounds in buildings or AC electrified railroads.

For information on AC mitigation, the reader is referred to NACE Standard Practice SP0177-2007 “Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems”.[2]

CONCLUSIONS

Stray current interference on a pipeline can cause severe local corrosion that could lead to a hazardous situation, product leakage and costly repairs. Therefore, every effort should be made to avoid interference problems and, if they exist, to mitigate their effects.

Stray currents can be classified as being either static or dynamic. Static interference currents are defined as those, which maintain a constant amplitude, direction and electrolytic path. Dynamic interference currents are defined as those, which continually vary in amplitude, direction and electrolytic path. Static interference is always caused by man-made sources; dynamic interference, however, can also be caused by telluric activity.

Stray current control at the source is the best method of stray current mitigation.

The use of bonds or cathodic protection systems to mitigate stray current corrosion can be very effective when properly designed and installed. It is very important that all field testing and remedial actions be conducted or taken in the presence of, or with the permission of, representatives of all companies/owners involved.

Sacrificial anode or impressed current cathodic protection can also be used to mitigate stray current.

Stray AC can cause corrosion and be a safety hazard.

REFERENCES

1. R. A. Gummow, “AC Corrosion – A Challenge to Pipeline Integrity,” Materials Performance, 38, 2 (Feb. 1999)

2. NACE Standard Practice SP0177-2007 “Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems”, NACE International, Houston, Texas

Chapter 5 - Design of Impressed Current Cathodic Protection

INTRODUCTION

The objective of this chapter is to provide corrosion control personnel with information necessary to design an impressed current cathodic protection system for underground structures.

This chapter will discuss the various parameters which must be considered in the design of an impressed current cathodic protection system. These parameters include the following:

1. Protective current requirements
2. Anode bed resistance-to-earth
3. Anode bed layout
4. Anode life expectancy
5. Rectifier sizing

REVIEW OF IMPRESSED CURRENT CATHODIC PROTECTION FUNDAMENTALS

Definition

Cathodic protection can be defined as a technique to reduce the corrosion rate of a metal surface by making that surface the cathode of an electrochemical cell. This is accomplished by applying current to the structure by means of an impressed direct current or attachment of a galvanic anode to the structure.

Cathodic protection makes a metallic structure the cathode of a purposely designed electrochemical cell thereby protecting it from corrosion. The protective current is either developed from within the cell or introduced to the cell from an external source which is large enough to overcome the effect of corrosion currents being discharged from the anodic areas of the structure. When the surface of the structure is fully polarized, corrosion of the structure is controlled. In a sense, the corrosion process is not eliminated but merely transferred to an expendable, or sacrificial, material (anode).

Theory of Operation

The impressed current cathodic protection system utilizes an external power source to provide a potential difference between the anode(s) and the protected structure. The anodes are connected to the positive terminal and the structure to the negative terminal of the power source. Current flows from the anodes through the electrolyte and onto the surface of the structure. It then flows along the structure and back to the power supply through an electrical conductor. Since the structure is picking up current from the electrolyte, the structure is protected. The protective current output of the power supply is adjusted to deliver sufficient current to overcome the corrosion currents trying to leave the anodic points on the structure. As the anodes discharge current they are consumed. Therefore it is desirable to use anode materials that are consumed at lower rates than magnesium, zinc, and aluminum which are used in sacrificial or galvanic systems. Special alloys and combination materials are used in impressed current systems to obtain a long, useful life expectancy from the system.

Application

The impressed current cathodic protection system, in most cases, utilizes a variable power source. Impressed current systems are capable of protecting large structures or structures which require greater magnitudes of current than can be provided economically by a galvanic anode system. These systems can be designed to protect bare (uncoated), poorly coated, or well coated structures. As the amount of surface area to be protected increases, the total current requirement increases and impressed current systems become the system of choice.

Advantages and Disadvantages

Impressed current systems can be designed for a variety of applications with a reasonable degree of flexibility. This is a distinct advantage of this type of system, along with the ability to increase or decrease the current output, either automatically or manually, by changing the output voltage. The disadvantages of the system are the increased maintenance requirements, tendency for higher operating costs, and possibility of contributing to stray current interference on neighboring structures.

INFORMATION USEFUL FOR DESIGN OF AN IMPRESSED CURRENT CATHODIC PROTECTION SYSTEM

Before embarking on the design of a system, certain information should be gathered, analyzed, and factored into the design:

1. What is the pipe material? Is it steel (including grade of steel), high silicon cast iron, wrought iron or other material? What is the known electrical resistance?

2. Is the line bare or coated? If coated, what is the coating material and what coating specifications were used?

3. If it is an existing line, is there a leak record? If so, information on the location and date of occurrence of each leak will positively indicate the more serious problem areas.

4. What is the pipe diameter, wall thickness and weight per foot? Is there any data on any changes in these items along the route of the line?

5. What are the location and construction details of all corrosion test points which have been installed along the line? If no test points have been installed for corrosion test purposes, determine locations where contact can be made with the pipeline for test purposes (other than by driving contact bars down to the pipe).

6. Is the line of all-welded construction or are mechanical couplers used?

7. What are the locations of branch taps?

8. What are the locations of purposely isolating flanges or couplers, if any, used to sectionalize the line or to isolate it electrically from other portions of the system or from piping of other ownership?

9. Obtain route maps and detail maps giving as much data as is available.

10. What are the locations of underground structures of other ownership that cross the pipeline to be surveyed? If any of these structures are cathodically protected, determine the location of cathodic protection current sources (particularly rectifiers) that may be in close proximity to the structure to be protected.

11. Location of possible sources of man-made stray current (such as DC electric transit systems or mining operations) that could affect the line under study.

12. Do any sections of the pipeline closely parallel (within 200 feet or so) high-voltage electric transmission lines? If so, what is the length of such exposure, how close is the pipeline to the towers, at what voltage does the electric line operate, and what method is used for grounding the towers? This information is significant because rectifier installations and isolating joints in well coated pipelines, closely parallel to high-voltage electric lines, may be damaged by induced AC voltage surges under

electric system fault conditions if preventive measures are not taken.

13. Is the line now operated at elevated temperatures, or will it be so operated in the foreseeable future? (High temperature could cause deterioration of coatings used and increase the current requirement to achieve corrosion control.)

14. Is AC power available to provide power to the rectifier?

DESIGN OF AN IMPRESSED CURRENT ANODE BED

General

There are several steps to be taken in designing an impressed current anode bed. The initial steps include:

- Selecting an anode bed site
- Selecting an anode bed type

Once the anode bed site and type have been selected, the designer can proceed to evaluate the different parameters required to complete the design of the selected impressed current anode bed.

Selecting an Anode Bed Site

The following factors should be taken into account when considering an anode bed site:

a. **Soil Resistivity** - Soil resistivity is one of the most important factors to consider when selecting an anode bed site. Soil resistivity is one major component in evaluating the anode bed resistance. The anode bed resistance is a critical component in the determination of protective current output and rectifier size. Usually, the lower the resistivity, the fewer number of anodes required to deliver a given current. In many cases, the area of lowest resistivity is considered a prime location for an anode bed site.

b. **Soil Moisture** - Another factor to consider in the selection of an anode bed site is the soil moisture at the proposed anode depth. In most cases, soil resistivity decreases as the moisture increases until the soil becomes saturated. When possible, anodes should be installed below the water table (assuming the water resistivity is not too high), or in areas of high moisture content such as swamps, ditches, creek beds, etc.

c. **Interference With Foreign Structures** - Metallic structures such as pipelines, underground metallic sheathed electrical cables, or well casings, may be subjected to stray current interference problems. Therefore, anode beds should be located away from foreign structures whenever possible. Local utilities should be contacted to determine if underground structures exist in the area of the proposed anode bed location.

d. **Power Supply Availability** - The selection of an anode bed site may be influenced by the availability of an economical source of power to be used to provide the required cathodic protection DC current.

e. **Accessibility for Maintenance and Testing** - The anode bed site selected must be accessible to construction vehicles for anode bed installation, testing and repairs.

f. **Vandalism** - Anode bed locations should be selected so as to minimize the potential for vandalism.

g. **Purpose of Anode Bed and Site Availability** - Two additional factors that have to be considered in the process of selecting an anode bed site are the intended purpose of the anode bed and the possibility of acquiring the required right-of-way for the installation. Is the intent of the anode bed to protect a long section of the pipeline (assuming the pipeline is well coated), or is it the intent to afford localized protection to a short section of a pipeline (poorly coated) of a structure? In the first case, the approach may be the installation of one remote type anode bed near the midpoint of the pipeline section, or perhaps the installation of a deep anode bed near the midpoint area. In the second case, the approach could be the installation of a distributed anode bed.

   Once a determination has been made as to the intent and purpose of the installation and the most suitable type of installation, the land availability should be investigated.

Selecting Anode Bed Type Based on Site Selection

Prior to selecting the anode bed type, it is wise to consider the major types of anode beds used and application conditions associated with each.

Distributed Anode Bed

A distributed anode bed is used to protect a limited area of the pipeline. The anode bed is generally installed close to the structure and, hence, is sometimes called a “closely coupled anode bed”. Distributed anode beds are used to reduce potential interference effects on neighboring structures, to protect sections of bare or ineffectively coated pipelines, and pipelines in congested areas where electrical shielding might occur with other anode bed types.

A distributed anode bed can be made of multiple individual anodes connected to a header cable. A distributed anode bed can also be one long continuous anode. This is referred to as a “linear anode”.

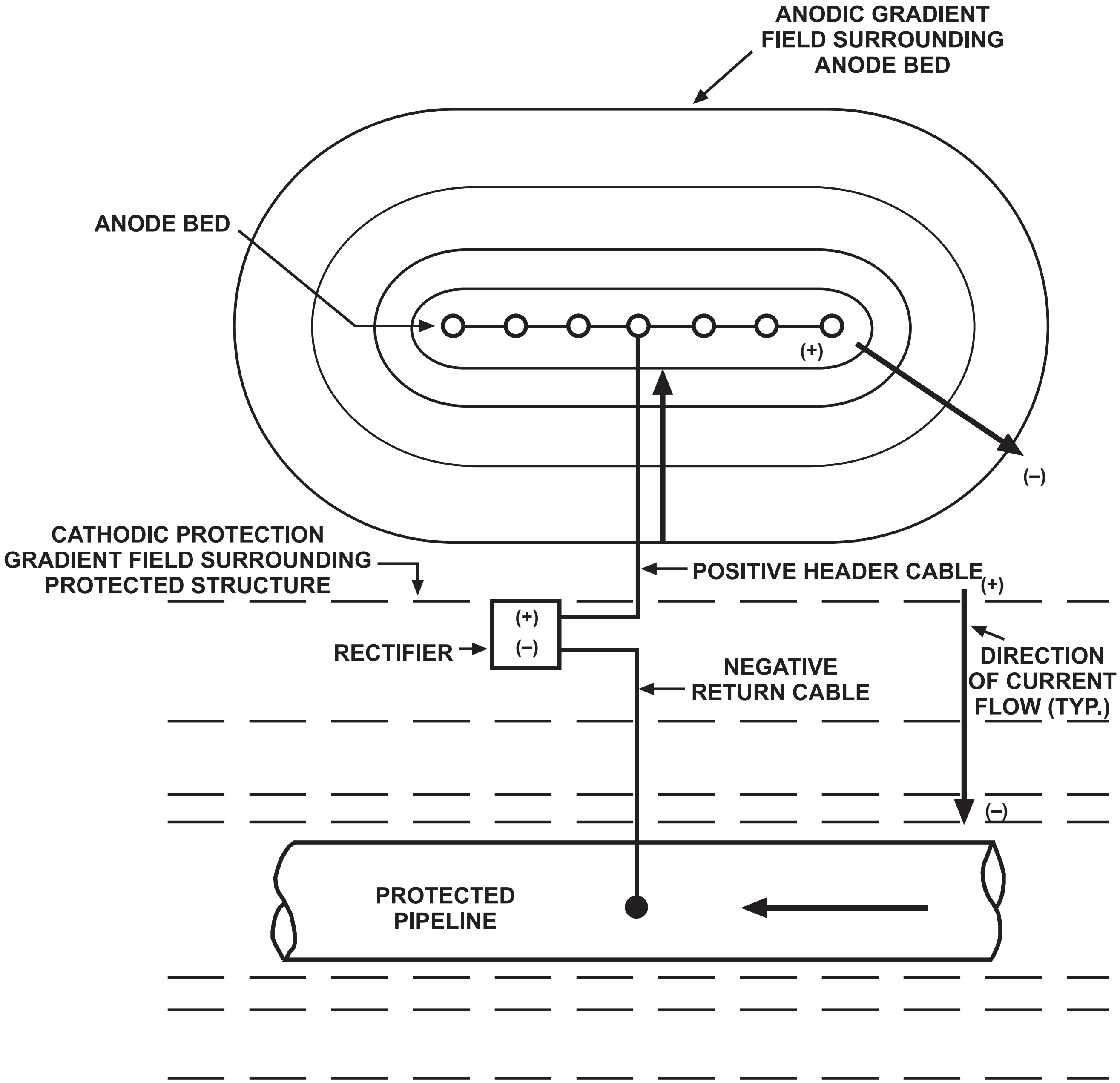
Remote Anode Bed

A remote anode bed, sometimes called a “conventional anode bed” or a “point-type” anode bed, consists of anodes installed in the earth at a distance away from the pipeline. This type of anode bed is normally used to distribute protective current over a broad area of the pipeline to be protected.

A remote anode bed used to protect a pipeline is usually installed perpendicular to the pipeline, and the first anode may be more than 100 feet away. The anodes are typically installed on 10 to 30 foot spacings.

Remote anode beds can also be installed parallel to or at an angle to the pipeline, depending on right-of-way availability. The main difference between a perpendicular and a parallel installation is that the gradient effect on the pipeline from a perpendicular anode bed would be less than from a parallel anode bed (assuming the line of parallel anodes is at a distance from the pipeline equal to that of the first anode in a perpendicular anode bed). Figure 5-1 is an example of a remote anode bed design with the anodes parallel to the lines to emphasize the anodic gradients around the anode bed and the cathodic gradients around the pipeline.

The term “remote”, as associated with this type of anode bed design, means that the pipeline is outside of the anodic gradient of the anode bed caused by the discharge of current from the anodes to the surrounding soil (referred to as “remote earth”). This would allow a better spread of the protective current to be achieved, thus protecting a larger section of a pipeline from one installation. In real life however, remote anode beds are installed at distances from a pipeline where the remaining gradient around the pipeline is normally small (not zero).



REMOTE ANODE BED OPERATION

FIGURE 5-1

Deep Anode Bed

A deep anode bed utilizes anodes installed electrically remote from the structure in a vertical hole drilled to a minimum depth of 50 feet and, in some cases, as deep as 1000 feet. This approach achieves similar results as a remote surface anode bed.

Deep anode beds are usually effective when high surface soil resistivities exist over deeper low-resistivity areas where the anodes are installed.

Hybrid Anode Bed

In some cases, such as on complex structures, different anode bed types are used in combination to afford complete protection to the pipeline. An example may be the case where a remote anode bed has been used to protect several miles of a well coated pipeline, but shielding from foreign structures occurs in a localized area. In this case, a distributed anode bed might be considered to supplement the effectiveness of the remote anode bed. This combination of anode beds is sometimes referred to as a hybrid approach.

The designer may find himself involved in cases where site availability is scarce and where the type of anode bed to be selected is dependent on the sites available. A similar case would develop if the size of the site available is restricted. These conditions may develop in urban areas or in instances in which the land owner may not wish to sell or lease any land for the installation.

Land limitations may dictate that the installation has to be restricted to the existing right-of-way, in which case a distributed type anode bed may be selected for a localized condition or a deep anode installation may be selected for protection of extended areas.

In cases where the site availability may dictate the type of anode bed, it would be advisable to analyze further the soil conditions to be able to determine which is the most economical type of design that would do a proper job.

As previously mentioned, soil with a high resistivity layer near the surface and a low or lower resistivity layer underneath would be well suited for a deep anode type of installation. This type of soil condition can be encountered along a pipeline at areas where a relatively shallow (sometimes slightly more than pipeline depth) surface soil overlies a high resistivity layer of rock which, in turn, overlies a layer of soil of relatively low resistivity. The current discharge from a deep anode bed in this type of soil arrangement could extend laterally for considerable distances and work its way up through the higher resistivity rock layer to the surface soil where the structure to be protected is installed.

In contrast with the above example, the case may be where the surface resistivity is low and the underlying soil is of high resistivity. In this case, a surface remote or distribution type of anode bed can be effectively utilized and a deep anode bed should not be considered.

In the cases where there are no restrictions to the type of anode bed to be utilized from any of the parameters listed in the preceding sections, economics would then be the deciding factor.

Tests Required for Anode Bed Design

The design of an impressed current anode bed is normally based on test data acquired in the field. The basic tests that should be conducted are soil resistivity and current requirement tests.

Soil resistivity tests are conducted along the route of the pipeline and at the locations selected for the anode bed installation.

Table 5-1 contains soil resistivity data obtained using the Wenner Four Pin Method. Referring to this data, let us assume that we are going to install a vertical anode bed to a depth of 10 feet. The weighted average soil resistivity to that depth (pin spacing) is shown as 19,533 ohm-cm. For design calculation purposes, an average resistivity of 20,000 ohm-cm should be used.

It should be noted again that the resistivity value used for design purposes should be obtained in the specific area where the anode bed will be installed, as there can be considerable variations in soil resistivity within short distances. An actual case example of this problem was an anode bed designed on the basis of soil resistivity data taken about 50 feet away from the foot of a hill. Because of right-of-way considerations, the anode bed was moved 30 feet towards the foot of the hill without new soil resistivity measurements. When the system was energized, the resistance of the anode bed was found to be about 10 times higher than it would have been at the location originally selected.

The second set of tests that should be conducted are current requirement tests to

TABLE 5-1
Typical Soil Resistivity Data

Galvanometer Dial Reading	Multiplier Setting	Resistance (Ohms)	Spacing (ft)	Factor	Resistivity (Ohm-cm)
2.4	10	24	2.5	191.5	11,490
1.6	10	16	5	191.5	15,320
10.2	1	10.2	10	191.5	19,533
6.2	1	6.2	15	191.5	17,801
2.6	1	2.6	20	191.5	9,958
8.2	0.1	0.82	25	191.5	3,926

determine the amount of current required to achieve protection of a pipeline/structure or a section thereof. In the event that the structure or pipeline is proposed and not yet installed, the current requirement must be estimated by assuming a current density.

A temporary anode bed must first be set up, preferably at the location of the proposed anode bed installation. The temporary anode bed may consist of several ground rods driven into the ground and connected to DC source such as a portable rectifier or a battery. Other buried structures can also be used as a temporary anode bed.

A creek or small lake, in close proximity to the structure requiring protection, can be used to set up a temporary anode bed. Household grade aluminum foil unrolled into the water and connected to a DC power source using clip leads can provide an excellent temporary anode bed for use when conducting current requirement tests.

Current requirement tests are conducted by energizing the temporary anode bed and taking “ON” and “OFF” potential readings along the pipeline/structure. While taking potential readings, the current output of the temporary anode bed is increased until protection is achieved in the entire pipeline/structure, based on established cathodic protection criteria, as discussed in Chapter 1 of this course. Figure 5-2 shows a typical setup for current requirement tests.

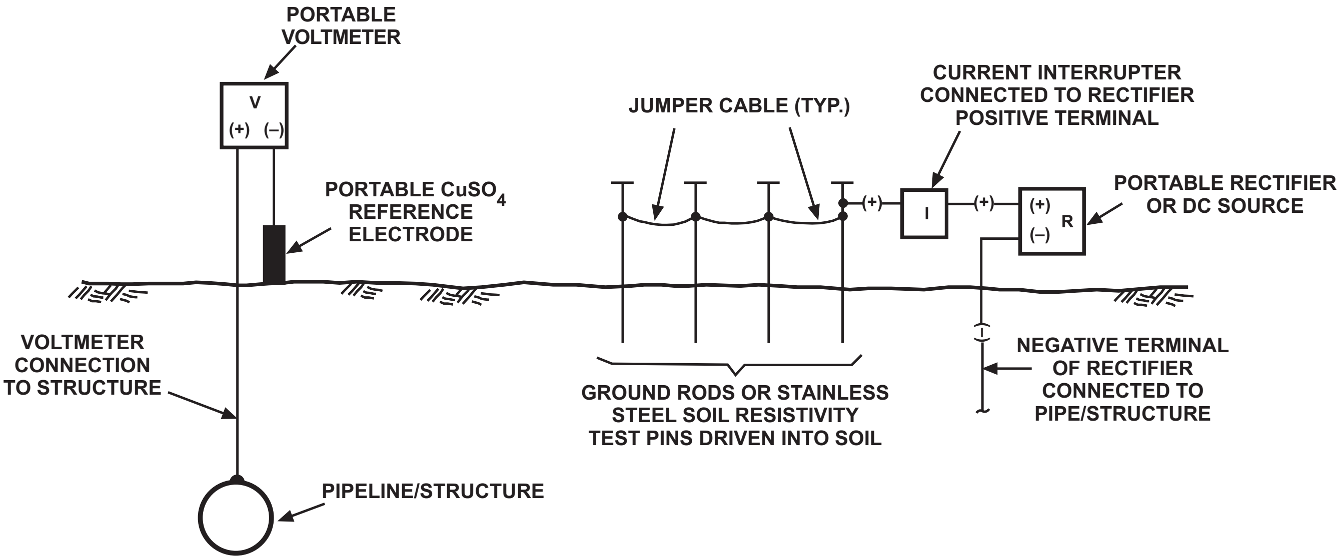
At times, it may be difficult to obtain an output from the temporary anode bed that is large enough to achieve full protection of the entire pipeline/structure. Should this be the case, the actual current requirements can be calculated by extrapolating the data obtained to the desired protective levels.

Determining Current Requirements for an Existing Structure - Example #1

As an example, let us consider a test setup in which the output of the temporary anode bed is 10 amperes, and the potential shifts obtained are:

Location	V-On	V-Off	ΔV	R
East End	-0.75 V	-0.45 V	-0.30 V	0.030 Ω
Midpoint	-0.95 V	-0.55 V	-0.40 V	0.040 Ω
West End	-0.71 V	-0.45 V	-0.26 V	0.026 Ω

From the above data it can be seen that the largest shift required to meet the -0.85 volt



TYPICAL CURRENT REQUIREMENT TEST SET UP

FIGURE 5-2

On protective criterion is 0.40 V, [-0.45 (East or West End) - (-0.85)] and the lowest shift obtained with 10 amperes is 0.26 V. The total current required can be calculated as follows:

$$\text{I-Req} = \text{I-Test} \;\; x \;\; \frac{\Delta\text{V-Req}}{\Delta\text{V-Low}}$$

Where:

I-Req = Total Current Required

I-Test = Applied Test Current

ΔV-Req = Voltage Shift Required to Meet -0.85 On Protective Criterion

ΔV-Low = Lowest Voltage Shift Obtained During Test

Solving for I-Req:

$$\text{I-Req} = 10 \;\; x \;\; \frac{0.40}{0.26} = 15.385 \;\; \text{Amperes}$$

A total of 15.385 amperes is required as a minimum to meet the -0.85 volt On criterion.

It is important to note that the amount of current required to cathodically protect a pipeline or structure is greatly affected by the condition of the coating on the structure. A bare structure may require many times the amount of current to protect the same pipeline/structure, if it were properly coated. Table 5-2 shows typical current requirements for a 5 mile section of 18-inch diameter steel pipe with various degrees of coating effectiveness.

