Basic Course

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TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

Chapter 1 – Basic Electricity

INTRODUCTION

It is important that the principles set forth in this chapter be thoroughly understood before proceeding to the material included in the remaining chapters of the Basic Course. Similarly, a complete knowledge of this chapter will be equally as important to understanding the subject matter included in the Intermediate and Advanced Courses.

The treatment of the material in this chapter is intended to provide a good practical understanding of the subject. This includes comprehension of key electrical terms, symbols, respective units, basic electrical circuits, exemplar calculations using Ohm's Law; and relevance to corrosion and corrosion-control applications.

ELECTRICAL FUNDAMENTALS

Physical Matter

Electricity is directly involved with the makeup of physical matter. Although we will not spend a great deal of time on atomic structure of matter, we need to explore the subject sufficiently to establish the stated relationship between matter and electricity.

What is "Matter"

"Matter" is that which makes up the substance of anything. It will occupy space and will have mass. It can be a solid, a liquid, or a gas. Whatever the form may be, however, it will be made up of atoms or of atoms and/or molecules. Atoms are the building blocks from which elements are comprised - an element being that form of matter which cannot be changed by chemical means. Examples of elements are copper (chemical symbol Cu) and oxygen (chemical symbol O). Molecules are combinations of atoms that comprise the smallest part of a substance that retains the physical characteristics of that substance. An example of a molecule would be the smallest part of copper sulfate ($CuSO_4$) which is a combination of copper (Cu), sulfur (S), and oxygen (O) atoms.

When we take a closer look at atoms, we find that they are made up of a nucleus which contains positively charged particles called protons and neutral particles called neutrons. The nucleus is surrounded by orbiting negatively charged particles called electrons. Each elemental atom has its own characteristic combination of a nucleus and electrons. In simple terms, electricity involves the flow of electrons in a solid conductor (metal or conductive non-metal such as graphite) in an electrical circuit. In electrolytes, such as water and moist soil, current flow is not due to electrons. Instead, it's associated with movement of ions, which are charged atoms or charged molecules.

Alternating Current vs. Direct Current

There are two general types of electricity which will be involved with corrosion and corrosion control work: alternating current (AC) and direct current (DC).

Alternating Current (AC)

Alternating current (AC) electricity is that which flows first in one direction and then in the opposite direction in accordance with an established pattern. This is what most commonly powers our homes and businesses, typically at 120 volts AC. For example, the usual AC power sources used in the United States have a frequency of 60 cycles per second. This is referred to as 60 Hertz (or 60 Hz). Many other countries use 50 Hz. A single cycle can be illustrated as shown in Figure 1-1.
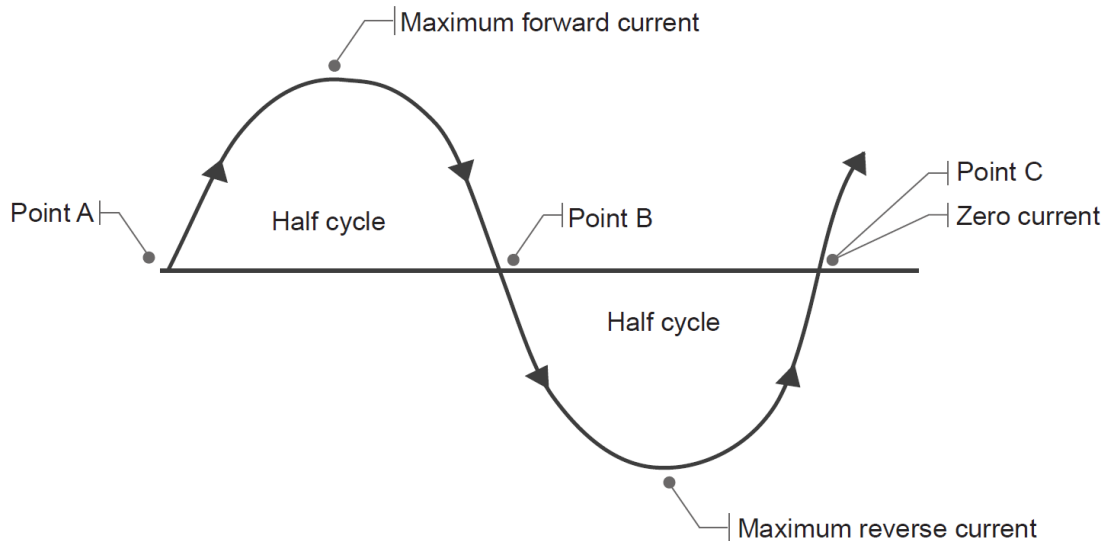
Figure 1-1: Alternating Current (AC) Sine Wave

As can be seen in Figure 1-1, the current flow at the beginning of the cycle (Point A) is zero. The current builds up to a peak in the forward direction and then drops back to zero at the end of the first half cycle (Point B). It then reverses its direction of flow and builds up to a maximum in the reverse direction. Following this, it again drops back to zero at the end of the second half cycle (Point C) (which is the end of one full cycle). At this point, it again reverses direction to start the next cycle.

From this, there are, in effect, two net current reversals for one full cycle. This means that for a normal 60 Hz AC power source, the current flow changes direction 120 times per second.

The shape of the normal current flow plot from the usual alternating current commercial power source is known as a sine wave.

Significance of Alternating Current

In the control of corrosion, commercial AC power sources are used as an energy source to power corrosion control equipment such as rectifiers (which convert AC power to DC power). These are discussed in Chapter 3.

AC can adversely affect metallic structures in the ground to cause touch-potential hazards or even corrosion. AC interference is discussed in-depth in the Advanced course.

Direct Current (DC)

Direct current (DC) electricity is that which flows constantly in one direction, rather than changing direction, as was discussed for AC.

An example of a pure direct current is that from a battery (typically, each at 1.5V DC) powering a common flashlight or a car battery at 12V DC. The red line in Figure 1-2 is representing a pure DC current flowing constantly in one direction. The blue line in Figure 1-2 is representing a pure AC current. The gray line in Figure 1-2 represents a Rectified DC current. Rectified DC can have a rippling effect which causes it to have a frequency of 120 cycles per second, or 120 Hertz (120 Hz) but without voltage and current reversal. The rippling can be smoothed out using components such as capacitors and inductors in the electrical circuit design.
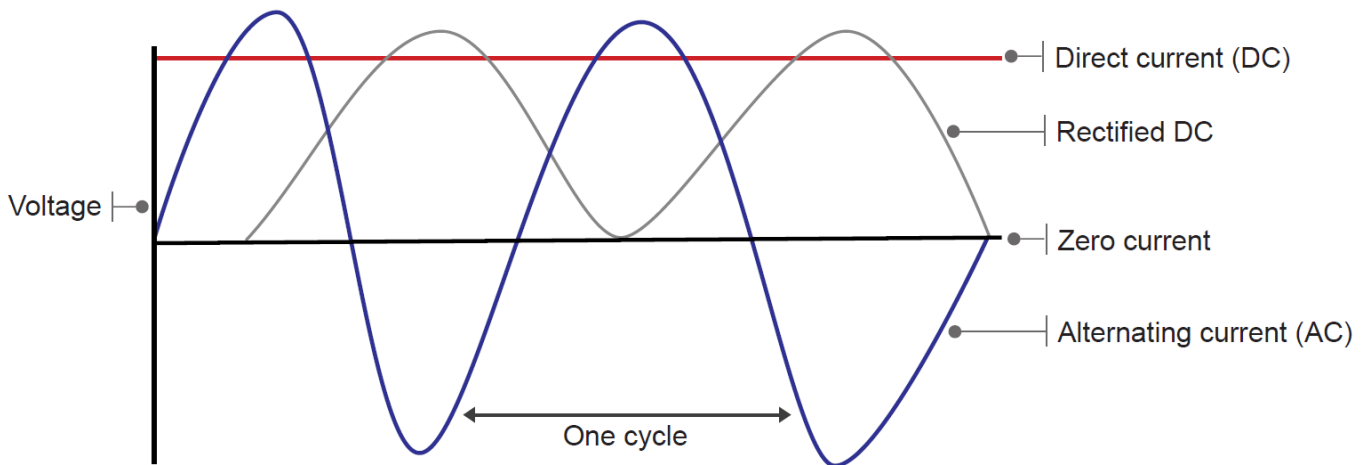
Figure 1-2: Significance of Direct Current

Significance of Direct Current

DC is commonly used in the application of cathodic protection (CP) and CP systems (to be discussed in Chapter 3). Additionally, it is directly involved in the various types of corrosion cells that are described in Chapter 2.

In this chapter, the prime emphasis will be on electrical fundamentals as they apply to DC circuits.

BASIC TERMS

A thorough knowledge of the various electrical units and terms involved in DC electrical circuits is necessary to understand the types of electrical circuits encountered in corrosion work so they may be properly analyzed and evaluated. These units and terms will be used in understanding the various sample calculations used throughout the Basic Course. Further, they will allow knowledgeable handling of the various types of DC circuits and conditions when encountered in the actual practice of detecting, evaluating, and addressing corrosion and corrosion-control issues in the field. Figure 1-3 demonstrates a simple Electrical Circuit. Refer to it while learning the various terms to see where they may apply.
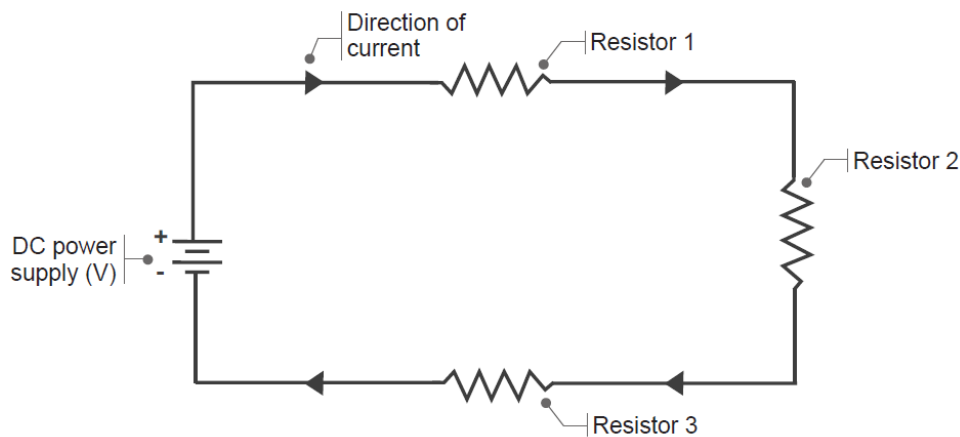
Figure 1-3: The Electrical Circuit

Voltage (V)

Potential difference between two points, expressed as a voltage, is what puts electrical charge (current) into motion. The volt is the basic unit of electrical "pressure" which forces an electrical current (electrons) to flow through a solid electrical circuit. In electrolytes such as water and moist soil, electrical current flow is associated with ions, not electrons. Voltage can be used to indicate electrical driving force in general. For example, the comparable term in a water system would be water pressure, expressed as pounds per square inch (psi).

The symbols representing electrical pressure in formulas which you may use in corrosion work will be either V (for volts) or E (for Electromotive Force or EMF -- which is also voltage).

Although 1 volt is the basic unit, there are instances where much smaller units are easier to use. One millivolt (mV) is one thousandth of a volt:

$$1,000mV = 1V$$
$$1mV = 0.001V$$

One microvolt (µV or µv) is one millionth of a volt:

$$1,000,000µV = 1V$$
$$0.1µV = 0.000001V$$

Ampere (I)

The ampere (often abbreviated as amp) is the basic unit of electrical current flow. The potential (voltage) difference between two points causes electrical current flow. In a solid electrical circuit, current is carried by negatively charged electrons; in electrolytes such as water and moist soil, current is carried by movement of ions. The comparable analogy for amps in a water system to express the rate of water flow could be gallons per hour. Where water flow would be indicated as gallons per hour, DC electricity would be indicated as electrons per second.

The symbol commonly used to represent current in formulas is the letter I. However, a calculated or measured current can be designated by the letter A, such as 12 A to represent 12 amperes. Typical applications will be discussed later in this chapter.

Although 1 ampere is the basic current flow unit, there are instances where very small fractions of an ampere may be involved in corrosion and corrosion-control work. Smaller units may then be more convenient to work with. One milliamp (mA) is one thousandth of an ampere, or:

$$1,000 mA = 1A$$
$$1 mA = 0.001A$$

For an even smaller unit, one microamp (μA) is one millionth of an ampere, or:

$$1,000,000 \mu A = 1A$$
$$0.1 \mu A = 0.000001A$$

Knowledge of current flow, its evaluation, and its measurement is particularly important in corrosion work since there is a direct relationship between the amount of current flow in a corrosion cell and the amount of corrosion experienced. Generally, the higher the current flow in a corrosion cell, the greater the amount of metal loss.

Resistance (R)

The ohm is the basic unit for resistance to the flow of electrical current. The usual symbol for resistance in formulas is the letter R. A calculated or measured figure for resistance may be represented by "ohms" or by the Greek letter omega (Ω); for example, 10 ohms or 10 Ω. Resistance is what makes it hard for current (amps) to flow within a circuit. It is the opposition that the electrons encounter while moving through a solid circuit; or opposition to the movement of ions in a poorly conductive electrolyte. With a set amount of voltage applied to an electrical circuit, the amount of current flowing through the circuit will decrease as the circuit resistance increases. Conversely, the current flow increases as the circuit resistance decreases. The comparable analogy for resistance in a water system is looking at the diameter of the pipe. More water (current) will be able to flow through the system if the pipe has a larger diameter (less resistance). If the pipe is a smaller diameter, less water (current) will be able to flow through it (more resistance).

Resistivity

The term resistivity is used to indicate the ability of a material to conduct electricity through it. It can be applied to both metallic and non-metallic materials.

Resistivity is commonly expressed as ohm-centimeters (ohm-cm) since we are focusing on a material with a cross-sectional area. The unit ohm-cm is the resistance between opposite faces of a cube of material which is 1 cm by 1 cm by 1 cm in size. In practice, a cubic centimeter of a material is never isolated for the purpose of

measuring its resistivity. Rather, the resistance across a body of the material of known dimensions is measured and the resistivity is determined by calculation.

In corrosion-control work, the greatest need for measuring resistivity is in connection with soils and waters as in the design of CP systems.

Polarity

The term polarity is important in determining the direction of conventional current flow in practical usage. The direction of conventional current flow in DC circuits is from positive (+) to negative (-). If for example, a 12-volt battery is connected to an electrical circuit, electric current will flow in the conventional sense from the positive (+) terminal of the battery through the circuit and back to the negative (-) terminal of the battery.

The flow of electrons in a corrosion cell (which is the basis for electric current) is from negative (-) to positive (+) which is in the opposite direction from conventional current flow. Although it is important to know this, conventional current flow will be used in the great majority of practical corrosion control applications.

Conductor

The term conductor is used to designate a member of an electrical circuit that readily carries an electrical current. This will commonly be used to mean a wire or cable; although in underground corrosion-control work, pipes or other metallic structures may serve as conductors.

Different metallic materials have different capabilities for carrying electric current. This is related to the resistivity of the material.

Table 1-1 compares the relative current carrying capability of some conductor materials commonly encountered in corrosion work based on copper.

Table 1-1: Relative Conductivity of Some Metals (Based on Smithsonian Physical Tables)

Material	Current Conducting Capability Based on Copper as 100%*
Copper (annealed)	100.0%
Aluminum	60.0%
Magnesium	36.8%
Zinc	27.6%
Brass	24.6%
Steel	9.6%
Lead	8.0%

*Relative percentages will vary depending on alloying components.

Although copper is obviously the best conductor material, a steel pipe (even though a relatively poor conductor material) can be a very good practical conductor because the amount/thickness of steel in the pipe is so much greater than the amount/thickness of copper in the usual copper wire or cable. For example, the resistance of 1,000 feet of 4/0 American Wire Gage (AWG) copper cable (which is approximately 0.54 inches in diameter) will have a resistance of around 0.051 ohms; whereas, the resistance of 1,000 feet of 12-inch steel pipe with 0.375-inch wall thickness will have a resistance of about 0.0058 ohms - roughly one tenth that of the heavy copper cable.

Insulator

An insulator or insulating material will have a very high resistance to the flow of electrical current and is used to confine or control the flow of current in electrical circuits. Examples are wire or cable jackets of rubber, neoprene, plastic, or similar insulating materials. On underground (or submerged) structures, insulating coatings of polymers are typically used to restrict the flow of current to or from the earth or water.

Insulating materials are also used to electrically isolate one metallic structure from another. When insulating materials are used for this purpose, they are called isolators or isolating devices.

OHM'S LAW

The worker in the field of corrosion-control of underground or submerged structures must have a thorough understanding of Ohm's Law as it applies to DC circuits. The law is a very simple formula that expresses the relationship between voltage, current, and resistance in a DC circuit.

The law states that one volt of electrical pressure will force one ampere of current through a circuit having a resistance of one ohm. This can be shown by the following formula:

$$V = I \times R$$

OR

$$\text{Volts} = \text{Amps} \times \text{Ohms}$$

This formula allows us to calculate the voltage applied to a circuit if the current flow and circuit resistance are known. For example, if we know that the current flowing through a circuit is 3.6 amps and the resistance of the circuit is 1.7 ohms, the voltage needed to cause the 3.6 amps to flow is 6.12V.

$$V = 3.6A \times 1.7\Omega = 6.12V$$

The Ohm's Law formula is flexible in that if any two components are known, the other can be calculated for an electrical circuit.

We have just covered the case where the voltage is the unknown component. Now consider the case where the current (I) is unknown while the voltage (V) and the resistance (R) are both known. To cover this, the formula is rearranged to:

$$I = \frac{V}{R}$$

OR

$$\text{Amps} = \frac{\text{Volts}}{\text{Ohms}}$$

As an example of the use of this form of the formula, assume that a voltage of 12.0V is applied to a circuit having a resistance of 3.5 ohms. Calculate the current flow by using the formula as just stated.

$$A = \frac{12V}{3.5\Omega} = 3.42A$$

There is one more form of the Ohm's Law formula to cover the case where the circuit current (I) and applied voltage (V) are known but the circuit resistance (R) is unknown. The formula is rearranged to:

$$R = \frac{V}{I}$$

OR

$$Ohms = \frac{Volts}{Amperes}$$

As an example, assume that 6.0V is applied to a circuit and that this forces 1.5A to flow through the circuit. Calculate what the circuit resistance must be to restrict the current flow to the 1.5 Amps.

$$R = \frac{6\ V}{1.5\ A} = 4\Omega$$

Ohm's Law is simple and easy to use. Just remember the basic formula V = IR. The other two forms (I = V/R and R = V/I) are simple rearrangements of the basic formula.

There is, however, one very important rule in the use of any of the three forms of Ohm's Law: Values entered in the formula must be in the similar units (i.e., 200mV vs. 0.200V). The following example will show how mixing units can cause a wrong answer. Assume that the applied voltage to a circuit is 2.0 volts and the current measured in the circuit is 1.0 milliamp. To calculate the circuit resistance, we use the formula, R = V/I. Do not do it by setting up the calculation as:

$$R = \frac{2\ V}{1\ mA} = 2\Omega$$

This equation is not right because volts and milliamps are not in the same unit.

What must be done is to convert the 1.0 milliamp to amps (1.0 mA = 0.001 Amp). Then the calculation becomes:

$$R = \frac{2V}{0.001A} = 2{,}000\Omega$$

The other approach would be to convert the voltage to millivolts. In this case, 2.0 volts = 2,000 millivolts. The calculation then is:

$$R = \frac{2{,}000mV}{1mA} = 2{,}000\Omega$$

Failure to observe the similar unit's rule can result in very serious errors in the design of corrosion control circuits. In the use of the basic form of the formula, V = IR, it should be noted that if current (I) is expressed as amps and resistance (R) is expressed as ohms, the result will be in volts. But if the current (I) is expressed as milliamps and the resistance (R) is expressed as milliohms, the result will be in millivolts which may be misleading. It is much better to convert the current to amps and the resistance to ohms and get the result in volts.

THE BASIC ELECTRICAL CIRCUIT

Figure 1-4 represents a simple, or basic, electric circuit which will be used to illustrate further applications of Ohm's Law. This will serve to solidify an understanding of the principles of the usage of the law.
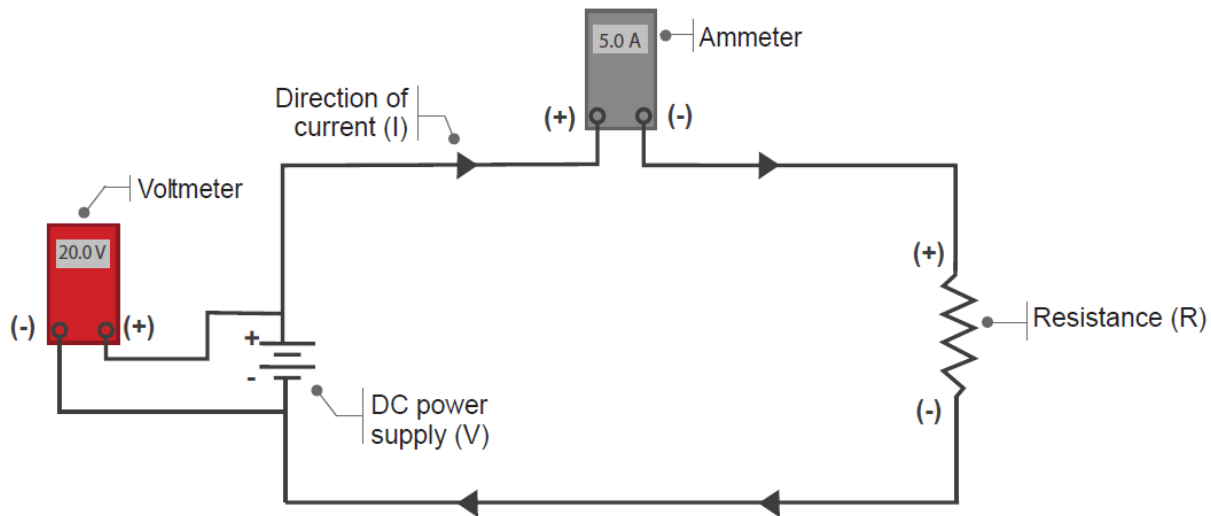
Figure 1-4: The Basic Electrical Circuit

Figure 1-4 shows all the circuit resistance confined to a simple resistor. Now assume that a DC power source providing current to a CP system for corrosion control has instruments indicating that the supply voltage (V) is 20 volts and the current flow (I) is 5 amps, the total circuit resistance (R) can be calculated by that form of Ohm's Law, R = V/I. Using the values given,

$$R = \frac{20\ V}{5\ A} = 4\Omega$$

In such a simple circuit, the entire voltage drop from the voltage source appears across the circuit resistance. To check this, Ohm's Law can be used in its basic form, V = IR. If the current is known to be 5 amps and the resistance was calculated as 4 ohms, then the voltage drop across the circuit resistance is 20 volts.

$$V = 5A \times 4\Omega$$

In another application of Ohm's Law to this basic circuit, if a 20-volt DC power source were connected across a known resistance of 4 ohms, the current flow (in the absence of an ammeter) can be calculated by that form of Ohm's Law, I = V/R.

$$I = \frac{20\ V}{4\Omega} = 5A$$

Based on the calculations, it is apparent that in the basic electrical circuit, all the current flows without change throughout the circuit and that all of the electrical voltage applied to the circuit appears as a voltage drop across the circuit resistance.

TWO BASIC TYPES OF ELECTRICAL CIRCUITS

Not all electrical circuits conform to the basic electrical circuit configuration described in the preceding section. There are two main types of electrical circuits you need to understand within corrosion and CP:

- Series Circuit (one path for current to flow)
- Parallel Circuit (multiple paths for current to flow)

In addition to using Ohm's Law to calculate the information within a circuit, there are a few electrical laws that govern these specific circuits. To correctly analyze these two different types of circuits, knowledge of Kirchhoff's Current Law and Kirchhoff's Voltage Law is essential.

Kirchhoff's Laws

Kirchhoff's Current Law applies to parallel circuits and states that as much current leaving the power source will return to it.

Kirchhoff's Voltage Law applies to series circuits and states that if all voltage drops are added up across all resistors within the circuit, it will equal to total source voltage.

The Series Electrical Circuit

Figure 1-5 represents an electrical circuit where the total circuit resistance comprises two or more load resistances which are connected in series. By "series," it is meant that the several load resistances are connected end-to-end and that the circuit current passing through each of the resistances will be the same. In a series circuit, current only has one path to flow. This in turn means that the voltage of the DC potential source applied to the circuit will be distributed across the several resistances in the circuit. According to Kirchhoff's Voltage Law, all of those voltage drops across the several resistors can be added to equal the total source voltage.
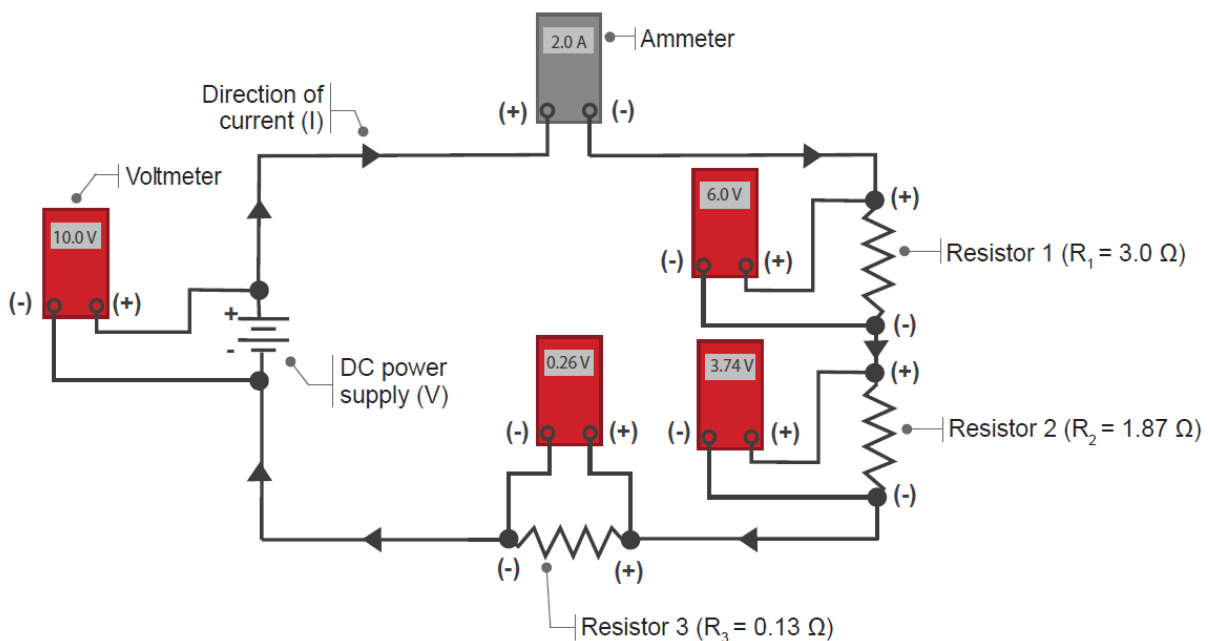
Figure 1-5: Series Electrical Circuit

To illustrate the Kirchhoff's Voltage law, assume that the following values are known with respect to the circuit of Figure 1-5:

DC power supply voltage (V) = 10 volts

Circuit current flow (I) = 2.0 amps

Resistor No. 1 (R_1) = 3.0 ohms

Resistor No. 2 (R_2) = 1.87 ohms

Resistor No. 3 (R_3) = 0.13 ohms

Calculate the voltage drops across the three resistances with the V = IR form of Ohm's Law.

Voltage Drop across R_1: 2A × 3 Ω = 6V

Voltage Drop across R_2: 2A × 1.87 Ω = 3.74V

Voltage Drop across R_3: 2A × 0.13 Ω = 0.26V

The sum of these voltages, V_t (Kirchhoff's Voltage Law), is:

$$V_t = 6V + 3.74V + 0.26V = 10V$$

This matches the power supply voltage as it should. Note that the voltage drops across the resistances are proportional to the ohmic values of the resistances - the higher the value of the resistance, the greater the voltage drop across it for a given value of current flow.

The sum of the resistances, R_t, in this example is:

$$R_t = 3.0Ω + 1.87Ω + 0.13Ω = 5Ω$$

This should match the value of total circuit resistance calculated from the known power source voltage and current; V = 10 volts and I = 2 amps. To check, use the R = V/I form of Ohm's Law.

Total Circuit Resistance ($R_1 + R_2 + R_3$):

$$R_t = \frac{10\ V}{2\ A} = 5Ω$$

For another application of the Figure 1-5 circuit, assume that we do not know the ohmic values of the resistances R_1, R_2, and R_3. All we know is the power source voltage (V = 10 volts) and current (I = 2 amps). The problem now is how to determine the amount of resistance in each resistor in ohms. It soon becomes apparent that not enough information is known to determine these values without taking an intermediate step.

The necessary intermediate step is to measure the voltage drop across resistances R_1 and R_2 using a suitable DC voltmeter. The reason for neglecting the drop across R_3 will become apparent shortly.

Assume that the intermediate step has been taken with the following values recorded.