DESIGN CALCULATIONS

The following examples show the various steps necessary to design a cathodic protection system for underground pipelines.

Existing Structures

For existing structures, the design can be based upon data obtained in the field through the previously mentioned current requirement testing to determine the actual current necessary to achieve cathodic protection.

TABLE 5-2
Typical Current Requirements Based On Coating System Effective Resistance

Effective Coating Resistance (1) (ohm-ft²)	Current Requirement (Amperes)
Bare Pipe (2)	187.50
10,000	3.73
25,000	1.49
50,000	0.75
100,000	0.37
500,000	0.075
1,000,000	0.0373
5,000,000	0.007
“Perfect Coating”	0.000015

(1) Effective coating resistance, as defined in the above table, of 10,000 to 25,000 ohm-ft² indicates poor application or handling during installation. Resistance of 100,000 to 5,000,000 ohm-ft² indicates good to excellent application. Installation in 1,000 ohm-cm soil.

(2) Bare pipe in this table is assumed to require a minimum of 1.5 milliamperes per sq. ft. of pipe surface. In practice, most design engineers use 2 milliamperes per sq. ft. for pipe-in-soil, unless the environment is acidic, contains high concentrations of chlorides, bacteria, or the pipe is operating at elevated temperatures. In these cases, as much as 3.5 to 5.0 milliamperes per sq. ft. may be required.

Determining Current Requirements for an Existing Structure - Example #2

A temporary anode bed is set up using 5 ground rods and a portable rectifier. The ground rods are driven approximately 1½ feet into the ground at 10-foot spacing. The measured output of the rectifier is 34 volts and 0.40 amperes. While interrupting the rectifier output, the following pipe-to-soil potential readings were taken at various locations with respect to a CSE, placed directly over the pipeline in the area under the influence of the temporary anode bed, and the change in potential (ΔV) was calculated.

PIPE-TO-SOIL POTENTIAL (Volts to CSE)			
Location	V-On	V-Off	ΔV
1	-0.592	-0.561	-0.031
2	-0.570	-0.523	-0.047
3	-0.603	-0.545	-0.058
4	-0.598	-0.527	-0.071
5	-0.693	-0.575	-0.118
6	-0.833	-0.635	-0.198
7	-0.865	-0.650	-0.215
8	-0.814	-0.611	-0.203
9	-0.731	-0.605	-0.126
10	-0.655	-0.590	-0.065
11	-0.630	-0.575	-0.055
12	-0.640	-0.580	-0.060

Step No. 1 - Using the lowest voltage shift (ΔV) measured during the tests, calculate the voltage shift required to satisfy the -0.85 volt On cathodic protection criterion.

ΔV-Low = Lowest Voltage Shift = -0.031 Volts at Location #1.

V-Off = -0.561 at Location #1.

ΔV-Req = Required Voltage Shift = -0.850 - (-0.561) = -0.289 Volts

Step No. 2 - Using these values, calculate the required current using the following equation:

$$\text{I-Req} = \text{I-Test} \times \frac{\Delta\text{V-Req}}{\Delta\text{V-Low}}$$

Solving for I-Req:

$$\text{I-Req} = 0.40 \times \frac{0.289}{0.031} = 3.73 \quad \text{Amperes}$$

Step No. 3 - Verify that, with an output of 3.73 amperes, a voltage of -0.85 volts can be achieved at the point of least negative "OFF" voltage obtained during the test.

V-Off = least negative "OFF" voltage = -0.523 Volts at Location #2
ΔV = voltage shift at Location #2 = -0.047 Volts
ΔV-Req = Required Voltage Shift = -0.850 - (-0.523) = 0.327 Volts

Using these values, calculate the required current using the following equation:

$$\text{I-Req} = \text{I-Test} \times \frac{\Delta\text{V-Req}}{\Delta\text{V}}$$

Solving for I-Req:

$$\text{I-Req} = 0.40 \times \frac{0.327}{0.047} = 2.78 \quad \text{Amperes}$$

Step No. 4 - The current required for achieving -0.85 volts On throughout the tested section of the pipe is 3.73 amperes.

There are several points that the designer should bear in mind when interpreting the results of current requirement tests:

1. The results indicate current requirement only in the area where the temporary anode bed was installed, and where the pipe-to-soil data indicated an influence from the anode bed.

2. If two or more anode beds are going to be installed for protection of an electrically continuous pipeline/structure, the effects of the anode beds are additive. Therefore,

if at a point of the pipeline, 1 anode bed with 1 ampere output achieves half of the required shift, and a second anode bed with 1 ampere output at a different location also achieves half of the required shift at the same location, the total current required is 2 amperes and not 2 amperes per anode bed.

3. The tests do not take into account future changes which might necessitate more current, such as additional deterioration of the coating.

In cases where the pipeline/structure has not been installed, or when current requirement tests are not feasible, current requirements can be estimated by selecting a current density and applying that current density to the pipeline surface area.

There are many different tables that have been published outlining current density requirements. One such table is shown as Table 5-3, and was taken from the NACE Corrosion Engineer's Reference Book.

As an example, if a proposed pipeline were to be coated and buried in relatively neutral (not alkaline nor acidic) but corrosive soil (due to non-homogeneous conditions), one might select 2 mA/ft^2 as the appropriate current density to establish the total current requirement. If the pipeline was anticipated to have a 95% coating efficiency, then 2 mA would be applied to each square foot of the 5% of the pipeline that was bare.

Determining Current Requirements for a Proposed Structure - Example

A 24-inch diameter pipeline 2 miles in length is being installed with a 95% efficient coating. Determine the total current required to achieve cathodic protection.

Step No. 1 - Calculate the area to be protected using the following formula:

$SA = \pi \cdot d \cdot L \cdot 0.05$

Where:

SA = Total Surface Area to be Protected (ft^2)

d = Outside Diameter of Pipeline (ft)

L = Length of Pipeline (ft)

0.05 = 5% of Pipe Requiring Protection (Bare Area)

π = 3.1415

TABLE 5-3
Approximate Current Requirements for Cathodic Protection of Steel

Environment		mA/ft²
Sea Water	- Cook Inlet	35 - 40
	- North Sea	8 - 15
	- Persian Gulf	7 - 10
	- US - West Coast	7 - 8
	- Gulf of Mexico	5 - 6
	- Indonesia	5 - 6
Bare Steel in Soil		1 - 3
Poorly Coated Steel in Soil or Water		0.1
Well Coated Steel in Soil or Water		0.003
Very Well Coated Steel in Soil or Water		0.003 or less

Solving for SA: $SA = \pi \cdot 24/12 \cdot 5280 \cdot 2 \cdot 0.05 = 3317.5\ ft^2$

Note that we must convert the data supplied to the proper units. The outside diameter must be converted from inches to feet and the length of the pipeline must be converted from miles to feet.

Step No. 2 - Calculate the current required based on a 2 mA/ft^2 current density using the following formula:

I-Req = I-Density x SA

Where:

I-Req = Total Current Required (Amperes)

I-Density = Current Density (A/ft^2)

SA = Total Surface Area to be Protected (ft^2)

Solving for I-Req: I-Req = $0.002 \cdot 3317.5 = 6.635$ amperes

Again, we must convert the data supplied to the proper units. The current density must be converted from mA/ft^2 to A/ft^2.

Regardless of the method that is used to determine the current required to achieve protection, it is wise to consider increasing that value in the design stage for future requirements over the life of the system. This increase may be necessitated by coating degradation or additions to the structure. Most designers add 20% to cover these requirements.

Determining the Number of Anodes

After obtaining all the field data required for the design of the anode bed, the next step is the selection of the type of anode to be used and the calculation of the number of anodes required. The factors to be considered when calculating the number of anodes are:

1. Anode Material
2. Rate of Consumption of Anode
3. Current Required for Protection
4. Shape and Size of Anode
5. Maximum Anode Material Density
6. Life Expectancy

Of the above items, Nos. 1, 2, 4, and 5 are interdependent. The consumption rate and maximum allowable density depend on the anode material as do the shape and size of the anodes.

The first step in this phase of the design should, in most instances, be the selection of the anode material. Items to be considered for this selection are environmental conditions, consumption rate, and sizes available.

Although not a general problem with most underground structures, there could be instances where the anode material could be subjected to acidic or alkaline soil environments which could be detrimental to the anode material. Under these conditions, it would be wise to check with the anode manufacturers to insure that the actual environment will not adversely affect the anode material. Another environmental factor that could affect the material selection is whether the anodes will be installed in soil or water, or a combination of both.

As mentioned in Chapter 3 of this course, there are many different anode materials that could be used for impressed current systems. Even scrap steel has been used for anode material. Scrap steel, however, has a high consumption rate (approximately 20 lbs/amp-year). The most commonly used anode materials for conventional anode bed installations in soil are graphite, high silicon cast iron and mixed-metal oxide. Normal operating densities range between 0.2 and 1.0 amp/ft^2 for graphite with an average rate of consumption of 2.0 lb/amp-year, and between 0.5 and 2.5 amp/ft^2 for the high silicon cast iron anode with an average consumption rate of 0.75 lb/amp-year. These consumption rates are markedly reduced if the anode is installed in coke breeze backfill.

The next step in the selection of the anode is to determine the sizes and shapes available. For soil installations, the 5-foot long anodes are normally used, and they are available in diameters ranging from 1½" to 4" (graphite and high-silicon iron only). The selection of the anode size will depend on the desired anode output and the required life expectancy.

Another variable to consider is the use of prepackaged canister anodes. These anodes consist of graphite, high silicon cast iron or mixed metal oxide anodes encased in a steel canister filled with a select backfill. As discussed in Chapter 3, “Materials for Cathodic Protection”, there are advantages and disadvantages to the use of canister anodes.

Now that we have selected the anode material and the type and size of the anode, we can proceed with calculating the number of anodes required.

Determining the Number of Anodes - Example

The current required to protect a pipeline (I-Req), based on current requirement tests, is 15 amps including spare capacity for future demand. High silicon cast iron anodes (2" x 60") are to be used in the anode bed design. The required anode bed life expectancy is 20 years.

Step No. 1 - Calculate the number of anodes required based on a consumption rate of 0.75 pounds per amp-year, a utilization factor (amount of anode material that can be lost to consumption before anode replacement is required) of 60%, and an anode weight of 60 lbs., using the following life expectancy formula:

$$\text{Desired Life} = \frac{\text{Weight x Utilization Factor}}{\text{I-Req x Consumption Rate}}$$

or

$$\text{Weight} =$$

$$\frac{\text{Consumption Rate x Desired Life x I-Req}}{\text{Utilization Factor}}$$

$$= \frac{0.75 \text{ x } 20 \text{ x } 15}{0.60} = 375 \text{ lbs.}$$

$$\text{Number of Anodes} = \frac{375}{60} = 6.25 = 7 \text{ anodes}$$

Step No. 2 - Calculate the number of anodes required based on a nominal current discharge per anode of 2.5 amps per anode (recommended output by manufacturer). Since the surface area of these anodes is 2.8 ft^2, the anodes would be operating at a current discharge density of approximately 0.9 amp/ft^2. This value falls within the range of 0.5 to 2.5 amp/ft^2 mentioned earlier in this chapter as the output range for this type of anode.

$$\text{Number of Anodes} = \frac{\text{Required Current}}{\text{Max. Output per Anode}}$$

$$= \frac{15}{2.5} = 6 \text{ anodes}$$

Based on the calculations in Step 1, the number of anodes required is 7.

An alternative approach to the method outlined above for the determination of the number of anodes required for a conventional anode bed is the "cut and try" method. With this method, an actual anode installation is made and tests are conducted to ascertain the degree of protection achieved. The number of anodes is increased until the desired level of protection is reached. Calculations should then be made to determine if the life expectancy would be met with this method. The size of the rectifier can be determined from the actual field tests.

Calculating the Anode Resistance-to-Earth

The next step in the design process is the calculation of the resistance-to-earth of the anodes. There are exceptions to this approach, such as in those cases in which the utility or the company has established a preferred range of anode bed resistance. If this is the case, then the preferred anode bed resistance becomes the primary factor in calculating the number of anodes required for the installation.

There are two basic approaches to calculating the resistance of an anode bed:

1. By using formulas
2. By using charts

The anode bed resistance-to-earth can be calculated using one of the following formulas, as applicable, for the anode bed design:

Single Vertical Anode (H. B. Dwight formula)

$$R_V = \frac{0.00521 \cdot \rho}{L} \cdot \left(\ln \frac{8 \cdot L}{d} - 1 \right)$$

Where:

R_V = Resistance-to-earth of single vertical anode in ohms

ρ = Effective soil resistivity in ohm-cm

L = Anode length in feet

d = Anode diameter in feet

Multiple Vertical Anodes in Parallel (Erling D. Sunde Formula)

$$R_V = \frac{0.00521 \cdot \rho}{N \cdot L} \cdot \left(\ln \frac{8 \cdot L}{d} - 1 + \frac{2 \cdot L}{S} \cdot \ln\left(0.656 \cdot N\right) \right)$$

Where:

R_V = Resistance-to-earth, in ohms, of the vertical anodes connected in parallel

ρ = Effective soil resistivity in ohm-cm

L = Anode length in feet

N = Number of vertical anodes in parallel

d = Anode diameter in feet

S = Spacing between anodes in feet

Single Horizontal Anode (H. B. Dwight formula)

$$R_H = \frac{0.00521 \cdot \rho}{L} \cdot \left(\ln \frac{4L^2 + 4L\sqrt{S^2 + L^2}}{dS} + \frac{S}{L} - \frac{\sqrt{S^2 + L^2}}{L} - 1 \right)$$

Where:

R_H = Resistance-to-earth, in ohms, of the horizontal anode

ρ = Effective soil resistivity in ohm-cm

L = Horizontal anode length in feet

d = Anode diameter in feet

S = Twice anode depth in feet

When using prepackaged anodes or anode backfills (such as coke breeze), the dimensions of the canister or the backfill column must be substituted in the formulas for the anode dimensions.

Using the anode resistance-to-earth formulas can be somewhat complicated and time consuming. Therefore, graphs have been developed such as the ones shown in Figures 5-3 and 5-4 to expedite the process of determining anode bed/anode resistance-to-earth.

Figure 5-5 shows a typical vertical anode design chart for an impressed current anode bed. The chart was developed on 2" x 60" anodes in an 8" x 7' column of 50 ohm-cm coke breeze backfill. The chart is based on anodes installed vertically in a straight line.

Calculating the Anode Bed Resistance-to-Earth Using a Formula - Example

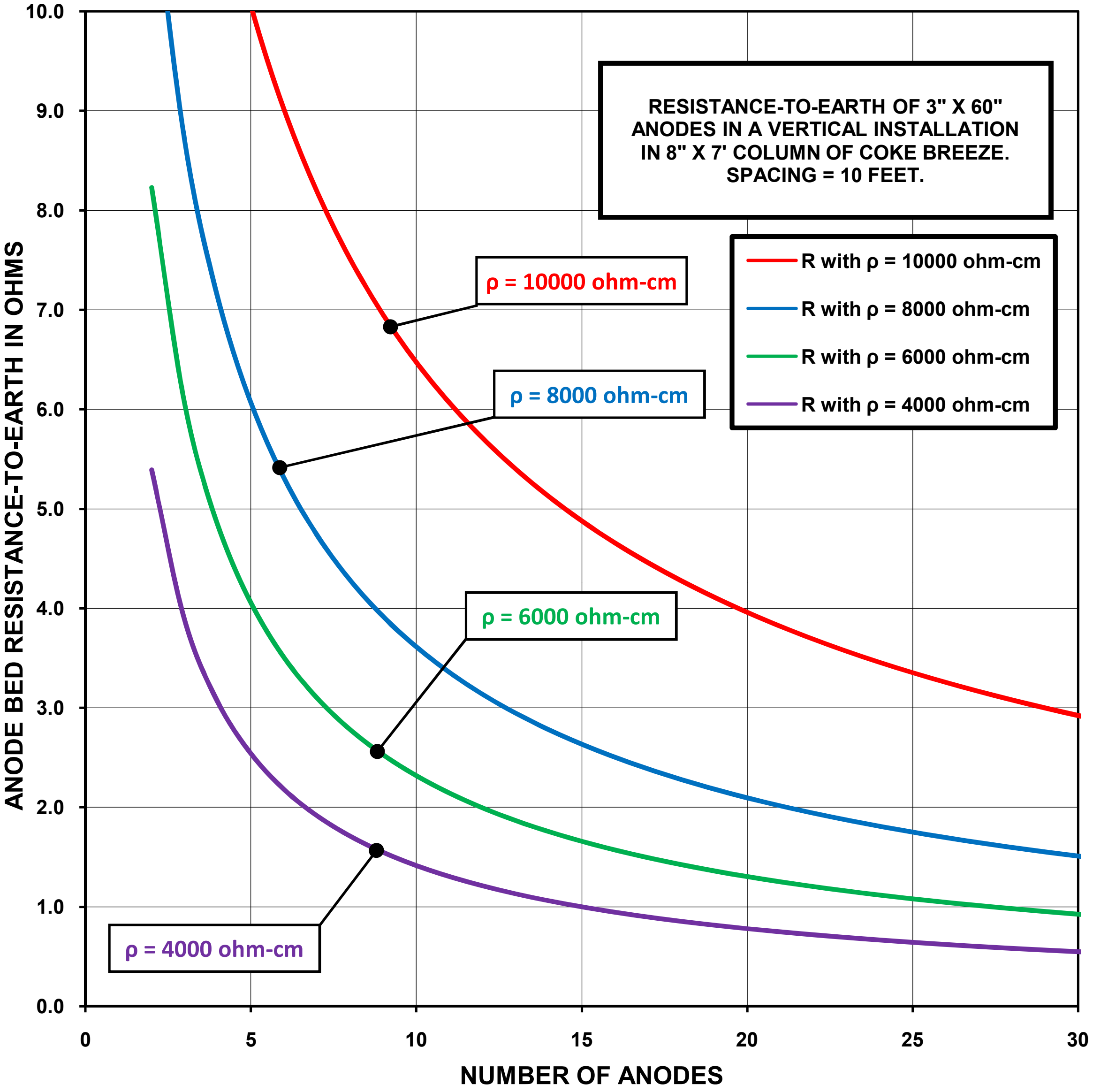
The following example shows how to use the formulas to determine the anode bed resistance-to-earth.

A conventional anode bed consisting of twenty-five (25) 2" x 60" anodes is to be installed in an 8" x 7' column of 50 ohm-cm coke breeze. Anodes are connected in parallel at 15' spacings. Soil resistivity is 10,000 ohm-cm.

Use Sunde's formula to calculate the anode bed resistance-to-earth:

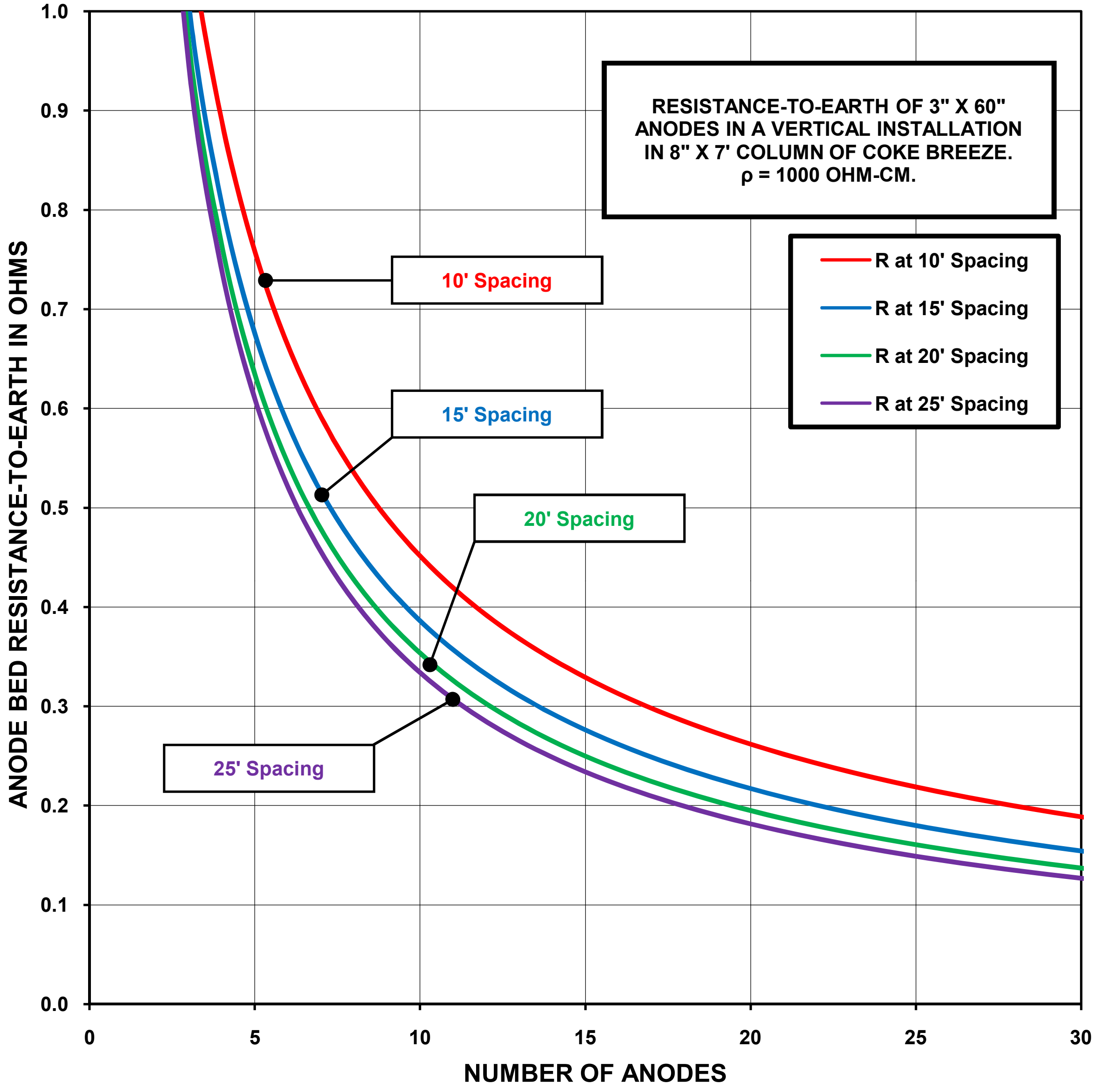
$$R_V = \frac{0.00521 \cdot \rho}{N \cdot L} \cdot \left(\ln \frac{8 \cdot L}{d} - 1 + \frac{2 \cdot L}{S} \cdot \ln(0.656 \cdot N) \right)$$

Substituting the values in the above formula:



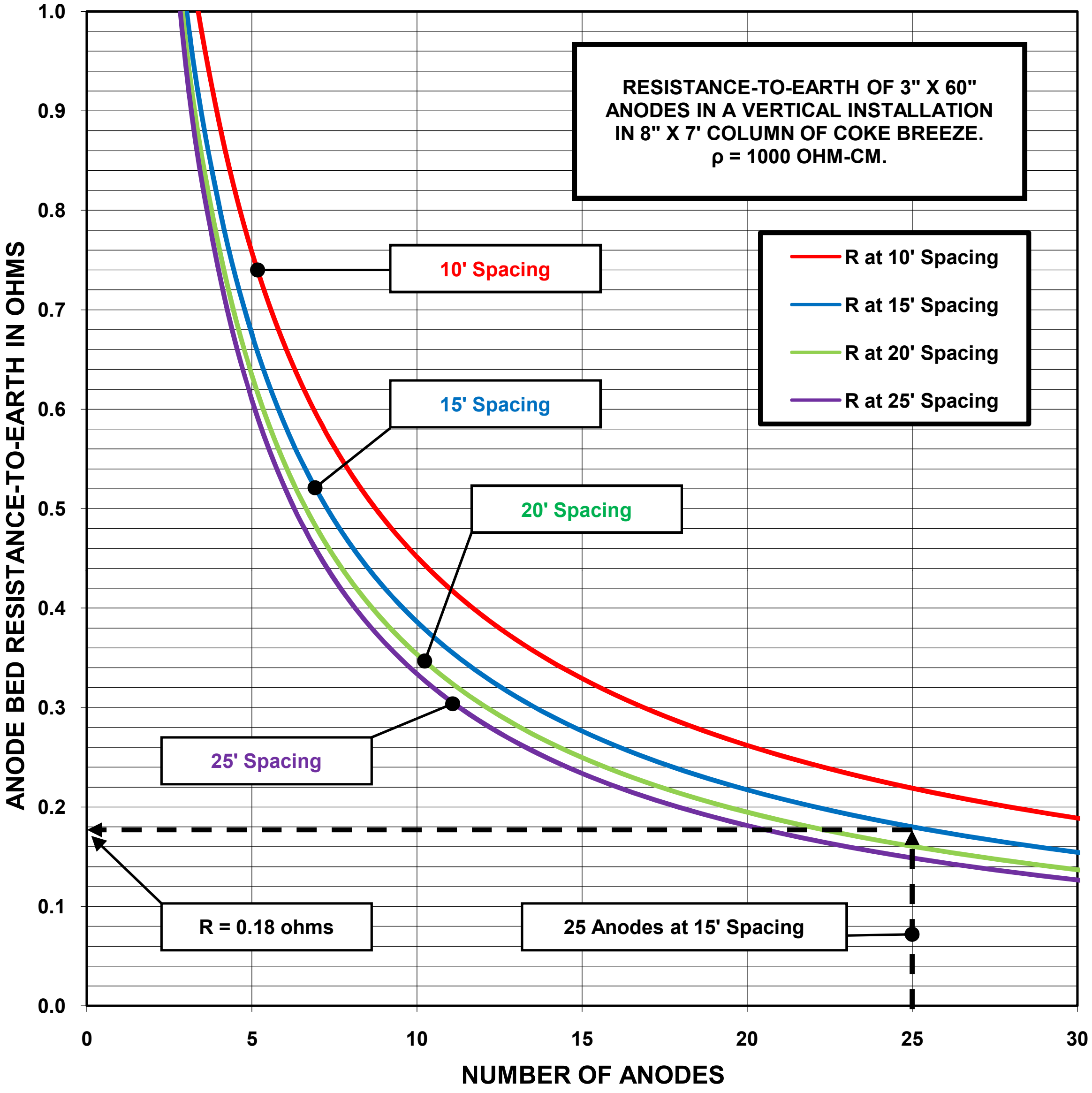
ANODE BED RESISTANCE-TO-EARTH
OF 8" x 7' ANODES AT 10 FT SPACING
AT VARIOUS SOIL RESISTIVITY VALUES

FIGURE 5-3



ANODE BED RESISTANCE-TO-EARTH
OF 8" x 7' ANODES IN 1000 OHM-CM SOIL
AT VARIOUS SPACINGS

FIGURE 5-4



USING A GRAPH TO DETERMINE ANODE BED RESISTANCE-TO-EARTH

FIGURE 5-5

$$R_V = \frac{0.00521 \cdot 10000}{25 \cdot 7} \cdot \left(\ln \frac{8 \cdot 7}{0.667} - 1 + \frac{2 \cdot 7}{15} \cdot \ln\,(0.656 \cdot 25) \right)$$

After making all the calculations, the result is:

R_V = 1.8 ohms

Calculating the Anode Bed Resistance-to-Earth Using a Chart - Example

The following example shows how to use the chart in Figure 5-5 to determine the anode bed resistance-to-earth.

Step No. 1 - Locate the number of anodes on the horizontal axis of the graph (25) and draw a vertical line up to the curve representing anodes at 15' spacing.

Step No. 2 - Draw a horizontal line from that point on the curve to the vertical axis of the graph and read the resistance which, in this case, is 0.18 ohm in 1,000 ohm-cm soil.

Step No. 3 - The resistance is directly proportional to the resistivity of the soil. Therefore, the resistance in 10,000 ohm-cm soil would be:

$$R_V = \frac{10000}{1000} \cdot 0.18 = 1.8 \text{ ohms}$$

Calculating Total Circuit Resistance

The total circuit resistance includes the following:

- Resistance-to-earth of the pipeline or structure
- Resistance of the CP system cables
- Resistance-to-earth of the anodes (anode bed resistance-to-earth)

The resistance-to-earth of the pipeline/structure may be significant or negligible, depending on length of pipe and soil resistivity. Using the values on Table 5-2 and assuming, for example, that the current requirements listed are necessary to shift the pipe-to-soil potential approximately 0.40 volt, then, applying Ohm’s Law, the resistance-to-earth values for those conditions range from 0.0021 ohm (0.40/187.5 - negligible) to 57.14 ohms (0.40/0.007 - very significant). The mid-range current requirement (0.37

ampere) represents a resistance-to-earth value of 1.081 ohms (0.40/0.37) which might be a significant percentage of the total circuit resistance.

The last factor to calculate for the circuit resistance is the resistance of the positive and negative cables. The first step would be to select the proper size of the cable. The cable size should be appropriate to carry the output current and to minimize the IR drop in the cable due to the current flow. Once the size of the cable is determined, the total length of cable to be used is multiplied by the per-foot resistance of the cable selected.

The next step is to calculate the total circuit resistance using the following formula:

R-Total = R-Anode Bed + R-Cable + R-Structure

Where:

R-Total = Total circuit resistance

R-Anode Bed = Anode bed resistance-to-earth

R-Cable = Linear resistance of cable

R-Structure = Pipeline/structure resistance-to-earth

Calculating Total Circuit Resistance - Example

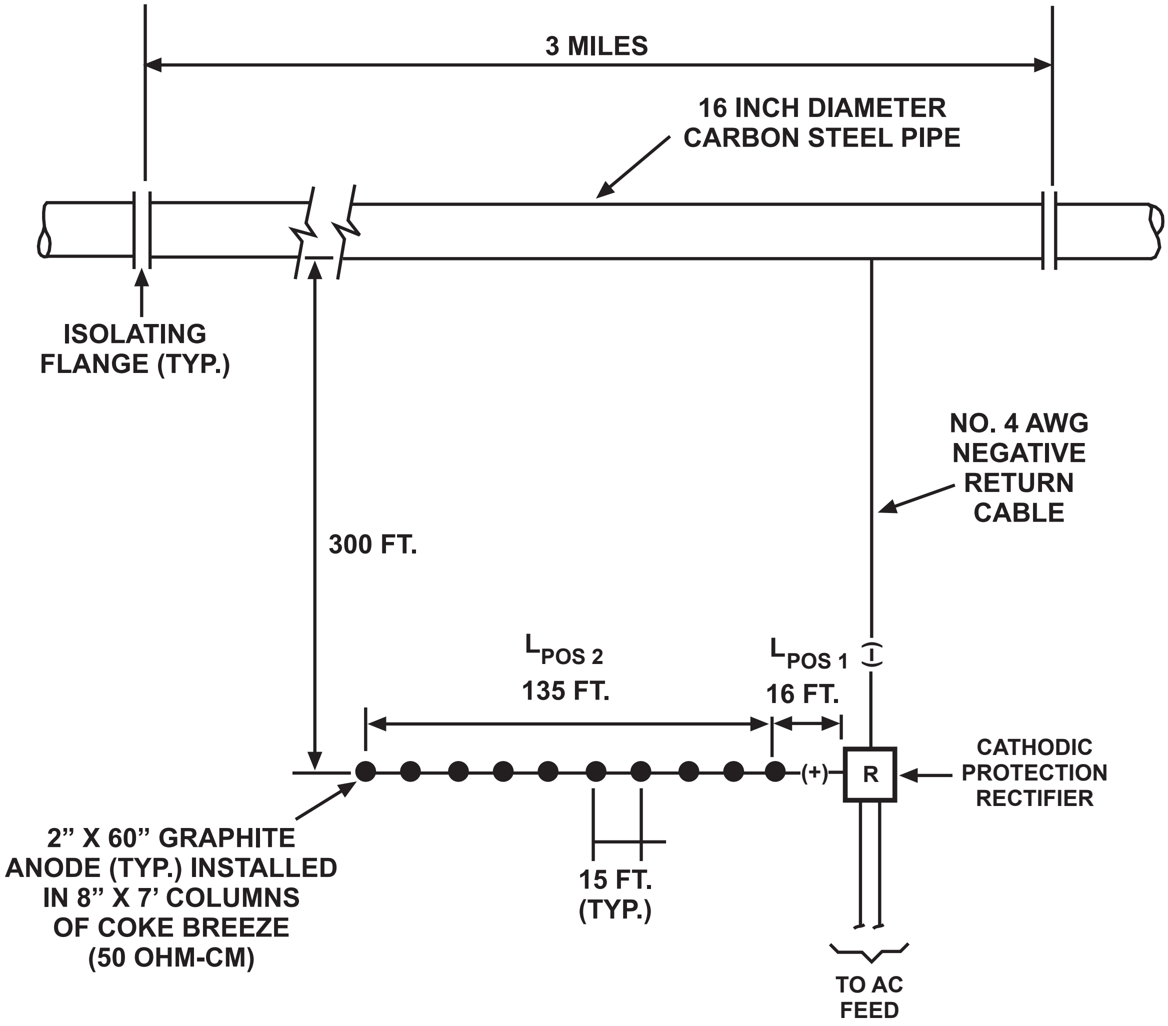
Calculate the total circuit resistance of the conventional anode bed shown in Figure 5-6, using ten (10) 2" x 60" graphite anodes in 8" x 7' columns of 50 ohm-cm coke breeze backfill. Soil resistivity is 8,000 ohm-cm. Current required for protection is 15 amperes. The pipe to be protected is 3-mile long, 16-diameter carbon steel pipe. Assume a coating resistance of 500,000 ohm-ft^2.

Step No. 1 - Calculate R-Anode:

$$\text{R - Anode Bed} = \frac{0.00521 \cdot \rho}{\text{N} \cdot \text{L}} \cdot \left(\ln \frac{8 \cdot \text{L}}{\text{d}} - 1 + \frac{2 \cdot \text{L}}{\text{S}} \cdot \ln(0.656 \cdot \text{N}) \right)$$

$$\text{R - Anode Bed} = 3.08 \text{ ohms}$$

Step No. 2 - Calculate R-Cable, based on the effective system cable length and the resistance of the cable per linear foot. The effective cable length of the system (referring to Figure 5-6) can be determined using the following formula:



TYPICAL REMOTE ANODE BED DESIGN

FIGURE 5-6

L-Cable = L-Neg + L-Pos1+ ½ L-Pos2

Where:

L-Cable = Effective cable length (ft)

L-Neg = Negative return cable length (ft)

L-Pos1 = Length of positive cable to first anode (ft)

L-Pos2 = Length of positive cable between first and last anodes (ft)

L-Cable = 300 +16 + 135/2 =383.5 ft

The cable resistance (R-Cable) can be calculated using the following formula:

R-Cable = R-Linear x L-Cable

Where:

R-Linear = Resistance per linear foot of cable based on a standard cable resistance table such as the one shown in Table 5-4. In this example, AWG #4 cable is being used which has a resistance of 0.2540 ohm per 1,000 ft.

L-Cable = Length of cable in ft.

R–Cable = 383.5 x 0.2540/1000 = 0.0974 ohm

Step No. 3 - Calculate R-Structure for the 3 miles of coated 16-inch diameter carbon steel pipe, assuming an average coating resistance (ACR) of 500,000 ohm-ft^2.

R-Structure = ACR/SA

Where:

ACR = Average Coating Resistance (ohm-ft^2) = 500,000 ohm-ft^2

SA = Surface area of pipe (ft^2) = 66,350 ft^2

R-Structure = 500,000/66,350 = 7.53 ohms

Step No. 4 - Calculate R-Total.

R-Total = R-Anode Bed + R-Cable + R-Structure= 3.08 + 0.0974 + 7.53 = 10.71 ohms

TABLE 5-4
Concentric Stranded Single Conductor Copper Cable Parameters

Size AWG	Overall Diameter Not Including Insulation (Inches)	Maximum DC Resistance @ 20°C (Ohms/1000 ft)	Maximum Allowable DC Current Capacity (Amperes)
14	0.0726	2.5800	15
12	0.0915	1.6200	20
10	0.1160	1.0200	30
8	0.1460	0.6400	45
6	0.1840	0.4030	65
4	0.2320	0.2540	85
3	0.2600	0.2010	100
2	0.2920	0.1590	115
1	0.3320	0.1260	130
1/0	0.3730	0.1000	150
2/0	0.4190	0.0795	175
3/0	0.4700	0.0631	200
4/0	0.5280	0.0500	230
250 MCM	0.5750	0.0423	255

Sizing the Rectifier or DC Power Supply

The final step in designing a conventional anode bed system is sizing the DC output of the power supply to be used. The following factors must have been determined in order to size the DC output of the power supply.

1. **Total Circuit Resistance (R-Total).** As indicated in the previous section, the total circuit resistance consists of the anode bed-to-soil resistance, the cable resistance and the pipeline (structure)-to-earth resistance.

2. **Total Current Required. (I-Req)** The total current required to protect the pipeline/structure based on current requirement tests. As mentioned earlier, the test results are normally increased by 20% or more to provide for future requirement increases.

3. **Back Voltage (V-Back).** The back voltage is the voltage that exists in opposition to the applied voltage between the anodes and the protected structure. Anode bed anodes with carbonaceous backfill will usually have a back voltage of about 2 volts. In areas of unusual soil composition, the back voltage may be slightly higher, but, for design purposes, 2 volts should be used unless experience in a specific area dictates otherwise.

Using these three factors, the minimum DC output of the power supply can be determined/calculated. The required current output of the power supply is equal to the total current required plus a percentage for later deterioration. The DC output voltage can be calculated using the following formula:

V-Req = I-Req x R-Total + V-Back

Where:

V-Req = Required Power Supply Voltage

I-Req = Total Current Required

R-Total = Total Circuit Resistance

V-Back = Back Voltage

Sizing the Rectifier or DC Power Supply - Example

Assume the pipeline in the previous example has a current requirement of 0.003 mA/ft^2 and calculate the required power supply voltage.

Step No. 1 - Calculate total current required, plus 20% for deterioration.

I-Req = Surface Area of Pipe x Current Density

I-Req = 66,350 ft^2 x 0.003 mA/ft^2 = 199 mA = 0.199 Amp

With 20% spare capacity I-Req = 0.199 x 120% = 0.239 Amperes

Step No. 2 - Calculate required power supply voltage using R-Total from previous example.

V-Req = I-Req x R-Total + V-Back = 0.239 x 10.71 + 2 = 4.56 Volts

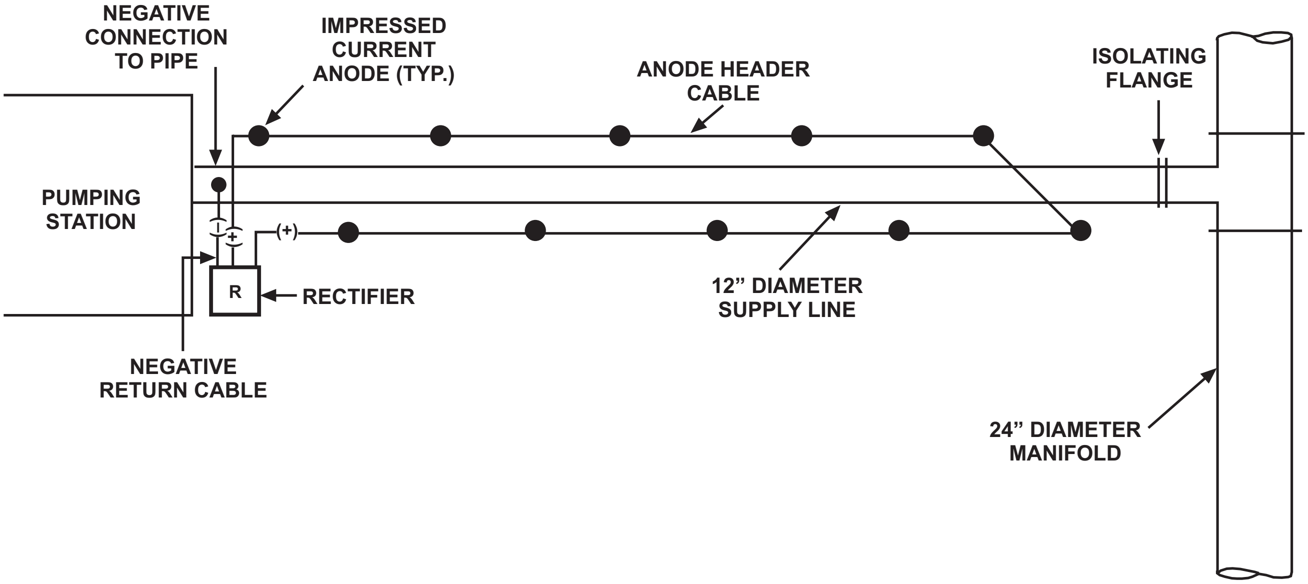
The required output rating as calculated is not what would be considered a standard off-the-shelf rating. The actual rating of the rectifier unit purchased should be based, whenever possible, on standard available ratings. In this case, the closest rating might be 4 amps and 8 volts.

DESIGN OF DISTRIBUTED ANODE BED

A distributed anode bed is installed in close proximity to the pipeline/structure to be protected. Distributed anode beds are used primarily when it is desired to protect a limited area of a pipeline, or to protect sections of a bare or coated pipeline in areas where electrical shielding precludes effective protection with remote anode bed installations. Figure 5-7 shows a typical distributed anode cathodic protection system.

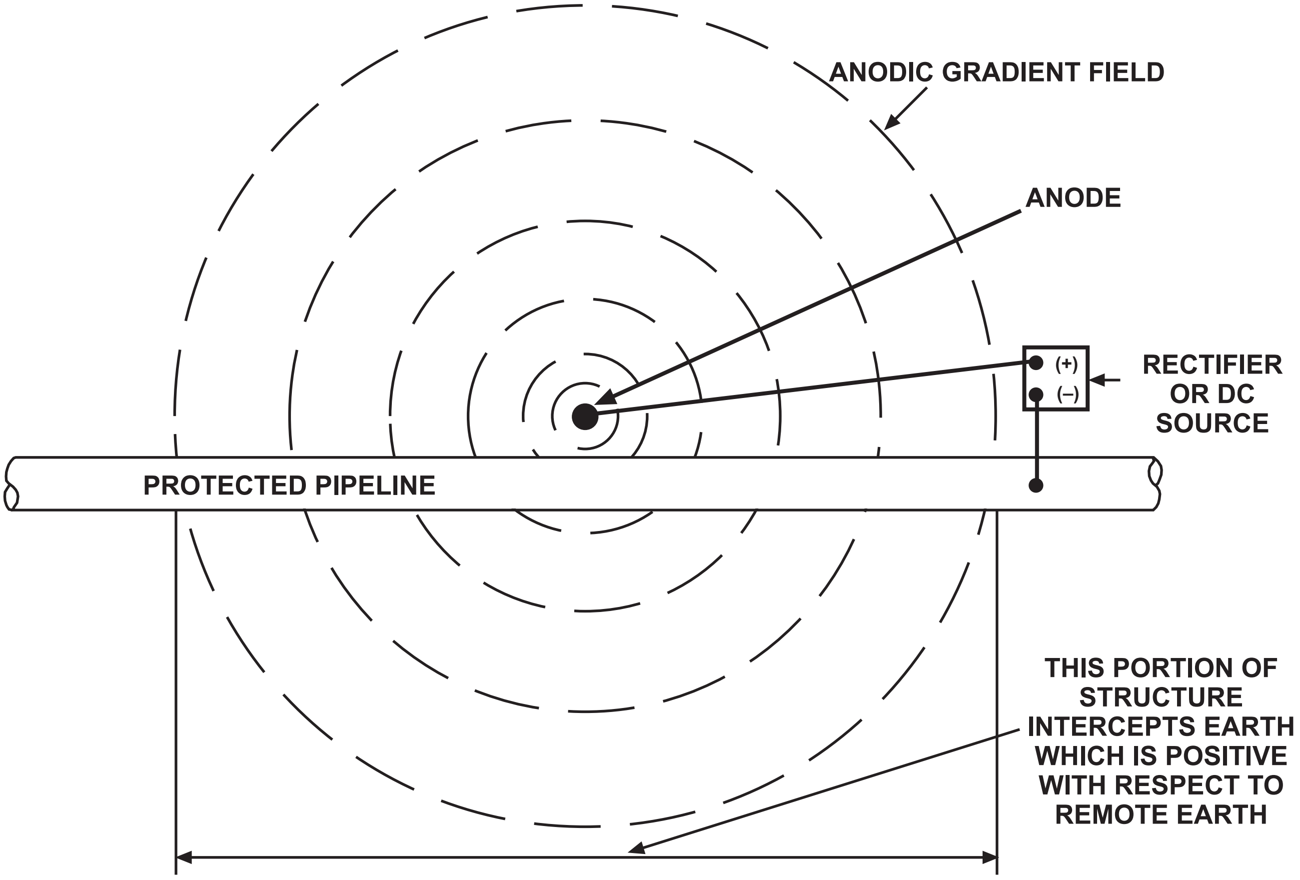
Many companies designed this type of anode bed using a combination of the current pickup by the structure and the gradient established in the soil by the anodes. The current pickup makes the potential of the pipeline/structure swing in the negative direction, while the anode gradient makes the soil surrounding the pipeline/structure swing in the positive direction. The result is an additive effect.

Figure 5-8 shows how one anode swings the potential of the earth in the vicinity of a structure. The earth potential swing concept involves having the protected structure intercept the anodic gradient field surrounding the distributed anode bed, as shown in



TYPICAL DISTRIBUTED IMPRESSED CURRENT ANODE SYSTEM

FIGURE 5-7



ANODE BED ARRANGEMENT FOR EARTH POTENTIAL SWING CATHODIC PROTECTION

FIGURE 5-8

the figure. The part of the structure that is within the gradient field of the anode bed is in soil which is electrically positive with respect to remote earth. This means that, within the anodic gradient field, the structure is negative with respect to adjacent earth, even though it may not be made more negative with respect to remote earth. Within the anodic gradient field, that part of the structure closest to the anode bed is normally most negative with respect to adjacent earth. Figure 5-9 shows how the gradient from the anode bed influences the potential of the pipeline-to-earth.

In designing a distributed anode bed, the designer considered that each individual anode created a gradient around itself and that the effect on the pipeline/structure is additive. Figure 5-10 shows the additive effect of two adjacent anodes.

A similar gradient effect is also created by a distributed anode bed that uses a linear anode.

The design of a distributed anode bed is similar to that of the remote anode bed as far as determining current requirements, calculating anode bed resistance-to-earth and sizing the DC output of the power supply.