Voltage drop across R_1 = 6 volts

Voltage drop across R_2 = 3.74 volts

This gives all the needed information. Using the R = V/I form of Ohm's Law,

$$R_1 = \frac{6\ V}{2\ A} = 3\ Ω$$

$$R_2 = \frac{3.74\ V}{2\ A} = 1.87Ω$$

We know from the power source voltage (10V) and current (2A) that by Ohm's Law, the total circuit resistance is 5 ohms.

$$R_t = \frac{10\ V}{2\ A} = 5\ Ω$$

Therefore, the value of Resistance No. 3 must be 5 ohms minus the sum of Resistances R_1 and R_2.

$$R_3 = 5\ Ω - (3\ Ω + 1.87\ Ω) = 0.13\ Ω$$

Note that the values of resistance agree with the values used earlier in the example - as they should.

Remember the following things with respect to a series circuit:

- The total current from the power source flows through each resistance element in the circuit.
- The sum of the voltage drops across the several resistance elements in the circuit must equal the voltage of the power source (Kirchhoff's Voltage Law).
- The sum of the ohmic values of the several resistance elements in the circuit must equal the total circuit resistance: $R_T = R_1 + R_2 + ... + R_N$

The Parallel Electrical Circuit

Equally as important as the series circuit is the parallel circuit. In a parallel circuit, there are multiple paths for current to flow. A parallel circuit has two or more load resistances connected that the positive (current input) ends of all resistances are connected together and the negative (current output) ends are connected together, instead of being connected end to end as is the case with a series circuit. According to Kirchhoff's Current Law, all of the current traveling through each parallel path can be added up to equal the total amount of current in the circuit. A parallel circuit is illustrated by Figure 1-6.
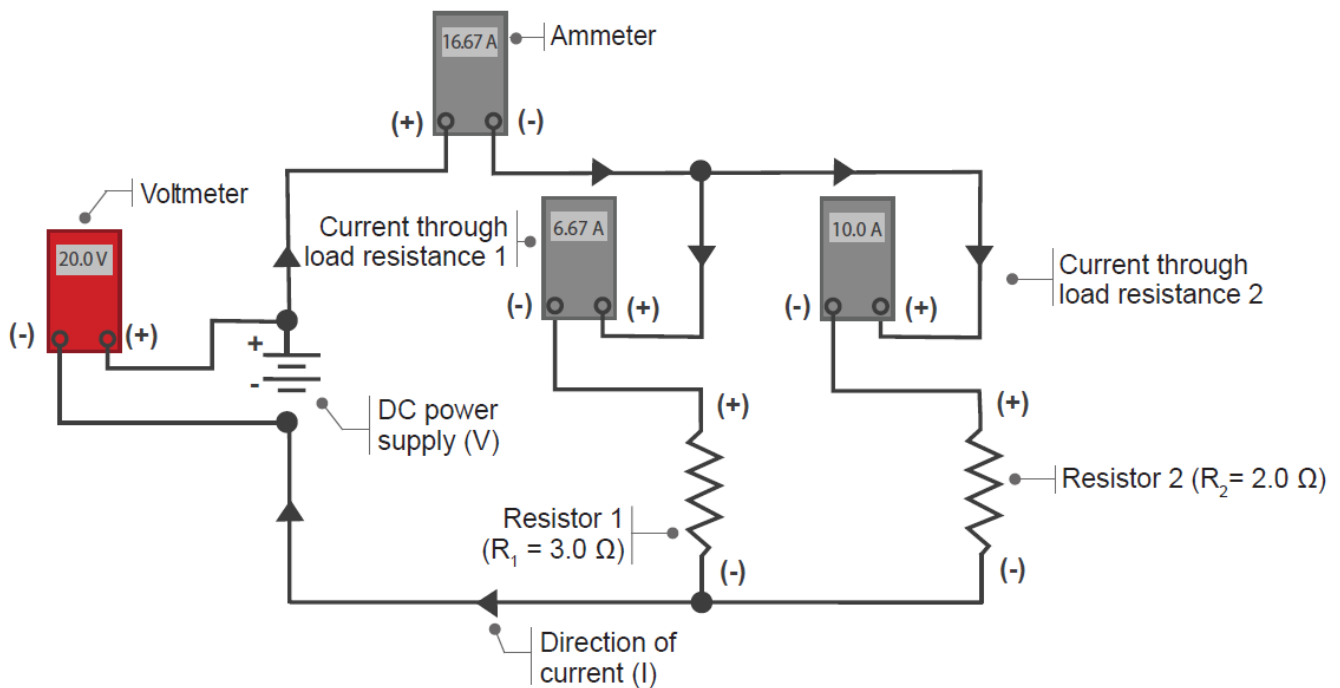
Figure 1-6: Parallel Electrical Circuit

As can be seen in Figure 1-6, the power source voltage will be impressed on each resistance element rather than being distributed, as is the case with a series circuit. Further, the power source current will be divided among the several resistance branches.

An example of how the parallel circuit works can be demonstrated by using the following values:

Power supply voltage (V) = 20 volts

Power supply current (I) = 16.67 amps

Resistor No. 1 (R_1) = 3 ohms

Resistor No. 2 (R_2) = 2 ohms

First, calculate the current flow (I_1 and I_2) through each load resistance branch. The voltage drop across each branch equals the power supply voltage (V) which is 20 volts. Then by Ohm's Law, I = V/R:

Current flow through R_1:

$$I_1 = \frac{20\text{ V}}{3\text{ }\Omega} = 6.67\text{ A}$$

Current flow through R_2:

$$I_2 = \frac{20\text{ V}}{2\text{ }\Omega} = 10\text{ A}$$

The sum of these two currents (Kirchhoff's Current Law) should equal the power source output current of 16.67 amps, which it does.

The easiest way to calculate the total resistance (R_P) of a parallel circuit is by using the simple Ohm's Law equation, if you know the total voltage (V) and total current (I). If this was the case, you could do the following calculation:

$$R_t = \frac{20\text{ V}}{16.67\text{ A}} = 1.2\text{ }\Omega$$

If you don't have enough information, then you can utilize the following equation, if you know all of your individual resistances thus R_P is equal to:

$$\frac{1}{\dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3} + \dfrac{1}{R_4} + \cdots + \dfrac{1}{R_N}}$$

OR

$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} + \cdots + \frac{1}{R_N}$$

In a parallel circuit, your total circuit resistance will always be less than the smallest resistor within the circuit. Another way of stating this is that every parallel path added to the circuit will decrease the total circuit resistance.

Remember the following important points with respect to a parallel circuit:

- The full power supply voltage is impressed across each parallel branch.
- The sum of the currents through the individual parallel branches must equal the total current output of the power source (Kirchhoff's Current Law).
- The parallel resistance of two or more branches will always be less than that of the smallest branch resistance.

Solving Electrical Circuits

In this section we've discussed how to use Ohm's Law, what the two main types of circuits are, and how to determine V, I and R. Table 1-2 summarizes the basic properties of Series versus Parallel circuits.

Table 1-2: Solving Electrical Circuits

Item	Series	Parallel
Voltage (V)	Add Up	Stay Same
	$V_t = V_1 + V_2 + V_3$	$V_t = V_1 = V_2 = V_3$
Current (I)	Stay Same	Add Up
	$I_t = I_1 = I_2 = I_3$	$I_t = I_1 + I_2 + I_3$
Resistance (R)	Add Up	V_t/I_t
	$R_t = R_1 + R_2 + R_3$	$R = \dfrac{V_t}{I_t}$
		OR
		$R_t = \dfrac{1}{\dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3}}$

Utilizing this chart while working through an electrical circuit will help you keep the circuit laws straight and assist you while performing calculations.

COMBINATION CIRCUITS

Electrical circuits can be a combination of series elements and parallel elements. A simple case is illustrated by Figure 1-7.
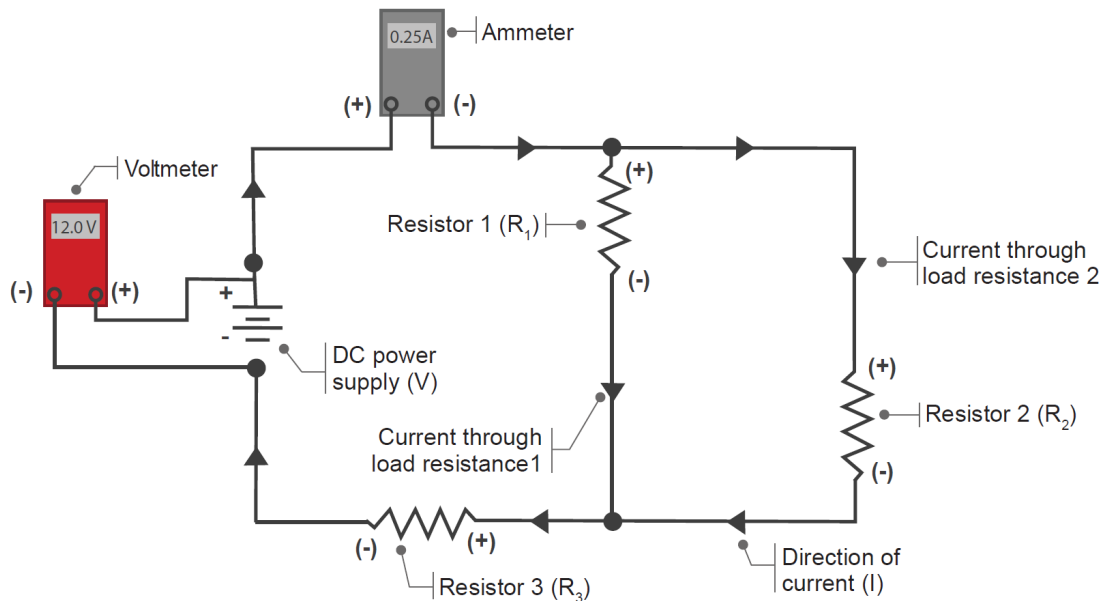
Figure 1-7: Combination Electrical Circuit

Calculation procedures applicable to such a combination circuit are in general accord with the principles covered in the sections on series circuits and parallel circuits. There are, however, certain important differences to be noted:

- The power supply output current divides between the two parallel branches R_1 and R_2 and then combines again after passing through these resistances. The full power supply current then passes through the resistance element R_3.
- The voltage drop across parallel branches R_1 and R_2 will be equal to each other.
- The amount of the voltage drop will be the power supply voltages minus the voltage drop across series resistance R_3.
- The effective circuit resistance will be the calculated parallel resistance of branches R_1 and R_2 plus the resistance of series resistance R_3.

Example of Parallel and Series Combined Circuit

Assume:

Power supply voltage (V) = 12 volts

Power supply current (I_P) = 0.25 amps

Resistor R_1 = 25 ohms

Resistor R_2 = 50 ohms

Resistor R_3 = 31.3 ohms

First, calculate the effective resistance of the two resistors in the parallel portion of the circuit:

$$\frac{1}{R_p} = \frac{1}{25} + \frac{1}{50} = 0.04 + 0.02 = 0.06$$

Therefore,

$$R_p = \frac{1}{0.06} = 16.67\Omega$$

Next, divide the power supply voltage (V) with the power supply current (I_P) to obtain the total resistance (R_t) of the three resistors in the circuit:

$$R_t = \frac{V}{I_p} = \frac{12V}{0.25A} = 48\Omega$$

Now, the value of the R_3 can be calculated by subtracting the effective resistance (R_P) of the two parallel resistors R_1 and R_2 from the total resistance R_t calculated previously:

$$R_3 = R_t - R_p = 48 - 16.67 = 31.33\Omega$$

Since the total current flowing through R_3 is 0.25 amps, the voltage drop (V_3) across R_3 can be calculated as follows:

$$V_3 = I_t x\, R_3 = 0.25\ x\ 31.33 = 7.83V$$

The voltage drop (V_P) across R_1 as well as R_2 will be the difference in the power supply voltage (V) and the voltage drop (V_3) across resistor R_3:

$$V_p = V - V_3 = 12 - 7.83 = 4.17V$$

The current flowing through R_1 will be:

$$I_1 = \frac{V_p}{R_1} = \frac{4.17}{25} = 0.167A$$

Similarly, the current flowing through R_2 will be:

$$I_2 = \frac{V_p}{R_2} = \frac{4.17}{50} = 0.083A$$

The currents I_1 and I_2 will combine at the junction before passing through resistor R_3:

$$I_1 + I_2 = 0.167 + 0.083 = 0.25A$$

Note that this is the same as the total current in the circuit as displayed by the ammeter.

Thus, Ohm's Law can be used to calculate I, V, or R if any two of these three parameters is known.

Chapter 2 – Corrosion Fundamentals

INTRODUCTION

Corrosion is a major problem associated with underground structures. Modern industrial plants, universities, hospitals, cities, and utility companies utilize many underground systems. Submerged areas of structures such as pipelines at river crossings and on the seabed, sheet piling, ship hulls are also subject to corrosion if some form of corrosion-control is not implemented. Corrosion failures can be expensive and can lead to shutdowns, hazardous conditions, occasional fires, or other catastrophes such as pollution of soil, water, and the atmosphere by leaking toxic products. This chapter describes the fundamental corrosion cell and its relation to underground structures. Similar principles would also apply to submerged areas of structures.

WHAT IS CORROSION?

Corrosion is an electrochemical reaction between a metal and its environment. Essentially, it is the tendency of a refined metal to return to its natural state as an ore. Corrosion always involves flow of an electrical direct current (DC) through an electrolyte (such as soil or water) from one point to another on a metal surface. This current is generated by a potential or voltage difference between the two points. Corrosion and Cathodic Protection (CP) are electrochemical processes.

There are many forms of corrosion. Metallic materials can be affected by corrosion to varying degrees depending on many factors such as alloy composition, fabrication, heat treatment, exposure environment, electrical contact with dissimilar metals, and stray currents. Strictly speaking, the term galvanic corrosion refers to accelerated corrosion of an active metal in electrical contact with a more noble metal (or conductive nonmetal such as graphite) in a common electrolyte like moist soil or water. Corrosion due to potential differences created by various factors on the same metal (i.e., flaws or scratches in conductive surface films that expose the base metal, variations in concentrations of salts and dissolved gases in the environment contacting the metal surface, highly stressed versus less-stressed areas, and so on) can be considered as forms of "micro-galvanic" corrosion. However, the term natural corrosion (or self-corrosion) is preferred when corrosion occurs on a single metal in the absence of electrical contact with a dissimilar metal (or a conductive nonmetal such as graphite). Stray current corrosion is excluded from the definitions of galvanic and self-corrosion. Natural (self) corrosion can manifest itself in various forms (i.e., general or uniform attack, pitting, crevice corrosion, stress corrosion cracking, erosion-corrosion, dealloying, intergranular attack, and microbiologically influenced corrosion). All forms of underground corrosion involve some type of electrochemical corrosion cells. In soils, moisture is essential for corrosion attack, which can be aggravated by increasing acidity (i.e., decreasing pH), dissolved oxygen content, concentration of dissolved salts, bacteria, cinders, etc.

ENERGY OF METALLIC STRUCTURES

To understand how corrosion occurs, we must first learn how we can accurately take readings on the metal to determine how much energy (corrosion potential) they have. Figure 2-1 depicts as a simple illustration of why metals corrode. Steel is produced from iron-ore (iron oxide), a stable, low energy material, found naturally in the earth's crust in certain geographical locations in the world. The iron-ore is reduced to iron by reaction with carbon (called metallurgical "coke") in a blast furnace at a temperature of 3,0000F (1,6500C). Other processes (such as alloy additions, refining, hot rolling in a mill, heat treatment, etc.) follow before iron becomes a steel pipe. Those processes introduce high energy into the steel which is now in a metastable state. When an unprotected steel or cast iron pipe is placed underground in a corrosive soil, it corrodes releasing the metastable energy as electrical current flow due to potential differences between microscopically-dissimilar areas on the metal surface. Corrosion is a natural process that returns the iron in the steel or cast iron back to its native or stable state, rust (which is iron oxide that is similar to the iron-ore from which the steel was made).
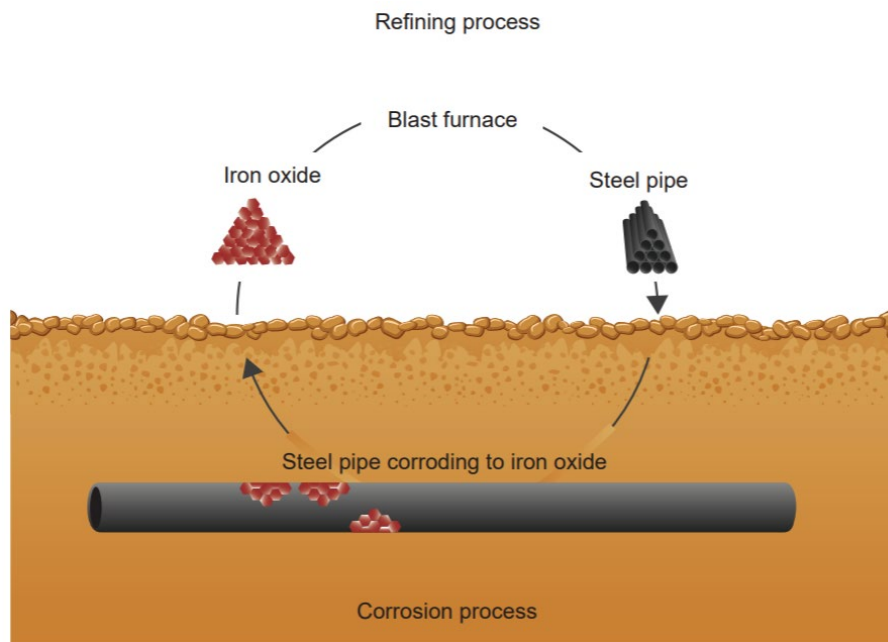
Figure 2-1: Steel – Manufacturing & Corrosion Process

All metals have a preferred stable state. Knowledge about their stable state allows us to rank different metals and determine how much energy (corrosion potential) they have and how likely they are to corrode. This is illustrated in Table 2-1, which is a practical galvanic series listing of metals according to their energy levels. The energy level is represented by what is called the electrode potential of a metal with respect to a reference electrode such as a saturated Copper-Copper Sulfate (CSE). Table 2-1 shows the measured potentials in neutral soils or waters; although such measurements can be made and reported for other environments of interest. Figure 2-2 illustrates how potential measurement of a metal in an electrolyte (water or moist soil) can be easily made in practice with the aid of a DC voltmeter and a reference electrode.
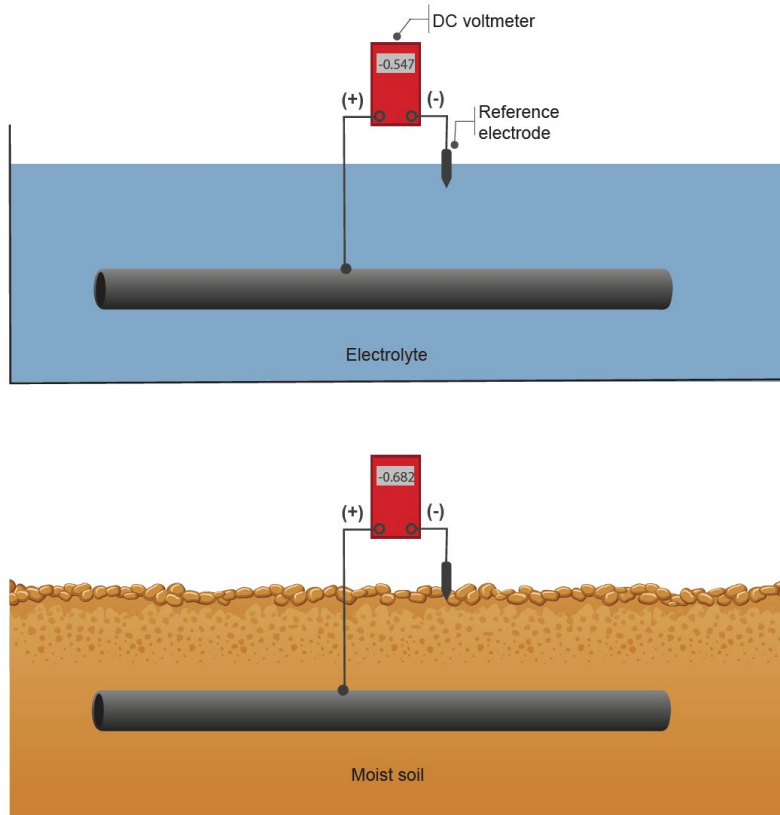
Figure 2-2: Potential Measurement

The values shown in Table 2-1 serve as a general guide only, since they may vary depending on the environment. It is important to note that the galvanic series indicates the relative tendency of metals to corrode but not their actual corrosion rates.

Table 2-1: Practical Galvanic Series

Most energy required for refining	Material	Potential (V)*	Greatest tendancy to corrode	Active
	High potential magnesium	-1.75		
	Magnesium alloy	-1.60		
	Zinc	-1.10		
	Aluminum alloy	-1.05		
	Clean carbon steel	-0.50 to -0.80		
	Rusted carbon steel	-0.20 to -0.50		
	Cast/ductile iron	-0.50		
	Lead	-0.50		
	Steel in concrete	-0.20		
	Copper	-0.20		
Least energy required for refining	High silicon iron	-0.20	Least tendancy to corrode	Noble
	Carbon, graphite	+0.30		

* Typical potentials measured between metal (when immersed in neutral soils or waters) and a copper-copper sulfate reference cell contacting the adjacent soil or water.

Generally, the more electronegative (active) the potential of a metal is, the more energy it has, and hence a greater tendency to corrode. Conversely, the more electropositive the potential of a metal is, the less energy it has and thus a lower tendency to corrode. Remember, electronegative and electropositive are relative terms. For example, let's compare Zinc and Copper in Table 2-1. While both of these metals exhibit negative potentials, Zinc (-1.10 V) is more electronegative than Copper (-0.20V). Alternatively, Copper is relatively more electropositive than Zinc. When comparing any two metals in the galvanic series, the metal with the more electronegative potential is called an anode (anodic or more active metal) and the more electropositive metal is called the cathode (cathodic or more noble metal). The terms anode (electronegative) and cathode (electropositive) are very important when we talk about Corrosion Cells.

If any two metals with different electrode potentials (i.e., voltage differences) are electrically connected to each other in a conductive electrolyte (such as moist soil or water), the potential difference between them is a driving force that will cause a flow of direct current (DC) from the more electronegative metal (anode), through the electrolyte (moist soil or water), to the more electropositive metal (cathode). As an example, if lead (-0.50V) and copper (-0.20V) are the pair of metals selected, the potential difference between them is 0.3 volt, with lead (electronegative) being the corroding anode; and copper (electropositive) the cathode, whose corrosion rate will be slowed or stopped. Accelerated corrosion of the anodic metal or alloy when electrically coupled to a cathodic metal or alloy in a corrosive electrolyte is called Galvanic Corrosion (sometimes referred to as Dissimilar metal corrosion or Bimetallic corrosion). Do not call this electrolysis! Electrolysis is the decomposition of water (for example, into hydrogen and oxygen) when an electrical current is passed through it.

As another example, take zinc (-1.10V) and carbon/graphite (+0.30V). The potential difference is 1.4 volts. When they are electrically coupled in an electrolyte the zinc will be the corroding anode and the carbon/graphite will be the non-corroding cathode.

FUNDAMENTAL CORROSION CELL

Now that we have learned about the galvanic series and anodic versus cathodic metals, we can introduce the Corrosion Cell. For corrosion to occur, there are four basic requirements:

1. A Common Electrolyte (Soil/Water)

    a. The anode and cathode metals must be immersed in the soil or water.

2. An Anode (Active Metal)

    a. This metal has a more electronegative (active) potential than the cathode.

3. A Cathode (Noble Metal)

    a. This metal has a more electropositive (noble) potential (or less electronegative) than the anode.

4. A Metallic Path between anode and cathode.

The anode and cathode must have a conductive electrical connection between the two, which is represented as a wire in Figure 2-3. This connection could also be a metal-to-metal contact, for example, as a result of bolting or welding the two metals together or via a jumper wire.

The corrosion cell in Figure 2-3 operates basically like a battery. In other words, an anode and a cathode are immersed in an electrolyte (water or moist soil) that contains ions. Ions are charged atoms or molecules

capable of carrying an ionic electric current. In pure water, a small number of water molecules ionize as hydrogen ions (H+) and hydroxyl ions (OH-) ions:

$$H_2O = H+ + OH-$$
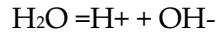
When an anode and cathode are connected to each other with via a metallic path (e.g., a jumper wire), the anode corrodes faster, generating metal ions by loss of electrons. Electrons are negatively charged particles that carry current in a metallic path:

$$M - ne- = Mn+$$
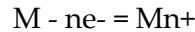
Where:

M = A metal

n = The number of electrons involved in the reaction

This is an anodic reaction which, in electrochemical terms, is referred to as oxidation (i.e., corrosion) regardless of whether oxygen is present or not. In the case of steel this would be iron (Fe) dissolving (i.e., going into solution as ferrous ions):

$$Fe - 2e- = Fe^{2+}$$
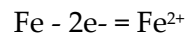
The electrons generated by an anodic reaction cannot stay in the metal but must be "consumed" by one or more cathodic reaction(s). Electrons cannot flow in an electrolyte but they can in a metal. Hence they flow from the anode via the metallic path to the cathode where they are consumed by the following cathodic reaction (hydrogen-ion reduction) which produces hydrogen gas (H_2), for example, in oxygen-free water or in acid environments:

$$2H+ + 2e = H_2$$
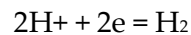
When dissolved oxygen (O_2) is present in the water, there is a very important additional cathodic reaction, oxygen reduction, which generates hydroxyl (OH-) ions:

$$1/2\ O_2 + H_2O + 2e- = 2OH-$$
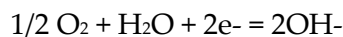
In the case of a single metal such as steel, microscopic anodic and cathodic areas are practically next to each other in the metal microstructure. In moist soil and water, the by-products of the anodic and cathodic reactions, the ferrous ions (Fe^{2+} from the anode) and hydroxyl ions (OH- from the cathode), combine to precipitate ferrous hydroxide, $Fe(OH)_2$:

$$Fe^{2+} + 2OH- = Fe(OH)2$$
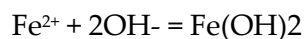
The ferrous hydroxide, $Fe(OH)_2$ can be converted further to ferric hydroxide, $Fe(OH)_3$:

$$4Fe(OH)_2 + O_2 + 2H_2O = 4Fe(OH)_3$$
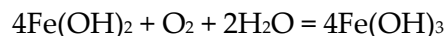
Ferric hydroxide, $Fe(OH)_3$ is the characteristic yellow/red rust corrosion product (iron oxide, Fe_2O_3) typically seen on corroding steel in soil, water and atmospheric environments when oxygen is present. In contrast, in acid environments, the ferrous ions remain in solution as the metal corrodes; and the corrosion product (Fe^{2+}) does not precipitate as rust on the steel surface.
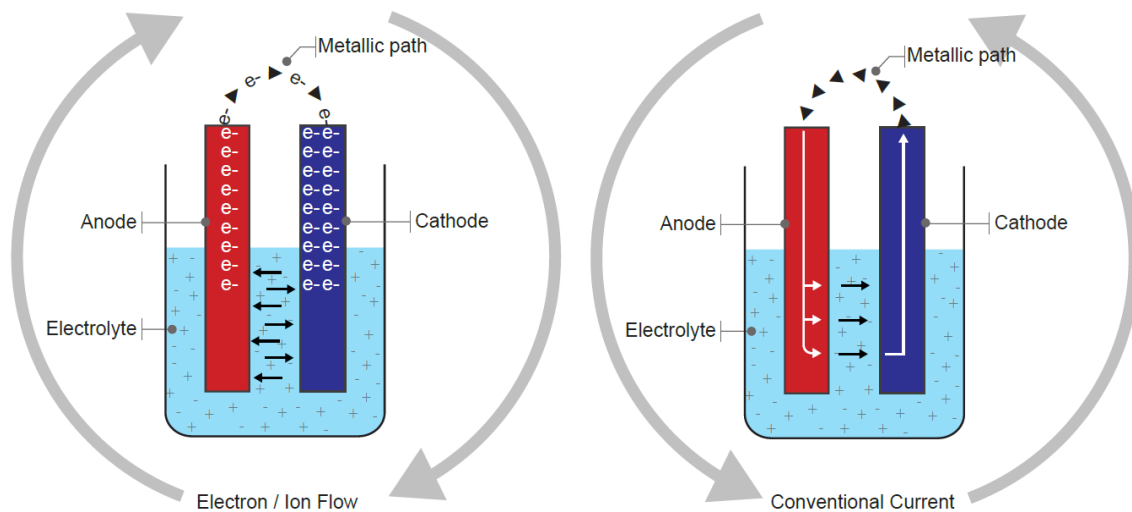
Figure 2-3: Fundamental Corrosion Cell

In Figure 2-3, if an ammeter is placed in the metallic path between the anode and cathode, it will display the amount and direction of current flow in the circuit. The concept of "conventional current", that electric current flows through the electrolyte from the anode to the cathode, arose nearly a hundred years before the discovery of electrons and development of the modern electrochemical theory of corrosion. The latter states that it is actually electrons that flow from the anode to the cathode through the metallic path, as shown in Figure 2-3. However, since an ammeter measures conventional current flow, it is still commonly assumed that electrolytic (i.e., ionic) current flows from the anode to the cathode in the electrolyte; and continues flowing as electric current from the cathode to the anode in the metallic path. In other words, the current flowing in the metallic path (i.e., where it can be measured using an ammeter) is the same current as the current flowing in the electrolyte where in which it cannot be measured directly. In reality, it is electrons that flow from the anode to the cathode via the metallic path. Electrons do not flow in an electrolyte. Conventional current flow in the electrolyte from the anode to the cathode in a corrosion cell can be called the corrosion current. Generally speaking, the greater the corrosion current, the higher the corrosion rate of the anodic metal.