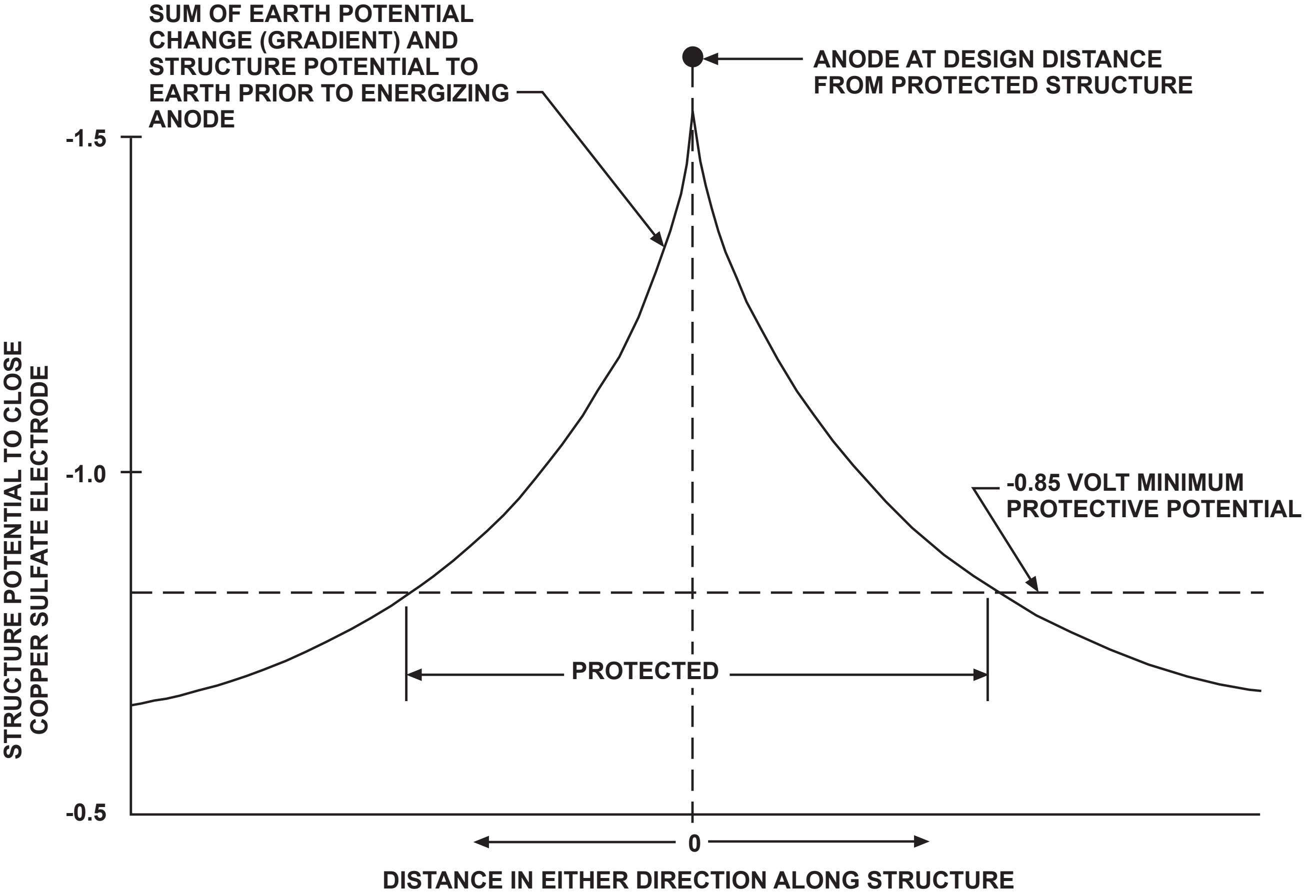
In designing a distributed anode bed, the sizing of the header cable is more critical than for a remote anode bed. This is due to the length of the header cable and the associated voltage drops across the it.

DESIGN OF DEEP ANODE BED

When it is desirable to install an anode bed system which has many of the operating characteristics of a conventional anode bed, but for which there is no space available at the desired site location, the only way to install the anodes at a distance from the pipeline/structure is to install them deep below the pipeline/structure.

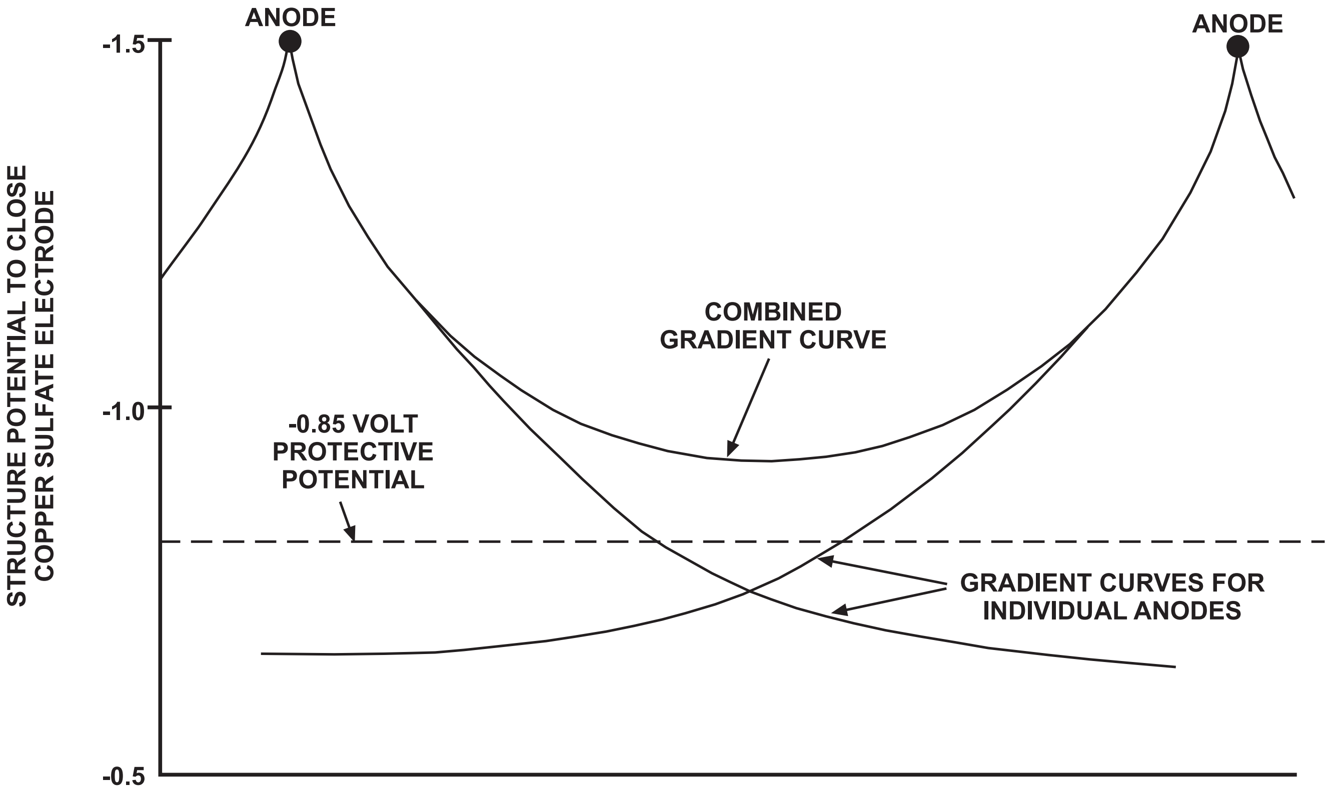
Deep anode beds are also used when the soil strata are so arranged that the upper layers of soil are of high resistivity with underlying layers of lower resistivity.

A deep anode bed is usually more expensive to build than a conventional anode bed of comparable capacity. In addition, the anodes of a deep anode bed are well below grade level and are inaccessible for maintenance should failure occur in the anode material or in the connecting cables. Although there are replaceable deep anode bed systems on the market, it may be more economical to abandon a malfunctioning system in place and install a new anode bed close to the original one, rather than to attempt system repairs.



POTENTIAL GRADIENT FIELD AROUND A VERTICAL ANODE

FIGURE 5-9



INTERACTION BETWEEN ADJACENT DISTRIBUTED ANODES

FIGURE 5-10

The design procedure for a deep anode bed is, for all practical purposes, the same as that for a conventional anode bed. The deep anode bed operates on the same concept as the conventional anode bed, making the protected pipeline/structure more negative with respect to the surrounding soil, as illustrated in Figure 5-11.

Graphite, high silicon cast iron and mixed metal oxide anodes in coke breeze backfill are often used for deep anode beds (see Figure 5-12).

Other designs include the use of a steel casing as the anode material itself, or in cases where the drilled hole stays open and the water table is high enough, plain anodes without special backfill are installed inside the hole. In all cases, the upper portion of the installation (normally 50 to 100 feet) does not discharge current in order to avoid the gradients in the area of the pipeline/structure. This can be accomplished by installing a plastic casing in that section of the hole or by covering that section of the steel casing with a high dielectric tape/coating.

However, it should be noted that, when designing a deep anode bed, the anode bed resistance-to-earth should be calculated using the total length of the backfill column install as illustrated by the following example:

Design of Deep Anode Bed - Example

A deep anode bed consists of four 2" x 60" high silicon cast iron anodes with a column 40 ft. long of coke breeze backfill in an 8" diameter hole. The effective soil resistivity at anode depth is 10,000 ohm-cm.

The deep anode bed resistance-to-earth can be calculated using H. B. Dwight's formula for a single vertical anode as follows:

$$\mathrm{R\text{-}Anode} = \frac{0.00521 \cdot \rho}{L} \cdot \left(\ln \frac{8 \cdot L}{d} - 1 \right)$$

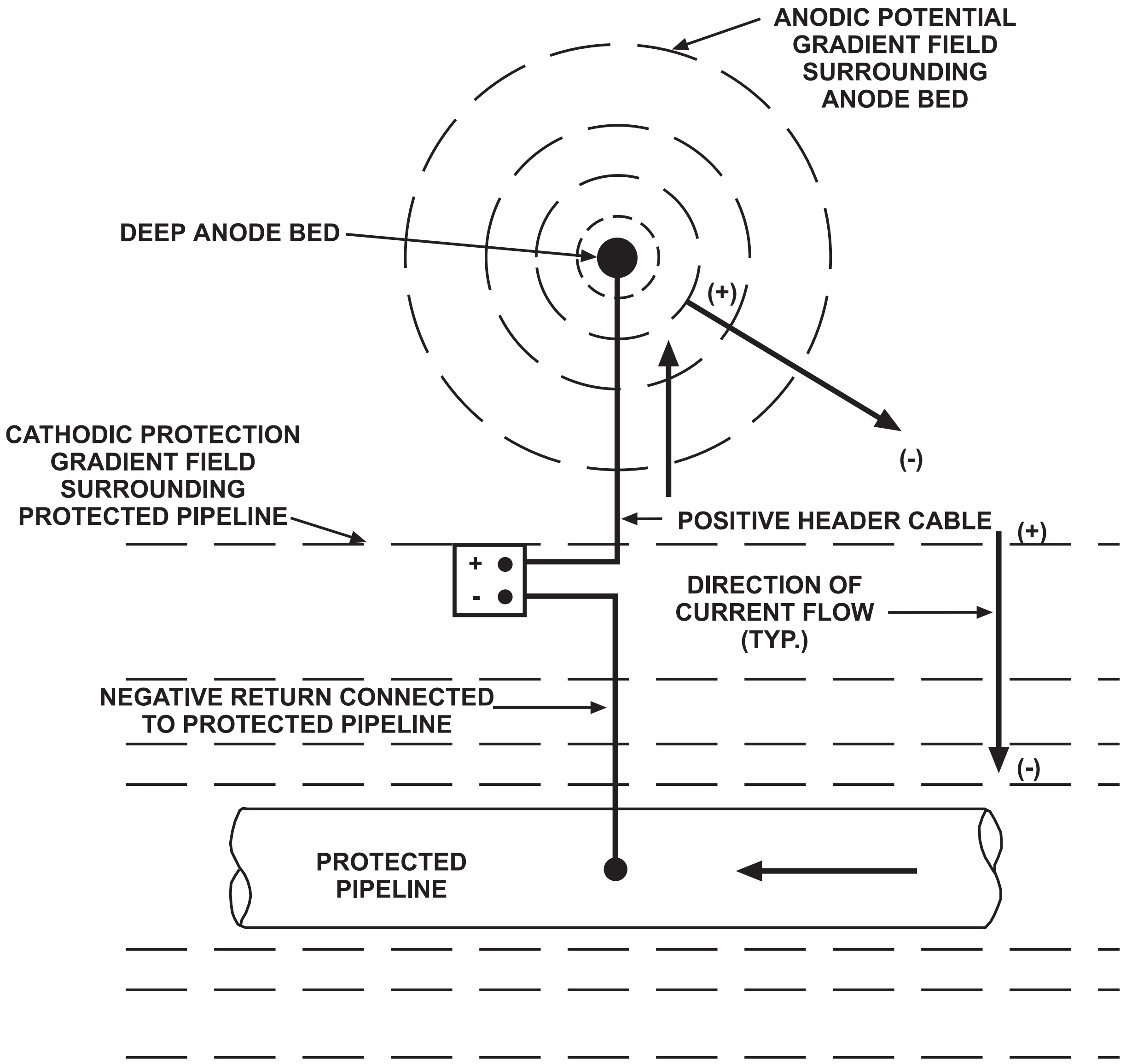
Where:

R-Anode = Resistance-to-earth of single anode

ρ = Effective soil resistivity = 10,000 ohm-cm

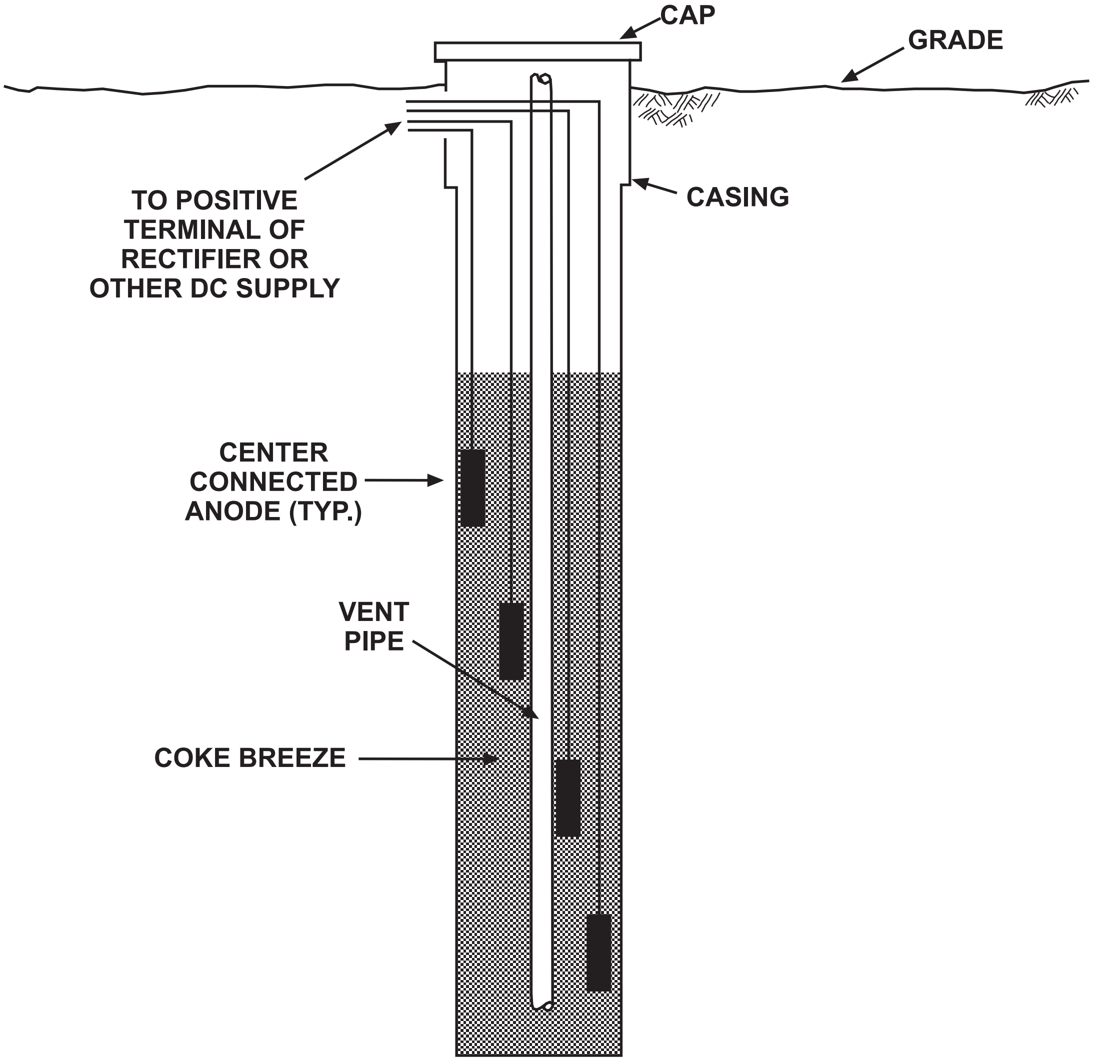
L = Anode length = 40 ft

d = Anode diameter = 8"/12 = 0.667 ft



TYPICAL DEEP ANODE BED OPERATION

FIGURE 5-11



TYPICAL DEEP ANODE BED

FIGURE 5-12

$$R_V = \frac{0.00521 \cdot 10000}{40} \cdot \left(\ln \frac{8 \cdot 40}{0.667} - 1 \right)$$

$$R_V = 6.73 \text{ ohms}$$

Many deep anode beds use conventional anodes with coke breeze backfill. One main problem that can develop with this type of installation is gas blocking. Chlorine gas evolves from the anode as a result of the current discharge. Gas blocking can render a deep anode bed useless. In order to eliminate, or at least reduce this problem, it is standard procedure to install a vent pipe which allows for the dissipation of the gas. Plastic materials not subject to deterioration by chlorine gas should be used for this vent pipe. Figure 5-12 shows the details of a typical deep anode bed.

Other problems associated with deep anode beds are:

1. Cable Insulation - Some types of cable insulation, such as the HMWPE, are attacked by chlorine gas and ozone. Special insulation, such as Kynar® or Halar®, should be used.

2. The anode-lead connection is a very critical point of the system, and steps should be taken to preclude later problems.

3. As the steel casing consumes, the resistance of the anode bed may increase because of the layer of iron oxide that develops.

CONCLUSIONS

Many parameters must be considered when designing an impressed current cathodic protection system. As previously discussed, these parameters include the following:

1. Current density required for protection
2. Life expectancy of installation
3. Anode bed layout
4. Anode bed resistance
5. Rectifier output

The corrosion control designer must be aware of these parameters to determine the most effective and economical system design.

There are basically three (3) different types of anode bed designs:

1. Remote or conventional
2. Distributed
3. Deep

Each type of anode bed has its own applications, and it is up to corrosion control personnel to ascertain which type would be more suited for each installation being considered.

Chapter 6 - Design of Galvanic Anode Cathodic Protection

INTRODUCTION

Galvanic anodes are an important and useful means for cathodic protection of pipelines and other buried structures. The application of cathodic protection utilizing galvanic anodes is nothing more than the intentional creation of a galvanic electrochemical cell in which two dissimilar metals are electrically connected while buried in a common electrolyte. In the “dissimilar metal” cell, the metal higher in the electromotive series (or more “active”) becomes anodic to the less active metal and is consumed during the electrochemical reaction. The less active metal receives cathodic protection at its surface due to the current flowing through the electrolyte from the anodic metal. The design of a galvanic cathodic protection system involves consideration of all factors affecting the proper selection of a suitable anode material and its physical dimension, placement, and method of installation to achieve a sufficient level of protection on the structure.

GALVANIC ANODE APPLICATION

General Uses

Galvanic anode installations are normally used for cathodic protection applications where relatively small amounts of protective currents are required and the resistivity of the electrolyte is low enough to permit their use. If current requirements are such that a large number of galvanic anodes would be required, it may be more economical to use an impressed current system, if possible.

Specific Uses

The following are some specific uses for galvanic anode cathodic protection systems:

1. For protecting structures where a source of DC or AC power is not available.

2. For clearing interferences caused by impressed current cathodic protection systems or other DC sources, where the interferences are not of great magnitudes.

3. For protecting sections of well-coated pipelines.

4. For providing hot-spot protection on bare pipelines where complete cathodic protection is impractical.

5. For supplementing impressed current systems where low spots or unprotected areas remain on the structure due to shielding effects or other reasons.

6. For temporary protection during construction of a pipeline until the impressed current system is installed.

7. For AC mitigation.

GALVANIC ANODE CATHODIC PROTECTION DESIGN PARAMETERS

Galvanic Anode Selection

The first step in designing a galvanic anode system is the selection of the anode material. Corrosion control personnel must consider the following to determine the most economical anode material to use:

1. Required amount of protective current
2. Total weight of each type of anode
3. Anode life calculations
4. Desired life of installation
5. Efficiency of anode types
6. Theoretical consumption rate
7. Driving potential
8. Soil or water resistivity
9. Cost of anode material
10. Shipping costs
11. Degree of skill required for installing the galvanic anode system

Table 6-1 shows some of these parameters for several anode materials. The order of priority of the above factors will probably change for each installation.

TABLE 6-1
Typical Operating Characteristics of Galvanic Anodes

Galvanic Anode Material	Theoretical Capacity (amp-hr/lb)	Actual Capacity* (amp-hr/lb)	Consumption Rates (lb/amp-yr)	Current Efficiency	Negative Potential to CSE (Volts)
Zinc (Mil-A-18001 U)	370	370	23.7	90%	1.10
Magnesium (H-1 Alloy)	1000	250 - 580	15 - 35	25 - 58%	1.40 - 1.60
Magnesium (High Potential)	1000	450 - 540	16 - 19	45 - 54%	1.70 - 1.80

* Based on shown current efficiencies.

Anode Current Efficiency

Anode current efficiency is a measure of the percentage of the total anode current output which is available in a cathodic protection circuit. The remaining current is dissipated in the self-corrosion of the anode material.

From Table 6-1 it should be noted that zinc has high current efficiency. Magnesium on the other hand, is shown to have an efficiency of approximately 50 percent. Although this efficiency figure is used quite commonly, it is not a constant and can be even less at low current outputs. Different magnesium alloys have different efficiency values.

Current Requirements

The determination of the amount of current required to protect a structure is one of the most important design parameters. Current requirements for a structure can be determined by conducting current requirement tests on the structure. This method was discussed in detail in the previous chapter for the design of the impressed current system. These approaches are identical for the galvanic anode system.

Electrolyte Resistivity

The selection of the galvanic anode material is primarily dependent upon the resistivity of the surrounding electrolyte (soil). As discussed in Chapter 3, the low driving potentials of the various galvanic anode material alloys limit their economical use to the lower resistivity soils. Zinc anodes are seldom used in soils with resistivity values greater than 1500 ohm-cm. Magnesium anodes are generally used in soils with resistivity values between 1000 and 10,000 ohm-cm. Ideally, the galvanic anode bed should be installed in the area of lowest resistivity. Soil resistivity surveys should be conducted as described in the Basic Course.