Accepting the idea of "conventional" current flow, the corrosion cell may be summed up as follows:

1. Current flows through the electrolyte from the anode to the cathode.

2. Corrosion occurs wherever positive metal ions leave the metal and enter the soil (electrolyte). The point where current leaves the metal is called the anode. Corrosion, therefore, occurs at the anode.

3. Current is picked up at the cathode. Corrosion at the cathode is slowed or stopped. The latter is the basis of cathodic protection. Polarization (hydrogen film build-up) occurs at the cathode.

4. The flow of current is caused by a potential (voltage) difference between the anode and the cathode.

As stated previously, Figure 2-3 showed the fundamental corrosion cell as a battery. Figure 2-4 shows how corrosion cells can develop on a bare pipeline that has local areas of steel with different energy levels, some anodic and some cathodic created by small differences in the microstructure or differences in concentrations of various species on the metal surface in an electrolyte. The arrows indicate conventional corrosion current flow from local anodic areas to the local cathodic areas through the electrolyte. From Figure 2-4 it can be inferred that the anodic areas (undergoing corrosion) are going to be steadily extinguished if the native potential is gradually shifted in the negative direction by application of slowly increasing cathodic current application to the pipeline from an external source (e.g., from sacrificial anodes or impressed current system). Polarization is

the shift in native corrosion potential of the local anodic areas, e.g., from -0.5 V to -0.58 to -0.6 to -0.65 and finally to -0.85 at which corrosion of steel would be practically stifled.
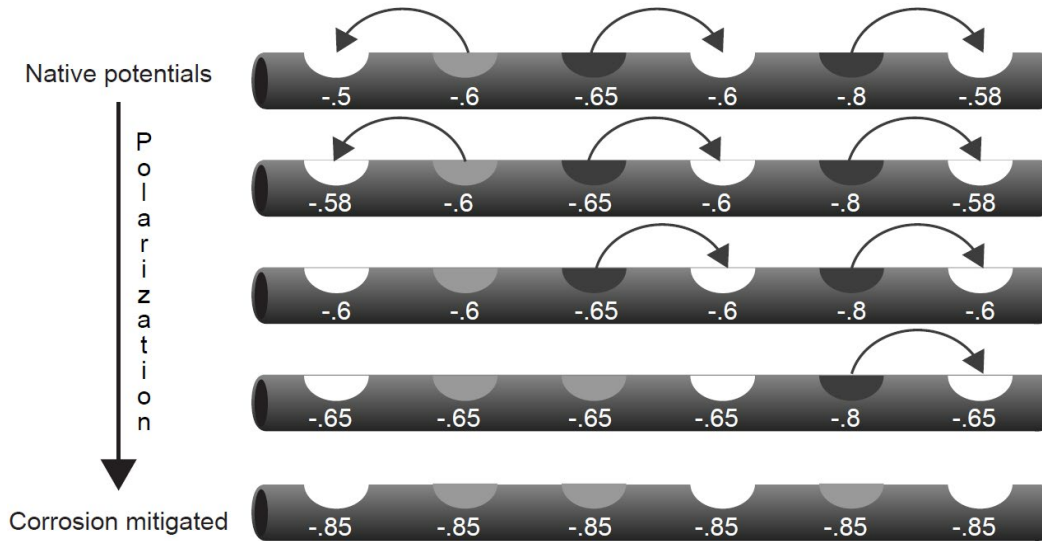
Figure 2-4: Fundamental Corrosion Cell as it Applies to a Pipeline
(An Electrochemical Cell B Conventional Current Cell)

TYPES OF GALVANIC AND NATURAL CORROSION

Dissimilar Metals (Galvanic Corrosion)

As stated earlier, the potential difference between dissimilar metals causes current flow between them when they are electrically coupled to each other in a given electrolyte (i.e., soil or water). The anode undergoes accelerated galvanic attack while corrosion of the cathode will slow down or stop.

Figure 2-5 shows a steel gas service line in electrical contact with a copper water line when there is no dielectric isolation between the two metals. From the galvanic series in Table 2-1, it is apparent that steel is more anodic (active) because of its more electronegative potential than copper. This means that the steel piping would be the anode and would corrode more rapidly in this galvanic couple and corrosion of the copper would be slowed or stopped. It should be noted that this is why copper has often been considered to be "corrosion free" when used underground. This relative corrosion freedom is gained at the expense of the steel or cast iron. In other words, the copper is "protected" while steel or cast iron corrodes at a faster rate. A dielectric union in the gas line, usually inserted near the gas meter, would electrically isolate the steel gas line from the copper water line. This would mitigate accelerated galvanic corrosion of the steel. However, the steel would still be susceptible to self-corrosion, for example at coating holidays underground; but the corrosion of the steel would be significantly slower than if it was not electrically isolated from the copper by a dielectric union.
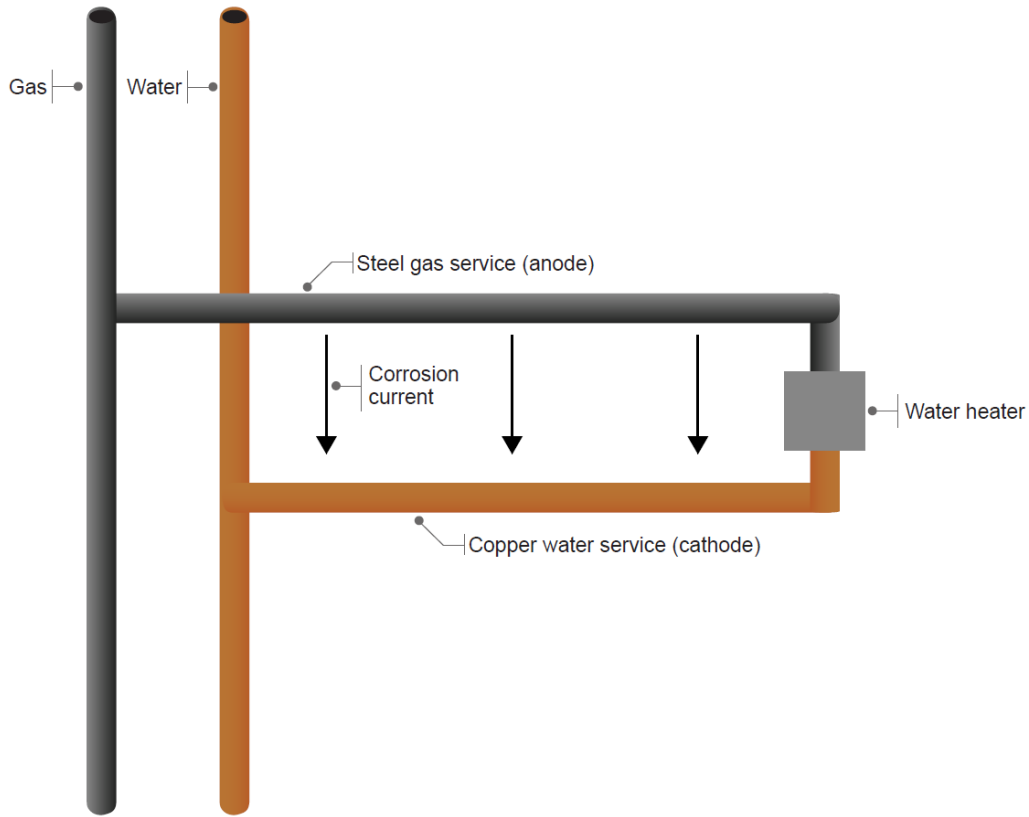
Figure 2-5: Natural Potential Different Between Metals

Dissimilar Surfaces

An example of corrosion of the same base metal but with dissimilar surfaces is the insertion of a piece of new steel pipe welded or bolted onto an old underground rusty steel pipe. Table 2-1 shows that due to the potential difference between the two, the new steel pipe is expected to corrode faster at holidays in the coating because its potential is more electronegative (active) compared to the rusty pipe (which is relatively more electropositive, or less electronegative). As depicted in Figure 2-6, contrary to expectation, a piece of new pipe used to replace a section that has failed from corrosion is not expected to last as long as the original piece (in the absence of some means of corrosion control, typically cathodic protection) because of this new steel-old steel relationship.
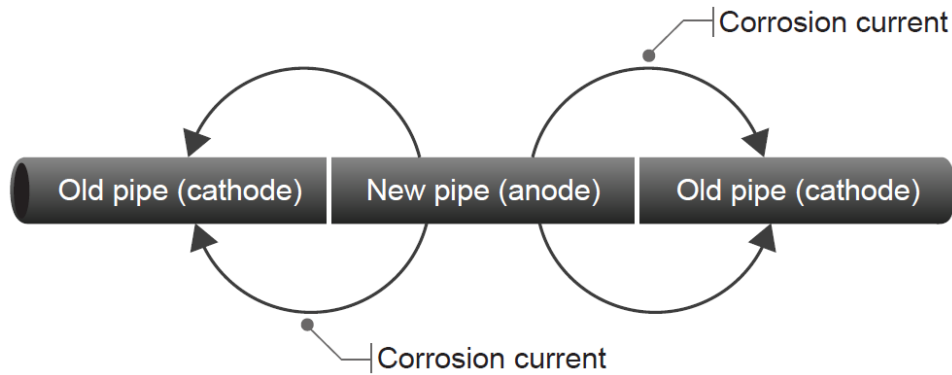
Figure 2-6: New-Old Pipe Cell

Another related example is differences in surface conditions on a pipe. In threaded pipe assemblies, if a pipe wrench is used on the piping, the teeth of the pipe wrench jaws can bite into the surface of the pipe exposing

bright metal at the teeth marks or "scars." After the pipe is buried in soil or immersed in water, these local pipe wrench scars will be anodic with respect to the adjacent cathodic areas of the same metal and will corrode quicker in the absence of adequate corrosion control. Also, when threads are cut into the pipe, the bright metal exposed by the thread cutting will likewise be anodic where exposed to soil or water and will corrode faster in the absence of suitable corrosion control. Figure 2-7 shows the more corrosion prone areas on underground piping. This applies to bare or coated pipe that is not galvanized (i.e., no zinc coating). In the case of galvanized pipe (i.e., with a zinc coating), corrosion of the zinc by galvanic (i.e., sacrificial) action could protect small areas of the exposed steel.
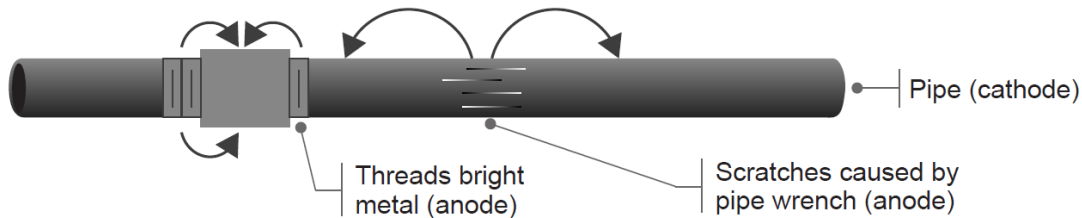
Figure 2-7: Corrosion Caused by Dissimilarity of Surface Conditions

Similarly, on existing underground pipe systems, if a sharp pointed probe rod is used to make electrical contact with the pipe during corrosion control test work (an old practice), the bright metal scars left by the probe rod will be anodic compared to the adjacent pipe areas. In the absence of corrosion control, dissimilar surface corrosion cells can develop at these scars.

An example of an electrically conducting surface film that can increase corrosion of the underlying base metal at flaws in the surface film is mill scale on steel. Mill scale is a thin and usually tightly adherent surface oxide film (Fe_3O_4, also called magnetite) formed on hot rolled steel in the steel mill. The potential between mill scale (cathode) and steel exposed at breaks in the mill scale (anode) can be in the range of 0.2 volt to 0.5 volt. In the absence of effective corrosion control on buried or immersed structures, corrosion of the exposed steel can be rapid since, typically, the corrosion current discharge is concentrated at the small areas of mill scale damage (Figure 2-8).
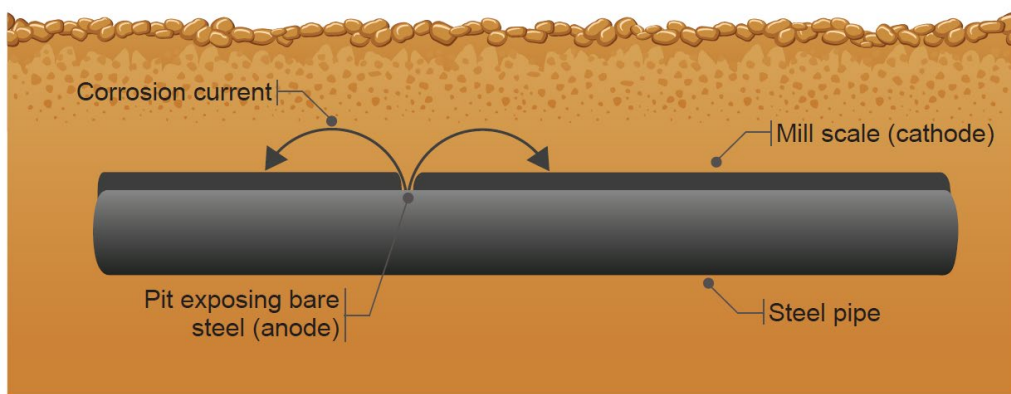
Figure 2-8: Pitting Due to Mill Scale

Dissimilar Soils

Just as dissimilar metals or surface dissimilarities are the source of electrical potential differences in corrosion cells, dissimilar soils can also be a source of potential difference. It is indeed rare to have a completely uniform soil in which an underground structure is buried. In the more usual case, there will be changes in characteristics of the soil from point-to-point along a buried structure. This is illustrated in principle in Figure 2-9 which shows a pipeline passing through two different soil types, Soil A and Soil B. It also shows that if the potential of the steel pipe in Soil A is measured with a voltmeter with respect to a reference electrode (such as saturated copper-copper sulfate electrode or CSE), it has a different potential from that similarly measured in Soil B. In the case shown, the difference between the two readings is 0.2 (i.e., 0.5 – 0.3) volts with Soil B being less electronegative (or relatively more electropositive) compared to Soil A (which is more electronegative). The corrosion current flow will then be from the more electronegative Soil A (anode) to the less electronegative (or relatively more positive) Soil B (cathode) through the soil from the cathode (Soil B) back to the anode (Soil A) through the pipe metallic path which completes the circuit. This makes the pipe in Soil A anodic and it will corrode faster than the section of the same pipe in Soil B.
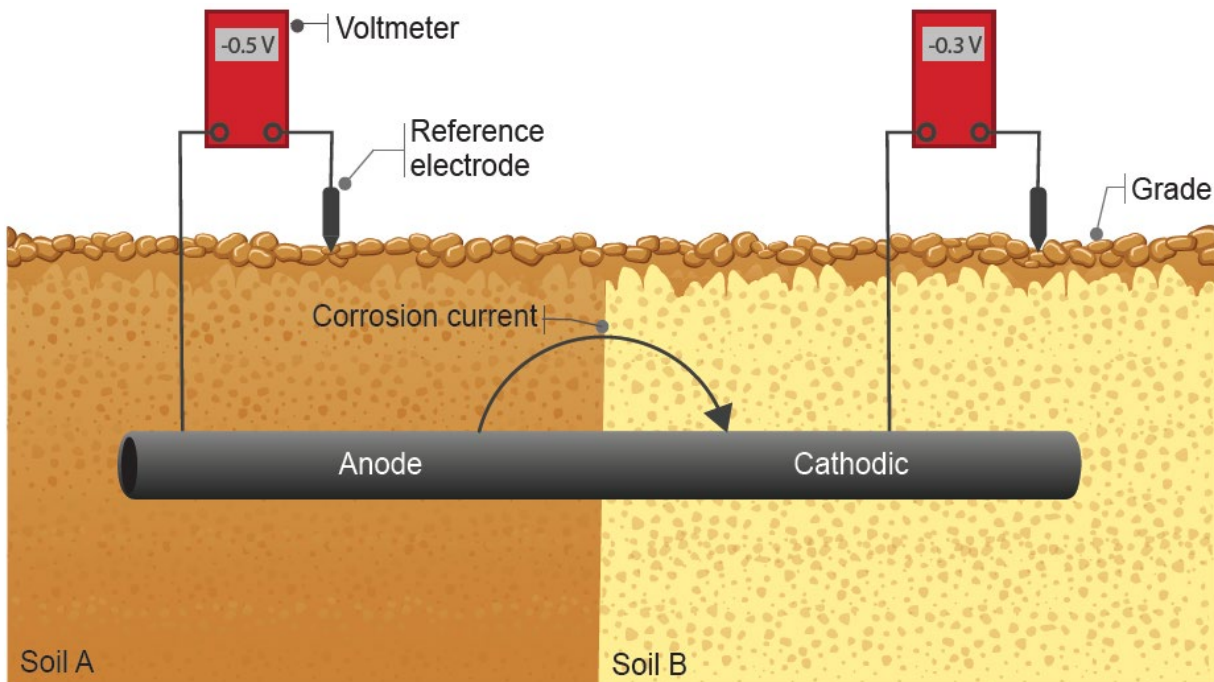
Figure 2-9: Dissimilar Soils as Source of Corrosion Cell Potential

Conditions are seldom as clearly defined as shown in Figure 2-9. By the time excavations are made for a buried pipe or structure and it is finally backfilled, there may be a mixture of different soil types in the backfill. This tends to create a condition illustrated in Figure 2-10 which leads to numerous localized anodic and cathodic areas along the pipe or structure. This is frequently observed when an old steel underground structure (such as a pipeline which has never had corrosion-control measures) is uncovered for inspection. Typically, there will be heavily corroded anodic areas adjacent to cathodic areas which look relatively unaffected.
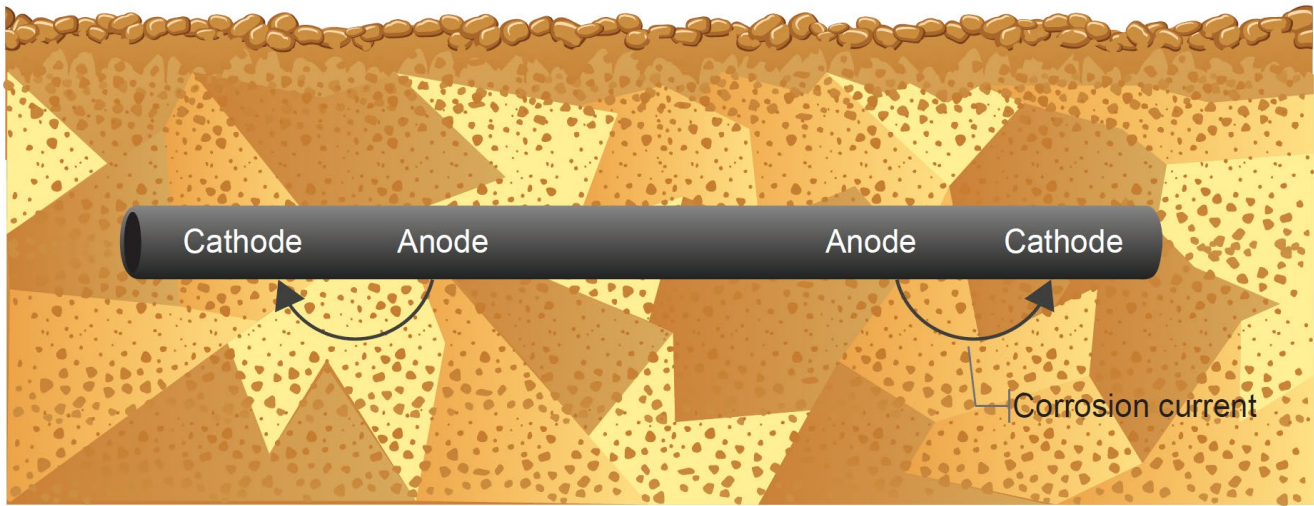
Figure 2-10: Mixture of Dissimilar Soils as Source of Corrosion Cell Potentials

Differential Aeration

Another source of electrical potential difference causing corrosion current to flow is differential aeration. This simply means that when oxygen from the air (aeration) is more readily available through the electrolyte to one part of a structure than to another, there will be a difference in potential between those two areas. When this condition exists, contrary to expectation, the part of the structure having restricted oxygen availability will be anodic and will corrode more rapidly than the part with more oxygen access. Differential aeration is also known as differential oxygenation.

A typical example of differential aeration on a buried pipe is illustrated by Figure 2-11 which shows the effect of restricted oxygen availability to the pipe under a paved road while there is good oxygen availability through the porous earth to the pipe on either side of the paved road. This happens even if the soil is otherwise uniform throughout the area around the pipeline., The area of pipe under the paving has a more electronegative potential than the pipe areas in the well-aerated soil on either side of the road. This means that the area under the road is anodic and the areas on either side are cathodic, which results in corrosion current flow in the directions shown in Figure 2-11.
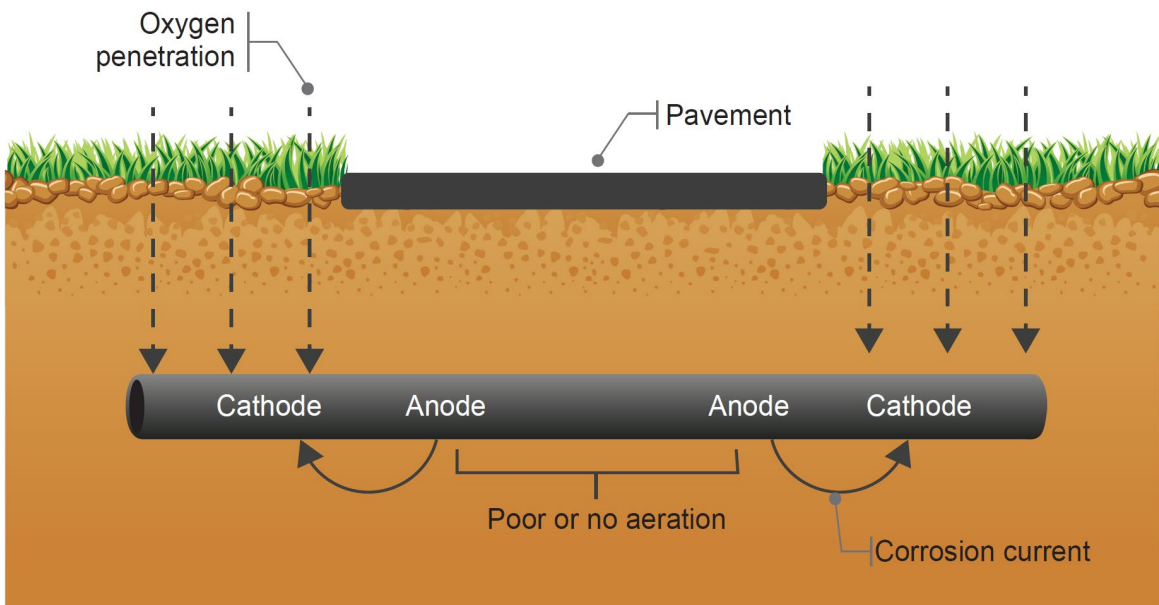
Figure 2-11: Differential Aeration as a Source of Corrosion Cell Potential

Another example of differential aeration is for a buried pipeline which has more compacted soil at the bottom of the trench (around the 6 o'clock position and relatively loose backfill around the top of the pipeline). There is greater oxygen availability to the top of the pipe compared the bottom. In this case corrosion current flow will be from the bottom of the pipe (anodic area) to the top (cathodic area). Corrosion failures will be more likely on the underside of the pipe (Figure 2-12). The bottom of the pipe is usually more difficult to repair.
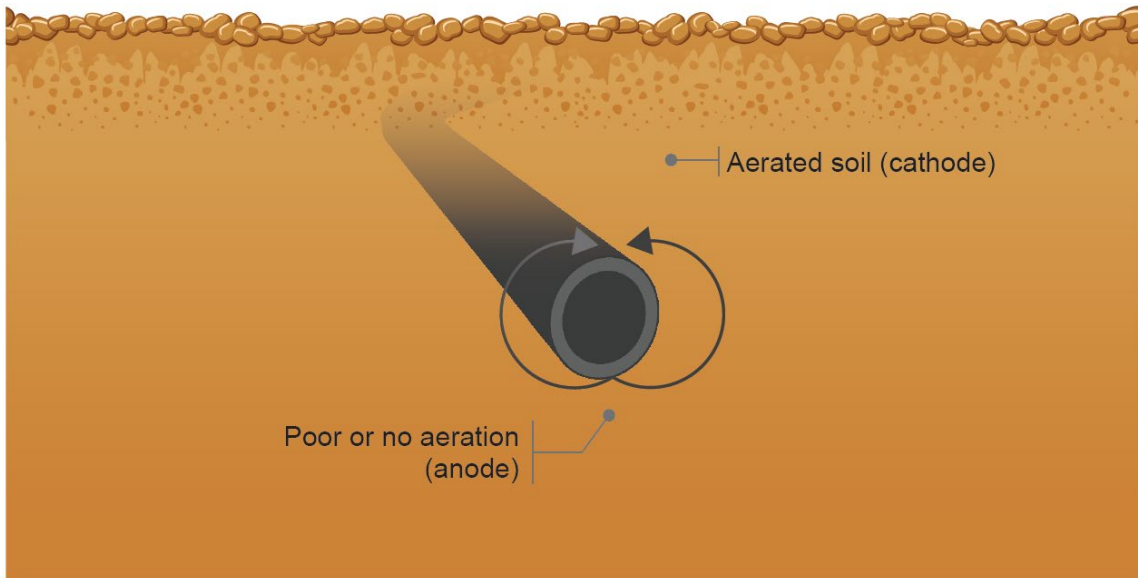
Figure 2-12: Corrosion Caused by Differential Aeration of Soil

Stress Corrosion

Stresses can be introduced into metals during manufacturing processes such as forging, bending, machining, welding, and during assembly (e.g., bolting). In underground or immersed structures, a more highly stressed area will be anodic (i.e., more prone to corrosion) than the adjacent, less stressed area. This is illustrated by the example in Figure 2-13 which represents an underground bend in the pipeline.
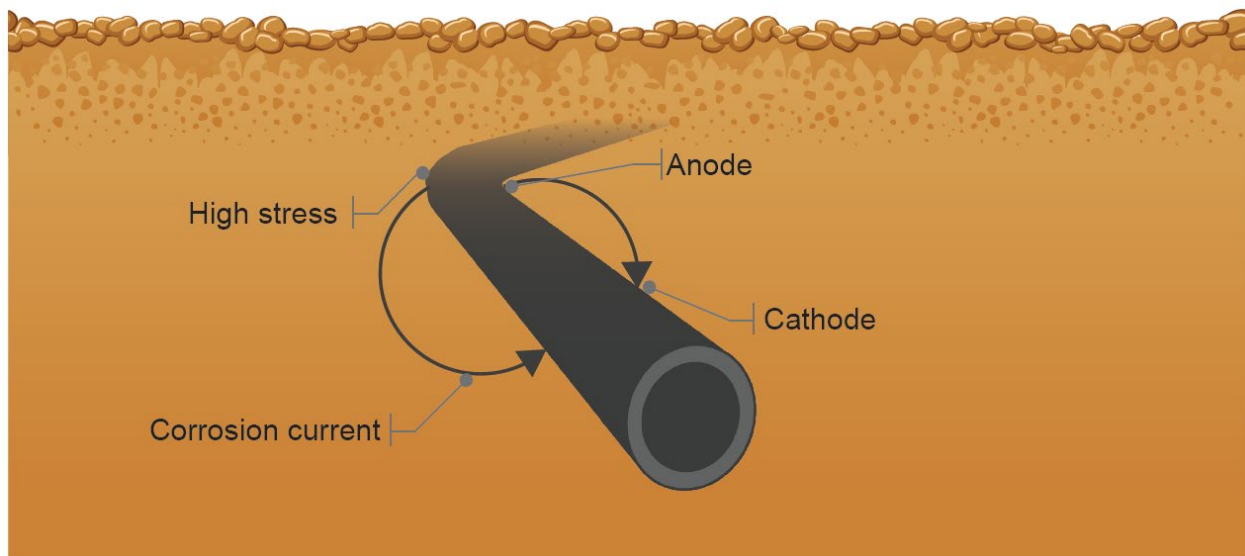
Figure 2-13: Differential Stress as a Source of Corrosion Cell Potential

Another example of stress corrosion is of bolts in a coupling which are often observed to neck down or even break in the middle. The center of the bolt is more highly stressed than other parts because of greater stress concentration at this location. This is depicted Figure 2-14.
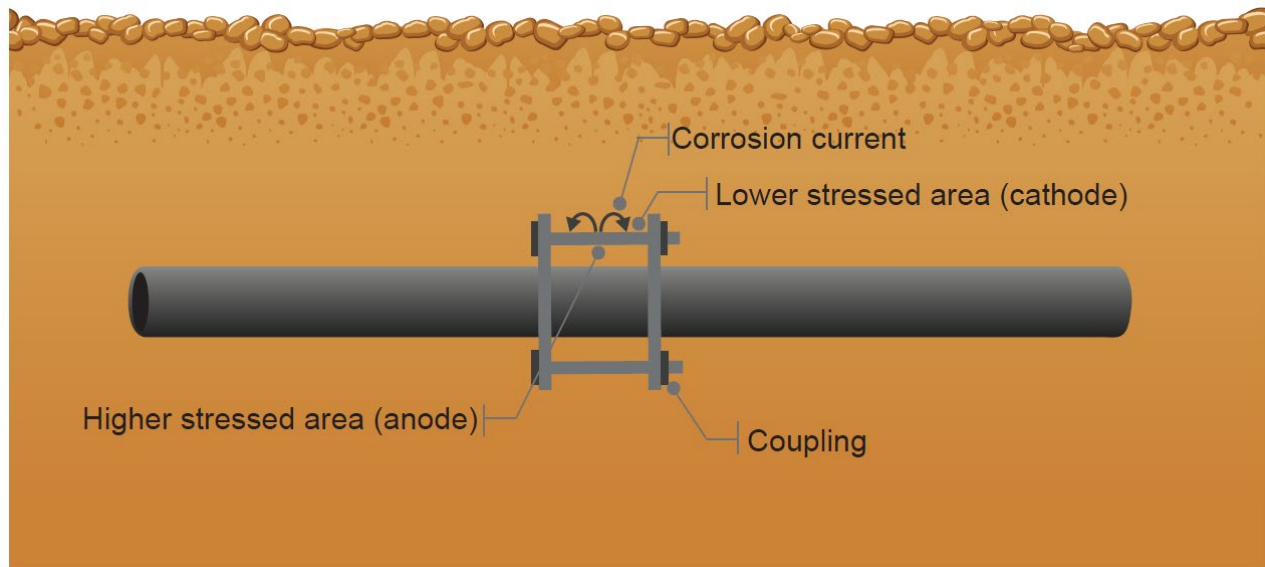
Figure 2-14: Stress Corrosion

Where high strength alloy steels are used in underground structures which are highly stressed (such as high-pressure pipelines), a phenomenon known as stress corrosion cracking (SCC) may be encountered. In such situations, another source of corrosion can start a corrosion pit which will act as a local stress raiser in the structure metal.

The resulting differential stress corrosion cell can then act in conjunction with the original corrosion cell as above except that cracks may develop in the structure metal at the base of the initiating pits and may result in catastrophic failures. Cracks can be "transgranular," where they propagate through metal grains or crystals; or they can be "intergranular," where they follow the boundaries of the metal grains or crystals. Sometimes, both transgranular and intergranular cracking can occur in the same metal microstructure.

The study of SCC has been the subject of intense research as the phenomenon is affected by many variables such as stress level, the metal alloy composition and impurities, nature of the environment, surface contaminants, temperature, metal electrode potential, and pH. An alloy which is resistant to SCC under a given set of conditions may behave quite differently under other conditions.

Cast Iron Graphitization

Cast iron contains nearly ten times the amount of carbon that is present in common structural steels. Two common types of cast iron pipes used underground are gray cast iron and ductile iron. In gray cast iron most of the carbon is present as a network of graphite flakes in the microstructure. In a corrosive environment the iron corrodes, leaving behind the graphite with the iron-oxide corrosion products trapped in place by the graphite. While the original shape and thickness of the pipe or structure may still appear to be largely retained even after many years of service, the corroded gray cast iron is a very weak material. Fractured surfaces of gray cast iron have a dull appearance compared to an unaffected shiny metal surface. This form of corrosion in gray cast iron is commonly known as "graphitization" or graphitic corrosion. The graphite, which is a soft material, can be easily cut or scraped away with a knife. Where gray cast iron is used in water mains, for example, the pipe may become heavily graphitized in severely corrosive areas and continue to carry water

through the earth-supported graphitic structure for decades. Eventually the pipe becomes so weak that a pressure surge or heavy traffic vibration will cause the pipe to rupture resulting in a major leak.

Graphitic corrosion can be accelerated by galvanic coupling to more noble metals and by stray currents. Significant corrosion of gray cast iron exposes large amounts of graphite in the microstructure. Graphite is most noble (conductive non-metal) in the galvanic series shown in Table 2-1. This situation can then accelerate corrosion of more active metals such as copper that are in electrical contact with the graphitized gray cast iron. In other words, initially when the gray cast iron is new, copper (cathode) accelerates corrosion of the cast iron (anode) by galvanic action. However, later when the gray cast iron is graphitized, the potentials of the copper and corroded gray cast iron are reversed (graphite is now the cathode and copper is the anode whose corrosion rate is accelerated by galvanic action).

As stated previously, graphite in gray cast iron is present as a network of intertwined flakes. In contrast, graphite in ductile iron is present as discrete nodules that are not interconnected as a network in the microstructure. Ductile iron is stronger than gray cast iron and isn't generally susceptible to graphitization because the graphite nodules do not "hold" the iron corrosion product (iron-oxide rust) in place, unlike gray cast iron where the graphite flakes do hold the rust in place. Thus, ductile iron tends to corrode and pit more like steel; i.e., if unprotected, its thickness generally and locally decreases with time.

Microbiologically Influenced Corrosion (MIC)

Colonies of certain types of bacteria can establish conditions on the surface of underground structures which cause more rapid attack in existing corrosion cells. One of the most significant microorganisms which can initiate and propagate corrosion is sulfate reducing bacteria (SRB). In anaerobic (i.e., oxygen-starved) conditions, SRB can reduce sulfate ions (SO_4^{2-}) present in the soil or water and produce hydrogen sulfide (H_2S) which has the characteristic smell of rotten eggs. At the metal surface, the metabolic activity of SRB consumes hydrogen which forms at cathodic surfaces of existing corrosion cells (described earlier in this chapter). This intensifies the action of the corrosion cell by depolarization of the hydrogen on the metal surface.

The SRB do not themselves attack the metal directly but produce a more corrosive environment (H_2S) which corrodes the steel, resulting in the formation of black iron sulfide (FeS) corrosion product. SRB are found in heavy, dense, waterlogged soils where oxygen availability is restricted in the anaerobic environment. They can also be active under deposits and disbonded pipeline coatings or wherever oxygen at local areas is absent. Bacteria also require organic materials as a food source, for example, from dead and decaying matter, oil/grease contamination from spills, rotting wood, etc.

Combinations of Corrosion Cell Effects

A corrosion problem at a given point on an underground structure is not necessarily confined to just one of the previously discussed types of corrosion cells. Two or more types of corrosion cells can be operate at the same time in corrosion attack on the metal; for example, a dissimilar soil corrosion cell, dissimilar metals, stress corrosion, anaerobic bacterial activity, etc.

Amphoteric Metals

Acidic (i.e., low pH) environments are typically aggressive towards many metals and alloys, while alkaline (higher pH) environments are more favorable for the same materials. However, some metals can corrode in both acidic and alkaline environments. Aluminum, zinc, lead, and tin, are examples of such metals which are referred to as "amphoteric."

Cathodic Corrosion

As stated previously, corrosion of a cathodic metal is normally slowed down or stopped when it is in electrical contact with an anodic metal in a corrosive environment. However, under certain conditions, corrosion of an amphoteric metal can actually increase even if it is the cathode.

Hydroxyl (OH-) ions form when oxygen is reduced at the cathode in oxygenated environments. Hydroxyl ions correspond to increase in alkalinity (i.e., increase in pH) at the cathode surface. If a sufficiently high concentration of hydroxyl ions is generated on the cathode surface, a susceptible amphoteric metal, such as aluminum can suffer from "cathodic corrosion", self corrosion of the metal under very alkaline (high pH) conditions. Similarly, a cathodic surface collecting high stray currents or receiving significant cathodic overprotection (Chapter 3) can generate significant alkalinity (i.e., high hydroxyl ion concentration) that can attack an amphoteric metal.

STRAY CURRENT CORROSION

Stray currents are defined as currents through electrical paths other than the intended circuit that can cause corrosion. This is not to be confused with naturally occurring galvanic corrosion current between anodes and cathodes on the same structure. Stray currents can be classified as being either Static or Dynamic.

- Static Stray Currents are currents that maintain constant amplitude and direction. Examples of typical sources are railroad signal batteries and impressed current CP systems

- Dynamic Stray Current are currents that are continually varying in amplitude and/or continually changing current direction. They can be caused by humans, or they may be caused by natural phenomena. Typical examples of human-caused sources are DC welding equipment, DC transit systems, mining operations, and Electrical Power Transmission. Natural sources, such as telluric currents, are caused by disturbances in the earth's magnetic fields due to sunspot activity

FACTORS AFFECTING THE RATE OF CORROSION

General

The amount of corrosion incurred by a metal is directly proportional to the amount of current leaving the surface and entering the electrolyte. This current is related to both the potential difference (voltage) between the anode and cathode and the circuit resistance in a corrosion cell. The total circuit resistance includes the resistance of the metallic path, the anode and cathode metals, and the electrolyte (e.g., soil or water)

Voltage, resistance, and current are related by Ohm's Law:

$$V = I \times R$$

Where:

V = Voltage (volts or millivolts)

I = Current (amperes or milliamperes)

R = Resistance (ohms or milliohms)

Essentially, Ohm's Law states that current is directly proportional to the voltage and inversely proportional to the resistance:

$$I = V/R$$

Corrosion rate is proportional to current density:

$$\text{Current density} = I/A$$

where, I is the total current being discharged from an Anode into the electrolyte (e.g., amps, milliamps, microamps, etc.), and A is surface area of the Anode from which current flows into the electrolyte (e.g., sq. ft., sq cm). Thus, current density can be reported as mA/ft^2, A/m^2, $\mu A/cm^2$, etc. The current density can be converted to corrosion rate using Faraday's Law.

Corrosion rate, the rate at which metal loses thickness, is typically reported as mils per year (mpy, where 1 mil = 0.001"). In metric units, corrosion rate is typically reported as mm/yr or $\mu m/yr$.

Conversions: 1 mpy = 0.001"/yr = 0.00254 mm/yr = 25.4 $\mu m/yr$

For carbon steel, current density of 1 $\mu A/cm^2$ = 0.93 mA/ft^2 ≈ 0.5 mpy

If the anode metal is bare, not coated, the corrosion current is discharged only from the wetted or buried surface area of the anode into the electrolyte. If the anode is covered with a non-conductive (e.g., epoxy) coating, current will be discharged only from holidays or scratches in the coating. Thus, a given amount of current flowing from a small anode area will have a much higher current density and hence a higher corrosion rate, compared to a large bare anode area discharging the same amount of current into the electrolyte.

Polarization

Polarization is the shift in potential of a metal (measured in volts or millivolts) due to current flow in the electrolyte, from or to the metal. Current flow from the metal into the electrolyte shifts the potential in the more positive (or less negative) direction, this is called anodic polarization. In a galvanic couple, corrosion of the anode is increased by anodic polarization of the anode. Conversely, current flow from the electrolyte into the metal shifts the potential in the more negative (or less positive) direction, this is called cathodic polarization. In a galvanic couple, corrosion of the cathode is decreased or stopped by cathodic polarization. Cathodic protection is cathodic polarization where the potential shifts in the negative direction when DC current is supplied from an external source such as a galvanic (sacrificial) anode and/or an impressed current system (ICCP) to a buried or immersed structure such as a pipeline.

Electrolyte Resistivity

In simple terms, Ohm's Law can be instructive in understanding the effect of electrolyte resistivity on corrosion rate. Resistivity is the inverse of conductivity.

Structures placed in high resistivity (low conductivity) electrolytes will generally tend to corrode less than those in low resistivity (high conductivity) electrolytes. For this reason, oxygen-containing salt water is generally more corrosive than fresh water, because salt water is more conductive (it has lower resistivity which allows more corrosion current flow). Apart from resistivity or conductivity alone, other factors can also influence corrosion rate. For example, if oxygen is removed from salt water, it becomes much less corrosive. A good polymer (e.g., epoxy) coating acts as a significant barrier to oxygen and water migration to the metal surface and hence mitigates corrosion so long as the coating is applied to a clean surface and the coating is free of holidays.

Voltage Difference Between Anode and Cathode

According to Ohm's Law, the greater the voltage difference between two metals in a galvanic couple, the greater the expected rate of corrosion of the anode. However, Ohm's Law does not address polarization which

can be influenced surface films on the metal, rate of oxygen diffusion to the metal surface, electrolyte pH, temperature, etc.. For example, for the same metal-to-metal geometry, potential difference between stainless steel and carbon steel is greater than that between copper and carbon steel. However, all other things being equal, galvanic corrosion rate of the carbon steel coupled to stainless steel is typically lower because the stainless steel polarizes more easily than copper galvanically coupled to carbon steel. In other words, carbon steel coupled to copper is expected to have a considerably higher corrosion rate despite the potential difference between the copper and carbon steel being lower than that between the carbon steel and stainless steel.

Anode/Cathode Ratio

The relative area between the anode and cathode greatly affects the rate at which the anode corrodes. If the anodic area is small in relation to that of the cathode (e.g., a galvanized fitting in a brass pipe for example - Figure 2-15 (Case A), the anode will corrode rapidly. This is because the corrosion current is concentrated in a small area (resulting in a high current density which is proportional to corrosion rate as stated previously) and because the large cathode may not polarize easily, thus maintaining a high rate of corrosion. When a large anode is connected to a small cathode (Figure 2-15 Case B), corrosion current is spread out over a large area. In this case, the corrosion current density is lower which typically results in a lower corrosion rate of the anode. Polarization may also play a key role here. In other words, the small cathode may polarize rapidly, and thus result in a lower corrosion rate of the large anode. The anode/cathode area ratio is most important when the two metals are buried or immersed in conductive (low resistivity) electrolytes. In high resistivity (low conductivity) electrolytes effect of anode/cathode area ratio is usually much less, such that a galvanic corrosion attack on the anode is typically less and concentrated near the junction with the cathode. This is also the case for dissimilar metal couples in atmospheric environments because any moisture film on the metal surfaces is thin and therefore not a very conductive environment. Stated another way, because the thin electrolyte film (moisture) in atmospheric conditions has greater resistivity, corrosion current flow is severely restricted and the anode/cathode interaction distance is typically limited to a fraction of an inch adjacent to the anode/cathode junction.
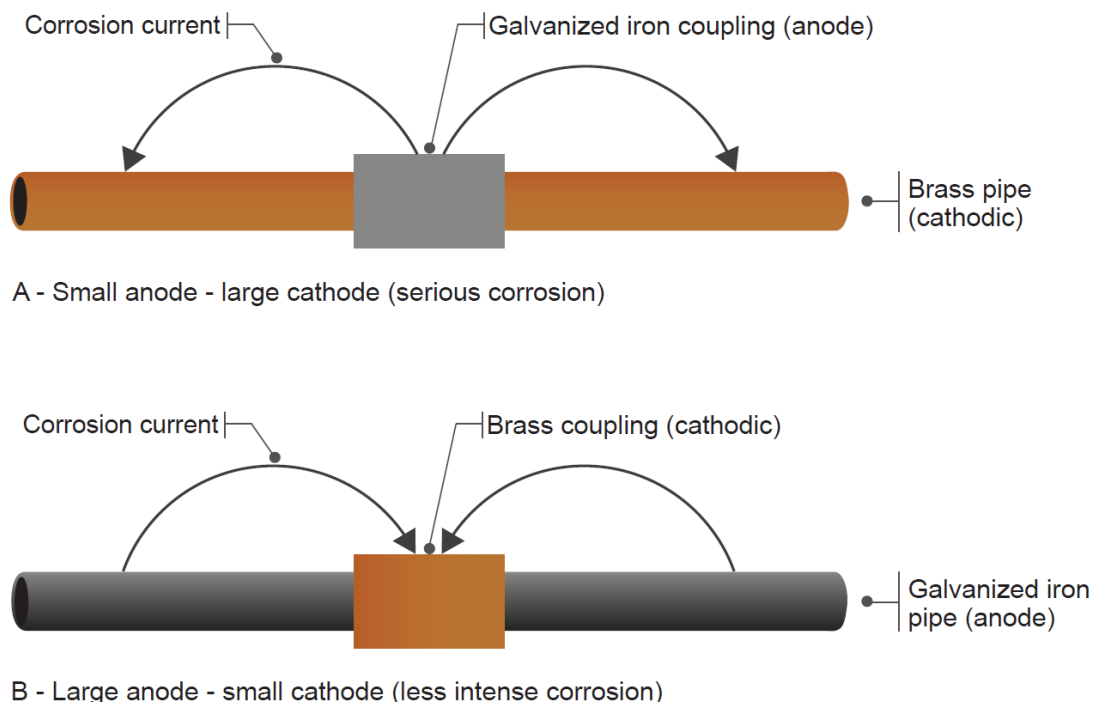
Figure 2-15: Anode-Cathode Size Relationship

Effect of the Metal Itself

Different metals corrode at different rates because of difference in the amount of energy stored in them. If we know how much energy is stored in them, we can calculate how much weight loss the metal will have if we know how much corrosion current there is and how long it will be flowing for. The rate of metal loss is expressed by Faraday's Law:

$$W = K \times I \times T$$

Where:

W = Weight Loss of Metal

K = Electrochemical Equivalent (atomic weight of metal/valency/Faraday's constant (96,485))

I = Corrosion Current in Amperes

T = Time in Years

Table 2-2 lists the electrochemical equivalent stated in grams per coulomb, and consumption rates of some typical metals in pounds per ampere-year. This is the weight of metal that will be corroded away by one ampere of direct current continuously discharging from a metal into a surrounding electrolyte for a period of one year.

Table 2-2: Consumption Rates of Typical Metals

Metal	Electrochemical Equivalent (Grams per Coulomb)	Consumption Rate (Pounds per Ampere-Year)	Volume of Metal Consumed (Cubic Inches per Ampere-Year)
Carbon * (C^{+++})**	0.4149×10^{-4}	2.89	36.99
Aluminum (Al^{+++})	0.9316×10^{-4}	6.48	69.99
Magnesium (Mg^{+++})	1.2600×10^{-4}	8.76	141.47
Iron (Fe^{++})	2.8938×10^{-4}	20.12	70.81
Nickel (Ni^{++})	3.0409×10^{-4}	21.15	67.06
Copper (Cu^{++})	6.5875×10^{-4}	45.81	142.89
Zinc (Zn^{++})	3.3875×10^{-4}	23.56	90.87
Tin (Sn^{++})	6.1502×10^{-4}	42.77	162.43
Lead (Pb^{++})	10.736×10^{-4}	74.65	181.68

*Carbon is not strictly classified as a metal but as a metalloid. It is still subject to consumption as a metal.

**Each metal is followed by its chemical symbol. The number of plus (+) signs following the symbol shows the valence for a typical anode reaction. The electrochemical equivalents are calculated on the valence shown. Other valences may apply under certain conditions for some metals.

Table 2-2 also includes the volume of the metal which will be removed per ampere-year. This is the critical figure as it illustrates the amount of metal that will be removed from, for example, a high-pressure steel pipeline for a given amount of current.

As an example, if a steel pipeline were discharging only 1 milliamp (0.001 ampere) current at coating holidays, the volume of iron removed per year would be 70.81 cubic inches per ampere year x 0.001 ampere or 0.07081 cubic inches. If concentrated in small areas (such as at defects in an otherwise good coating), this is sufficient to cause approximately six ¼-inch "cylindrical" holes (each 1/4-inch diameter and 1/4-inch deep with straight edges), in a pipe wall in one year. For hemispherical pits, each 1/4-inch in diameter and 1/8-inch deep, it would be about 18 holes. This example shows how important it is to control the discharge of even seemingly small amounts of current from underground steel structure into the surrounding earth or water at holidays in a coating. Application of effective CP plays a key role in mitigating corrosion, especially at holidays in the coating.

Corrosion rates and volumes of metal removed vary considerably (Table 2-2). Of the metals shown, lead has the greatest corrosion rate and the greatest volume loss. This emphasizes the critical need for effective corrosion control on, for example, lead sheaths on underground power and telephone cables. Formerly, lead sheaths were used widely but new construction favors plastic sheathing.

Passivation of the Metal Surface

The ability of a metal to form a protective film greatly affects the rate at which it will corrode. The surface film is often an oxide and is generally invisible. The development of such films is the reason for the corrosion resistance of metals like aluminum, chromium, stainless steels, titanium, copper, lead, and others.

If a passive film breaks down locally, passivity may be restored by species in the environment (usually dissolved oxygen) if they are readily available to reach those areas. However, localized corrosion can occur in crevices (e.g., under gaskets and O-rings at flanged joints) or as pits under deposits on susceptible grades of stainless steel where free access of dissolved oxygen is restricted. In such situations, corrosion-control requires selection of a more resistant alloy or application of another suitable corrosion-control technique. It should be noted that there are many grades of stainless steel and not all are equally resistant in all environments. For example, the typical kitchen-sink grade of stainless steel would be unsuitable for use in seawater applications where a much higher-grade material would be required; or CP would be needed for the lower grade stainless steel.

There are cases where some materials can corrode in certain environments and develop protective corrosion product films. An example of this is "weathering steel" that contains a small addition of copper (plus sometimes small amounts of other elements) in the steel composition. Adherent protective rust films can form on weathering steels in mild atmospheric environments that have minimal contaminants, frequent rain-washing (that removes the contaminants) and drying of the surfaces by sunlight. Such films can provide long-term protection without the need for a coating. However, it is very important to note that protective films do not form reliably in areas with high levels of contaminants, high humidity, close to the ocean, or subject to deicing salts. Protective films do not form on weathering steels on shielded areas, nor on underground and submerged structures. In such areas, coatings must be used, supplemented by CP on buried and submerged areas. While weathering steels have been used very successfully in many applications for decades, a complete understanding of environments where they do and don't work is essential before selecting this material to avoid expensive failures, repairs, or replacement.

Another case of protective corrosion product films is the green patina (corrosion product) that forms on copper and its alloys and can provide long-term protection in atmospheric environments. Examples include the Statue-of-Liberty, copper roofs on buildings and church steeples, and bronze statues.

Chapter 3 – Corrosion Control Methods

INTRODUCTION

In this chapter, we will outline various methods and procedures that are common for controlling this type of corrosion.

SUMMARY OF CORROSION CONTROL METHODS

Following are the types of corrosion control methods applicable to galvanic corrosion problems. Some of these methods are applicable to other categories of corrosion problems as well.

- Coatings
- Cathodic protection (CP)
- Isolating joints

COATINGS

Wherever direct current flows from an underground metallic structure into a surrounding electrolyte (earth or water), the metal will be consumed (corroded) at the points of current discharge. Following simple logic, if an isolating barrier (a coating) were to be placed between the metal and the surrounding electrolyte with no coating faults, corrosion current could not flow and there would be no loss of metal.

If a coating is to perform as stated previously, it must be perfect and it must remain perfect. On extensive underground structures (i.e., pipelines) it is not economically or practically feasible to apply an isolating coating that will meet these criteria, due to many factors that can cause the coating to become imperfect.

To illustrate the difference between a perfect coating and one that has imperfections, Figure 3-1 shows the difference in corrosion performance under the two conditions. The corrosive environment shown is that for a structure in dissimilar soils, as was first shown in Figure 2-9.
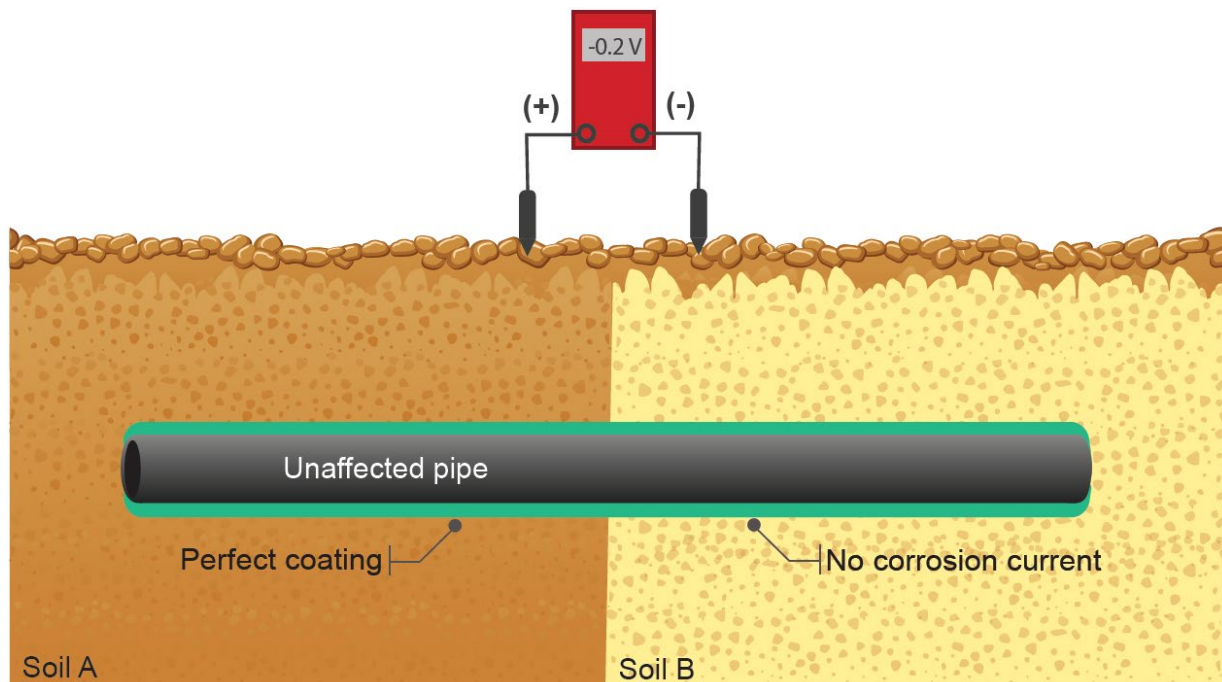
Figure 3-1: Pipe with Perfect Coating in Dissimilar Soils

Figure 3-1 shows that even though there is a galvanic voltage difference of 0.2 volt between Soil A and Soil B, the isolating barrier interposed by the perfect coating prevents current flow to or from the pipe to complete an electrical circuit. With no current flow to or from the pipe, there can be no corrosion on the pipe exterior surface.
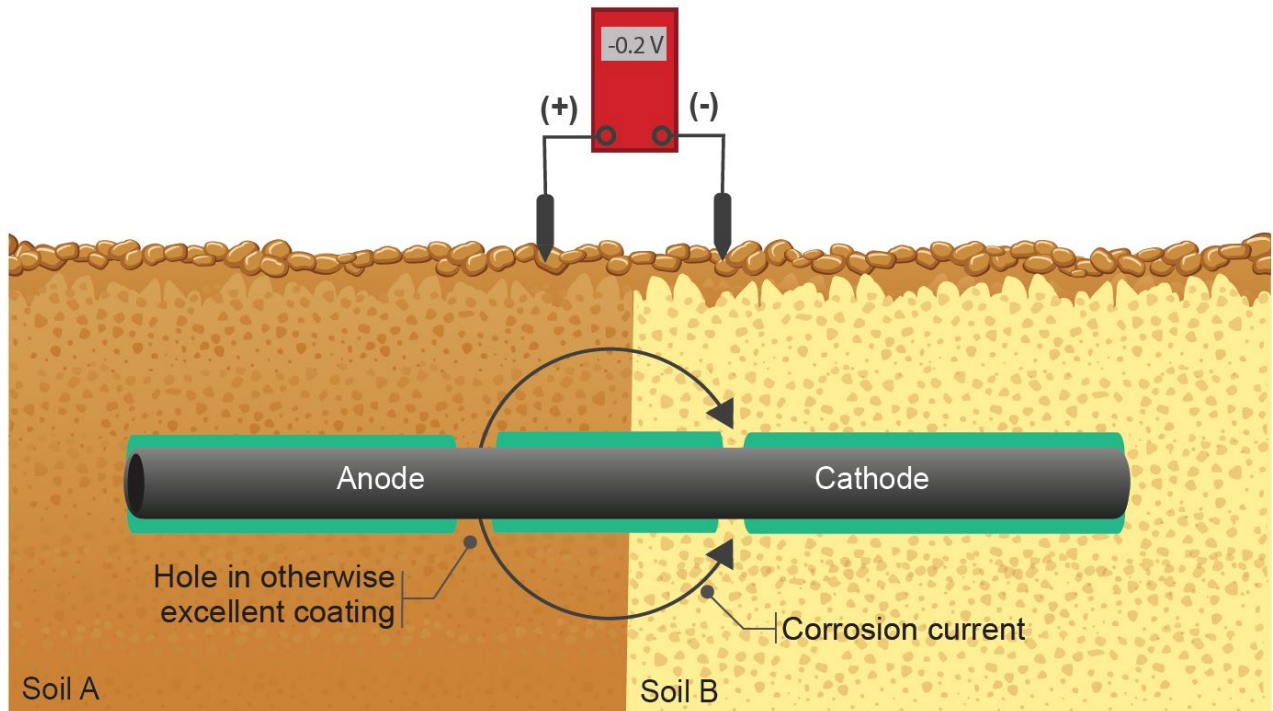
Figure 3-2: Pipe with Flawed Coating in Dissimilar Soils

Figure 3-2 shows what happens when an otherwise excellent coating develops pinholes, scrapes, or other imperfections (known as coating holidays or faults) which can expose small areas of pipe surface to the surrounding earth. With the exposed areas at coating flaws, there is now a path for current to flow because of the existence of the dissimilar soil galvanic corrosion cell driving potential. Current will now discharge from the pipe at coating flaws in anodic areas (and cause corrosion at these locations) and will return to the pipe at coating flaws in cathodic (non-corroding) areas.

In Chapter 1, it was pointed out that one of the factors controlling the amount of corrosion current flowing (and amount of metal loss) in a given galvanic corrosion cell is circuit resistance. The presence of an isolating coating, even though flawed, will substantially increase the total circuit resistance. This means that the total galvanic cell current flow will be substantially less. This means that the amount of metal corroded away during a given period of time will be less than would occur if the structure were uncoated under otherwise similar conditions.