Total Circuit Resistance

Total circuit resistance depends upon the following:

- Resistance-to-earth of anode bed - R_{ANODE}
- Resistance of interconnecting cables - R_{CABLE}
- Resistance-to-earth of the cathode (pipe/structure) - R_{PIPE}

The electrical circuit equivalent of the current output of a galvanic anode is depicted in Figure 6-1.

It should be noted that as corrosion personnel develop experience, they will be able to determine the conditions under which some of the above factors can be considered negligible.

Anode Bed Resistance-to-Earth - R_{ANODE}

The resistance-to-earth of the galvanic anode bed is more critical than that of the impressed current system due to the fact that the driving voltage of the anodes Is limited. The current output is limited by the potential difference between the structure and the anode material.

The resistance-to-earth of a galvanic anode system can be calculated using the same formulas used to determine the resistance-to-earth of the impressed current anode bed.

Calculating the Resistance-to-Earth of a Galvanic Anode Bed - Example

Calculate the resistance of a galvanic anode bed consisting of six prepackaged 60 lb zinc anodes (5" x 66" long) spaced 15' apart, center-to-center, average soil resistivity in the area is 1,500 ohm-cm.

$$R_{ANODE} = \frac{0.00521 \cdot \rho}{N \cdot L} \cdot \left(\ln \frac{8 \cdot L}{d} - 1 + \frac{2 \cdot L}{S} \cdot \ln 0.656 \cdot N \right)$$

Where:

R_{ANODE} = resistance-to-earth of the total number of vertical anodes in parallel (ohms)

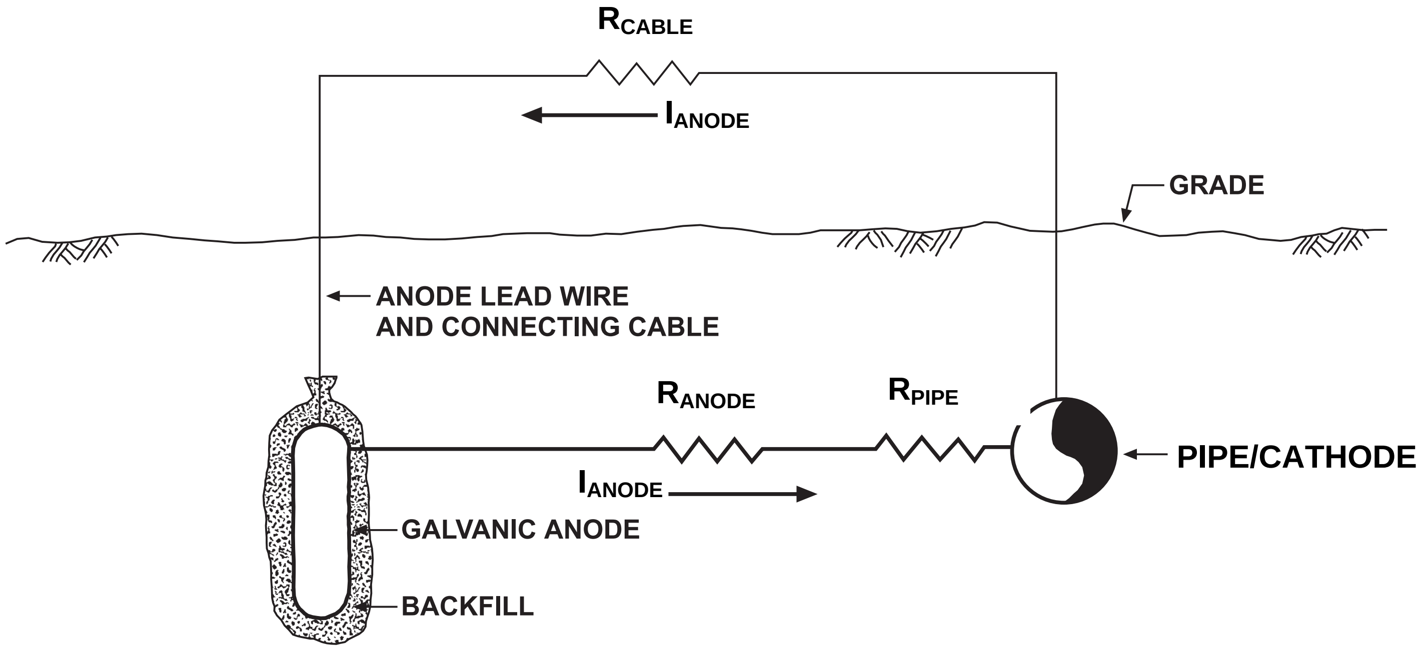
ρ = electrolyte resistivity (ohm-cm)

L = length of anode (feet)

d = anode diameter in feet

N = number of anodes in parallel

S = spacing between anodes in feet



GALVANIC ANODE SYSTEM
ELECTRICAL CIRCUIT

FIGURE 6-1

$$R_{ANODE} = \frac{0.00521 \cdot 1500}{5.5 \cdot 6} \cdot \left(\ln \frac{8 \cdot 5.5}{0.417} - 1 + \frac{2 \cdot 5.5}{15} \cdot \ln \quad 0.656 \cdot 6 \right)$$

$$R_{ANODE} = 1.10 \text{ ohms}$$

Resistance of Interconnecting Cables - R_{CABLE}

The resistance of the interconnecting cables (R_{ckt}) is normally negligible in the design of galvanic anode cathodic protection systems. The voltage drops in the cables are usually insignificant because of the low current output of this type of installation. When the resistance of the interconnecting cables is to be included in the overall system resistance, R_{CABLE} can be calculated for all practical purposes, using the following formula:

R_{CABLE} = Resistance per ft of cable (from Table 6-2) x Length of cable

Pipe Resistance-to-Earth - R_{PIPE}

The pipe resistance-to-earth is the resistance between the pipe and the electrolyte.

This value can be measured directly or it can be calculated from the average coating resistance (ACR) and then using the following formula:

R_{PIPE} = ACR/SA

Where:

R_{PIPE} = Resistance of pipeline to earth (ohms)

ACR = Average Coating Resistance (ohm-ft^2)

SA = Surface Area of pipeline (ft^2)

Calculating Pipe Resistance-to-Earth from Average Coating Resistance - Example

If a 10-mile section of 36" diameter pipe has an average coating resistance (ACR) of 50,000 ohms-ft^2, the pipe resistance-to-earth (R_{PIPE}) can be calculated as follows:

TABLE 6-2
Resistance of Concentric Stranded Copper Single Conductors

Size AWG	Max. DC Resistance @ 20º C (ohms/1000 ft)
14	2.5800
12	1.6200
10	1.0100
8	0.6400
6	0.4030
4	0.2540
3	0.2010
2	0.1590
1	0.1260
1/0	0.1000
2/0	0.0795
3/0	0.0631
4/0	0.0500
250 MCM	0.0423

Step No. 1 - Calculate surface area of pipeline:

SA = π x pipe diameter (ft) x length of pipe (ft)

SA = 3.14 x (36/12) x (10 x 5280)

SA = 497,376 ft^2

Step No. 2 - Calculate pipe resistance-to-earth :

R_{PIPE} = ACR/SA = 50,000 ohm-ft^2/497,376 ft^2 = 0.10 ohm

Anode Life

Having arrived at an anode configuration that will produce the required current output is not sufficient in itself. An examination of the estimated life of the anodes must be undertaken in order to determine whether the design will provide protection for a reasonable period of time. The following expression may be used to calculate the estimated life of the anode:

$$\text{Years Life} = \frac{\text{CAP} \times \text{A} \times \text{E} \times \text{UF}}{\text{Hr} \times \text{I}}$$

Where:

CAP = Theoretical capacity (amp-hours/lb)

A = Anode weight (lbs)

E = Current Efficiency expressed as a decimal

UF = Utilization Factor - typically 85% expressed as a decimal (0.85)

Hr = Hours per year

I = Current (amps)

The utilization factor accounts for a reduction in output as the surface area of the anode decreases with time, limiting the anode output. This is the point at which the anode should be replaced even though the anode metal may not be entirely consumed. This factor is usually assumed to be 0.85.

1. For magnesium:

$$\text{Years Life} = \frac{0.114^{*} \times A \times E \times UF}{I}$$

2. For zinc:

$$\text{Years Life} = \frac{0.0424^{*} \times A \times E \times UF}{I}$$

* These constants are derived by dividing the theoretical capacity by the number of hours in a year.

Calculating Anode Life - Example

Let's compare the life expectancy of ten pound anodes of magnesium and zinc, each discharging 0.1 amp. Assume 90% current efficiency for zinc and 50% for magnesium. Each anode is assumed to require replacement when it is 85% consumed.

Using the formulas above, the life expectancies work out as follows:

1. For magnesium:

$$\text{Years Life} = \frac{0.114 \times 10 \times 0.50 \times 0.85}{0.10} = 4.8 \text{ years}$$

2. For zinc:

$$\text{Years Life} = \frac{0.0424 \times 10 \times 0.90 \times 0.85}{0.10} = 3.2 \text{ years}$$

The calculated life figures reflect the effect of different rates of consumption of the two metals as well as the effect of current efficiency.

Designing a Galvanic Anode CP System Using Formulas - Example

Let's design a galvanic anode cathodic protection system for a well-coated pipeline that is 36" OD and 2500 ft long. The average soil resistivity in the area is 1000 ohm-cm. The desired system life expectancy is 20 years.

Step No. 1 - Choose the anode material. Based on the fact that magnesium has a higher capacity (amp-hr/lb) and a lower consumption rate (lb/amp-yr) than zinc (see Table 6-1) magnesium is selected.

Step No. 2 - Calculate the surface area (SA) to be protected:

$SA = \pi$ x pipe outside diameter (ft) x length of pipe (ft)

$SA = 3.14 \times (36/12) \times (2500)$

$SA = 23{,}550 \text{ ft}^2$

Step No. 3 - Calculate current requirements. The anode bed should be designed to achieve a satisfactory amount of polarization. After polarization, galvanic anodes tend to self-regulate and the current output at the anode bed will decline while protection is maintained. As a rule of thumb, the amount of current required to polarize the pipe is four times the amount of current required to maintain protection.

a. Current required to maintain protection (I_{REQ}) on the pipe can be calculated as follows, assuming a current requirement of 0.003 mA/ft^2, typical for a well coated, electrically isolated pipe. This is based on 1.5 mA/ft^2 of exposed metal and on 0.2% coating damage.

$I_{REQ} = 0.003 \text{ mA/ft}^2 \times SA$

$I_{REQ} = 0.003 \text{ mA/ft}^2 \times 23{,}550 \text{ ft}^2$

$I_{REQ} = 71 \text{ mA} = 0.071$ Amperes

b. The current required to polarize (I_{POLAR}) the pipe, by rule of thumb, is based on a current requirement of 0.012 mA/ft^2 (4 times the current required for protection). This also approximated the current required should coating deteriorate to a total of 0.8% damage from the initial value of 0.2%.

$I_{POLAR} = 0.012 \text{ mA/ft}^2 \times SA$

$I_{POLAR} = 0.012 \text{ mA/ft}^2 \times 23{,}550 \text{ ft}^2$

$I_{POLAR} = 283 \text{ mA} = 0.283$ Amperes

Step No. 4 - Determine the minimum amount of anode material (W) required to provide an anode bed life of 20 years, based on the current required to polarize the pipe.

$$\text{Years Life} = \frac{0.114 \times W \times E \times UF}{I_{POLAR}}$$

$$20 = \frac{0.114 \times W \times 0.50 \times 0.85}{0.283}$$

Solving for W, W = 117 lbs of magnesium

Based on the weight of anode material calculated above, it appears that 7 - 17 lb anodes (4" x 4" x 17"), with backfill outer dimensions of 7.5" x 24", will provide sufficient anode material for the desired life.

Step No. 5 - Calculate the anode bed resistance-to-earth (R_{ANODE}) for the anode bed assuming center-to-center anode spacing of 15 feet.

$$R_{ANODE} = \frac{0.00521 \cdot \rho}{N \cdot L} \cdot \left(\ln \frac{8 \cdot L}{d} - 1 + \frac{2 \cdot L}{S} \cdot \ln 0.656 \cdot N \right)$$

$$R_{ANODE} = \frac{0.00521 \cdot 1000}{7 \cdot 2} \cdot \left(\ln \frac{8 \cdot 2}{0.625} - 1 + \frac{2 \cdot 2}{15} \cdot \ln \ 0.656 \cdot 7 \right)$$

R_{ANODE} = 0.99 ohm

Step No. 6 - Calculate the pipe resistance-to-earth (R_{PIPE}) assuming an average coating resistance (ACR) of 15,000 ohm-ft^2.

R_{PIPE} = ACR/SA

R_{PIPE} = 15,000 ohm-ft^2/23,550 ft^2

R_{PIPE} = 0.64 ohm

Step No. 7 - Calculate the connecting cable resistance (R_{CABLE}) assuming the use of approximately 105 ft of No. 6 AWG wire.

R_{CABLE} = Resistance of wire x length

R_{CABLE} = 0.403 ohm/1000 ft x 105 ft

R_{CABLE} = 0.042 ohm

Step No. 8

Calculate anode bed current output (I_{ANODE}). Assume the anode potential to be -1.55 volts and you want to polarize the pipe to -1.0 volt.

$$I_{ANODE} = \frac{\text{Anode Potential} - \text{Cathode Potential}}{R_{ANODE} + R_{PIPE} + R_{CABLE}}$$

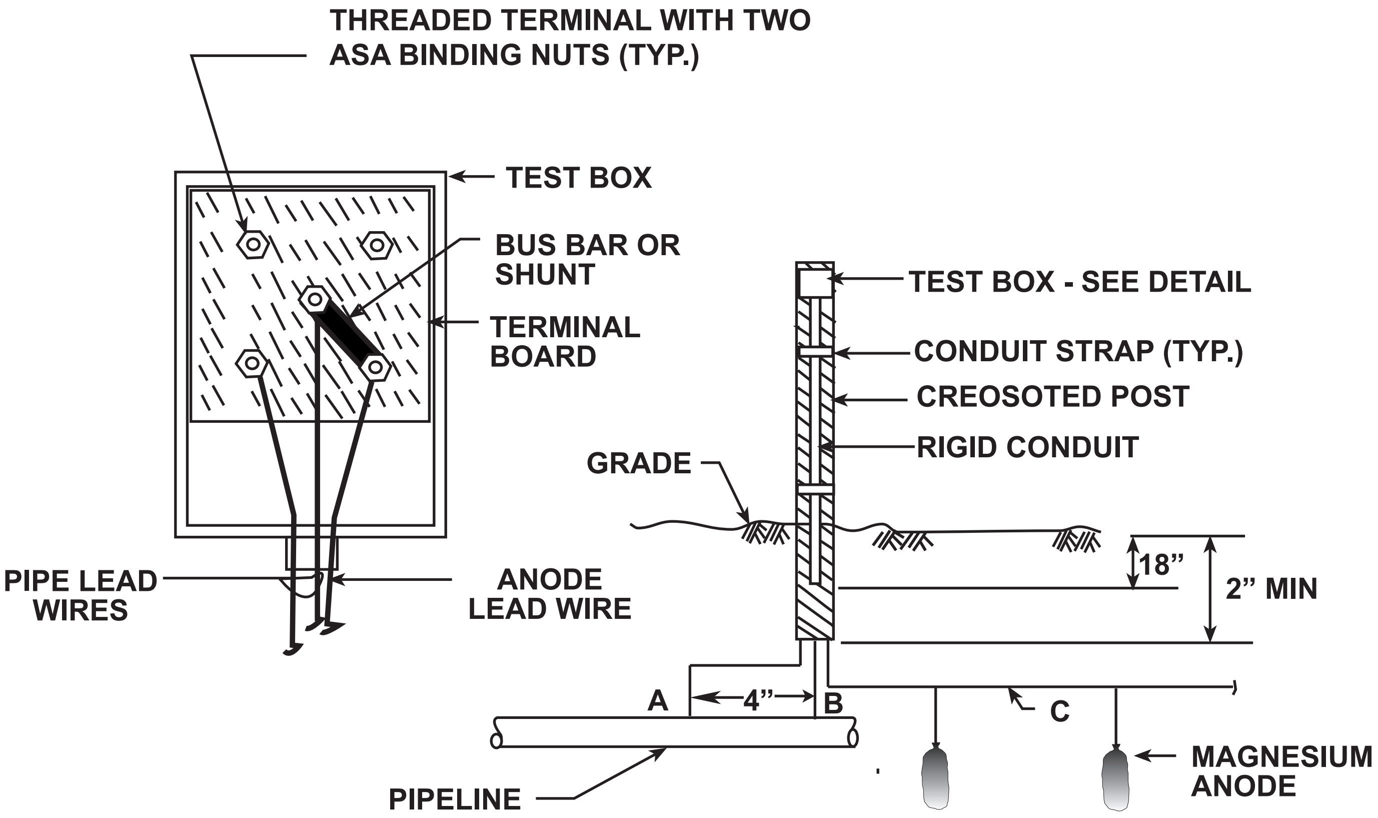
$$I_{ANODE} = \frac{1.55 - 1.0}{0.99 + 0.64 + 0.042} = 0.329 \text{ Ampere}$$

The anode bed current output (I_{ANODE}) calculated above exceeds the previously calculated current values required to polarize and protect the structure, therefore the design will be effective in providing cathodic protection. Once the pipe polarizes (usually within a few months), the anode current will drop to the protective level of about 0.071 amperes, thus further extending anode life. Also, using the polarizing current in these calculations allows for coating deterioration over time.

Figure 6-2 shows a detail of a typical system layout for this design.

Simplified Calculations

From the previous example, we can see that it can be rather time consuming to calculate the various resistive factors required to design a galvanic anode bed, and often certain assumptions must be made that result in an approximate current output calculation. The output of magnesium and zinc anodes has been fairly well documented under varying conditions, and many graphs, tables, and charts have been developed. These references can be used by corrosion control personnel to provide a simplified and reasonably accurate means of determining anode current outputs under normal operating



TYPICAL GALVANIC ANODE
SYSTEM INSTALLATION

FIGURE 6-2

conditions. One such reference, widely used, was developed by D. A. Tefankjian(1). The following equations can be used to determine the current output for magnesium or zinc anodes, utilizing correction factors provided in Tables 6-3 and 6-4.

Bare or Poor Coating	Good coating
$I_{MAG} = \dfrac{150000 \cdot F \cdot Y}{\rho}$	$I_{MAG} = \dfrac{120000 \cdot F \cdot Y}{\rho}$
$I_{ZN} = \dfrac{50000 \cdot F \cdot Y}{\rho}$	$I_{ZN} = \dfrac{40000 \cdot F \cdot Y}{\rho}$

Where:

I_{MAG} = current output for magnesium anode in milliamperes

I_{ZN} = current output for zinc anode in milliamperes

ρ = soil resistivity in ohm-cm

F = anode shape factor from Table 6-3

Y = driving voltage factor from Table 6-4

These equations assume a minimum soil resistivity of 500 ohm-cm and a distance between anode and structure of 10 feet. The equations and factors were developed based on bare or poorly coated structures. Because of the increased circuit resistance occurring with well coated structures, the calculated current value should be reduced by 20 percent. This can be done by multiplying I_{MAG} or I_{ZN} as shown above, by 0.80.

Designing a Galvanic Anode CP System Using Simplified Calculations - Example

Let's calculate the number of anodes required to protect 10,000 feet of well coated, electrically isolated 16" OD pipe at a pipe-to-soil potential of 0.85 volts in a soil of 2500 ohm-cm. Assume a current requirement of 1.5 mA/exposed square foot of metal and coating damage of 1%. Use 32 lb pre-packaged standard alloy magnesium anodes and design for a 20 year anode life.

TABLE 6-3
Anode Shape Factors (F)

Anode Weight (lbs)	Anode	Factor (F)
Standard Anodes		
3	(Packaged)	0.53
5	(Packaged)	0.60
9	(Packaged)	0.71
17	(Packaged)	1.00
32	(Packaged)	1.06
50	(Packaged - anode dimension 8" dia x 16")	1.09
50	(Packaged - anode dimension 5" x 5" x 31")	1.29
Long Anodes		
9	2.75" x 2.75" x 26" backfill 6" x 31"	1.01
10	1.50" x 4.50" x 72" backfill 4" x 78"	1.71
18	2.00" x 2.00" x 72" backfill 5" x 78"	1.81
20	2.50" x 2.50" x 60" backfill 5" x 66"	1.60
40	3.75" x 3.75" x 60" backfill 6.5" x 66"	1.72
42	3.00" x 3.00" x 72" backfill 6" x 78"	1.90
Extra-Long Anodes		
15	1.6" dia x 10' backfilled to 6" dia	2.61
20	1.3" dia x 20' backfilled to 6" dia	4.28
23	2.0" dia x 10' backfilled to 8" dia	2.81

TABLE 6-4
Driving Voltage Correction Factors (Y)

P/S	Standard Magnesium	High-Potential Magnesium	Zinc
-0.70	1.21	2.14	1.60
-0.80	1.07	1.36	1.20
-0.85	1.00	1.29	1.00
-0.90	0.93	1.21	0.80
-1.00	0.79	1.07	0.40
-1.10	0.64	0.93	--
-1.20	0.50	0.79	--

TABLE 6-5
Multiple Anode Adjustment Factors

No of Anodes in parallel	Adjustment Factors (anode spacing in feet)			
	5'	**10'**	**15'**	**20'**
2	1.839	1.920	1.946	1.965
3	2.455	2.705	2.795	2.848
4	3.036	3.455	3.625	3.714
5	3.589	4.188	4.429	4.563
6	4.125	4.902	5.223	5.411
7	4.652	5.598	6.000	6.232
8	5.152	6.277	6.768	7.035
9	5.670	6.964	7.536	7.876
10	6.161	7.643	8.304	8.679

Step 1 - Calculate the surface area (SA) to be protected.

Total SA = π x pipe outside diameter (ft) x length of pipe (ft)

Total SA = π x (16/12) · 10000 = 41,888 ft^2

Exposed SA to be protected = 41,888 x 1% = 419 ft^2

Step 2 - Calculate the current required:

419 ft^2 x 1.5 mA/ft^2 = 629 mA

Step 3 - Calculate the anode current output: (i_{MAG})

$$I_{MAG} = \frac{120000 \cdot F \cdot Y}{\rho} \Rightarrow I_{MAG} = \frac{120000 \cdot 1.06 \cdot 1.00}{2500}$$

I_{MAG} = 50.9 mA = 0.0509 amps

Step 4

Calculate the number of anodes required:

$$\text{Number} = \frac{\text{current requirement}}{\text{anode output}}$$

$$\text{Number} = \frac{629 \text{ mA}}{50.9 \text{ mA / Anode}}$$

$$\text{Number} = 12.4 \text{ or } 13 \text{ anodes}$$

Anodes could be spaced evenly along the line at intervals of 10,000/13 or about every 769 feet.

Step 5

Calculate anode life:

$$\text{Life} = \frac{0.114 \times W \times E \times UF}{\text{Current (amps)}}$$

$$\text{Life} = \frac{0.114 \times 32 \times 0.50 \times 0.85}{0.0509}$$

Life = 30.5 years

The twenty year design life is satisfied.

Other Factors

The calculated result assumes an even distribution of current over the calculated length of pipe, which is not realistic. The greatest is in close proximity to the anode and decreases with distance. Therefore, assuming uniform coating and soil, a greater amount of current is available to the pipe closest to the anode. The attenuation of current is more pronounced as coating quality decreases, so an individual galvanic anode protecting a “hot spot” on a bare pipe will protect a much smaller area of pipe than that indicated above. For a series of individually connected anodes, the potential increase on the pipe that results between adjacent anodes, is additive.