Do not conclude from the preceding paragraph that corrosion of a coated structure is not serious. The corrosion cell current flowing, even though reduced, is concentrated at the metal exposed at holes in the coating. This means that at current discharge points in anodic areas, the current discharge density in terms of milliamps per unit area can be higher than would be the case if the same structure were entirely bare. Because of this, a structure (i.e., a coated high-pressure pipeline) can ,in the absence of other corrosion control measures, experience its first leak sooner than would have been the case if the pipeline had been installed bare (without coating). This can be true even though the total metal loss is less than on the bare pipe because of the reduced total corrosion cell current.

Some of the reasons why it is difficult to maintain a perfect coating on large diameter underground piping are:

- Defects at the factory
- Damage during transportation of piping
- Undetected handling damage during construction
- Stones or debris in backfill that force their way through the coating
- Soil movement or structure movement with pressure changes
- Tree roots working through coating
- Excavations by others which expose the structure and damage the coating with excavation equipment

Even with these hazards, the use of suitable coatings and good application and maintenance practices can result in a coating which is initially 99.9% perfect or better -- and which will decrease only a few percentage points with time. This indicates that the majority of the structure surface will be free of coating damage. It is the remaining bare surface area that needs additional corrosion control measures.

In addition to reducing the total corrosion hazard from galvanic corrosion cells, coating on a structure will also reduce stray current damage by increasing the circuit resistance. This reduces the amount of current pickup. Even so, the total stray current can be much greater than that resulting from galvanic corrosion cells. At points of stray current discharge on coated structures the concentration effect at coating imperfections can be much more intense than under galvanic corrosion cell exposure with very rapid structure penetration. Again, additional corrosion control measures are needed to supplement the coating.

Further detailed treatment of coatings on underground structures is included in Chapter 4.

WHAT IS CATHODIC PROTECTION?

Cathodic protection (CP) is a technique used to slow the rate of corrosion on a metallic structure by making it the cathode in an electrochemical cell.[1] It works by making the entire metallic structure the same energy level at all locations so there are no local anodic and cathodic sites on it. This concept is shown on the bottom pipeline in Figure 3-3. If we are able to shift all of the energy level differences on a pipe to the same number, there will be no voltage difference, which means there is no corrosion current.
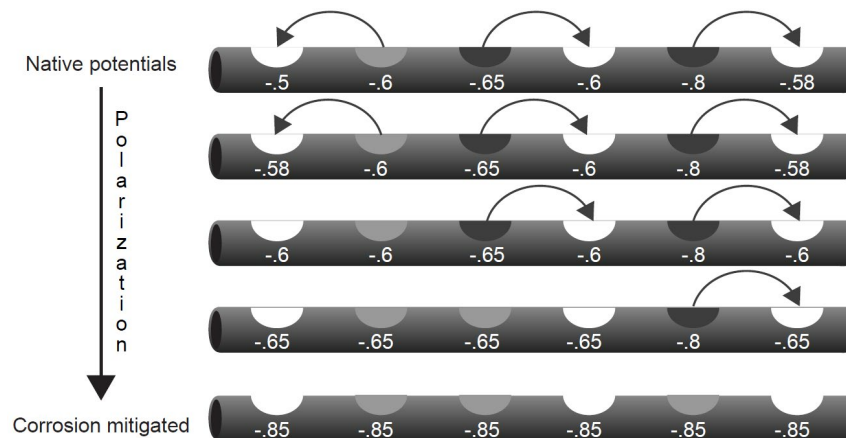
Figure 3-3: Energy Level of Steel Pipe

CP is an effective method of corrosion control. It can be used to control corrosion on bare underground structures. It is commonly used as a supplement to coatings on underground structures.

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[1] (Peabody 2001)

Theory of Cathodic Protection

The basic theory of CP is simple. In Chapter 1 it was discussed that corrosion (metal loss) happens at the anode and no corrosion happens at the cathode. Using this knowledge, if an anode is connected outside of the structure, the anode will sacrifice itself to protect the structure. All the local anodic and cathodic areas on the structure itself will be shifted to the same potential (Figure 3-3), and then corrosion should stop. This is exactly what CP does.

Direct current (DC) is forced to flow into the earth through a sacrificial anode outside the structure and then through the earth to the structure to be protected. The sacrificial anode sacrifices itself to protect the structure. The amount of current forced to flow onto the structure is adjusted to a level which will nullify current discharge on the structure. What had been local anodic and cathodic areas on the structure are now polarized (shifted) to the same number with no voltage difference.

In theory, once the entire exposed metal surface of the structure is collecting current from the electrolyte, the entire structure becomes a cathode and corrosion stops. Hence the name "cathodic protection" for this method of corrosion control.

How Cathodic Protection Works

Figure 3-4 illustrates how CP works. As can be seen in Figure 3-4, some source of DC potential forces current to flow through a wire or cable connection from the protected structure to the anode bed, then through the earth to all metal surfaces of the structure which are exposed to surrounding earth or water, and finally along the structure itself to the drainage cable connection to complete the circuit. It should be noted that current which flows from an underground structure through a metallic connection (such as the CP drainage cable) does not cause corrosion of the structure.
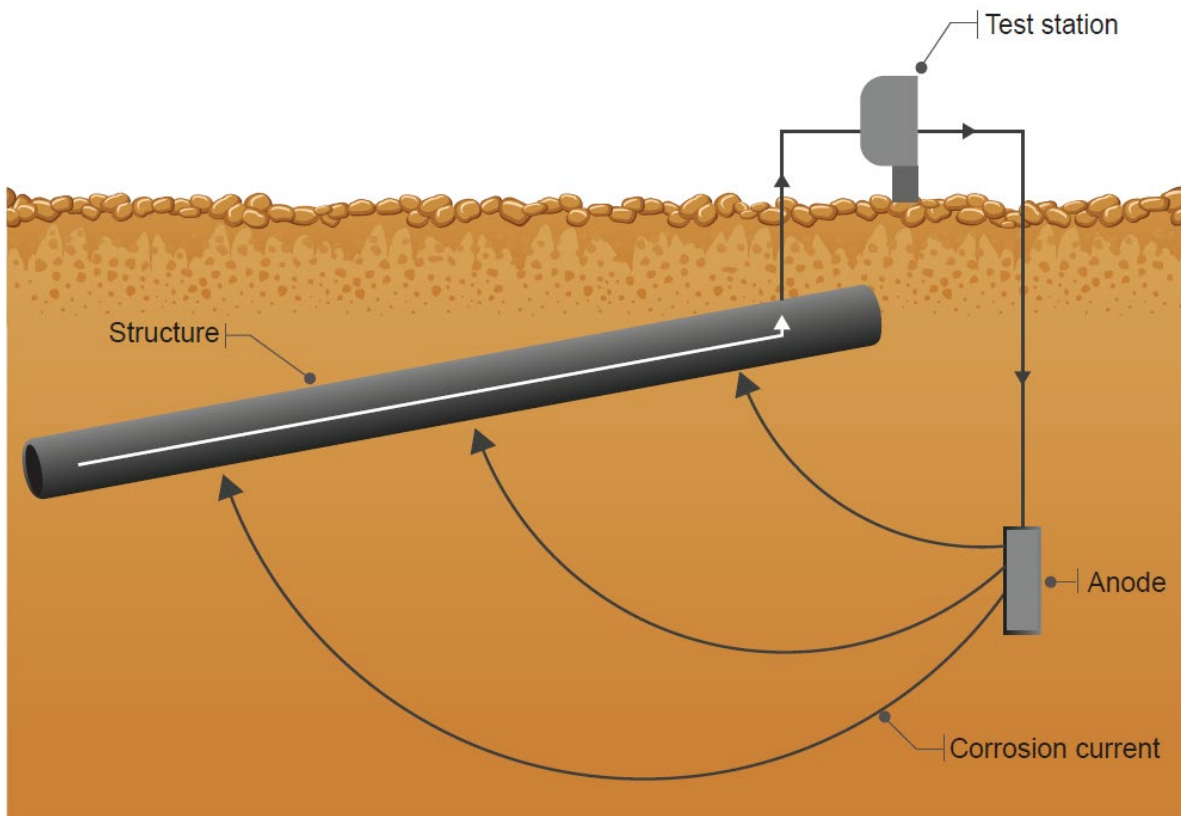
Figure 3-4: How Cathodic Protection Works

In Chapter 2, it was established that any metal that discharges direct current into a conducting electrolytic environment (earth or water) corrodes. This, then, means that the sacrificial anode bed of Figure 3-4 should corrode - and it does. It can be said that in one sense, CP does not eliminate corrosion; it simply transfers the corrosion from the structure being protected to the CP sacrificial anode bed. The anode bed can be replaced periodically without endangering the working structure. Further, anode beds are typically designed to permit discharge of the desired amount of current for a period of years before replacement is necessary.

The amount of current to be discharged from any single CP installation will depend largely on the amount of exposed metal on the structure (or portion of a structure) to be protected by that installation.

At this point, it is important to stress the difference between cathodically protecting an uncoated underground structure and protecting the same structure with a good coating serving as an isolating barrier between structure and adjacent earth or water. If, for example, a bare structure was found to require 100 amperes of CP current to attain complete protection, the same structure with a good coating might require less than one ampere for the same degree of protection.

To take an actual case, a 70-mile length of 26-inch diameter natural gas pipeline with an excellent coating buried in a low resistivity corrosive environment could, during its early life, be completely cathodically protected throughout its length with the current from a single flashlight battery. Had this pipeline been bare, the current required would have been in the order of 2,500 amperes under the most optimistic conditions based on a current consumption of only one milliampere per square foot of bare surface (a typical minimum amount for a new-steel bare structure).

Note that there is no fixed ratio that can be used between current required to protect a bare structure and current to protect the same structure if coated. It depends on the quality of the coating used, the type of structure, and the design of the CP installations used.

The preceding paragraphs do demonstrate, however, that CP and coatings when used together, comprise an effective team. The coating isolates the structure from the electrolyte (soil/water) which provides corrosion protection for the bulk of the structure surface while the CP current seeks out and protects metal exposed to the environment.

Granting that the theory of CP is simple, the question always arises as to how it can be known that full CP has actually been attained on an underground structure. There are several criteria that can be used. These are discussed in detail in the advanced course. At this point, however, one criterion in common usage should be mentioned. This is the measurement of the potential between the structure and a standard reference electrode contacting the environment (i.e., a copper-copper sulfate reference electrode). In the case of steel structures, such potential (energy) measurements made before applying CP will typically (depending on the structure) be in the range of -0.2 volts to -0.8 volts with respect to a copper-copper sulfate reference electrode. With the application of CP current, these structure potentials will move in the more negative direction. When values of at least -0.85 volt are reached at all points, it is a good practical indication that enough CP current has been applied to stop corrosion. It is always possible that there can be local unusual conditions where less than full protection is reached in small areas -- these may not be revealed by the potential measurements taken. With good structure construction practice and effective coatings (if coatings are used), these "unusual" situations or anomalies should be at a minimum.

Types of Cathodic Protection

Figure 3-4 indicates that direct current is forced to flow along the wire from the cathodically protected structure to the sacrificial anode. Forcing current to flow along a wire implies the presence of a driving potential (or voltage). This will always be present as part of a CP installation.

There are two general types of CP installations which differ primarily in the way a voltage is obtained to force CP current through its circuit. These two types are commonly referred to as galvanic (or sacrificial) CP and impressed current cathodic protection.

Galvanic (or Sacrificial) Cathodic Protection

When we use the word "galvanic", we might conclude that a galvanic potential is what forces the current to flow. This is, in fact, the case. This type of CP depends on the voltage difference between dissimilar metals to cause a current to flow. A sacrificial anode that is more negative than the steel is put into the ground. That anode will then start corroding, protecting the structure.

Practical use is made of a dissimilar metal corrosion cell, as was discussed in Chapter 1. In this practical use, however, a dissimilar metal cell is needed that has a substantial driving potential (voltage) between the two metals. For example, if a steel structure is to be protected, the practical galvanic series (Table 3-1) indicates that the initial voltage difference between magnesium alloy and steel could range from -0.8 volt to -1.4 volts (depending on the condition of the steel). This voltage difference can be used to an advantage since, in the steel-magnesium couple, the steel is cathodic, and the magnesium is anodic.

Table 3-1: Practical Galvanic Series

Most energy required for refining	Material	Potential (V)*	Greatest tendancy to corrode	Active
	High potential magnesium	-1.75		
	Magnesium alloy	-1.60		
	Zinc	-1.10		
	Aluminum alloy	-1.05		
	Clean carbon steel	-0.50 to -0.80		
	Rusted carbon steel	-0.20 to -0.50		
	Cast/ductile iron	-0.50		
	Lead	-0.50		
	Steel in concrete	-0.20		
	Copper	-0.20		
Least energy required for refining	High silicon iron	-0.20	Least tendancy to corrode	Noble
	Carbon, graphite	+0.30		

* Typical potentials measured between metal (when immersed in neutral soils or waters) and a copper-copper sulfate reference cell contacting the adjacent soil or water.

The essentials of a galvanic CP installation are shown in Figure 3-5. The anode material can be magnesium (as shown), zinc (lower cell voltage -- used in low resistivity soils generally), or aluminum (lower cell voltage -- particularly useful in a sea water environment). The chemical backfill (Figure 3-5) is normally used with buried magnesium or zinc anodes to obtain uniform anode consumption and maximum anode efficiency. The anode material is normally available in cast shapes of various sizes to fit the requirements of differing galvanic anode CP installation designs.
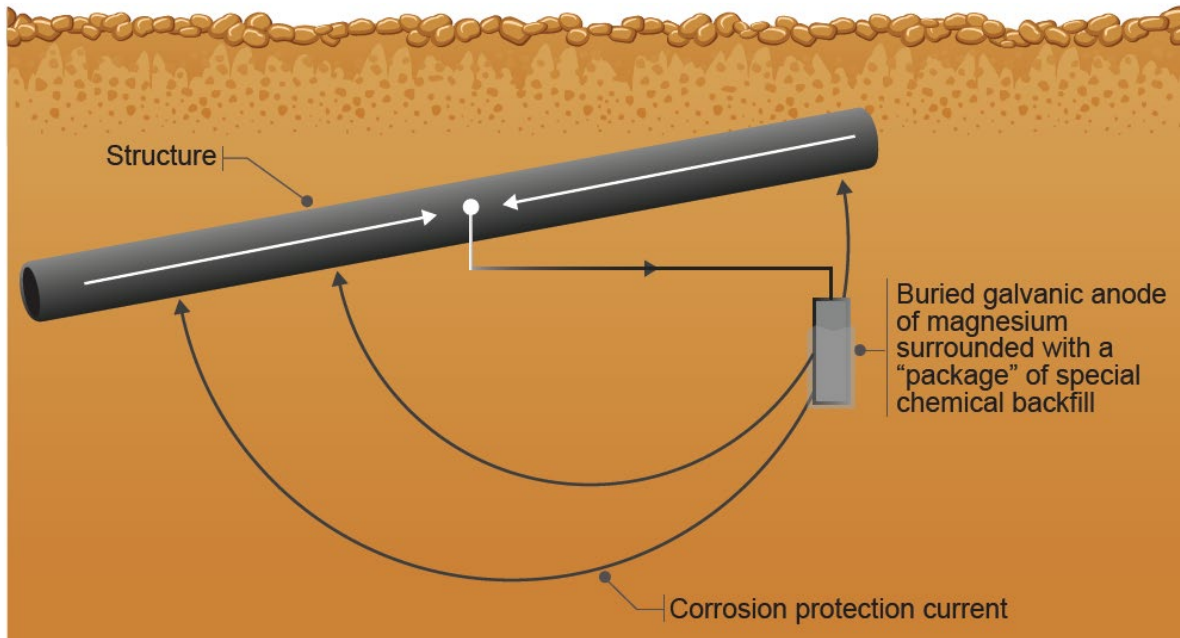
Figure 3-5: Galvanic Anode Cathodic Protection

For very small current requirement at one location, a single galvanic anode may be sufficient. If more current is needed, several anodes may be connected in parallel. Whatever the current output designed for a particular installation may be, the design typically provides for sufficient anode material to discharge design current for a selected period of years before replacement is necessary. This is based on the electrochemical equivalent of the anode metal used with allowances for anode efficiency and replacement before the anode is completely gone.

Galvanic anode installations have the following advantages:

- They are self-powered. No dependence on outside sources of power
- Low maintenance requirements
- Minimum probability of stray current interference on other underground structures
- Easy to install during construction
- Uniform current distribution, due to how they are spaced

Galvanic anode installations have the following disadvantages:

- Limited current output due to low driving potential
- Cannot control the current output
- Anodes will be consumed and need replacement

Impressed Current Cathodic Protection

Where galvanic anode installations are self-powered, impressed current installations utilize a separate, external, source of power to provide CP direct current. The current from this source is impressed on the circuit between the structure to be protected and the anode bed. The essential components of such a system are shown in Figure 3-6.
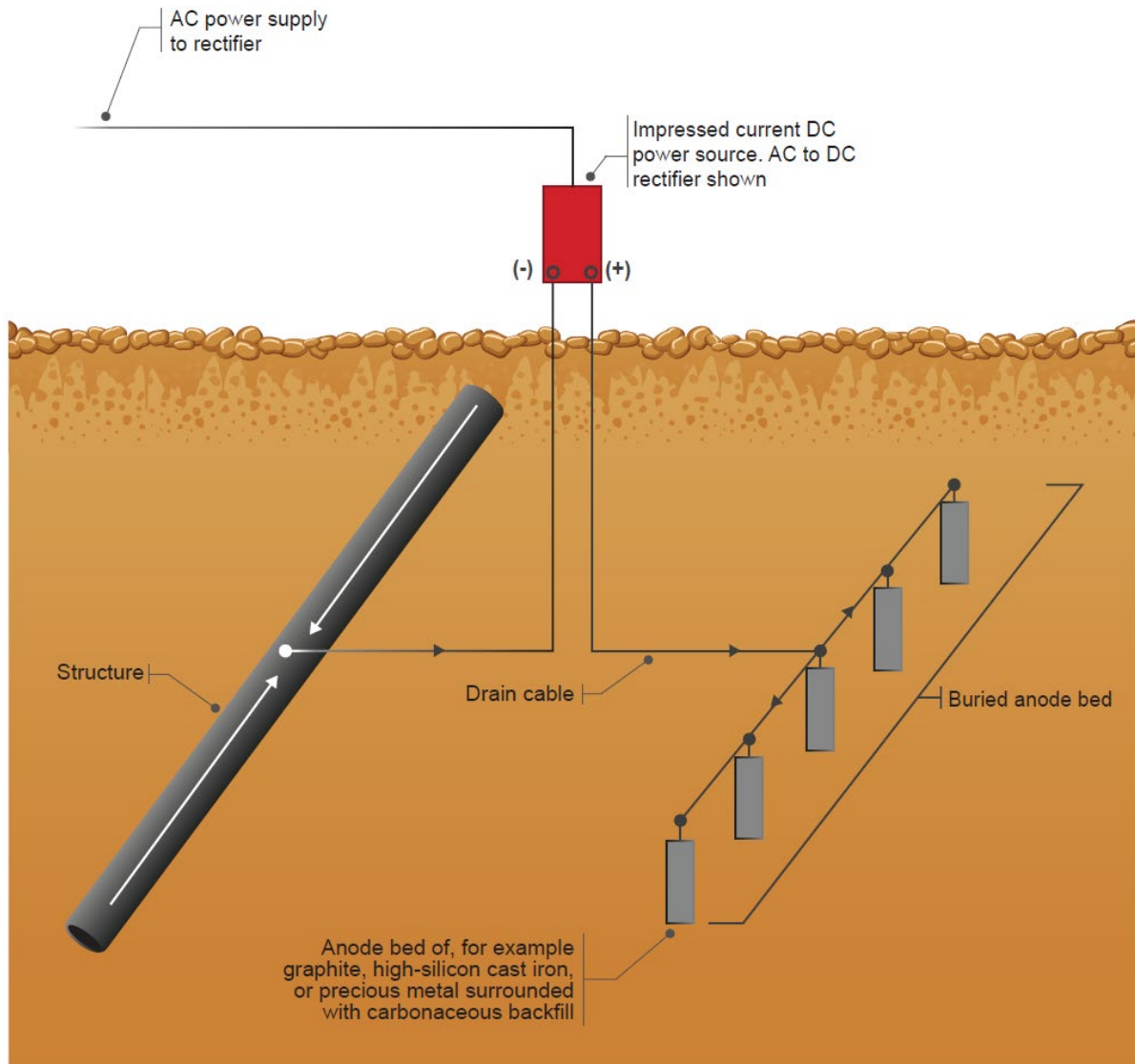
Figure 3-6: Impressed Current Cathodic Protection

An AC to DC transformer rectifier is shown as the DC source in Figure 3-6. Such devices are widely used in CP work. Basically, they convert AC power from a commercial source (such as 120, 240, or 440 volts, single phase or three phase), step down the AC voltage to a more useable level, and then rectify it to DC. The DC output voltage can normally be adjusted so that the desired current can be forced to flow through a range of circuit resistances. Rectifiers are available with a wide range of current output capacity and DC output voltage.

Although the rectifiers more commonly used are those having a fixed output, once adjusted to suit a specific CP installation, there are automatically controlled rectifiers with solid state control circuitry. Units can be obtained which will maintain a desired current output with changes in the circuit resistance. Others

are available which will maintain a fixed potential (energy) measurement by changing the rectifier current as needed to maintain that potential.

Other sources of DC power can also be used. Among these are engine-generator sets which use propane or natural gas to power the engine; solar panels which convert sunlight to DC energy; thermoelectric generators which use a fuel source to heat a series of metallic thermal junctions which generate direct current; and (in some areas) windmill generators which develop the needed DC energy.

Figure 3-6 illustrates one type of anode bed with anodes installed vertically near the surface at a selected design spacing and connected in parallel. The anodes can be installed horizontally. The line of anodes can be perpendicular to the structure rather than parallel to it, as shown. In other designs, the anodes may be placed in a single deep hole (sometimes hundreds of feet deep) to reach a favorable soil formation or to avoid stray current effects on other underground structures in the area. These are commonly referred to as deep anode groundbeds.

The anodes, since they discharge current, will corrode. In order to attain maximum life, low-consumption-rate materials (i.e., graphite, high-silicon cast iron, magnetite, or precious metals) are used. Additionally, such anodes are normally backfilled with a carbonaceous material (i.e., coke breeze or graphite particles) which tends to be consumed by the current discharged before the basic anode material is seriously attacked. The usual anode bed design is such that sufficient anode material is provided to last a period of years at the design current output before replacement is necessary.

Impressed current installations have the following advantages:
- A wide range of DC voltage and current output capacities. This provides great flexibility in system design
- High output for a single groundbed
- Single installations which will protect much larger structures (or portions of structures) than is usually possible with single galvanic anode installations
- Works in high-resistivity environments
- Effective on uncoated or poorly coated structures
- Typically have a longer life than a galvanic CP system

Impressed current installations have the following disadvantages:
- Greater maintenance requirements than for galvanic anode installations
  - 49 CFR 192.465 requires inspections six times per calendar year, with the time between inspections not to exceed 2.5 months
- Dependence on availability of a dependable power supply or fuel supply
- Continuing cost of energy where AC power or a fuel supply is required
- Vulnerable to power outages
- A greater possibility of stray current interference on other underground structures than is the case with galvanic anode installations
- Overprotection can cause issues
  - DC interference
  - Coating disbondment
  - Hydrogen embrittlement

Cathodic protection is applicable to structures subject to galvanic corrosion. It also can be used to offset the effects of lesser stray currents, such as those from relatively remote man-made sources or from telluric currents.

The details of CP system designs are not covered in this introduction to CP. Further information on the construction and design of such systems is contained in the intermediate and advanced courses.

ISOLATING JOINTS

This method of corrosion control utilizes various isolating devices which are inserted in pipelines (or other structures where applicable) and will block the flow of electrical current without disturbing the functional CP requirements of the structure itself.

Isolating joints are useful to:

- Separate dissimilar metals
- Confine CP current to a structure (or portion of a structure) to be cathodically protected
- Confine and reduce the effect of stray current to manageable proportions (where applicable)

An example of the use of isolating joints is illustrated by Figure 3-7. The application shown is the electrical isolation of a new steel pipe replacement in an old steel pipeline system. If severe corrosion has occurred on a section of old pipeline and that section is replaced by a piece of new pipe welded into the old line, the piece of new pipe will be anodic and will corrode with relative rapidity because of being electrically joined to adjacent cathodic old pipe sections.
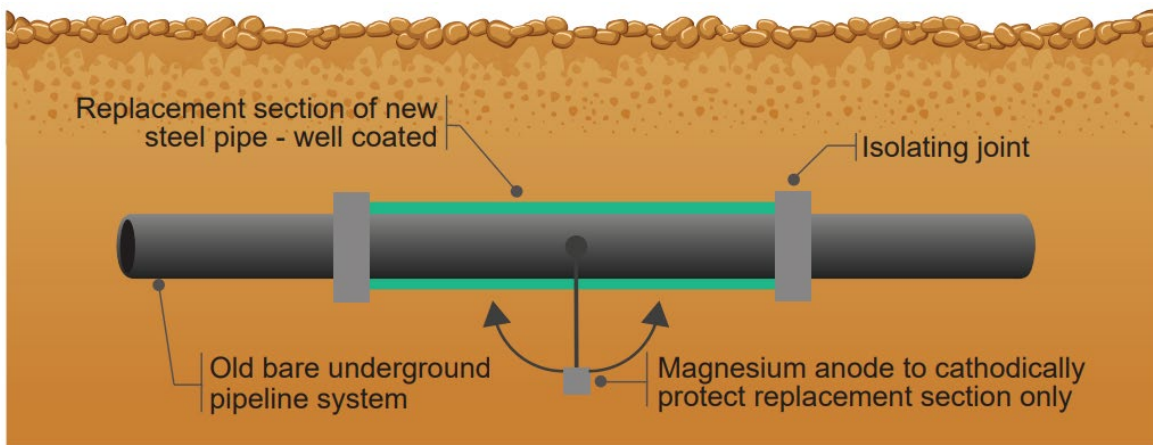
Figure 3-7: An Application of Isolating Joints

An effective replacement procedure, as illustrated, is to make the replacement with well-coated pipe which is electrically isolated from the adjacent system by use of isolating joints. This nullifies the effect of the new steel - old steel galvanic couple. Corrosion is further controlled on the replacement by use of galvanic anode(s) for CP of the replacement. The isolating joints serve to confine the CP current to just the replacement section.

Typically, isolating joints in common usage include but are not limited to, isolating flange sets, isolating compression couplings, proprietary weld-in prefabricated devices, and isolating unions or isolating bushings for threaded pipe assemblies.

Chapter 4 – Introduction to Pipeline Coatings

INTRODUCTION

General – Below Grade Piping

Coatings are the first line of corrosion protection for buried piping. Without the proper use of pipeline coatings, a cost-effective corrosion control program cannot be maintained. Chosen and applied properly, a pipeline coating can extend the design life of a piping system to well over 50 years. However, to be most effective, a pipeline coating must be used in conjunction with cathodic protection. The better the coating, the less cathodic protection is required.

A pipeline coating is a barrier between the pipe and the electrolyte (soil or water) to keep all the corrodents away from the pipeline steel.

As you learned in Chapter 2, there are four components in the fundamental corrosion cell: anode, cathode, electrolyte, and metallic pathway. There will be no corrosion if we eliminate any one of those components. A coating eliminates the electrolyte by isolating the pipe from it.

An effective pipeline coating system must possess excellent cohesive strength and adhesive bond strength to the pipe, be resistant to water penetration, and provide good electrical (dielectric) resistance.

Adhesive strength is a measure of how well the coating is bonded to the pipe. Cohesive strength is a measure the ability of a coating film layer not to pull apart internally or stay bonded to itself.

Desirable properties of coatings:

- Ease of application
- Good adhesion to pipe – adhesive strength
- Good cohesive strength
- Good resistance to mechanical damage
- Flexibility
- Resistance to flow
- Water resistance
- Electrical resistance – dielectric strength
- Chemical and physical stability
- Resistance to soil bacteria
- Resistance to marine organisms
- Resistance to cathodic disbondment
- Resistance to soil stress

Laboratory Coating Tests

Laboratory testing can predict the performance of coatings in the field. Coating manufacturers perform testing on their coatings before marketing them, and users often perform testing on prospective coatings before specifying them. Some tests that are performed are:

- Cathodic Disbondment – When coatings are exposed to cathodic protection currents, the resulting electrochemical reactions force the coating to disbond, losing adhesion to the pipe. The test simulates a coating exposed to these conditions by putting a small hole in the coating on a plate, submerging that area in a saltwater solution and applying a voltage across the coating using a platinum anode with the steel plate as the cathode. The conditions in testing are more severe (more voltage and higher temperature) than in the field to accelerate the disbondment and allow the test lab to quickly compare coatings' performances against each other. This test is run at a combination of 70˚F, 165˚F, and 180˚F; and for a duration of 24 hours, 48 hours, and/or 28 days. This is the most import laboratory test for how below grade coatings will perform in the field.

Figure 4-1: Cathodic Disbondment Test at 149˚F, 3.5 Volts of Cathodic Protection, and for 24 Hours

- Hot Water Soak Adhesion – This test is similar to cathodic disbondment in that it immerses a coated plate in salt water. There is no holiday and no voltage. This test is run at 167°F and/or 200°F. After 24 hours, 48 hours, and/or 28 days the plate is removed from the water, dried, and the coating is inspected for adhesion with a utility knife by cutting a rectangle in the coating and then attempting to remove the coating with a utility knife. The rating scale is visual and based on percentage of the coated rectangle that can be removed.
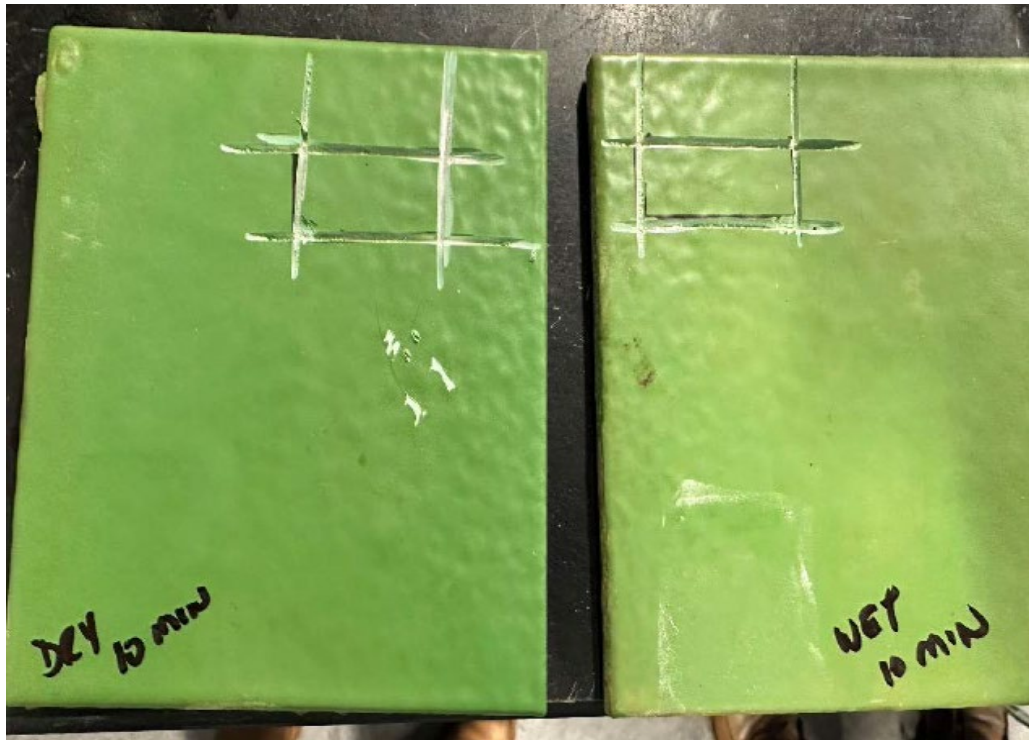
Figure 4-2: Hot Water Soak Adhesion Test

- Dry Adhesion – There are many methods of determining the dry adhesion of a coating. One of the more common is to glue a fixture, called a dolly, to a coated plate and then use mechanical, pneumatic, or hydraulic pressure to attempt to pull the dolly off of the plate. It is then possible to determine the adhesion in pounds per square inch (psi).

Figure 4-3: Dolly Pull Off Adhesion Test

- Flexibility – Flexibility of the coating is important during construction and installation of the piping. Piping is bent in the field to change direction of the pipeline or follow the terrain. One-inch by eight-inch straps of coated plate are cooled in a freezer to prescribed temperatures (often 0°F, -18°F, or 32°F) and then bent to a specific degree or until the coating cracks.

Figure 4-4: Bend Test

- Impact Resistance – Below grade coatings are subject to soil stress and potential mechanical damage, especially during backfilling, covering the piping with soil after it is placed in the ditch. Impact resistance is measured in the lab using a 3/8″ round metal ball bearing which is dropped from increasing heights with increasing weights until the substrate is exposed. The determination if the substrate is exposed is done by electrical inspection (holiday detection/jeeping) discussed in the next section.

Electrical Inspection of Coatings

Any time the steel (sometimes called a substrate) is exposed to the environment this is a defect, sometimes called a holiday. The defects can be microscopic, just large enough to allow water or air to penetrate. An electrical inspection tool called a holiday detector is used to search for these defects. By using a criterion of 125 volts per mil (one mil=1/1,000 inch) of minimum specified coating thickness, one can pinpoint "holidays" or defects in the coating without dielectrically breaking down the coating. NACE SP-0188 lists standard test procedures for setting the holiday detector voltage when electrically inspecting for coating defects. If there is uncertainty in the field as to the proper setting, one may test simply by creating an intentional holiday in the coating. By running the holiday detector over the flawed coating area several times, one can determine through trial and error the proper setting. Normally this is done by listening to a "jeeping or beeping" sound emitted when the detector finds a holiday.

Figure 4-5: Holiday Detector

When using a holiday detector, it is best practice to check the voltage with a separate, calibrated voltmeter. Specialty voltmeters are available from the holiday detector manufacturer. It is also extremely important to keep the tail piece grounded to the earth to complete the circuit. When it is not possible to achieve a proper ground to the earth, one must ground the tail piece directly to the pipe.

Surface Preparation Standards

Pipeline coatings are applied either at a coating facility or in the field. In either case, proper surface preparation of the pipe is the most critical factor in the successful performance of a coating. AMPP has published standards listing various degrees of surface preparation. SSPC SP1 - Solvent Cleaning, SSPC SP6/NACE #3 - Commercial Blast Cleaning, or SSPC SP10/NACE#2 - Near-White Metal Blast Cleaning are generally the preferred surface preparation processes required prior to the application of any coating in a coating facility or in the field. These cleanliness standards require abrasive blasting.

SSPC SP2 - Hand Tool Cleaning and SSPC SP3 - Power Tool Cleaning methods of surface preparation are sometimes utilized in the field for repairing small coating defects.

The surface preparation prior to the application of a plant or field applied coating must always meet the coating manufacturer's specifications. Different coatings require different levels of surface cleanliness and surface profile. Failure to meet all the manufacturer's requirements may result in premature coating failure. Studies by AMPP have shown more than 75% of coating failures are due to inadequate surface preparation.

PLANT APPLIED COATINGS

General

Several types of pipeline coating materials are applied in a factory where controlled conditions and repetitive coating may be performed with excellent coating performance at the lowest costs.

Fusion Bonded Epoxy

The fusion bonded epoxy (FBE) process of coating pipe has gained widespread industry acceptance over the past 50 years. FBE is normally applied with a thickness minimum between 14 to 16 mils. The process involves the baking of powder epoxy onto a pipe surface heated between 425-488°F. An SSPC SP10/NACE #2 - Near-White Metal Blast Cleaning surface preparation is required prior to coating application. It is also critical in the surface preparation stage that all chlorides (salts) be removed with an acid wash and subsequent deionized water wash at >1,500 psi. The coating application is precise. Strict quality assurance standards need to be monitored (via inspection) throughout the coating process. Each shift a sample of coated pipe is subjected to all of the tests listed in the Laboratory Coating Tests section. FBE is susceptible to chalking in direct ultraviolet (UV) exposure and it typically overcoated with a UV resistant coating when stored outdoors for more than 12 months. Figure 4-6 shows pipe with a UV protectant clearcoat reaching the end of its service life and starting to disbond.

Figure 4-6: Pipe in Yard with Factory Applied FBE

Extruded Polyethylene

Another plant applied coating that has been around for over 50 years is extruded polyethylene coating. Part of the surface preparation requires removal of moisture and contaminants from the pipe surface. SSPC SP10/NACE #2 - Near White Metal Blast Cleaning is the standard surface preparation. The coating is comprised of an asphaltic-rubberized 10 mil mastic adhesive that is flowed onto the pipe surface. Through heating and cooling processes, an extruded polyethylene layer is then applied over the adhesive. The extruded polyethylene layer of normally 40 mil thickness is basically a mechanical barrier, which serves to lessen the amount of impact experienced during the shipping, handling, backfill, etc. Extruded polyethylene coating ranges from 40 to 60 mil thickness. A sample of coated pipe is subjected to all of the tests listed in the Laboratory Coating Tests section for each shift. While extruded polyethylene is falling out of favor with transmission companies, it is still in use somewhat for distribution lines.

Figure 4-7: Extruded Polyethylene

Three-Layer Polyethylene or Polypropylene

Three-layer polyethylene or polypropylene coating is another plant applied coating that has been around for over 50 years. Part of the surface preparation requires removal of moisture and contaminants from the pipe surface. SSPC SP10/NACE #2 - Near White Metal Blast Cleaning is the standard surface preparation. The coating is comprised of an FBE layer at 7+ mil. Then a layer of copolymer adhesive is applied. Through heating and cooling processes, an extruded polyethylene (or polypropylene) layer is then extruded over the adhesive. The extruded polyethylene layer of normally 20-75 mil thickness or more is a mechanical barrier, which serves to lessen the amount of impact experienced during the shipping, handling, backfill, etc. Each shift, a sample of coated pipe is subjected to all of the tests listed in the Laboratory Coating Tests section. Three-layer polyethylene and propylene are less favored in the US and North America compared with FBE.

Coal-Tar Enamel and Asphalt Enamel

Coal-Tar Enamel and Asphalt Enamel coatings applied at the coating plant were used extensively in the past. However, due to environmental constraints, very few if any coating plants still apply hot coal-tar or enamel coatings. Normally, the Tar, Glass, and Felt (TGF) or the Tar and Felt (TF) systems of the past were very popular. Most coal tar and enamel coatings were comprised of 120 mils plus in thickness. As a lot of rehabilitation work still involves coal-tar and asphalt enamel coated pipe, it is imperative to use field-applied repair coatings that are generically compatible with coal-tar enamel and/or asphalt enamel. Note that coal tar and asphalt enamel coatings applied prior to 1980 may contain asbestos fibers.

Figure 4-8: Coal Tar Epoxy

Liquid Epoxy

Liquid epoxy applied at the coating plant is used as a primary coating as well as an Abrasion Resistant Overcoat (ARO) for trenchless installation like horizontal direction drill (HDD) or bore pipe. The liquid epoxy is generally applied by spraying.

Figure 4-9: Plant Applied Liquid Epoxy

Other Plant Applied Coatings

Other plant applied coatings that can be considered specialty-type coatings include epoxy polymer concrete, concrete epoxy, polyurethane epoxy, and dual-layer fusion bonded epoxy. Many of the specialty-type plant coatings are becoming popular because they fill an application need. HDD and boring of pipeline has become a common installation practice in the pipeline industry due to environmental concerns associated with wetlands and land-use. Most of the specialty coatings possess excellent impact resistance qualities, which make them good candidates for that type of application, as well as providing extra backfill protection in rocky areas.

FIELD APPLIED COATINGS

General

Once the pipe is shipped to the jobsite from the coating plant, the field coating of girth welds and repair of damaged areas becomes important. Various types of field applied coatings used for repair or girth welds during new pipeline installation include liquid epoxy coatings, hot-applied tape, cold-applied polyethylene tape, heat-shrink sleeves, and fusion bonded field-applied epoxy.

Note: It is always best to use the same or similar field coating for weld joints as the plant applied coating and a coating compatible with the plant applied coating for coating repairs. With FBE being the preferred plant applied coatings, two-part liquid epoxies are the most used field coating.

Liquid Epoxy

Liquid epoxy includes many formulations including ones with other chemistries added, like urethane.

Liquid epoxy in its various forms is being used extensively in the field for coating repair, mainline application to girth welds, coating of uncoated pipe sections, and as a field applied ARO for HDD and bore pipe.

Liquid epoxy coatings are used due to their high electrical resistance, resistance to soil stress, high abrasion resistance, and ease of application. Liquid epoxies may also be used as an effective internal pipe lining for flow enhancement and internal corrosion. Due to its abrasion resistance, liquid epoxies will stand up to pigging operations on internally lined pipes.

Field surface preparation for liquid epoxies is normally SSPC SP10 - Near- White Metal Blast Cleaning with a sharp angular profile at 2 to 5 mils. The blast media is normally coal slag or garnet. As always, verify the surface preparation requirements with coating manufacturer. Abrasive blasting may be accomplished with hand blasting or an automated blast ring.

Care must be taken to ensure the air supply for blasting and sprayable cartridge application is clean, dry, and oil free. Driers may be used to condition the air.

Field application is accomplished via hand (brush, pad, or roller application), sprayable cartridge, plural component hand spray, and automated spray ring. Normal film thickness is between 20 and 50 mils for normal corrosion protection applications. A thicker film is required for bore pipe applications. The required film thickness must be verified with the coating manufacturer as thicker films can become brittle.

Wax Tapes

Commonly referred to as wax tape or petrolatum tape, these tapes are composed of a fabric carrier that is impregnated with various types of waxes including petrolatum and microcrystalline.

Wax tapes are applied extensively in the field for wide ranging applications where surface preparation options are limited and areas such as coating transitions, sweating pipelines, soil to air interfaces, flanges, valves, and environmentally sensitive areas.

Wax tapes are used due to their surface tolerant nature and compatibility with most types of anti-corrosion coatings. In some situations, abrasive blasting is not an option for surface preparation. Generally, with wax tapes the only surface preparation required is an SSPC SP2 or SP 3 cleaning. This requires only a wire brush or power tool cleaning. An anchor profile is not required.

Once all loose mill scale, rust, paint, and other contaminants are removed, a primer is typically applied by gloved hand, brush, or roll in a very thin layer. Once the primer has been applied, the wax tape is spirally wrapped using a 1" or 55% overlap depending on the type of tape and the situation.

If applied to an irregular surface such as a flange or valve, a molding (profiling) mastic can be applied to fill any voids and to create a smooth profile to wrap with the wax tape. Profiling mastic is sometimes called "bird seed."

In certain applications where mechanical damage is a concern, a protective outerwrap (i.e., a PVC tape or a moisture cured fiberglass wrap) can be applied over the wax tape.

Figure 4-10: Applying Outerwrap Over Wax Tape

Viscoelastic Tape

Viscoelastics are amorphous non crystalline a-polar polyolefin coatings. Their semi solid compound properties fall between a solid and a liquid. Viscoelastic coatings are used for girth welds, coating transition areas, soil to air interface areas, pipeline rehabilitation, casing end seals, tank chimes, and bell & spigots.

The minimum surface preparation required for most applications is an SSPC SP2 or SP 3 cleaning (hand and power tool cleaning). A primer is typically not required. Once all loose mill scale, rust, paint, and other contaminants are removed, the viscoelastic coatings are applied by spirally wrapping. Once applied, the layers will adhere to itself and the substrate. Generally, a protective outerwrap (i.e., PVC Tape, PE Tape, or moisture cured urethane wrap) is applied over the viscoelastic coating with significant tension.

One unique feature of viscoelastic coatings is the "self-healing" effect. Due to the tension of the protective outerwrap and the semi solid nature of the viscoelastic compound, if damaged during backfill, the compound may flow into limited sized areas and prevent a holiday.

Viscoelastic mastic compounds are available for applications that involve irregular surfaces such as flanges, valves, cad welds, and casing end seals, which can then be overwrapped with the viscoelastic coating.

Figure 4-11: Viscoelastic Tape Coating

Hot-Applied Tape

Hot-applied tape is generally a 60-80 mil bitumen tape product that consists of a blend of tar and high-temperature scrim. Hot-applied tape is used in conjunction with a primer.

The tape is heated with a weed burner or wide mouth burning torch and applied to the pipe. On some types of hot-applied tape, a glossing over on the outside surface of the tape provides a degree of quality control to the application and is often recommended. Hot-applied tape should be spiral wrapped tightly around the pipe utilizing a 50% overlap of product. The purpose of using a 50% overlap is to provide better resistance to soil-stress. Hot-applied tape is highly recommended as a coating repair for existing coal-tar enamel and asphaltic type coatings.

Hot applied bitumen tape possesses good dielectric strength and excellent chemical resistance. Hot-applied bitumen tape provides good conformability and performance when properly heated with tension. Clean, dry surface preparation of SSPC SP1 - Solvent Cleaning, SSPC SP2 - Hand Tool Cleaning, or SSPC SP3 - Power Tool Cleaning are required for its application.

Figure 4-12: Hot-Applied Tape

Cold-Applied Tape

Cold-applied polyethylene tape with an elastomeric synthetic-butyl adhesive is available in thickness ranging from 30 mils to upwards of 65 mils. Most cold-applied tape requires a liquid primer with its application. Some cold-applied tapes have an integrated primer and do not require a liquid primer if the temperature is over 40°F. However, a clean and dry surface preparation including SSPC SP1 - Solvent Cleaning, SSPC SP2 - Hand Tool Cleaning, or SSPC SP3 - Power Tool Cleaning as minimal surface preparation is required. When possible, using a primer with any tape or heat shrinkable system provides a superior application.

Viscoelastic coatings, described previously, is a type of cold-applied tape; they use amorphous viscoelastic adhesive instead of synthetic-butyl adhesive. Viscoelastic coatings have some of the same advantages of other cold applied tapes like only requiring SSPC SP2 – Hand Tool Cleaning or SSPC SP3 Power Tool Cleaning for minimum surface preparation. Most viscoelastic coatings do not require a primer. Thicknesses for viscoelastic coatings are generally in the 50-100 mil range and in aggressive soils an outerwrap is preferred.

In the case of HDD or boring applications of pipeline, other field-applied coating materials should be considered. Rock shield and/or select backfill should always be used as an option when harsher than normal soil conditions exist.

Figure 4-13: Cold Applied Tape

Heat-Shrink Sleeves

The heat-shrink sleeve is another method of coating girth welds. The heat-shrink sleeve is normally 70-90 mils in thickness and consists of cross-linked polyethylene. On the surface of the sleeve, there are built-in design features that indicate to the user when enough heat has been applied to the shrink-sleeve.

With the shrink-sleeve application, a filler material/sealant should be used over the longitudinal seams and girth weld beads. A pre-cut shrink-sleeve of correct length with a width of 12" or 18" is wrapped around the girth weld area. Heat then is applied with a torch proceeding from the weld seam outward towards the edge of the sleeve. Upon completion of the heating process, a closure strip is often applied over the end of the lap to ensure that a 3" to 4" overlap of material is maintained on top.

When possible, using a primer with any tape or heat shrinkable system provides a superior application.

Fusion Bonded Epoxy

The FBE type of field application for girth welds can be used on any diameter pipe coated with FBE at the coating plant. It becomes more economical when large diameter pipe is being coated and/or where substantial footage is involved. The process is similar to the plant coating application, whereby the pipe must be cleaned per SSPC SP1 – Solvent Cleaning then abrasive blasted to an SSPC SP10 - Near-White Metal Blast Cleaning. An induction heater heats the pipe to 425-488°F. FBE epoxy powder is then flocked/sprayed onto the weld surface using a shrouded applicator that transverses around the circumference of the pipe. Typically, several passes of the application sprayer are required to achieve the specified coating thickness.

By using the FBE process in the field, one can achieve a plant-type coating that is superior in terms of application. Tight standards regarding surface preparation (SP 10) and application temperature must constantly be maintained. A certified coatings technician is usually hired to monitor the coating operation.

Figure 4-14: FBE Coated Pipeline

Maintenance Coatings

Until now, the discussion has centered on pipeline coatings used for new construction. However, several of the field coatings discussed previously (i.e., hot-applied coal-tar tapes, cold-applied polymer tapes and liquid epoxies) are also used for maintenance applications. In addition, liquid mastics, sealants, hot-applied waxes, cold-applied petrolatum/waxes, liquid coal-tar epoxies, high-temperature tapes, and flange-fillers are used for numerous maintenance coating applications. All these coatings work well within their limits and need to be verified to confirm their compatibility with the parent or plant pipeline coatings.

As a result of in-line inspections (ILI), "hot-spot" or "bell-hole" reconditioning and recoating frequently requires the use of heavy-duty maintenance coatings. Many of these coatings are selected based on past experience, cost, and their compatibility with existing coatings found on the pipe. Heavy-duty reconditioning coating materials usually include hot-applied coal-tar tape, cold-applied mesh-backed tape, hot-applied wax, and liquid epoxy. The coating selection again is based on field conditions and compatibility with the parent coating of the pipeline.

Coating of Exposed Pipelines

Another reconditioning application involves exposed piping installed on bridges and engineered spans. In these instances, atmospheric corrosion has corroded the pipe and/or disturbed the original coating through UV degradation. A UV resistant coating is needed.

Generally, above grade piping is coated with the same materials as any other above grade steel requiring protection. The standard system is zinc rich primer, epoxy midcoat, and polyethylene topcoat. The total system is usually 9-15 mils thick.

Risers, valve stems, and other below ground to above ground transition areas are another application that require reconditioning. Some of the most severe corrosion occurs at the pipe-soil and air interface area of a riser. A good system is to bring the below grade coating up at least 12 inches above grade level, and then overcoat that with a UV resistant topcoat down to 12 inches below grade.

Bolted couplings and flanges, valve pits, and fittings associated with the maintenance of piping would be another type of field coating application. In these instances, ease of application with a "field friendly" coating material are of paramount importance. A liquid mastic or a petrolatum/wax type of application have been used frequently in these situations. In wet conditions or where pipe constantly sweats, petrolatum/wax tape coatings are appropriate along with moisture cured specialty liquid coatings.

High Temperature Coatings

Another area where existing coatings often become deteriorated and sometimes fail is on high-temperature discharge header type applications. These areas are found at natural gas compressor sites where pipe runs out from the compressors to the aftercoolers. In the past, plant applied coatings were used because little else was available at that time. Coal-tar epoxy, high temperature amine epoxy or high temperature cold applied tape with primer or high temperature cold-applied petrolatum/wax tape were used to recondition those areas. Now higher temperature resistant FBE or two-part liquid coatings are being used.

Coating of Flanges and Flange Bolts

As part of an atmospheric inspection program, operators check flanges and bolts within flanges. There are numerous ways to coat existing flange bolts and arrest the corrosion process. One method involves pumping flange-filler with a caulking gun into the flange until the entire area is filled. This stops any corrosion processes

from continuing. The flange-filler, however, must not shrink, must provide dielectric resistance, and must be easily removable upon re-entry into the flange.

Another method involves flood coating the flange with hot-applied wax coating.

After filling the flange annular space, a flange band or flange tape needs to be applied to keep the flange filler material from leaking out of the flange.

Another common method is to prime the flange and bolt area and then fill the gaps and smooth the sharp transitions with a mastic material, often called "bird seed." Then a tape coating (wax or mastic based) is used to complete the system. An outerwrap may be used in areas with aggressive backfill.

A better solution can be to use precoated studs and nuts with a factory applied zinc primer and Teflon containing topcoat.

Outerwrap

When coatings will be exposed to aggressive installation methods like HDDs and road bores, it may be advantageous to apply outerwrap over the corrosion coating and even over the ARO. These outerwraps are often composites consisting of a woven fabric impregnated with a moisture cured resin that harden after exposure to water. These wraps are applied with significant hand tension in a spiral method with a 50% overlap resulting in two or four total layers of protection. These wraps are considered sacrificial, as their only purpose is to protect the corrosion coating underneath. Success has been found with applying the outerwrap to the first few joints of pipe on the HDD/bore, on just the girth weld area to mitigate the extra damage from the height of the girth weld being forced through the hole, or on the entire string of pipe. Many types of these outerwraps are non-shielding and the corrosion coating underneath can be holiday detected through them.

Figure 4-15: HDD Pull Head with Outerwrap Before Pulling

Figure 4-16: Outerwrap on Girth Weld After Pullback

CONCLUSION

In conclusion, there are many excellent plant-applied and field-applied pipeline coatings on the market today. However, not every coating is good for all applications. Assistance from an expert when choosing coatings is paramount. Surface preparation is the key to all coatings' success.

Chapter 5 – Potential Measurements

INTRODUCTION

While performing underground Cathodic Protection (CP) work, making accurate potential (energy) measurements on metallic structures is critical to assessing corrosion. If measurements are not made correctly or unsuitable instrumentation is used, inaccurate conclusions on the need for corrosion control can be the result. Also, when potential measurements are used for evaluating the effects of a CP system, inaccurate potential readings can lead to entirely incorrect conclusions regarding the performance of that system.

POTENTIAL MEASUREMENTS

When a metallic structure is in an electrolyte (soil or water), a voltage measurement can be made on that metallic structure in reference to another metal or reference electrode. This is called a potential measurement. In other words, a potential reading is telling us how much energy the metallic structure has compared to what it is referencing. The potential (voltage) measurement has many names, including native potential, static potential, or corrosion potential. To take potential measurements, an understanding of the instrumentation used is extremely important.[2]

INSTRUMENTATION

Voltmeters

Voltmeters can be classified as analog or digital. Voltmeters used for measuring potentials between a structure and a reference electrode contacting earth should be of the high resistance type to avoid serious error in the measurement itself.

An analog voltmeter uses a moving needle or pointer that takes a position on a calibrated scale from which the electrical quantity being measured can be read. The movement of the pointer is known as a "D'arsonval movement." The operating principle is based upon electrical current passing through a coil to form an electromagnetic field. The intensity of the moving coil magnetic field is proportional to the amount of current passing through the coil. Even though a voltmeter measures electrical potentials, it is still a current-operated device.

A digital voltmeter is entirely electronic and uses a digital readout module to display the digital characters as the applied electrical signal changes. There is no actual physical movement. The input resistance of the digital voltmeter is typically very high (ten mega-ohms or higher). The high input resistance means that the current taken from the external circuit will be very small. The advantage of this is that there will be very little voltage drop through the external circuit.

Figure 5-1: Digital Voltmeter

Another digital voltmeter that can be used in corrosion work is a variable impedance meter (Figure 5-2). Instead of having a set impedance, a variable impedance meter allows the user to switch between different impedance levels to attain the most accurate reading through the external circuit.

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[2] (Peabody 2001)

Figure 5-2: Variable Impedance Meter

Effect of Voltmeter Resistance on Potential Being Measured

In corrosion control work on underground structures, the most common potential measurements are taken between the structure and a reference electrode contacting the surface of the earth. The resistance between the structure and the connections to the voltmeter can be very high - in some cases thousands of ohms. This resistance is called the external resistance, R_e.
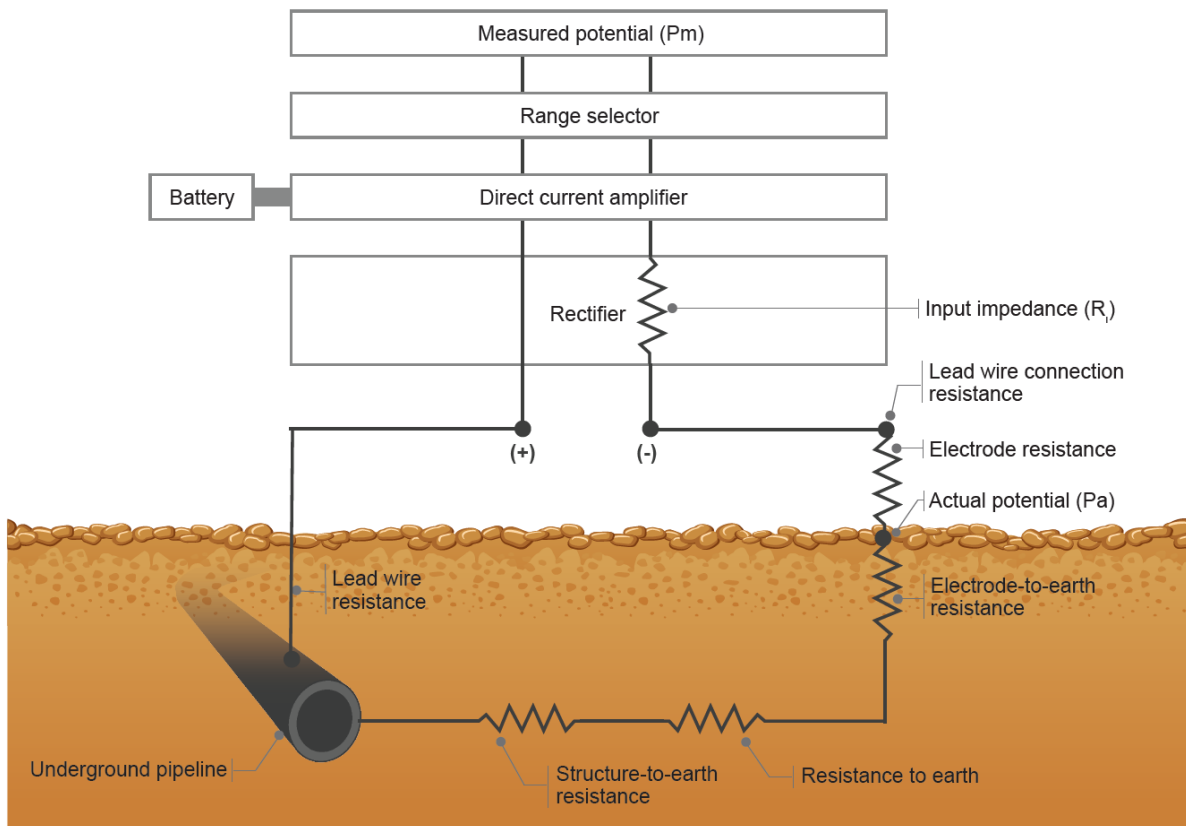

Figure 5-3: Digital Voltmeter Operation Showing Components of External Resistance (Re)

To obtain accurate potential measurements, the internal input resistance of the meter (R_i), referred to as the meter impedance, must be very high with respect to the external resistance (R_e). Failure to understand and observe this fact will lead to inaccurate field data due to error in the potential measurement.

The importance of taking accurate potential data cannot be overemphasized. These measurements are not only required for compliance reports but are also essential to determine the effectiveness of CP.