Anodes are commonly connected in parallel in order to achieve higher current output at a given location. The approximate current output of a group of anodes can be calculated by multiplying the calculated current output of a single anode by the appropriate adjusting factor indicated in Table 6-5.

Calculating the Current Output of Multiple Anodes in Parallel - Example

The current output ($I_{\text{ANODE BED}}$) of six 32-lb pre-packaged standard alloy magnesium anodes connected in parallel can be calculated as follows, based on a current output of 50.88 mA for an individual anode. Assume an anode spacing of 10 feet.

$I_{\text{ANODE BED}}$ = 50.88 mA x Adjusting Factor (from Table 6-5)

$I_{\text{ANODE BED}}$ = 50.88 mA x 4.902

$I_{\text{ANODE BED}}$ = 249.41 mA

SPECIFICATION AND MAINTENANCE OF GALVANIC ANODE INSTALLATIONS

Specifications must be written to insure that the materials and methods, upon which the design has been predicated, are utilized. There should be no deviation from these specifications unless approved by the person in charge of design. Inspection should be performed during system installation to guarantee that the specification of material and procedures are adhered to.

The maintenance of galvanic anode systems consists of routine surveys and, when necessary, repairs/replacement. A survey to determine the operating levels of the system should be conducted annually and the data recorded in a permanent log.

Current measurements will enable the life of the anode to be predicted, and their timely replacement scheduled accordingly. Additional anodes should be installed where low potentials warrant their installation. Damaged facilities should be repaired to ensure that adequate levels of protection are maintained.

CONCLUSIONS

As was the case with the design of the impressed current cathodic protection system, the design of the galvanic anode system warrants the consideration of various factors. These factors include the following:

1. Soil resistivity
2. Current Requirements
3. Anode Material Selection
4. Life Expectancy

The resistivity of the soil and the resistance to earth of the structure being protected have a great impact on design and system performance when using galvanic anodes. This is due to the fact that the driving potential of the system is limited to the natural potential difference between the anode material and the structure being protected.

Reference

1. Tefankjian, D.A., 1974. “Application of Cathodic Protection”. Proceedings of the 19th Annual Appalachian Underground Corrosion Short Course, pp 122-138.

Chapter 7 - MIC Inspection and Testing

INTRODUCTION

Microbiologically induced corrosion (MIC) has been actively studied in recent years because of its potentially deleterious effect on important underground structures, such as pipelines. The most well known bacteria associated with pipeline corrosion are the sulfate reducing bacteria (SRB). These bacterial are active in deaerated environments often associated with wet, poorly drained soils (that promote oxygen exclusion), require a nutrient that is near the pipe and often the carbonaceous material of the coating, and have a sulfurous (rotten eggs) odor associated with the sulfate reduction process. If conditions change, they may become dormant and another type of bacteria may become active. Because bacterial live in communities, there is also a synergistic effect among them whereby the reaction products of one may act as a nutrient for another. Thus, it is important to test for more than one type of bacteria. However, it is important to recognize also that the presence of bacteria does not necessarily mean that they are active or that they pose a threat to the integrity of the structure.

Research studies have shown that MIC can be characterized by the chemical, biological, and metallurgical features associated with the suspected site. The type and form of pitting corrosion is often distinctively associated with MIC. Chemical and biological data are supportive, and are useful for estimating whether a potential for MIC exists.

The following sections give a procedure for inspecting the dig site, assessing the coating and steel at coating damage and suspected MIC areas; sampling the soil, groundwater, or pipe-surface products for MIC testing; carrying out the MIC testing using commercially available field test kits; and visually inspecting the corroded areas for MIC characteristics.

SITE INSPECTION

Before excavation of the pipeline, the topography of the surrounding area of the dig and the soil type should be noted. This information is useful in assessing the likely conditions that can support various types of bacteria. For example, low, wet areas with clay soils collect and hold water, and tend to exclude oxygen to promote deaerated conditions. Soils with more sand or rock allow water and/or air to migrate more readily to the pipe and promote more aerated conditions. Higher elevations with rocky soils tend to be better drained and drier, and tend to promote more aerated conditions.

Exposure of the pipe should be slow and careful to avoid damage to the pipe and areas of sampling. Remove soil from the pipe surface carefully to expose the coating surface. Do not remove any products adhering to the coating surface. Note and record the following on an appropriate form:

- Coating type (e.g., coal tar, asphalt, bitumen, tape), type of damage (e.g., disbonding, holidays, blistering, seam tenting, cracking, and wrinkling), extent of damage (% of exposed area), and location (circumferential and longitudinal position on pipe in relation to weld seams and coating seam, if present)
- Corrosion and/or cathodic protection surface products present
  - Location (see above)
  - Type (e.g., deposit, nodule, or films)
  - Color (e.g., brown, black, white, or gray)
  - Smell (e.g., none, earth, rotten eggs)
- Soil type (e.g., sand, gravel, silt, clay, rock)
- Soil moisture (e.g., wet, dry).

Do not remove any coating or surface products at this time. Only the person performing the field test should remove coating or products from the pipe surface at his discretion until testing is complete.

COATING INSPECTION

Coating inspection for MIC testing purposes should precede any other type of coating evaluation planned.

Identify likely area of MIC or other forms of corrosion from the visual inspection above. Carefully remove the damaged coating using a clean knife to expose the steel beneath. If a liquid is present, take a sample using a syringe or cotton swab following procedures to be described below for testing purposes. If the area is not to be tested for MIC, the steel surface condition and liquid pH should be evaluated.

Visually inspect the steel surface for corrosion. Where possible, use a gauge to measure the depth of corrosion. Also, determine the length of the corroded area in relation to the circumferential and longitudinal position.

The pH of the liquid may be tested using hydrion paper or its equivalent. Carefully slice the coating to a length to allow the test paper to be slipped behind the coating. Press the coating against the pH paper for a few seconds and remove, then remove the pH paper. Note and record the color of the paper in relation to the chart provided with the paper. Determine the pH of groundwater away from the pipe in the ditch if possible for reference. Compare the two pH values to determine if the pH near the pipe is elevated. An elevated pH indicates the presence of cathodic protection current reaching the pipe. A pH above about 9 would be considered elevated for most soils. It is not uncommon to determine a pH of 12 to 14 for well protected steel.

MIC AND DEPOSIT SAMPLING

Once the pipe is exposed, the soil and any suspected deposits must be sampled and tested immediately. The coating around the suspected area of corrosion should be carefully removed using a knife or similar instrument. Sample contamination must be kept to a minimum. Therefore, avoid touching the soil, corrosion product, or film with hands or tools other than those to be used in sample collection and provided with the test kits.

MIC SAMPLING AND TESTING

A minimum of three samples should be collected and tested. Two samples should be taken from one or more of the following locations:

- Undisturbed soil immediately next to the exposed pipe steel surface or at an area of coating damage

- A deposit associated with visual evidence of pipe corrosion

- A scale or biofilm on the steel surface or the backside of the coating

- Liquid trapped behind the coating.

The third sample should be taken from fresh, undisturbed soil at pipe depth, at least 1 m transverse to the pipe. This location, such as the ditch wall, will act as a reference from which to determine if the bacteria count near the pipe is elevated.

Additional samples may be taken and tested from other locations where bacterial activity is suspected.

Collect the soil, film, or liquid sample following the detailed procedures outlined in the test kit. Inoculate the vials at the dig site. Mark the side of each vial with the appropriate dilution number, as well as the tray next to it, using a permanent marker. Each tray should be marked to identify the following:

- Date and time sample collected
- Location where the sample was taken
- Location of the dig site.

This same information must be put on the original box in which the sample tray is to be stored. The box of samples should be stored at ambient temperature with the box top closed; it is not necessary to incubate the samples at elevated temperature. All unused test kits should be stored in a refrigerator to prolong shelf life.

After one (1), two (2), and five (5) days, view the sample bottles and record the result. Use the rating number (1 through 5) corresponding to the highest bottle number to give a positive result. Also, record the number of the type of response, such as 2-Cloudy, shown on the Positive Reaction Sheet supplied with the test kit. At the end of 15 days, record the final results. Typically, the results are unchanged after about two to five days of incubation.

Each test kit tests for the presence and count (bacterium/ml) of four (or five) types of viable bacteria.

A test kit that tests for four types of bacteria tests for:

- Sulfate reducing bacterial (BlO-SRB)
- Acid producing bacteria (RIO-APB)
- Aerobic bacteria (BIO-AERO)
- Anaerobic facultative bacteria (BlO-THIO)

A test kit that tests for five types of bacteria tests for:

- Sulfate reducing bacterial (BlO-SRB)

- Acid producing bacteria (BIO-APB)
- Aerobic bacteria (BIO-AERO)
- Iron-related (depositing) bacteria (BIO-IRB)
- Low-nutrient bacteria (BIO-LNB).

The presence and viability of these four (or five) types of bacteria are tested in each of the four (or five) colored strings of bottles in each tray. The bottles in each string contain a fast-acting nutrient specific to the bacterium tested. Some test kits give a quantitative indication of the viability of each bacterium from 10 to 10^5 bacterium/ml by the serial dilution of the sample and subsequent growth in each string; other test kits give a quantitative indication from 10 to 10^4 bacterium/ml.

SUPPORTING ANALYSES

Corrosion and other types of deposits on the pipe may be analyzed in the field using the test kit to assist in interpretation of MIC and other corrosion, or cathodic protection products. This kit can be used to qualitatively analyze for the presence of carbonate (CO_3^{+2}), sulfide (S^{-2}), ferrous iron (Fe^{+2}), ferric iron (Fe^{+3}), calcium (Ca^{+2}), and hydrogen (H^{+1}, pH) ions.

Collect a sample of soil, deposit, film, or liquid from the area of interest. Use only a clean knife or spatula provided with the test kit. The films or deposits may be from the steel surface, coating surface, interior of a corrosion pit, or the backside of the coating. In all cases, note the color and type of sample. Carefully transfer the sample to the test kit vial for testing. Follow the detailed procedure given in the test kit instruction sheets. For comparison purposes, obtain a reference sample taken at least 1 m from the previous collection site.

Record the results of the analysis on the Results Sheet provided with the kit or in a company designated format. Determine the likely type of deposit according to the characteristics shown below. A corrosion film other than a carbonate, an oxide for example, may only show the presence of ferric or ferrous ion, but with a pH that is similar to that of the reference sample or lower. In addition, cathodic protection films may not necessarily show the presence of calcium or carbonate, but will have an elevated pH compared with the reference sample. For most types of soils, the pH is greater than about nine (9). An elevated pH is not usually associated with the presence of SRB.

Positive Result	SRB	Corrosion Film	Corrosion Oxide	CP Film
CO_3^{-2}		Yes		Yes
S^{-2}	Yes			
Fe^{+2}	Yes	Yes	Yes	
Fe^{+3}		Yes	Yes	
Ca^{+2}				Yes
pH				Elevated

METALLURGICAL INSPECTION

The form of the corrosion pits associated with MIC is reasonably distinctive. These features can be observed in the field with the unaided eye or a low power microscope.

After any films or products sampled above have been obtained from a corroded area, the remaining product should be removed using a clean spatula or knife, being careful not to scratch the metal. Clean any remaining material with a clean, dry, stiff brush, such as nylon-bristle brush. Do not use a metal brush if possible, because the metal bristles will mar the pit features. If not all of the product can be removed with this method, use a brass bristle brush in the longitudinal direction only. Dry the area with an air blast or an alcohol swab. A shiny metallic surface of the pit suggests the possibility of active corrosion. However, judgment must be used to differentiate this condition from one created by scraping the steel surface with a metallic object, such as the knife or spatula use to clean the surface or obtain the sample product.

Examine the corroded area newly cleaned first visually with the unaided eye. Then use a low power magnifying lens at 5X to 50X power to examine the detail of the corrosion pits. MIC often has the following features:

- Large craters up to 2 or 3 inches (5 to 8 cm) in diameter or more
- Cup-type hemispherical pits on the pipe surface or in the craters
- Sometimes the craters or pits are surrounded by uncorroded metal

- Striations or contour lines in the pits or craters running parallel to longitudinal pipe axis (rolling direction)

- Sometimes tunnels can be seen at the ends of the craters also running parallel to the longitudinal axis of the pipe.

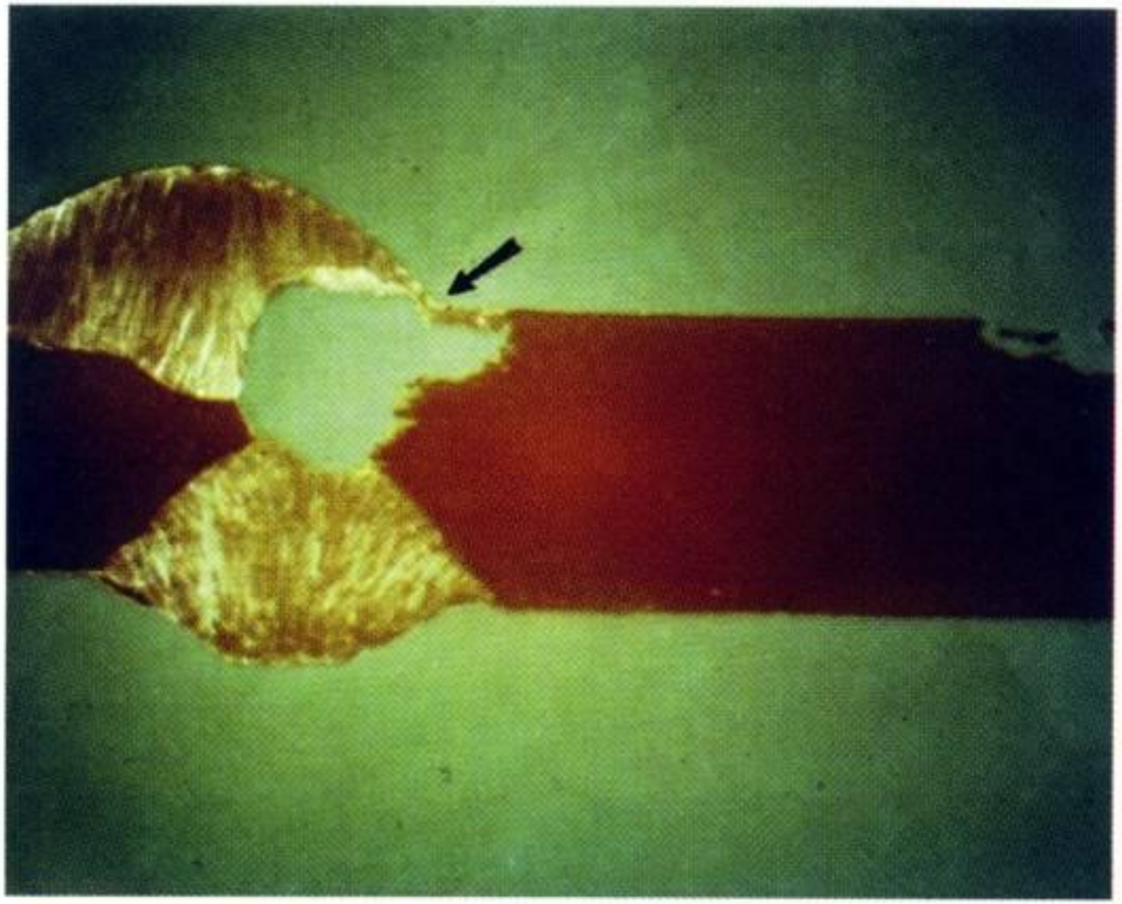
Some examples of these features are shown in other materials. The cupping action of the pits is a result of the local action of the bacteria. The striations follow the rolling direction of the steel made into the pipe and are believed to be a result of preferential attack of the steel microstructural components.

ACKNOWLEDGMENT

This chapter was written by K. C. Garrity and was edited by the AUCSC Curriculum Committee.

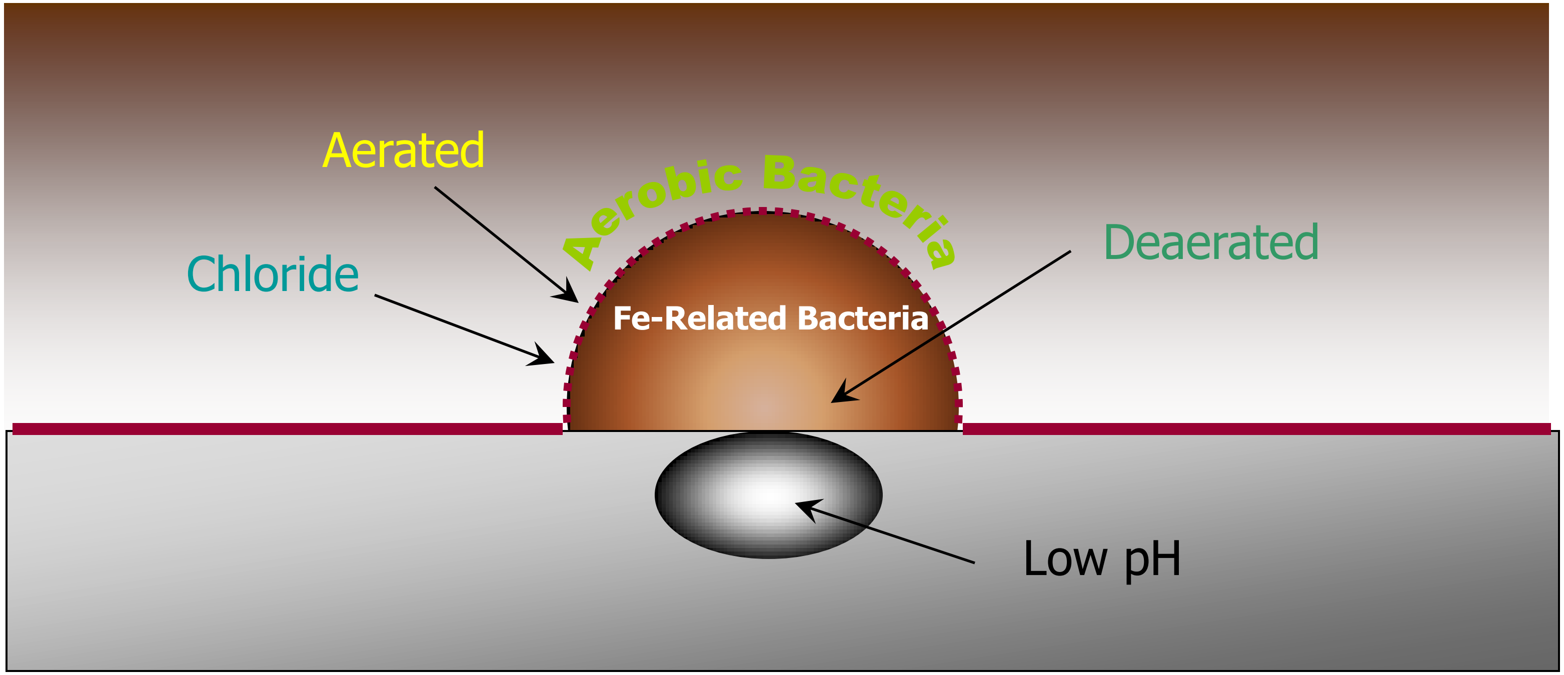
MIC OF 304 SS WELD

Under Tubercle Illustrated



From Little, Wagner,
and Mansfeld

TUBERCLE BUILD-UP WITH IRON-RELATED BACTERIA

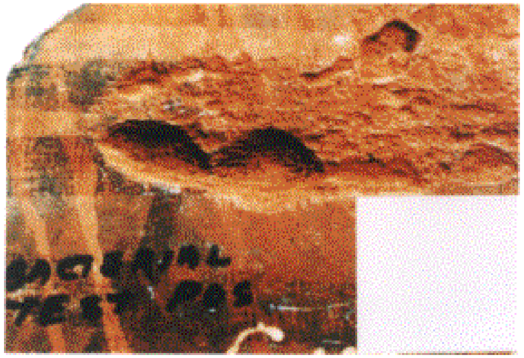


IRB Create a Differential Oxygen Corrosion Cell with Low pH Environment

METALLURGICAL

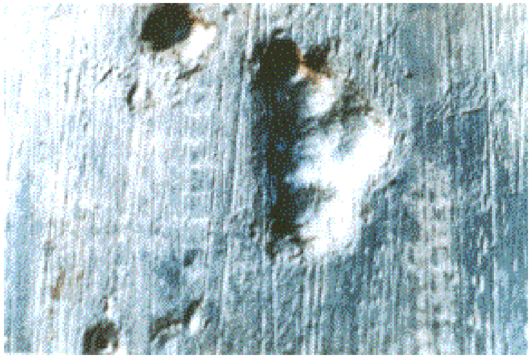
Pope and GRI

a. Striations in cupped pit bottoms



b. Corrosion in pit

c. Pit products in b. removed



d. Brushed cupped pits in c.