Modern digital voltmeters, such as those used today for potential measurements, have a very high meter impedance (R_i), typically 10 megohms or more. This impedance is the same for all the voltage ranges on the instrument. When these instruments are used, the external resistance seldom causes a problem.

It is important to use the correct voltmeter when making potential measurements. As mentioned earlier, accurate potential measurements are essential to provide the data required for compliance reports and to establish the effectiveness of CP. A 10 megaohm meter impedance is generally enough for a digital voltmeter to eliminate significant errors, but in certain conditions a higher megaohm meter may be required.[3]

Care and Storage of Instruments

Corrosion test equipment needs to be treated with care. For reliability, it must be treated as delicate equipment during transportation and field use. Instruments must be kept clean and maintained in good working order. When instruments are returned to storage between field usage, they should be inspected and calibrated (where necessary) for the next time needed. Any batteries should be removed to prevent the possibility of battery leakage which may cause internal corrosive damage to the instrument.

REFERENCE ELECTRODES

To get accurate, repeatable readings, we need to have a stable reference point. A reference electrode has a stable and repeatable potential and can be used to measure the potential of other metals.[4] An analogy that helps with this is asking the question: How tall is the ceiling in the room you currently are in? 10 feet? 8 feet? Whatever the amount, a follow-up question would be 10 or 8 feet from what? The floor, most likely; this is your reference point or your zero point. That same logic applies to taking potential readings. All potential readings need to be in reference to something known.

In corrosion control testing of underground metallic structures, we frequently need to measure the voltage potential between the structure and its electrolyte (soil or water). We can measure the potential difference between the structure and some other metal that is also in contact with the electrolyte, but the problem with this is we don't know what that reference point is. It is not as simple as inserting the end of the test wire into the ground or connecting it to a steel or copper rod in the electrolyte even though a reading can be obtained. These readings are useless as they are not in reference to a known, stable, repeatable reference point. Further, they will not be applicable to some of the criteria for protection since the potential reading would be inaccurate.

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[3] (NACE International TM0497-2018)
[4] (NACE International SP0169-2013)

This problem was solved with the development of reference electrodes which are used to contact the electrolyte. The reference electrode is a known, stable reference point. A reference electrode is simply a device that is used to contact the electrolyte and be connected to one terminal (negative side) of the voltmeter; the other terminal (positive) of the voltmeter is connected to the structure a potential is taken from (Figure 5-4).
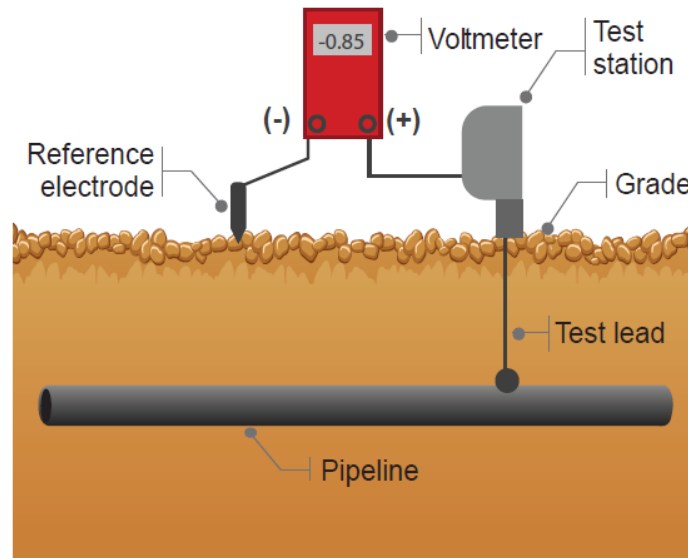

Figure 5-4: Reference Electrodes

To be suitable, a reference electrode must have a stable "half-cell potential." A reference electrode is one-half of a corrosion cell consisting of a metal in a solution of its metal ions. The "half-cell" potential is constant if the concentration of metal ions in the solution around the metal remains constant.

Copper\Copper Sulfate Electrode (CSE)

The most common reference electrode used in underground CP testing is the saturated copper/copper sulfate reference electrode. This electrode is sometimes referred to as "a half-cell," "copper sulfate," "$Cu/CuSO_4$," or "CSE." The components of a typical saturated copper/copper sulfate reference electrode are shown in Figure 5-5.
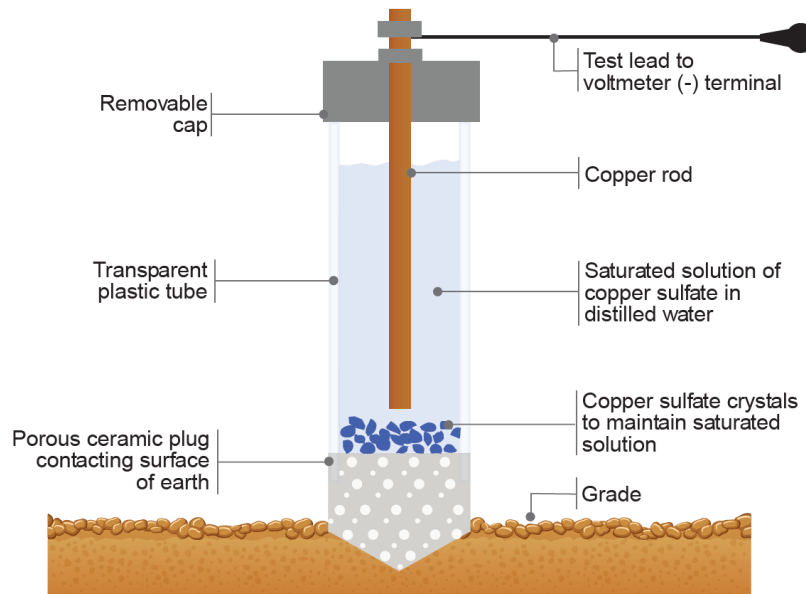

Figure 5-5: Copper-Copper Sulfate Reference Electrode

As previously stated, in order for a reference electrode to be suitable, it must have a constant half-cell potential or reference point. This is accomplished by having the concentration of metal ions in the solution around the metal remain constant. With the saturated copper/copper sulfate reference electrode, this is achieved by having a constant concentration of copper ions (saturated) in the solution around the copper rod.

Use & Care of a Copper Sulfate Electrode (CSE)

The saturated copper/copper sulfate reference electrode is simple and reasonably rugged but there are precautions that must be observed for accurate results.

1. The copper rod must be cleaned regularly so that it is bright and shiny and free of contaminants. The copper rod should be cleaned by using a new, unused, non-metallic scouring pad or sandpaper.

   a. Oxide-type sandpaper cannot be used since it will introduce unwanted metals into the surface of the copper rod.

   b. Do not touch the copper rod with bare fingers after it has been cleaned.

2. The copper sulfate solution must clear and free of contaminants. Only deionized or distilled water can be used for this solution. There are gels and antifreeze solutions made specifically for use in copper/copper sulfate reference electrodes, if desired. Lastly, only high-purity copper sulfate should be used.

3. The tube must contain a saturated solution of copper sulfate. To ensure this, there must be copper sulfate crystals visible in the solution. If no crystals are visible, more will need to be added.

4. The porous plug (ceramic or wood) provides electrical contact between the reference electrode and earth. Verify the porous plug is free of damage and debris.

   a. If the plug is dry, the measured potentials may be inaccurate. When new electrodes are prepared, the wood plugs should be moistened for at least 24 hours prior to use.

   b. Ceramic plugs are usually fast wetting and can be used shortly after the reference electrode is made.

   c. When the electrode is not in use, the porous plug should be covered with a protective cap to prevent it from drying out.

5. Best practice is to verify the accuracy of the field electrode periodically. To verify accuracy, the field electrode will have to be calibrated to a calibration electrode. A calibration electrode is a reference electrode that has not been used in the field so that it remains uncontaminated by the electrolyte. A new reference electrode can be prepared and used as a calibration electrode.

   a. The field electrode can be checked against the calibration electrode by placing the two electrodes' porous tips together in a glass or plastic container with water in it (Figure 5-6).

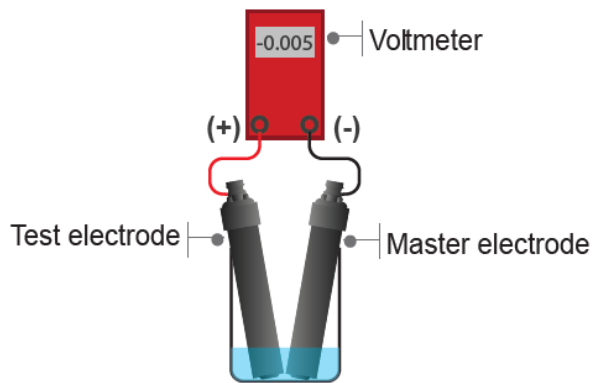   b. In general, if the voltage difference between the calibration electrode and field electrode is more

Figure 5-6: Calibrating Electrodes

than 10 millivolts, the field electrode should be cleaned and remade.

   c.   Once the field electrode is remade, calibration will need to be done again.

   d.   Some companies may require the voltage difference to be less than 10 millivolts.

Temperature Effect on Potential Readings

The potential measurement, although basically constant in other respects, is subject to some variation with changes in the temperature of the copper sulfate electrode above or below a median point of 77°F. Typical temperature corrections are made when a fluctuation of $\pm$ 18°F from 77°F happens.[5] This potential change is in the order of 0.5 mV per °F.

$$mV_{CSE} * = \ -mV_{CSE} + (\frac{0.5mV}{°F})(T - 77°F($$

Where:

$mV_{CSE}* =$ corrected potential

$mV_{CSE} =$ potential read

T =   temperature in °F of copper sulfate solution

If a potential reading measured to a saturated copper/copper sulfate reference electrode is -800mV, it would, for example, be:

- At an electrode temperature of 87°F:

       = -800mV + 0.5 mV (87°F-77°F)

       = -800mV +0.5mV (10)

       = -795mV$_{CSE}$*

- At an electrode temperature of 57°F:

       = -800mV + 0.5 mV (57°F-77°F)

       = -800mV + 0.5mV (-10)

       = -810mV$_{CSE}$*

Knowledge of this effect could be useful when making critical measurements. In summary, readings taken while the reference electrode is at a lower temperature become more electronegative.

Ultraviolet Rays (UV) Effect on Potential Readings

The other characteristic is an ultraviolet (UV) effect caused by sun striking the copper sulfate electrode. If this happens, it can create inaccuracies in the potential readings collected. This is a factor when sunlight enters the clear window on the reference electrode. The best practice is to place a piece of tape over the clear window so that no sunlight can enter the reference electrode.

Silver/Silver Chloride Reference Electrode (SSC)

A second type of reference electrode that a corrosion worker should be aware of is the saturated silver/silver chloride electrode for use in sea water. This would be used, for example, when working in environments where chlorides (salts) are present, like offshore pipelines and drilling platforms.

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[5] (NACE International 2013)

The need for this arises because chlorides in the environment will contaminate the copper sulfate solution in the saturated CSE reference electrode. This will cause the CSE electrode to be out of calibration. The saturated silver/silver chloride reference electrode does not contain a solution that can be contaminated.

The half-cell potential of the saturated silver/silver chloride seawater reference electrode in 25 ohm-cm seawater is 0.05 volts more negative than that of the saturated copper/copper sulfate electrode. In order to convert saturated silver/silver chloride reference electrode readings to saturated copper/copper sulfate reference electrode readings, add -0.05 volts to the potential reading taken in SSC.[6] For example:

-840mV to SSC in seawater

= -840mV + (-50mV)

= -890mV to CSE

Zinc Reference Electrode (Zn)

A third type of reference electrode that a corrosion worker should be aware of is the zinc reference electrode. Zinc reference electrodes are used in underground, seawater, or freshwater environments.

The half-cell potential of the underground zinc reference electrode at 77°F is 1.1 volts more negative than that of the saturated copper/copper sulfate electrode. In order to convert zinc reference electrode readings to saturated copper/copper sulfate reference electrode readings, add -1.1 volts to the potential reading taken in Zn.[7] For example:

+210mV to Zn

= +210mV + (-1100mV)

= -890mV to CSE

ELECTRICAL SAFETY CONCERNS DURING POTENTIAL MEASUREMENTS

While taking potential measurements, there are a few safety items to be aware of to protect yourself and others from hazards.

- Verify the equipment being used is in good working order
- Inspect insulated test leads and terminals for scrapes, cracks, breaks, and nicks
    - Replace insulated leads if any damage is found
- Take an AC potential on the desired structure first to verify there is no touch potential hazard, utilizing an electrically safe approach. If AC potential is 15VAC or greater, that is a hazard that needs to be mitigated.[8]

Stop working on potential readings and call the appropriate personnel to discuss the safety concern. For more information on AC potential hazards and safety concerns, refer to NACE SP0177.

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[6] (NACE International TM0497-2018)
[7] (NACE International TM0497-2018)
[8] (NACE International SP0177-2019)

STRUCTURE-TO-EARTH POTENTIAL MEASUREMENTS

With an understanding of the instrumentation requirements, limitations, and the use of reference electrodes, consideration can be given to their use in making various types of potential measurements. Structure-to-electrolyte measurements is the most common type made in underground corrosion control work.

Operator Qualifications (OQ)

Prior to performing this task, clients who operate or maintain DOT jurisdictional pipelines typically require Operator Qualifications (OQ). OQs are a set of operator identified evaluations which ensure an individual possesses the appropriate knowledge, skill, and ability to perform the task, and recognize and react to Abnormal Operating Conditions (AOCs).

Basic Steps to take an AC Potential Measurement

Take an AC potential on the desired structure first to verify there is no touch potential hazard, utilizing an electrically safe approach. If AC potential is 15VAC or greater, that is a hazard that needs to be mitigated. Stop working on potential readings and contact your supervisor on the touch-potential hazard.

To take an AC potential measurement:

1. Verify the multimeter is in good working order and that it is calibrated.

2. Calibrate the reference electrode (Use & Care of a Copper Sulfate Electrode (CSE)).

3. Connect the positive lead from multimeter/data logger to the structure itself or test station.
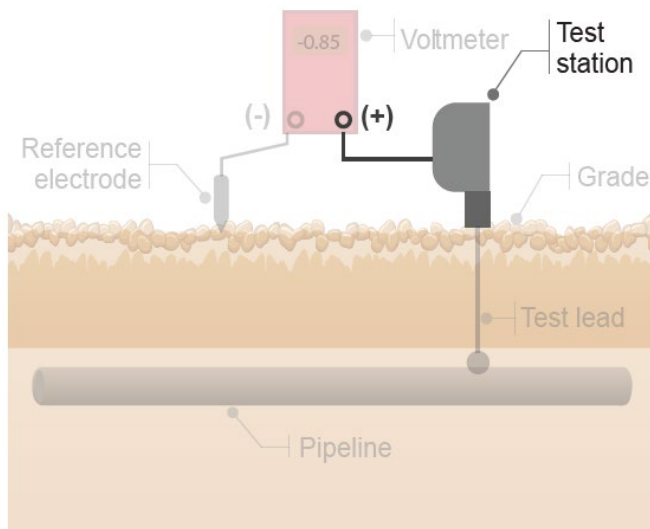
4. Connect the negative lead from the multimeter/data logger to the reference electrode that is contacting the electrolyte (soil/water).
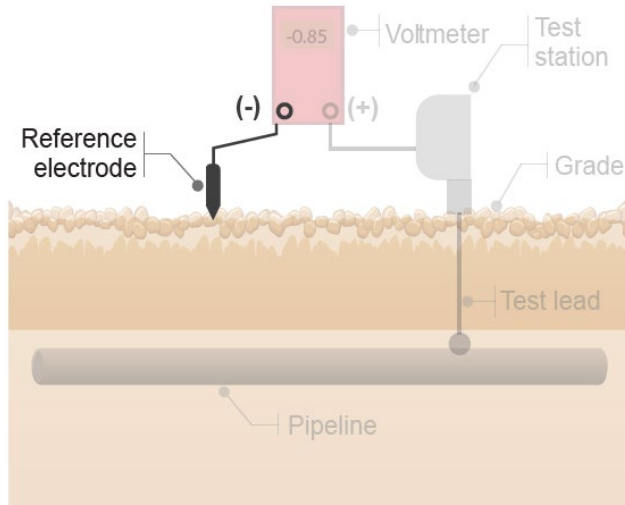
5. Turn multimeter to VAC setting.

6. Take readings and document the following information:

    a. Date

    b. Polarity of reading

    c. Unit of reading

    d. Location of reading

    e. Photographs (as required)

Basic Steps to take an DC Potential Measurement
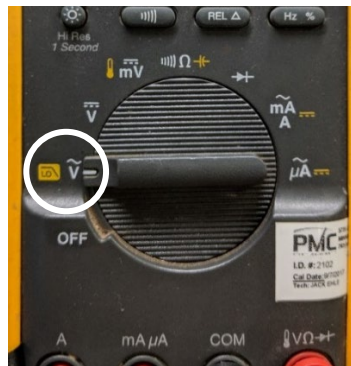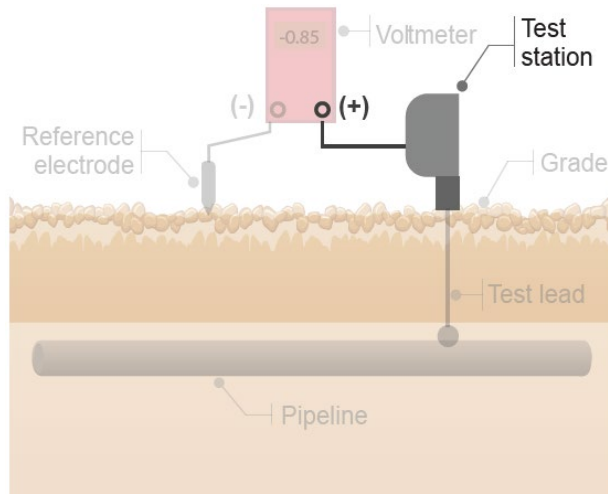
1. Verify Multimeter is in good working order and that it is calibrated.

2. Calibrate reference electrode (Use & Care of a Copper Sulfate Electrode (CSE)).

3. Connect the positive lead from multimeter/data logger to the structure itself or test station.

4. Connect the negative lead from the multimeter/data logger to the reference electrode that is contacting the electrolyte (soil/water).

   a. If soil conditions are dry, "waterpacking" may be required to decrease the contact resistance of the reference electrode.

      i. "Waterpacking" is when water is poured onto the ground at the location where a potential reading is being taken to increase the conductivity of the ground, which can help in providing a more accurate reading.

5. Turn multimeter to VDC setting.

6. Take readings and document the following information:

    a. Date

    b. Polarity of reading

    c. Unit of reading

    d. Location of reading

    e. Photographs (As required)
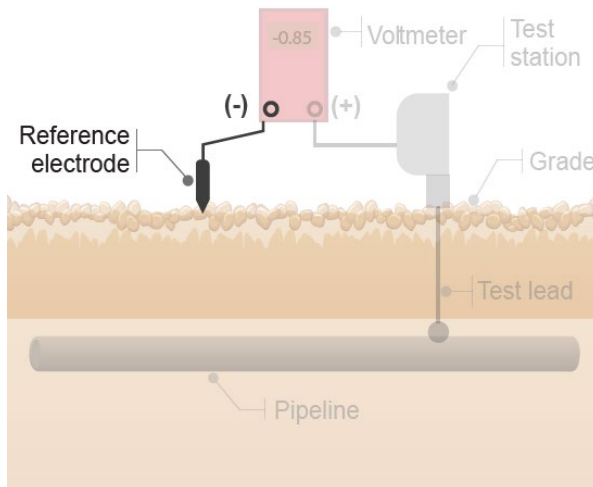
The potential measurement, commonly called the pipe-to-soil potential, should be made using a high input resistance voltmeter (typically 10 megohm or higher)[9] connected between the pipe and a reference electrode located on the earth as close as is practicable to the pipeline (Figure 5-7).
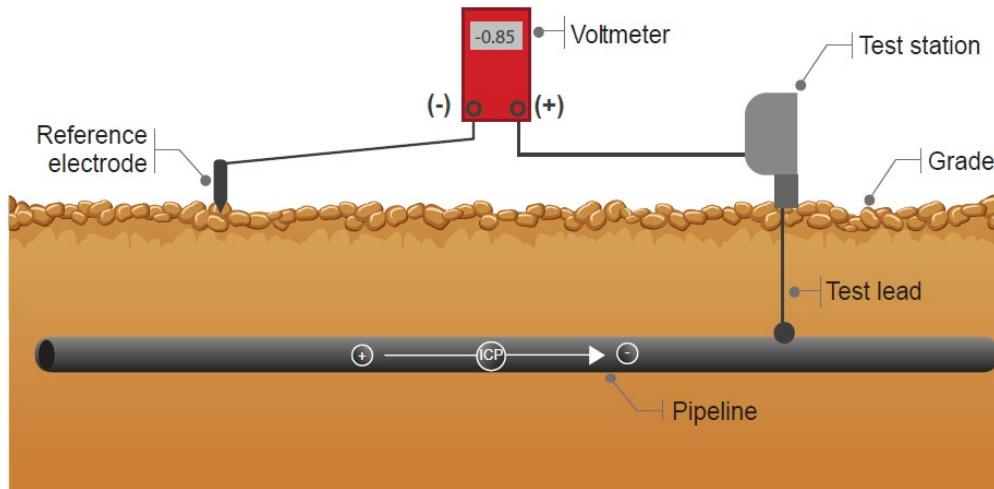
Figure 5-7: Pipe-to-Soil Potential Measurement

On Figure 5-8, it will be noted that the negative (-) terminal of the voltmeter is connected to the reference electrode with the positive (+) terminal connected to the pipe. This is the preferred method. With this polarity, pipe-to-soil potentials are normally negative values (such as -0.850 volts).
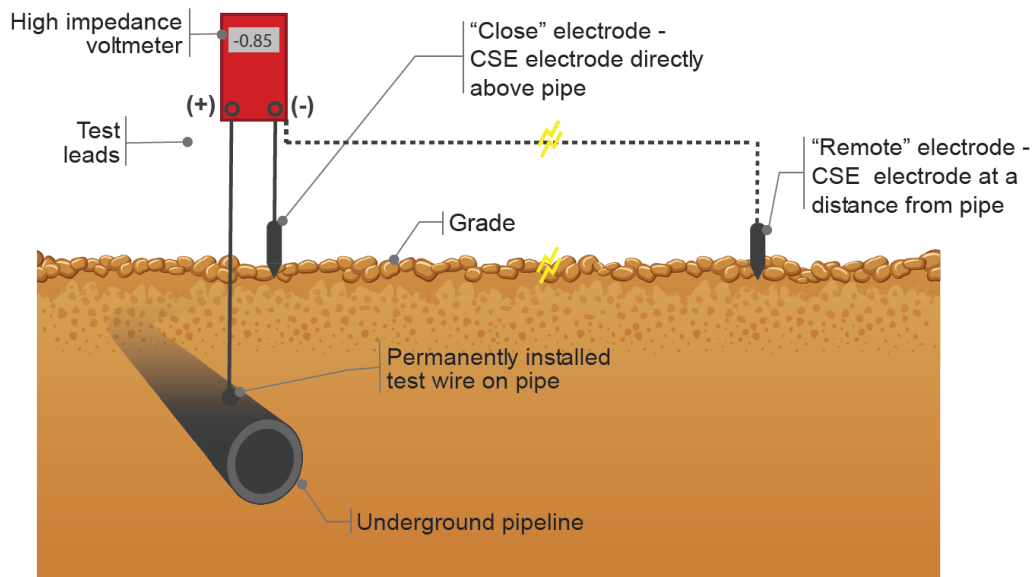
Figure 5-8: Structure-to-Earth Potential Measurement

There can be situations in strong stray current exposure areas where the structure can be positive with respect to the reference electrode (reversed polarity from that shown on Figure 5-8). Readings are then recorded accordingly (such as +0.425 volts). This means that the structure is very strongly anodic and subject to possible heavy corrosion damage.

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[9] (NACE International TM0497-2018)

IR Drop Consideration

When taking a pipe-to-soil potential with CP current flowing or ON, it includes an IR drop (error) in the reading, due to current and resistance in the measurement circuit. This potential measurement not only includes the pipe's polarized potential (E_P) within the influence of the reference electrode, but also the voltage drop in the soil (IR_{soil}) between the reference and the pipe, and the voltage drop in the pipe (IR_{pipe}) between the point of contact to the pipe and the point of measurement. With the CP current ON (applied), the voltmeter measures the total potential difference without being able to distinguish the pipe polarized potential (E_P).

$$V_m = E_p + IR_{soil} + IR_{pipe}$$

In this equation, the IR drops are additive since their polarity is same as E_P and the voltmeter will indicate that the pipe is more electronegative than the actual polarized potential (E_P) because of the IR drop (error) present while current is flowing. It is these IR drop voltages which must be considered for valid comparison to the criteria.
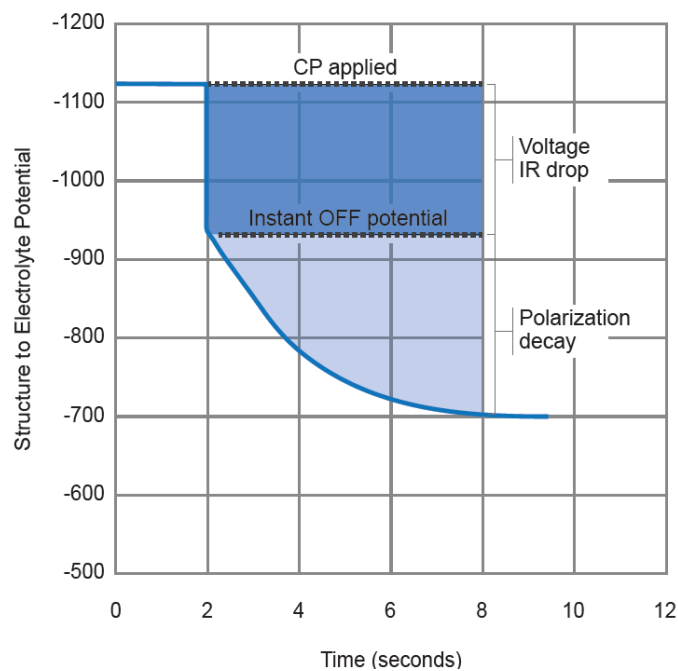
Figure 5-9: Typical ON vs. Instant-OFF vs. Native Reading

Reference Electrode Placement

Figure 5-8 illustrates the most common location a reference electrode is placed while conducting a potential measurement on an underground pipeline. The figure shows, with solid lines, potential measurement to a "close" reference electrode directly above the pipe. This is the most common location the reference electrode should be placed, as it should be as close to the structure as practical so that it has minimum effect on the potential caused by voltage drops in the earth resulting from direct current flowing to or from the pipe.[10]

The dashed line is showing a test lead extension to a "remote" reference electrode location. This may be used on bare pipelines or complex underground systems in checking CP coverage to verify that "long line" corrosion cells have been neutralized. Long line cells being anodic and cathodic areas separated by some distance as opposed to those which may be a few feet or a few inches apart.

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[10] (NACE International TM0497-2018)

As a rule of thumb, the area "seen" by a reference electrode on a bare structure is that subtended by an angle of roughly 120° (Figure 5-10).

Figure 5-10: Area "Seen" by Reference Electrode on a Bare Structure
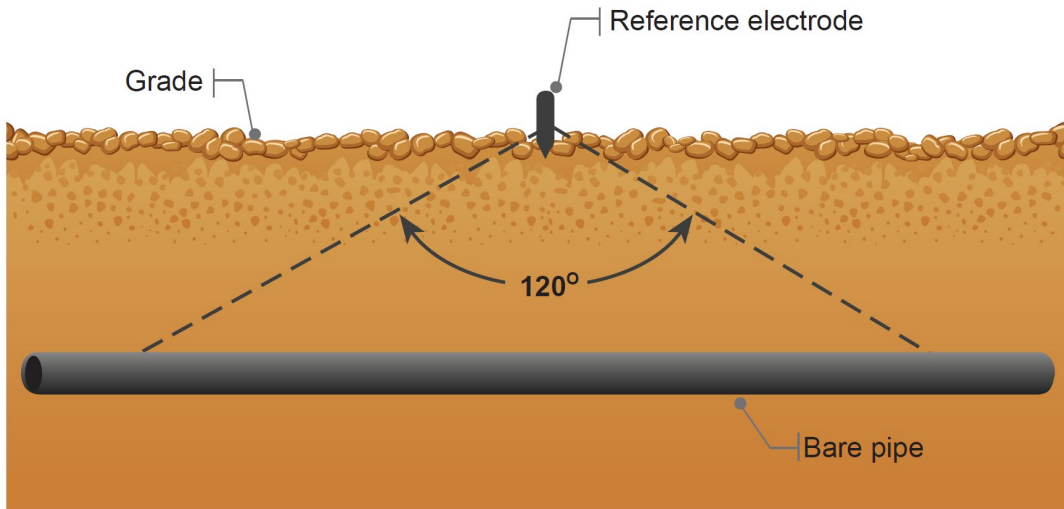
For this reason, the close reference electrode "sees" only a relatively small portion of the bare structure as opposed to the remote reference electrode location.

A "remote" reference electrode is a reference electrode location which is electrically remote from the structure being tested. There is no fixed distance figure for this. It can be determined in the field (for a bare structure) by the following:

1. Take and record a potential reading between the structure and a reference electrode placed 50 feet from the structure, for example.

2. Move the reference electrode further away from the structure by approximately 50-foot increments in a direction perpendicular to the structure.

    a. The structure-to-reference electrode potential is measured and recorded at each location until there is no significant change in the reading from one point to the next. This is an indication that electrically remote earth has been reached.