MICROBIOLOGICAL
Aerobic and Anaerobic

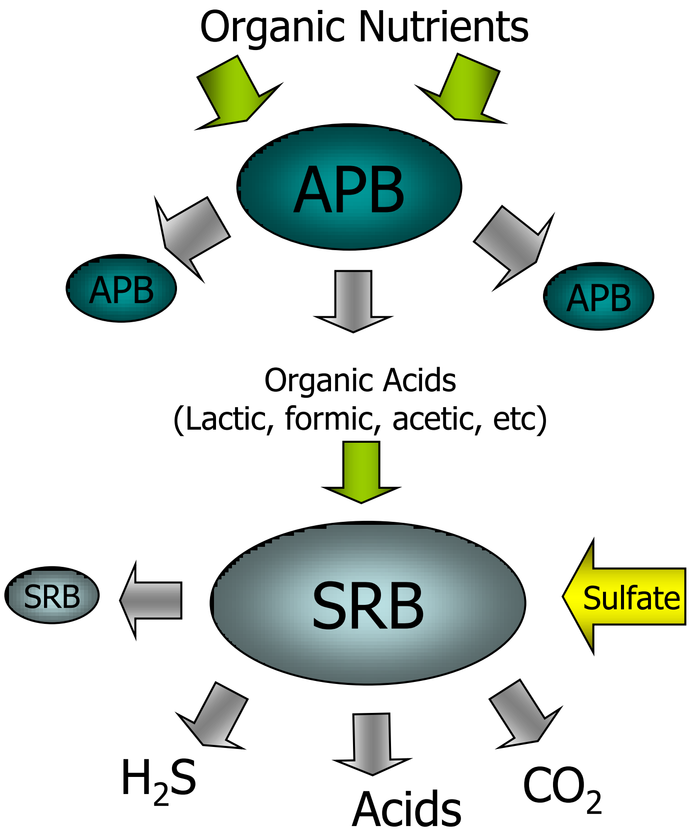
- Aerobic Require O_2 and Nutrient
- Consume O_2 and Produce Organic Acids Corrosive to Steel
- Protection Requirements Less Well Defined

- Occur with Anaerobic Bacteria
- Form Complex Communities Dominated by Acid Producing Bacteria
- MIC a Result of Microbe Community, Not SRB Alone

MICROBIOLOGICAL COMMUNITY

Example APB and SRB

- Organic Nutrients Feed APB
- APB Products Nutrients for SRB
- SRB Fed by Organic Acids and Sulfate
- Produce more APB and SRB
- Chlorides with Acids (H^+) Lower pH and Corrode Steel



MICROBIOLOGICAL

SRB Theory (Anaerobic)

- $8H_2O \Rightarrow 8OH^- + 8H^+$
- $4Fe \Rightarrow 4Fe^{+2} + 8e^-$ (A)
- $8H^+ + 8e^- \Rightarrow 8H$ (C)
- $SO_4^{-2} + 8H$ +Bacteria $\Rightarrow$ $\Rightarrow$ $S^{-2} + 4H_2O$
- $Fe^{+2} + S^{-2} \Rightarrow FeS$ (A)
- $3Fe^{+2} + 6OH^- \Rightarrow 3Fe(OH)_2$ (A)
- FeS Depolarizes

- Need Nutrient
  - Soil biomass
  - Coating adhesive
- Need No or Low O_2
  - Wet soil
  - Low areas
  - Crevices
- More Protection (Current) Needed to Overcome Effects

MIC TESTING

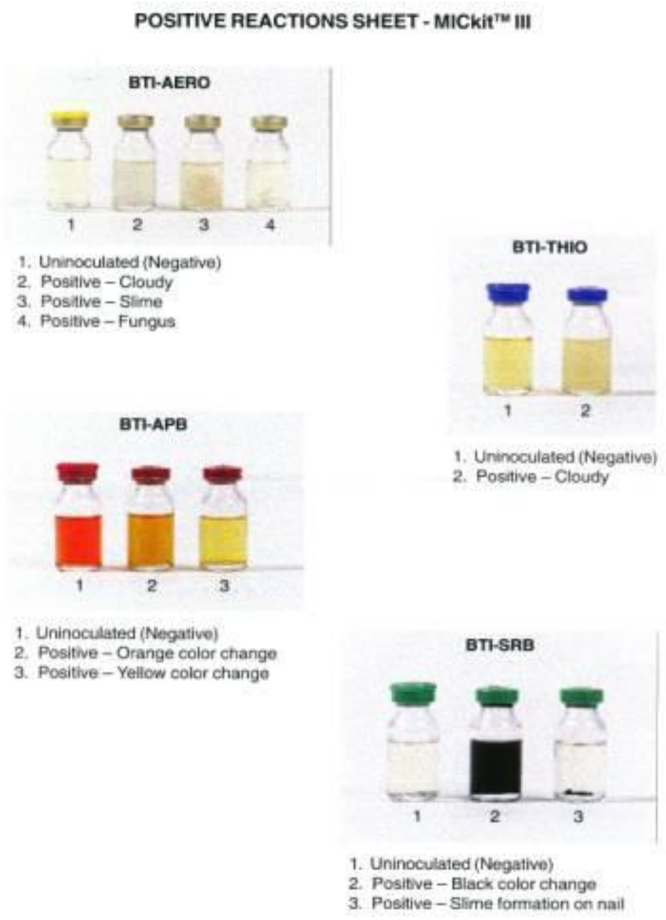
- Field Test Kits for Viable Bacteria
  - SRB, APB, anaerobic, aerobic, iron related
  - Bacteria count—10 to 10^5 (10^4) colonies/ml
- Test Soil or Surface Product
- Create Slurry
- Inoculate Culture Media Vials
- Compare After 2 - 5 Days, 15 Days

TEST KIT INTERPRETATION

- Presence of Bacteria Not Conclusive of MIC
- SRB Often Do Not Dominate
- Not Uncommon to Find All Tested Bacteria Present
- Interpret Indications with Caution
  - 1 to 3 bottles – may have problem
  - 1 to 5 bottles – possible problem

CULTURE TEST

Results



POSITIVE REACTIONS SHEET - MICkit™ III

BTI-AERO

1. Uninoculated (Negative)
2. Positive – Cloudy
3. Positive – Slime
4. Positive – Fungus

BTI-THIO

1. Uninoculated (Negative)
2. Positive – Cloudy

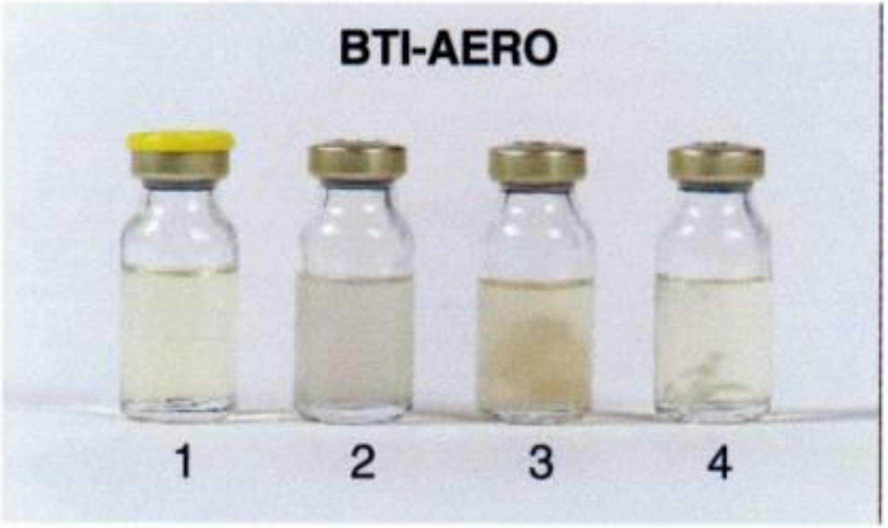
BTI-APB

1. Uninoculated (Negative)
2. Positive – Orange color change
3. Positive – Yellow color change

BTI-SRB

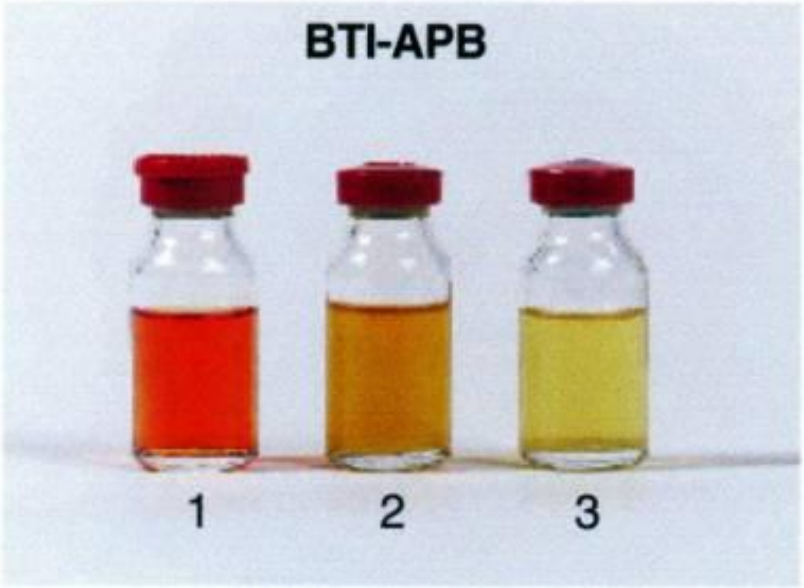
1. Uninoculated (Negative)
2. Positive – Black color change
3. Positive – Slime formation on nail

Aerobic Bacteria Test



1. Uninoculated (Negative)
2. Positive – Cloudy
3. Positive – Slime
4. Positive – Fungus

APB Bacteria Test

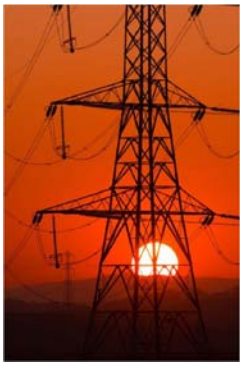


1. Uninoculated (Negative)
2. Positive – Orange color change
3. Positive – Yellow color change

AUCSC Advanced Course

Period 3

AC Interference Mechanisms and Mitigation Strategies



Prepared for AUCSC by
Kurt Lawson
Mears Group, Inc.

Purpose

- To discuss electrical safety hazards on pipelines during construction and operation
- To illustrate how pipelines are electromagnetically coupled to HVAC transmission and distribution lines
- Provide methods for recognizing hazards and protection from hazards
- Impact on Corrosion
- Basic Mitigation Strategies

AC Interference Safety and Risk to Personnel

Lightning & Fault Safety

These procedures may not be sufficient to prevent personal injury resulting from lightning or a fault.

- Work should be suspended when there is the possibility of lightning
- Work should be suspended when there is the higher possibility of a line fault.

Human Resistance To Electrical Current

DRY SKIN	1,000,000 TO 5,000,000 OHMS
WET SKIN	1,000 OHMS
STANDING OR LYING IN WATER	150 OHMS
INTERNAL BODY-HAND TO FOOT	400 TO 500 OHMS
INTERNAL BODY-EAR TO EAR	(ABOUT) 100 OHMS

60 Hz ALTERNATING CURRENT VALUES AFFECTING HUMAN BEINGS

CURRENT	EFFECTS
1 mA OR LESS	NO SENSATION - NOT FELT
1 TO 8 mA	SENSATION OF SHOCK - NOT PAINFULL INDIVIDUAL CAN LET GO AT WILL MUSCULAR CONTROL NOT LOST.
8 TO 15 mA	PAINFUL SHOCK - INDIVIDUAL CAN LET GO AT WILL - MUSCULAR CONTROL NOT LOST.

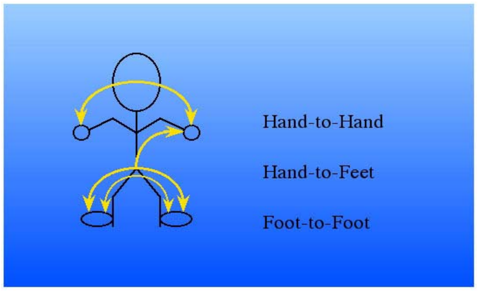
60 Hz ALTERNATING CURRENT VALUES AFFECTING HUMAN BEINGS

CURRENT	EFFECTS
I5 TO 20 mA	PAINFUL SHOCK -MUSCULAR CONTROL LOST, CANNOT LET GO.
20 TO 50 mA	PAINFUL SHOCK -SEVERE MUSCULAR CONTRACTIONS1 BREATHING DIFFICULT.
50 TO 100 mA (POSSIBLE)	VENTRICULAR FIBRILLATION -DEATH WILL RESULT IF PROMPT CARDIAC MASSAGE NOT ADMINISTERED.

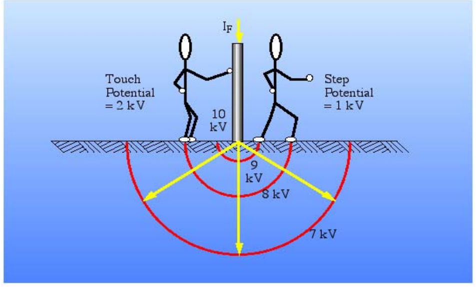
60 Hz ALTERNATING CURRENT VALUES AFFECTING HUMAN BEINGS

CURRENT	EFFECTS
100 TO 200 mA (CERTAIN)	DEFIBRILLATOR SHOCK MUST BE APPLIED TO RESTORE NORMAL HEARTBEAT. BREATHING PROBABLY STOPPED.
200 mA AND OVER	SEVERE BURNS - SEVERE MUSCULAR CONTRACTIONS CHEST MUSCLES CLAMP HEART AND STOP IT DURING SHOCK (VENTRICULAR FIBRILLATION IS PREVENTED), BREATHING STOPPED - HEART MAY START FOLLOWING SHOCK OR CARDIAC MASSAGE MAY BE REQUIRED.

Possible Body Current Paths



Possible Body Current Paths



Measurement and Safety Equipment

Equipment List:

- Two digital multimeters
- Two test leads at least 10 feet in length
- Clamp on AC ammeter
- Two earth contact probes preferably half cells

Measurement and Safety Equipment

- Rubber insulating gloves of at least 600V dielectric strength

Identifying Shock Hazards

Methodology

- The method employed is similar to how DC pipe-to-soil potentials are acquired
- Half cell needs to be placed in soil, and connected to the voltmeter before connection to the pipe.

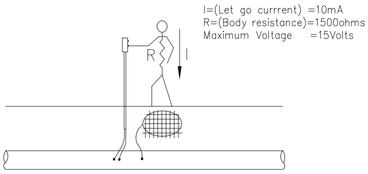
Identifying Shock Hazards

When to take AC voltage measurements

- Before work begins on a section of pipeline that parallels an HVAC transmission line
- Before working in close proximity to the parallel section of pipeline that is parallel to an HVAC transmission line

Hazardous AC Levels

Any AC measurement that exceeds 15 Volts AC across a span that is 10 ft. wide or less. Data is based on diagram shown below.

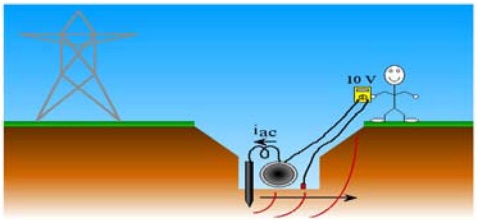


Hazardous AC Levels

Measured AC Voltage	Significance	Monitor	Mitigate
Less than 4V AC	Not Significant	N	N
Between 4V AC and 15V AC	Moderate	Y	N
At 15V AC or above	Significant	Y	Y

Hazardous AC Levels

The importance of proper measurement distance

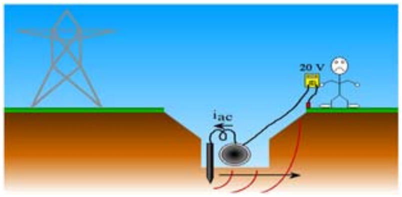


Distance is too short

(Image Courtesy of NACE International)

Hazardous AC Levels

The importance of proper measurement distance



Appropriate measurement span of 10 feet

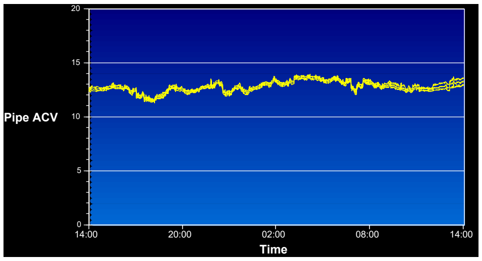
(Image Courtesy of NACE International)

Hazardous AC Levels

The importance of recorded measurement over time

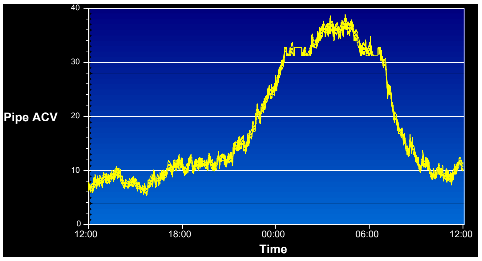
- Induced AC voltages can change over time
- Initial measurements may indicate a non hazardous level.
- Environmental factors may affect AC voltages

Hazardous AC Levels



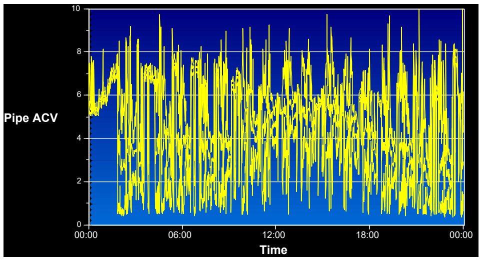
Voltage vs. time with relatively constant load conditions
(Image Courtesy of NACE International)

Hazardous AC Levels



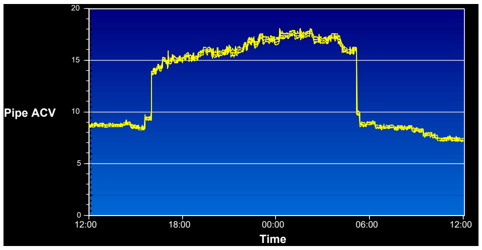
Voltage vs. time showing a load change
(Image Courtesy of NACE International)

Hazardous AC Levels



Voltage vs. Time – Rapidly Changing Load
(Image Courtesy of NACE International)

Hazardous AC Levels



Voltage vs. Time -- Effects of Circuit Switching
(Image Courtesy of NACE International)

Discussion of AC Corrosion

- Reported since 19th Century
- Effects not well understood
- Studies in 1950's and 1960's concluded AC Corrosion effects were .1-1.0% of DC Effects
- Recent Studies have related metal removal power of AC
    - < 20A/m^2 – no corrosion
    - 20 – 100A/m^{2} - corrosion is unpredictable
    - >100A/m^2 - corrosion is likely
- Electrochemical Model can be used to explain process

Cause of AC Corrosion on Pipelines

- Induced AC Leading to AC current discharge at Holidays.
- Contributing factors
  - Good coating quality leading to higher induced voltages and concentration effects.
  - Low soil resistivity leading to high discharge currents at Induced AC voltage.
- **AC Current Density**
  - **$I_{Density} = 8*V_{AC} / d\rho\pi$**

Required AC Voltage to Produce 100 A/m²

1 cm² Holiday in 10 ohm-m Soil

$$V_{ac} = \frac{i_{ac}\rho\pi d}{8}$$

$$V_{ac} = \frac{(100\ \text{A/m}^2)\ (10\ \Omega\cdot\text{m})\ (3.14)\ (0.011\text{m})}{8}$$

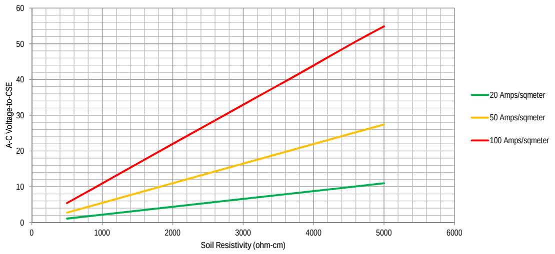
$$V_{ac} = 4.4\ \text{V}$$

A-C Corrosion as a Function of Holiday Current Density

No Corrosion Expected	$i_{ac} < 20$ A/m²
Corrosion Unpredictable	20 A/m² $< i_{ac} <$ 100 A/m²
Corrosion Expected	$i_{ac} > 100$ A/m²

Cathodic Protection is Not Effective in Controlling A-C Corrosion.

AC Voltage vs. Resistivity for Three Current Densities

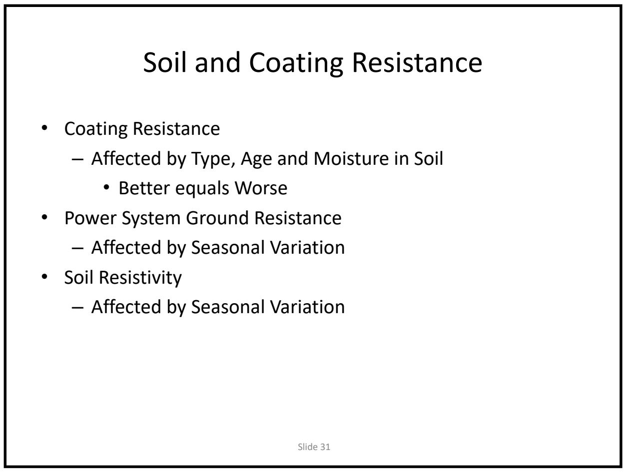


Parameters Affecting Interference

- Geometry
- Soil and Coating Resistivity
- Transmission System Operating Characteristics

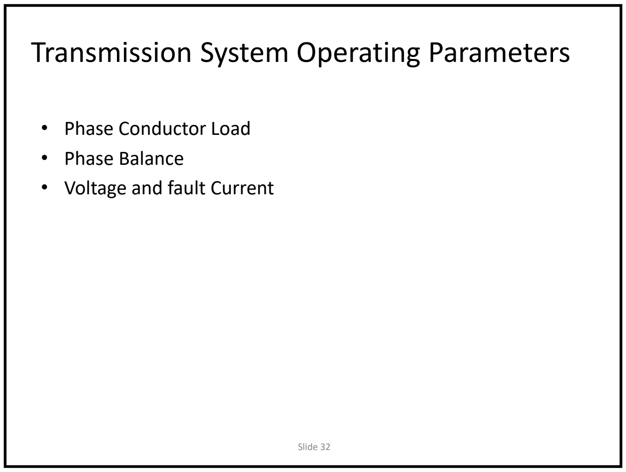
Geometry Factors

- Separation
- Depth Of Cover
- Pipe Diameter
- Angle of Collocation
- Tower Footing Design
- Phase Conductor Spacing and Average Distance Above Ground



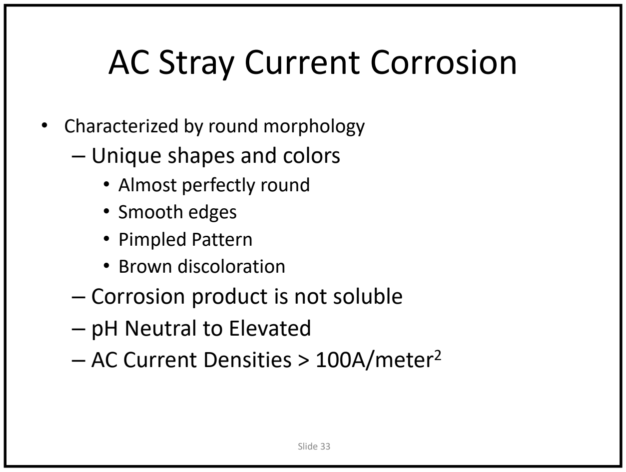
Soil and Coating Resistance

- Coating Resistance
  - Affected by Type, Age and Moisture in Soil
    - Better equals Worse
- Power System Ground Resistance
  - Affected by Seasonal Variation
- Soil Resistivity
  - Affected by Seasonal Variation



Transmission System Operating Parameters

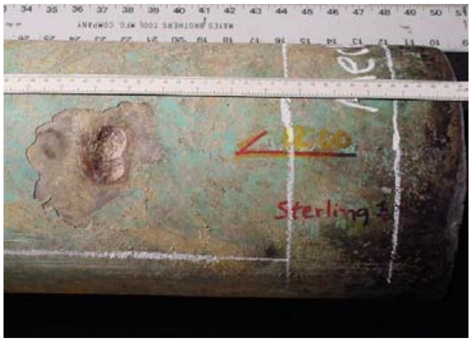
- Phase Conductor Load
- Phase Balance
- Voltage and fault Current



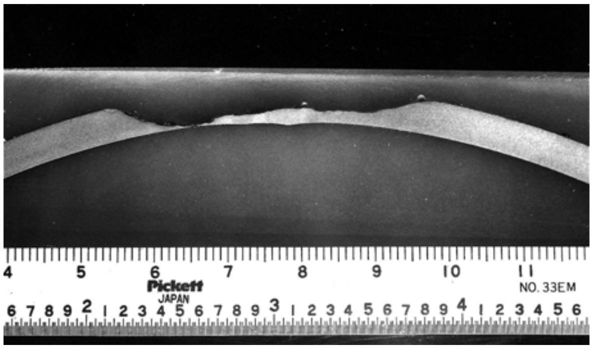
AC Stray Current Corrosion

- Characterized by round morphology
  - Unique shapes and colors
    - Almost perfectly round
    - Smooth edges
    - Pimpled Pattern
    - Brown discoloration
  - Corrosion product is not soluble
  - pH Neutral to Elevated
  - AC Current Densities > 100A/meter^2

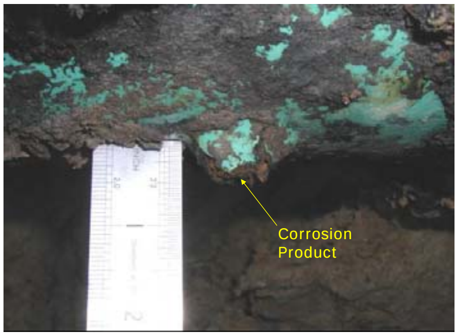
AC Corrosion on FBE Coated Pipeline Leaked 18 months After Installation



Metallographic Section



AC Corrosion on FBE Coated Pipeline

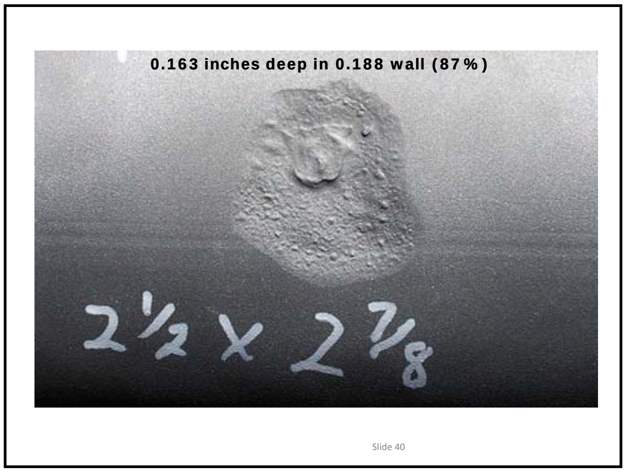


0.053 inches deep in 0.188 wall (28%)

37

38

39



0.163 inches deep in 0.188 wall (87%)

Review/Conclusions

- AC corrosion exists
- Higher AC currents accelerate attack
- Possible at commercial frequencies
- Excessively High Corrosion rate
- No consensus on mechanism
- Scatter, testing conditions often not representative of real life

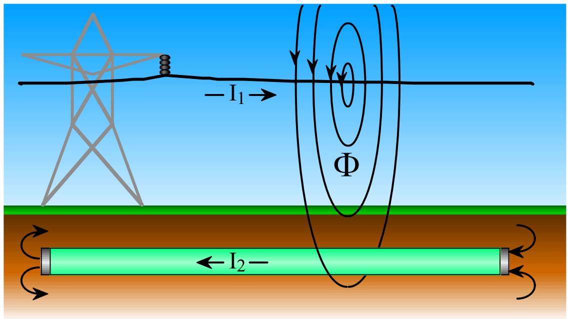
The electrical power grid in North America consists of three general circuit classifications

- Bulk or high voltage transmission lines from the generation source to primary substations typically run at 230 kV (kilovolts), 345 kV or 500 kV- and now 750 kV!
- Sub-transmission lines between major distribution centers operate at 69 kV, 115 kV, 138 kV or 161 kV.
- The distribution system at the customer level operates at 4.2 kV, 7.5 kV, 12.5 kV or 34.5 kV.
- From a practical standpoint HVAC lines 69 kV and under rarely have high enough phase load or available fault current to significantly affect the pipeline unless it is directly under the transmission line.

HVAC INTERFERENCE EFFECTS

- Electromagnetic induction is the primary effect of the HVAC transmission line on the buried pipeline during normal (steady state) operation
- Conductive effects are primarily a concern when a fault occurs in an area where the pipeline is in close proximity to the transmission line and the fault currents in the soil are high
- Capacitive effects are primarily only a concern during construction when sections of the pipeline are above ground
- If these electrical effects are great enough during steady state normal operation or during a fault, a potential shock hazard exists for anyone that touches an exposed part of the pipeline, pipline damage can occur and AC corrosion mat occur.

Electromagnetic Coupling with Buried Pipeline



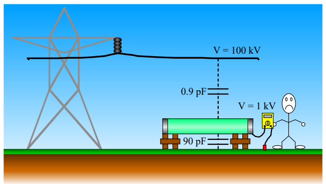
Electromagnetic (Inductive) Coupling

- Magnitude is a function of line current not voltage.
- Power transfer is
  - Proportional to line current
  - Proportional to length of parallelism
  - Inversely proportional to separation distance
- Can result in high voltages on long sections of pipeline.

Capacitive Coupling

RESULTS FROM ELECTROSTATIC CHARGES ON ABOVEGROUND METALLIC STRUCTURES.

EXTREMELY HAZARDOUS CONDITIONS MAY EXIST DURING PIPELINE CONSTRUCTION.



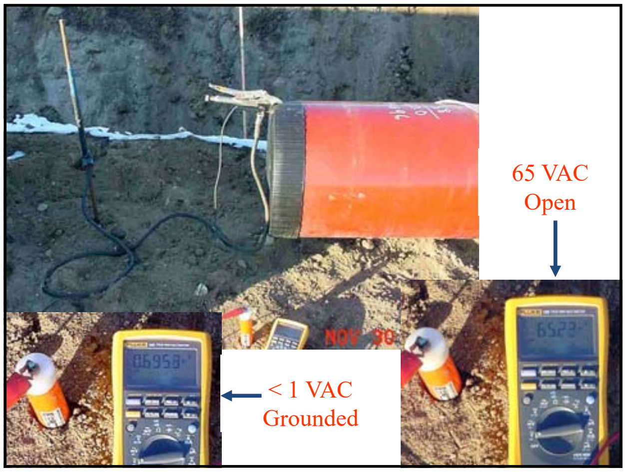
A function of line voltage, not current.
Can result in high voltages on short sections of pipeline, only if the pipeline is insulated from the earth.
Results in the transfer of very small amounts of electrical power to the pipeline, and so the current which can be transferred to a human body is relatively small.

Obvious Hazards During Construction

Not so Obvious Hazards During Construction

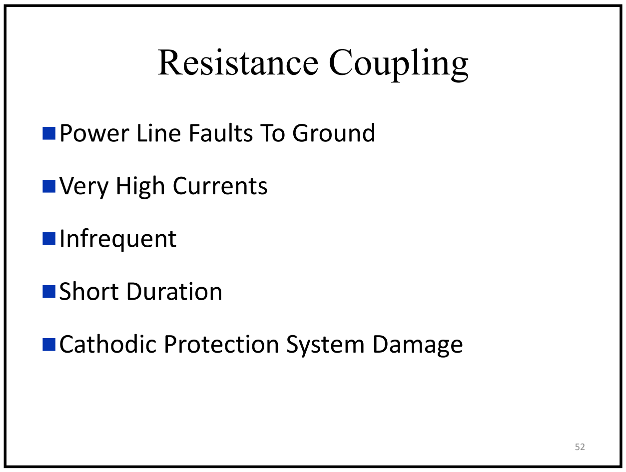
178 VAC!

242 VAC!!



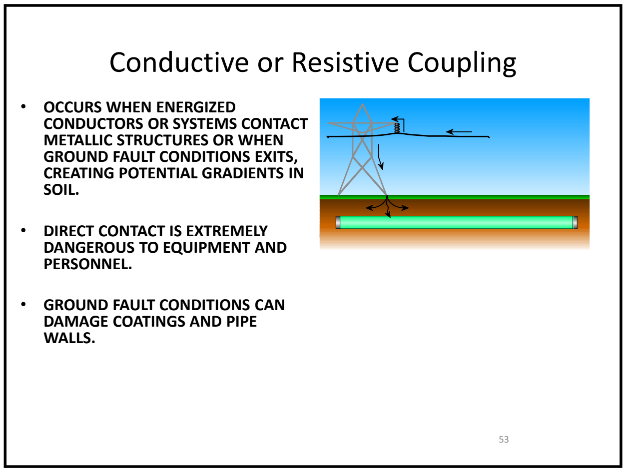
65 VAC
Open

< 1 VAC
Grounded



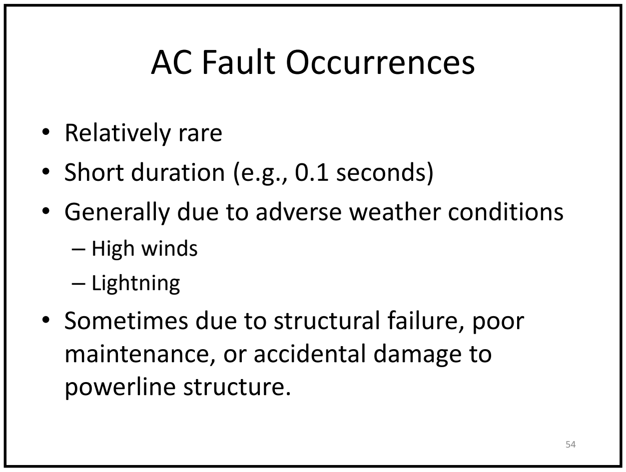
Resistance Coupling

- Power Line Faults To Ground
- Very High Currents
- Infrequent
- Short Duration
- Cathodic Protection System Damage



Conductive or Resistive Coupling

- OCCURS WHEN ENERGIZED CONDUCTORS OR SYSTEMS CONTACT METALLIC STRUCTURES OR WHEN GROUND FAULT CONDITIONS EXITS, CREATING POTENTIAL GRADIENTS IN SOIL.
- DIRECT CONTACT IS EXTREMELY DANGEROUS TO EQUIPMENT AND PERSONNEL.
- GROUND FAULT CONDITIONS CAN DAMAGE COATINGS AND PIPE WALLS.



AC Fault Occurrences

- Relatively rare
- Short duration (e.g., 0.1 seconds)
- Generally due to adverse weather conditions
  - High winds
  - Lightning
- Sometimes due to structural failure, poor maintenance, or accidental damage to powerline structure.

Risk to Personnel

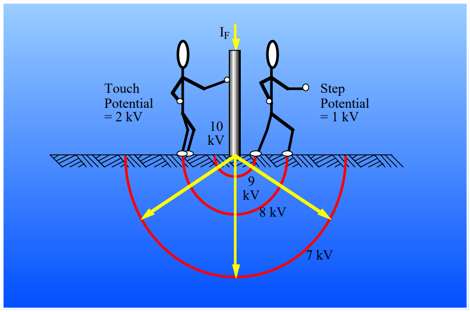
- Touch Potential (Normal Steady State and Fault Conditions)
  - Risk of Lethal Voltages And Current When Contacting A Structure
    - CP Test Stations
    - Valves
    - Aboveground Pipe Features
- Step Potential (Fault Conditions)
  - Risk of Lethal Voltages And Current When Standing with feet 1 meter apart

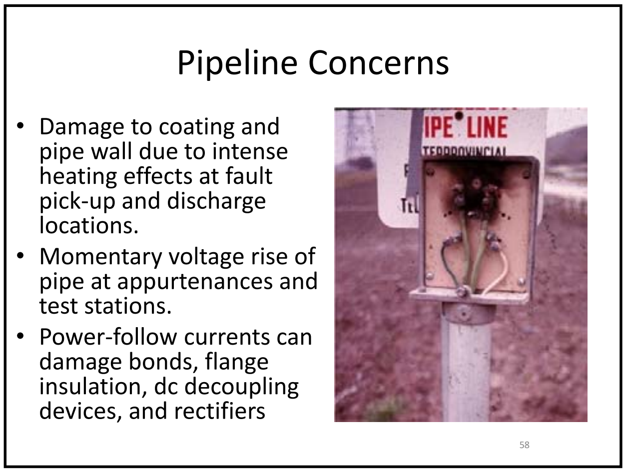
Nature of Power System Faults

- 70 % of AC Transmission Faults are Phase-to-Ground
  - Lightning
  - Insulator Failure
  - Mechanical Failure

Touch & Step Potentials

at an Energized Grounded Structure





Pipeline Concerns

- Damage to coating and pipe wall due to intense heating effects at fault pick-up and discharge locations.
- Momentary voltage rise of pipe at appurtenances and test stations.
- Power-follow currents can damage bonds, flange insulation, dc decoupling devices, and rectifiers

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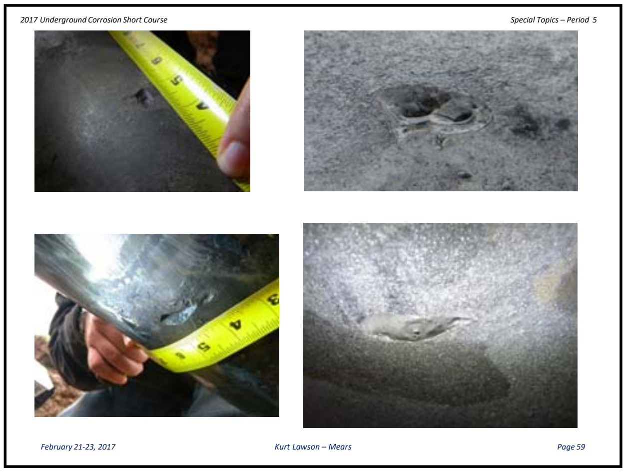
58



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Parameters Affecting Interference

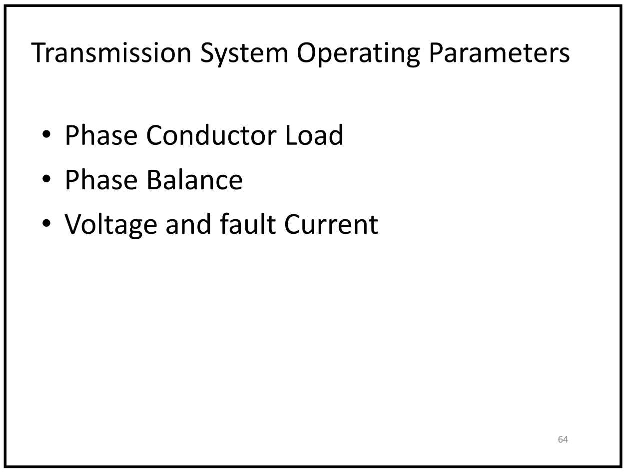
- Geometry
- Soil and Coating Resistivity
- Transmission System Operating Characteristics

Geometry Factors

- Separation
- Depth Of Cover
- Pipe Diameter
- Angle of Collocation
- Tower Footing Design
- Phase Conductor Spacing and Average Distance Above Ground

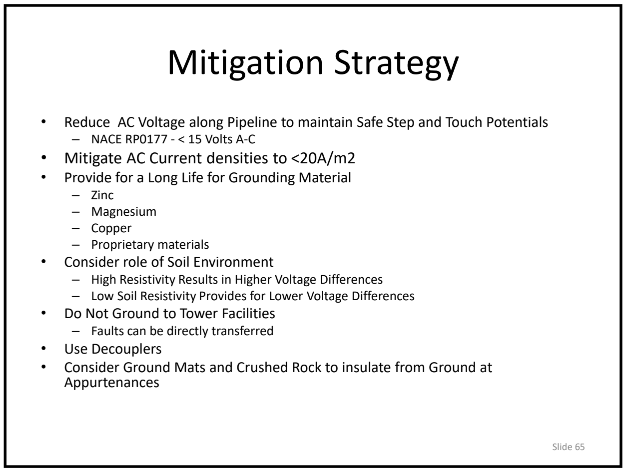
Soil and Coating Resistance

- Coating Resistance
  - Affected by Type, Age and Moisture in Soil
    - Better equals Worse
- Power System Ground Resistance
  - Affected by Seasonal Variation
- Soil Resistivity
  - Affected by Seasonal Variation



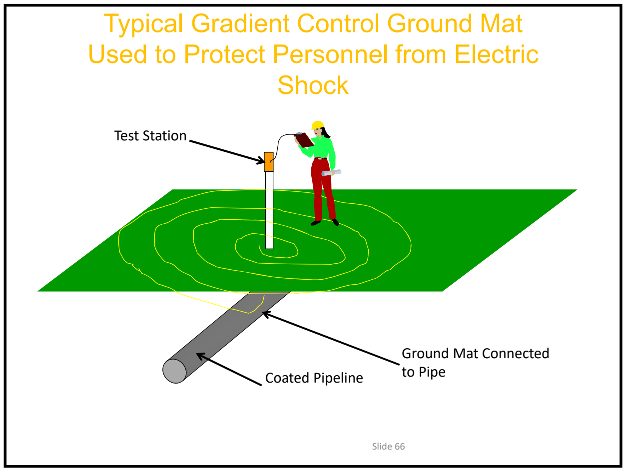
Transmission System Operating Parameters

- Phase Conductor Load
- Phase Balance
- Voltage and fault Current



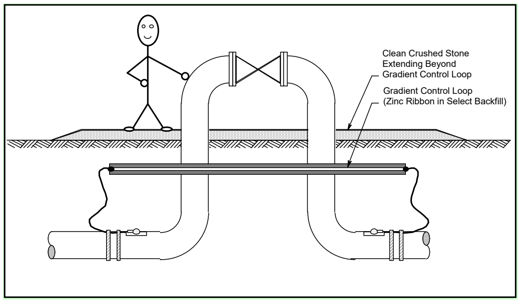
Mitigation Strategy

- Reduce AC Voltage along Pipeline to maintain Safe Step and Touch Potentials
  - NACE RP0177 - < 15 Volts A-C
- Mitigate AC Current densities to <20A/m2
- Provide for a Long Life for Grounding Material
  - Zinc
  - Magnesium
  - Copper
  - Proprietary materials
- Consider role of Soil Environment
  - High Resistivity Results in Higher Voltage Differences
  - Low Soil Resistivity Provides for Lower Voltage Differences
- Do Not Ground to Tower Facilities
  - Faults can be directly transferred
- Use Decouplers
- Consider Ground Mats and Crushed Rock to insulate from Ground at Appurtenances



Typical Gradient Control Ground Mat Used to Protect Personnel from Electric Shock

Mitigation of Touch Potentials
at Above-Ground Appurtenance



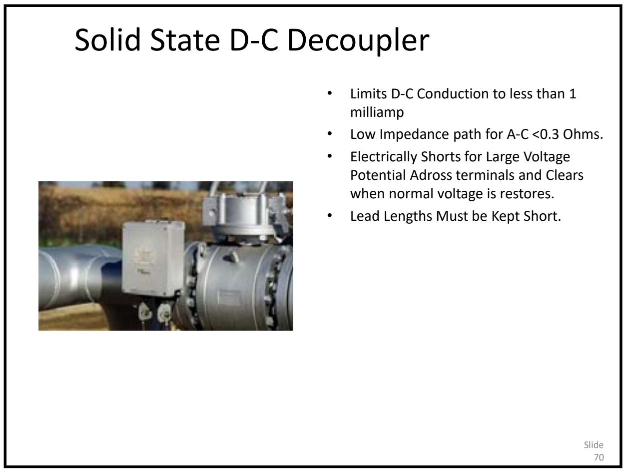
Power Corridor Test Stations
Dead-Front Test Station

- Best choice for personnel safety
  - Plastic construction
  - Prevents accidental contact with voltages on leads & terminals
- Good choice for public safety
  - Cover is lockable
  - Lock is plastic & cover can be broken open

05 April 2019

Solid-State DC Decoupler

- High DC impedance
- Low AC impedance
- Passes steady-state induced AC current
- Rated for lightning and AC fault current
- Fail-safe construction
- Third-party listed to meet electrical codes
- No power source req'd



Solid State D-C Decoupler

- Limits D-C Conduction to less than 1 milliamp
- Low Impedance path for A-C <0.3 Ohms.
- Electrically Shorts for Large Voltage Potential Adross terminals and Clears when normal voltage is restores.
- Lead Lengths Must be Kept Short.

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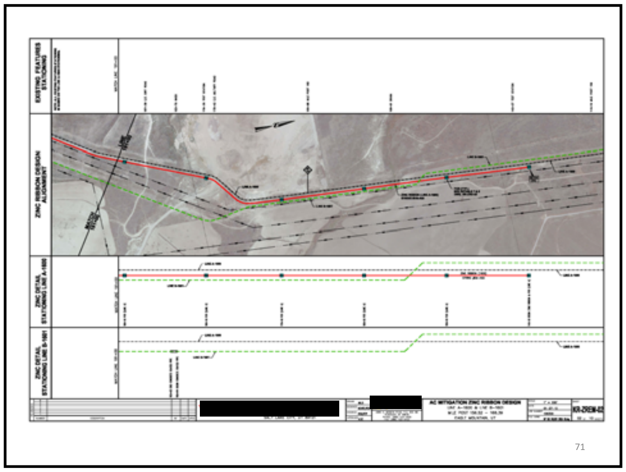

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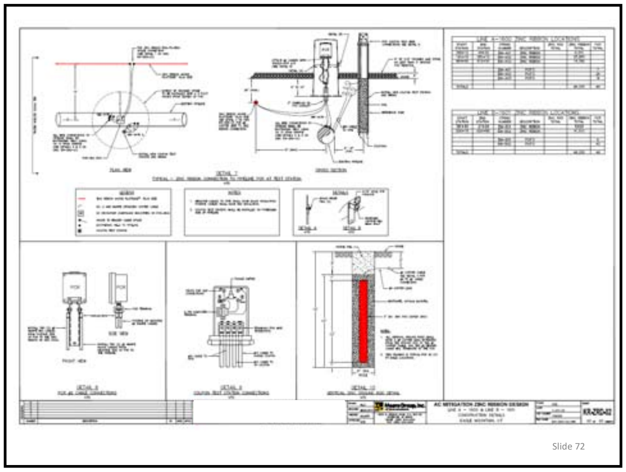

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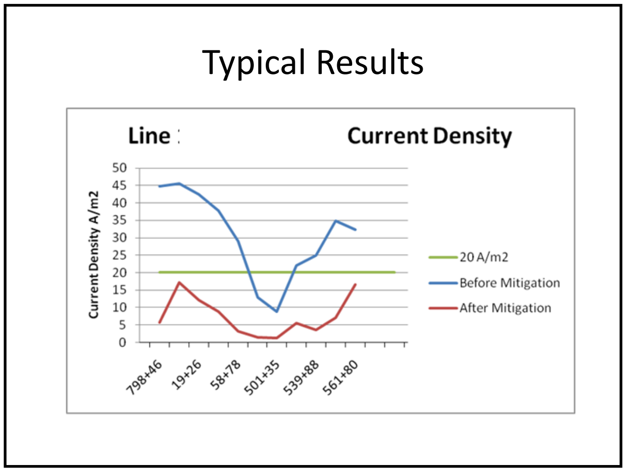

Typical Results

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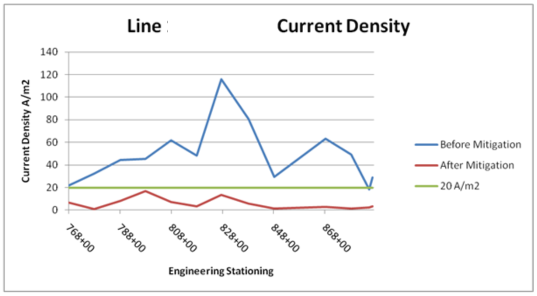
Typical Results



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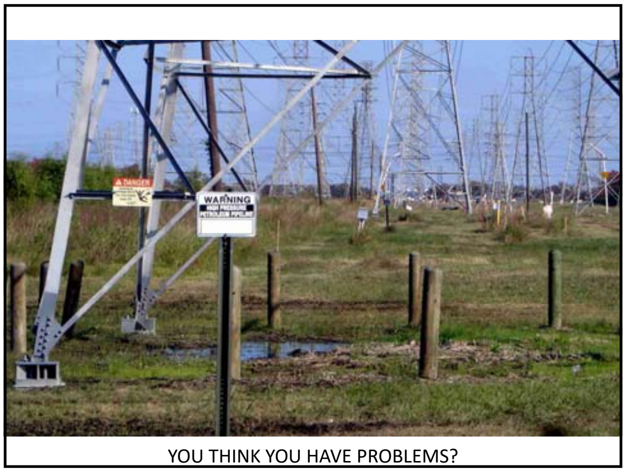

YOU THINK YOU HAVE PROBLEMS?

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