For large bare pipelines, for example, this distance could be several hundred feet (this is not always the case). The reason for this is because of variations in earth resistivity and its geological structure - both affecting the distance from the bare structure needed to encompass essentially all of the structure-to-earth resistance.

In contrast to bare structures, the structure-to-earth resistance for well coated structures includes the resistance across the coating as the major element of the total structure-to-earth resistance. For this reason, a "close" reference electrode location at a coated structure is, for practical purposes, in the equivalent of electrically remote earth.

Because the amount of corrosion current flowing to or from a well-coated pipe is extremely small, there is little possibility of significant voltage drops in the earth around the pipe. This means that a close reference electrode position directly above the pipe is essentially the same as one at a remote location. This would not be the case if there were strong stray earth currents in the area from some external DC source.

Point-to-point changes along the surface above a coated pipe tend to be much more gradual than on bare pipe.

POTENTIAL SURVEYS

Potential surveys are useful when making a detailed evaluation of the performance of CP systems. Potential surveys can be made in various ways.

Close-Interval Potential Survey (CIPS)

CIPS is a potential survey that consists of making close-interval measurements at regularly spaced intervals to a saturated CSE reference electrode along extensive structures such as pipelines.[11] The Intermediate course covers this specific survey in more detail. Refer to NACE SP0207 for more information on performing CIPS.[12]

Common to all survey methods is the need to locate a pipeline so that the reference electrodes are placed directly above the pipe as the survey progresses. This is normally done with a pipe locator operator (moving ahead of the data acquisition team) who locates and stakes the line.

Although a more detailed discussion of potential survey work and analysis thereof is contained in the Advanced Course, Figure 5-11 is included to give an initial idea of what might be expected of plotted data from a pipeline potential survey. The figure gives an indication of atypical survey taken along a section of a coated pipeline.
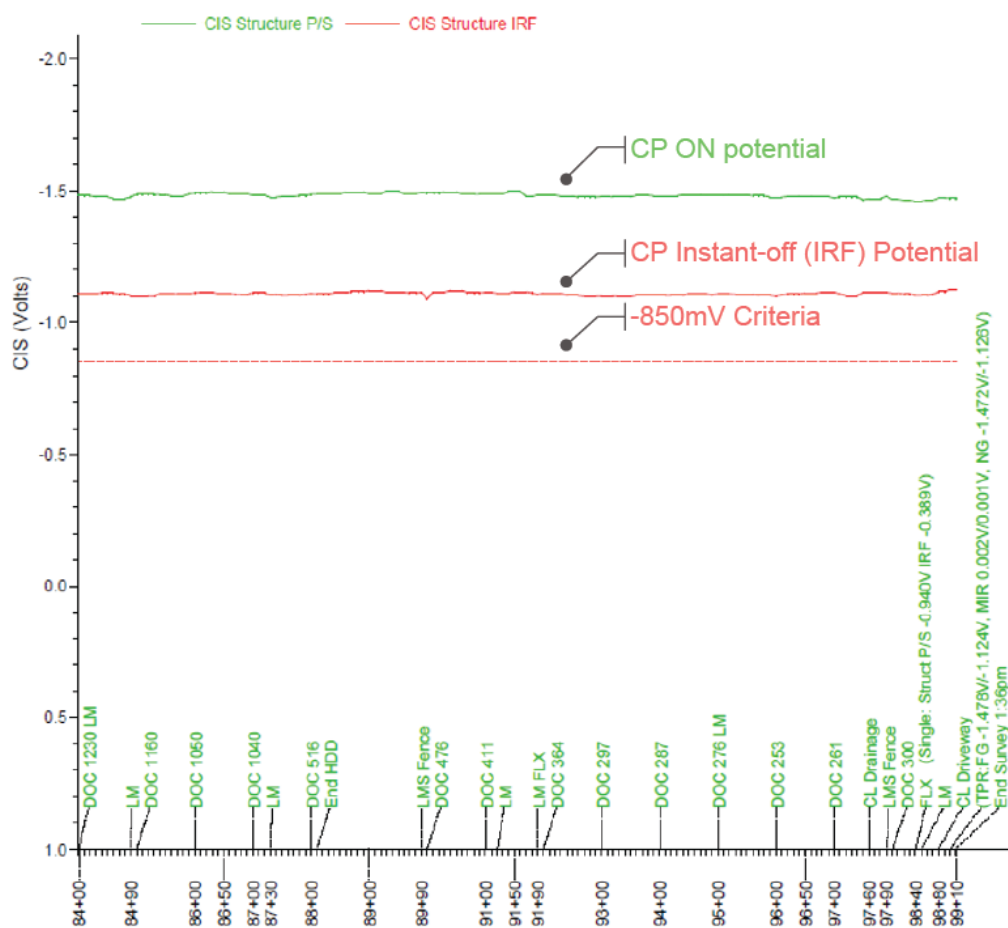

Figure 5-11: Plotted Potential Survey Data

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[11] (NACE International TM0497-2018)
[12] (NACE International SP0207-2007)

POLARIZATION EFFECTS ON POTENTIAL

The nature of a potential measurement between the structure and a saturated CSE reference electrode contacting adjacent earth was discussed in IR Drop Consideration. At this point, it is appropriate to explore the effect of polarization (and depolarization) on such a reading.

Polarization is the deviation from the open circuit potential (native potential) of an electrode resulting from the passage of current.

Figure 5-12 shows the general shape of a polarization curve. If a voltmeter is connected to measure a structure to CSE potential at a test point on a non-protected structure, a native potential (in the absence of stray current effects) will be observed as represented by the horizontal line of Figure 5-12. If, while watching the voltmeter, CP current is applied to the structure, there will be an immediate potential increase (more negative shift) caused by voltage drop in the earth resulting from CP current flow to the structure. This will be followed by a more gradual increase as cathodic polarization builds up to protect the structure.
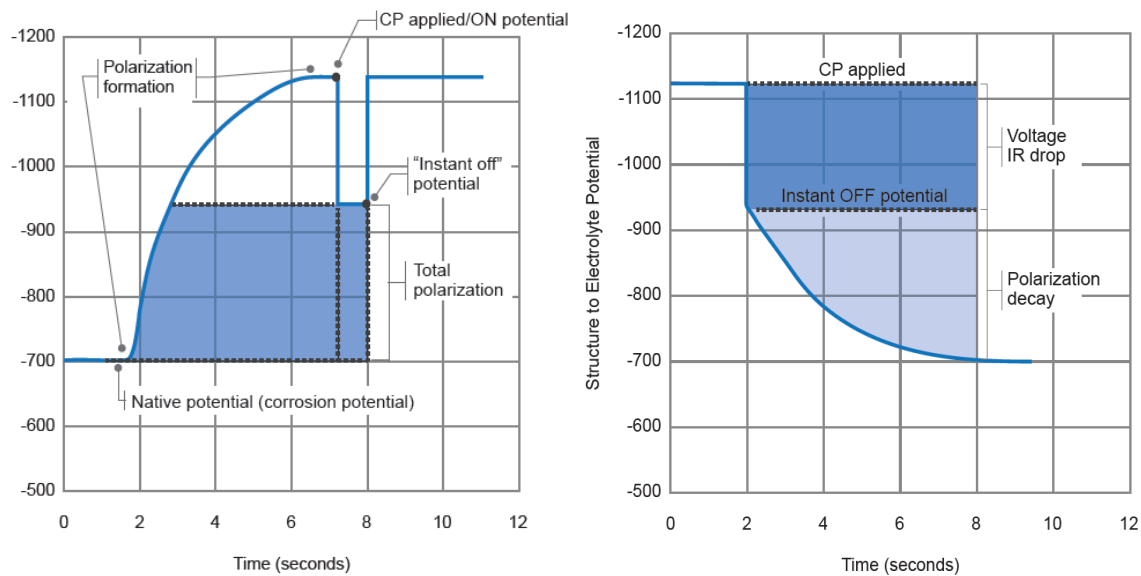
Figure 5-12: Polarization (Left) and Depolarization (Right)

If the structure is bare or poorly coated, the time required for full polarization may be days or weeks because of the large areas to be polarized. On the other hand, a very well-coated structure can polarize very quickly.

Figure 5-12 also represents the reverse situation showing depolarization when CP current is interrupted. Under depolarization, as opposed to polarization, depolarization of a poorly-coating structure tends to be relatively rapid during early stages compared to the rate of depolarization on a well-coated structure.

CRITERIA FOR CATHODIC PROTECTION

Although a more complete discussion of criteria for CP is included in the Intermediate Course, there are two potential-dependent criteria standards, which should be mentioned here:

- -850mV Polarized Potential (Instant-OFF)
- 100mV Cathodic Polarization

-850mV Polarized Potential (Instant-OFF) Criterion

This criterion states that adequate protection is achieved with "a structure-to-electrolyte potential of -850mV or more negative as measured with respect to a saturated CSE reference electrode."[13] The polarized potential is defined as "the potential across the structure/electrolyte interface that is the sum of the corrosion potential and the cathodic polarization."[14] The polarized potential is measured directly following interruption of all current sources and is often referred to as the OFF or instant-OFF potential. The difference in potential between the native potential and the OFF or polarized potential is the amount of polarization that has occurred as a result of the application of the CP. As previously stated, the difference in potential between the ON potential and the OFF potential is the error in the ON potential introduced as a result of voltage drops in the electrolyte (soil) and metallic return path in the measuring circuit. This is commonly referred to as IR drop.

100mV Cathodic Polarization

This criterion uses at least 100mV of structure polarization as an indication of adequate CP. This can be determined on a structure where all sources of CP current affecting that structure can be interrupted at the same instant. With a voltmeter set up to measure structure to CSE potential readings prior to interrupting the current, watch the voltmeter as the CP current is interrupted. Normally there will be an immediate drop followed by a slight hesitation (particularly detectable on an analog voltmeter) which is the start of the depolarization curve. Note the voltmeter reading at that point. Then if there is at least 100mV of depolarization beyond that point, the criterion has been met. If the structure is one that depolarizes very slowly, it could take quite some time to reach the 100mV of depolarization. In this case, it may be helpful to plot potential change with time and then extend the curve to see if it appears that the 100mV of depolarization will be attained. If the indications from this are positive, it is then worthwhile to continue the test until the objective is attained.

MONITORING CATHODIC PROTECTION SYSTEMS

Potential measurements are used to periodically verify that CP on a structure, once attained, continues to be effective. This monitoring can be performed on pipelines by periodic over-the-line potential surveys (CIPS), as discussed earlier in this chapter. At intervals between complete surveys, pipe-to-soil potentials can be measured at test points along the line (Test Point Survey).

There is one caution that should be observed when taking such measurements at test points. This is to avoid placing the reference electrode close to a buried galvanic anode connected to the line. If the reference electrode is placed on the surface above such an anode, the potential reading between pipe and reference electrode will include the voltage drop in the earth caused by current discharge from the galvanic anode. For this reason, the reading obtained will not reflect the correct potential between pipe and earth, due to the IR (error). For example, if the reference electrode were placed above a magnesium anode, the reading between pipe and CSE electrode might be -1,150mV which looks just great, whereas; with the reference electrode above the pipe 15 feet away from the magnesium anode, the reading might be only -650mV. This is quite another story since the pipe is not fully protected if using the -850mV criteria. An alternative approach to minimize IR error would be to collect interrupted readings and measure the polarized OFF potential in addition to the current applied ON potential.

As a rule of thumb, it would be well to place the reference electrode at least 15 feet from the nearest working galvanic anode. Any abnormally high readings could lead one to suspect the presence of a galvanic anode even if its existence is not known. Checking potentials either side of the high reading point should then clarify the matter.

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[13] (NACE International SP0169-2013)
[14] (NACE International SP0169-2013)

Chapter 6 – Current Measurements

INTRODUCTION

In Chapter 5 we learned about measuring voltages. In this chapter we are going to learn about measuring another part in Ohm's Law: Current.

CURRENT MEASUREMENTS

Introduction to Current

Electrical current is the flow of electrons along a conducting path. It is the spark in the circuit or the item that gives energy to our devices. It is typically expressed in units of amperes. The letter "I" is commonly used to designate current. The letter "I" originated from the term "current intensity." Wires and pipes are examples of conductors in corrosion control testing.
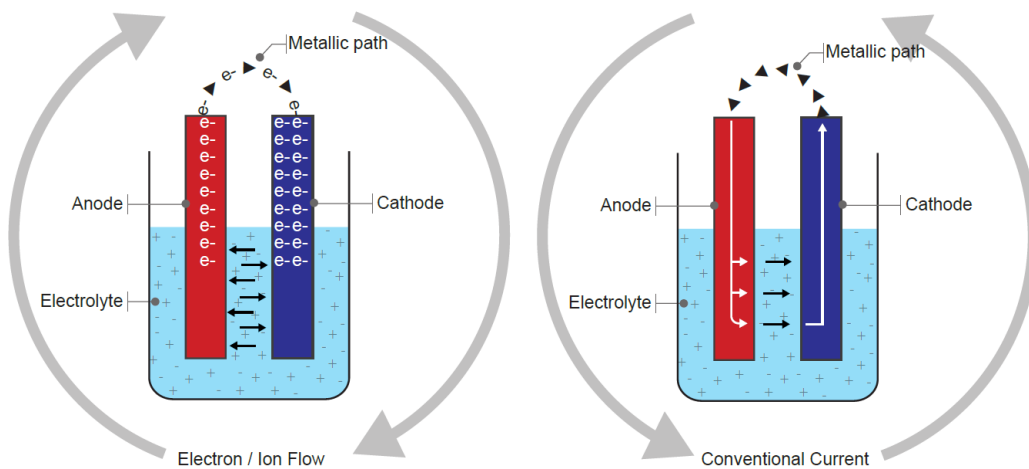
Figure 6-1: Fundamental Corrosion Cell

In corrosion control testing there are many instances where we may want to know how much current is flowing including:

- Current output from a rectifier
- Current output from a galvanic anode
- Current flow through a bond
- Current flow across a bonded electrical isolation device
- Current flow on a pipeline
- Test current for performing tests like a current requirement or resistance test
- Current flow on a coupon test station

In corrosion control testing there are a several methods that can be used to measure current including:

- Measuring the voltage across a shunt and calculating current using Ohm's Law
- Measuring the voltage across a pipeline span and calculating current using Ohm's Law
- Using an ammeter
- Using a clamp-on ammeter

Electrical Safety Concerns During Current Measurements

While taking current measurements, there are a few safety items to be aware of to protect yourself and others from hazards.

- Verify that the equipment being used is in good working order
- Inspect insulated test leads and terminals for scrapes, cracks, breaks, and nicks
- Replace insulated leads if any of the above are found
- Wear appropriate PPE during current measurements
- Always take an AC potential on the desired structure first to verify that there is no touch potential hazard, utilizing an electrically safe approach. If AC potential is 15VAC or greater, that is a hazard that needs to be mitigated[15]
    - Stop working on potential readings and call the appropriate personnel to discuss the safety concern. For more information on AC potential hazards and safety concerns, refer to NACE SP0177.

Measuring Current with a Shunt

The most common way that corrosion testers measure current is by using a shunt. A shunt is a resistor that has a known, constant resistance value. Shunts are installed at rectifiers, bonds, and other locations so that current can be measured without opening the circuit.

To determine current flow through a shunt, the voltage across the shunt is measured and the current is calculated using Ohm's Law or a "Shunt Factor." A Shunt Factor is a rearrangement of Ohm's Law which simplifies the calculation of current.

The current direction is determined by the polarity of the measurement. Current flows from positive (+) to negative (-). If the measurement is positive, the current is flowing from the positive meter connection toward the negative meter connection.

Figure 6-2 shows some common shunts.
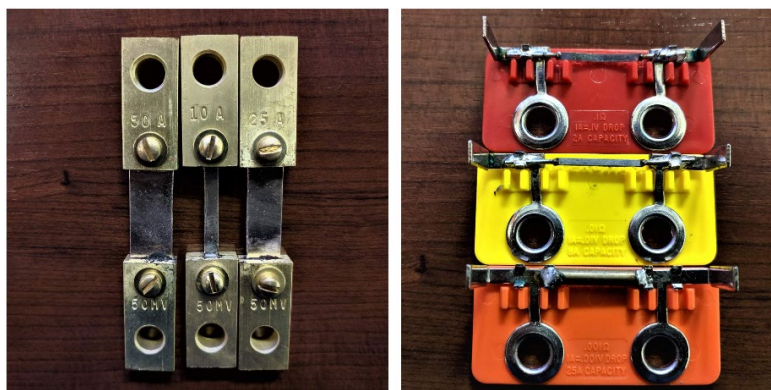
Figure 6-2: Cathodic Protection Shunts

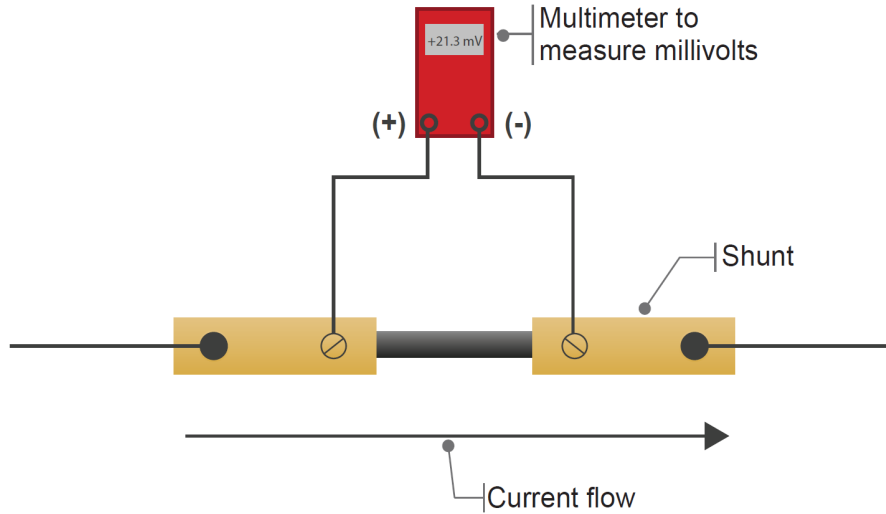[15] (NACE International SP0177-2019)

Measuring mV Across a Shunt

Complete the following to take a mV reading across a shunt.

1. Turn multimeter to mVDC.

2. Connect meter leads to each tab on the shunt. Readings need to be taken off the tabs on the shunt for most accurate reading.

3. Record polarity of reading (mV reading) and the Shunt rating so current can be calculated.

Calculating Current Through a Shunt

Refer to Figure 6-3 for an example of using a shunt to measure current.
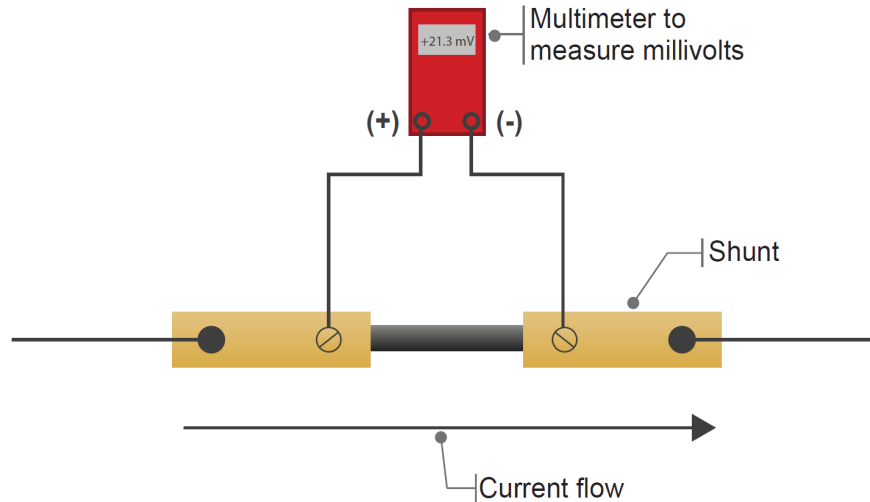

Figure 6-3: Measuring Current with a Shunt

To calculate current through a shunt using Ohm's Law:

- Measure the voltage across the shunt, typically in millivolts
- Convert the voltage from millivolts to volts
- Calculate the current using this form of Ohm's Law: I = V/R, where R is the resistance of the shunt in ohms

Using Ohm's Law:

$$A = \frac{0.0213 \text{ V}}{0.005 \text{ } \Omega} = 4.26 \text{ A}$$

Voltage across shunt = 21.3 mV

Resistance of shunt = 0.005 Ω

Convert mV to V, 21.3 mV = 0.0213 V

A simpler way to calculate current through a shunt is to use a shunt factor. A shunt factor is a rearrangement of Ohm's Law that simplifies calculating current from the millivolt reading. A shunt factor is in units of A/mV. It is calculated by dividing the current rating of the shunt by its millivolt value. Most cathodic protection (CP) shunts have a millivolt value of 50mV. Some shunts have their rating and value stamped on them, as seen in Figure 6-2. Using a Shunt Factor:

I = mV x Shunt Factor

$$A = 21.3 \text{ mV x } 0.2 \frac{A}{mV} = 4.26 \text{ A}$$

Current rating of shunt = 10 A

Millivolt value of shunt = 50 mV

Shunt Factor = 10 A/50 mV = 0.2 A/mV

Measuring Current Flow on a Pipeline

Current flow on a pipeline can be determined by measuring the voltage drop across a pipe span and calculating the current using Ohm's Law. In effect, we are using the pipe as a shunt. To determine the resistance of the pipe span, we can either estimate it using a pipe resistance table or by measuring it directly.

2-Wire Current Test

To estimate the resistance of a pipe span using a pipe resistance table we need to know:

- The length of the pipe span
- The size of the pipe
- The wall thickness of the pipe

Table 6-1 shows the resistance per foot for various steel pipes.

Table 6-1: Resistance of Steel Pipe [1]

Nominal Pipe Size (in)	Outside Diameter (in)	Wall Thickness (in)	Weight per Linear Foot [2] (lbs)	Resistance per Linear Foot [3] (u Ω)
2	2.375	0.154	3.65	79.2
4	4.5	0.237	10.8	26.8
6	6.625	0.280	19	15.2
8	8.625	0.322	28.6	10.1
10	10.75	0.365	40.5	7.13
12	12.75	0.375	49.6	5.82
14	14	0.375	54.6	5.29
16	16	0.375	62.6	4.61
18	18	0.375	70.6	4.09
20	20	0.375	78.6	3.68
22	22	0.375	86.6	3.34
24	24	0.375	94.6	3.06
26	26	0.375	102.6	2.82
28	28	0.375	110.6	2.62
30	30	0.375	118.7	2.44
32	32	0.375	126.6	2.28
34	34	0.375	134.6	2.15
36	36	0.375	142.6	2.03

(1) From "Control of Pipeline Corrosion", NACE, 1967, Peabody.

(2) Based on steel density of 489 lbs/ft^3.

(3) Using 18 :S -cm resistivity for steel:

R = (16.061 x 18 u Ω -cm) / weight per foot in pounds

= 289.1 / weight per foot

= resistance of one foot of pipe in u Ω

Figure 6-4 shows the connections for measuring the voltage drop across a pipe span. The arrow on the pipeline indicates the direction of current flow for the instrument polarity shown. As with a shunt, the current direction is determined by the polarity of the measurement. Current flows from + to -. If the measurement is positive, the current is flowing from the positive meter connection toward the negative meter connection.
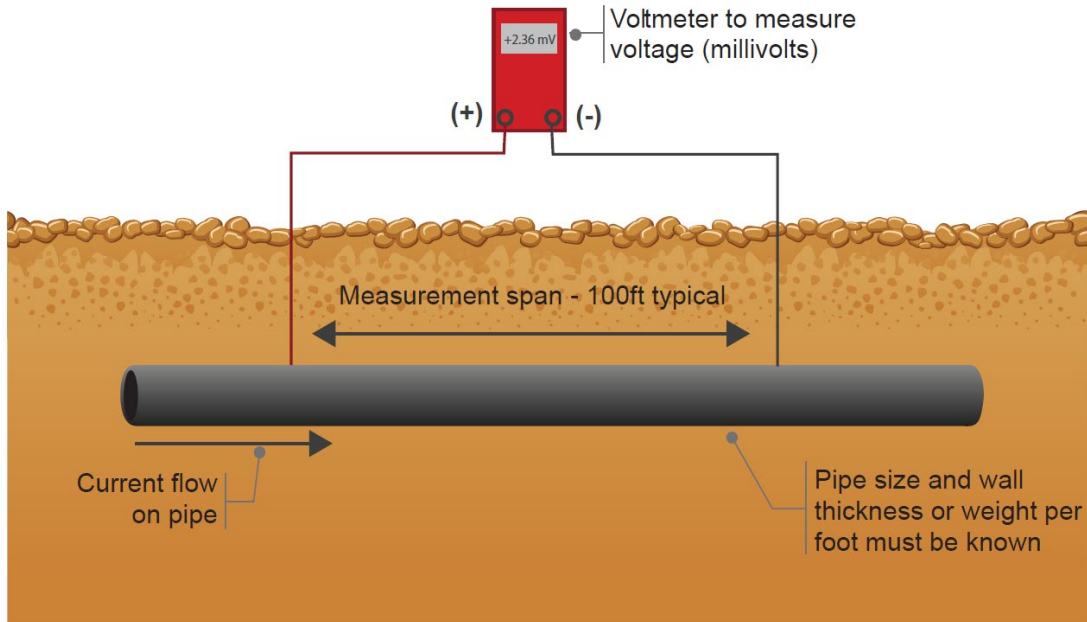
Figure 6-4: Measuring Current Flow on a Pipeline

As you can see in Figure 6-4, we measure 2.36 mV across a 100-ft. span of 12-inch, 0.375" WT (wall thickness) pipe.

First, we need to calculate the resistance of the span. Looking at Table 6-1, a 12-inch, 0.375" WT pipe has a resistance of 5.82 micro-ohms per foot. For a 100 ft. span:

R = 100 ft. x 5.82 micro-ohms/ft = 582 micro-ohms

582 micro-ohms = 0.000582 ohms

2.36 mV = 0.00236 V

Apply Ohm's Law:

$$A = \frac{0.00236 \text{ V}}{0.000582 \text{ } \Omega} = 4.055 \text{ A}$$

4-Wire Current Test

A more accurate way to determine the resistance of a pipe span is to measure it. In order to measure the resistance across a pipe span there must be four wires, with two wires at each end of the span (Figure 6-5).

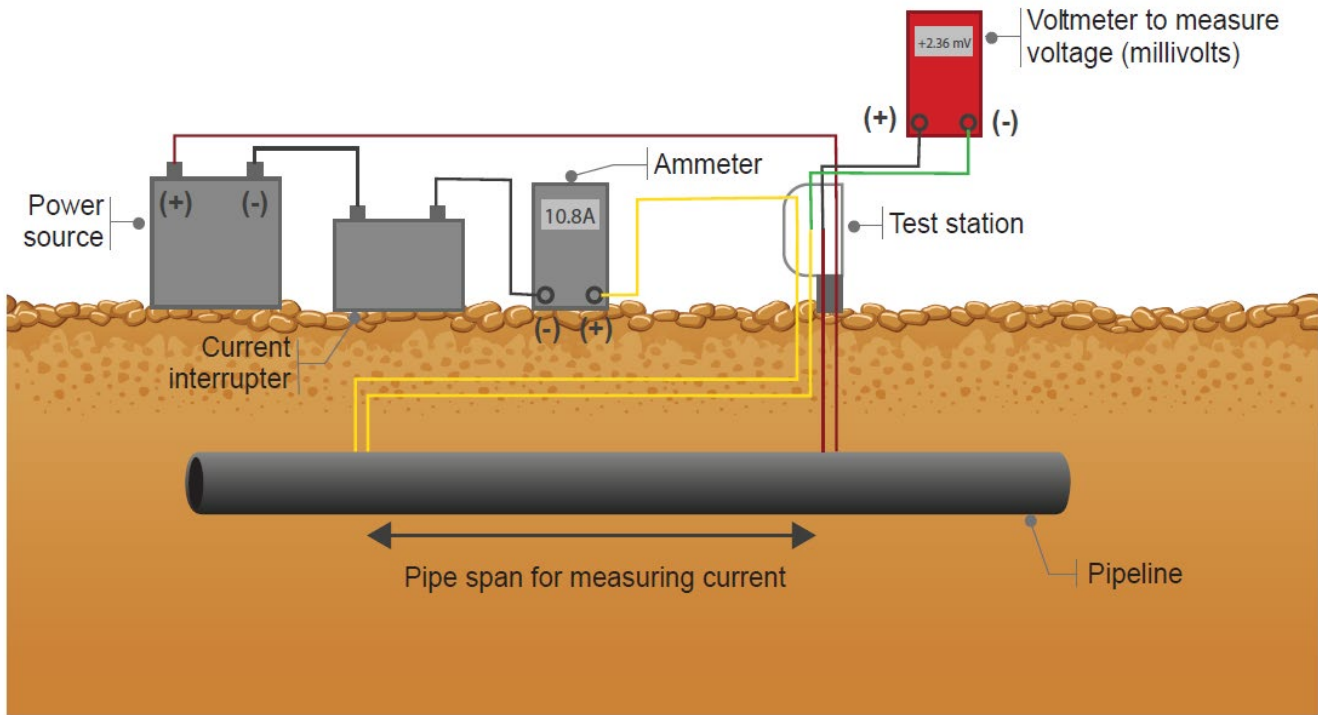**Figure 6-5: Calibrating a Current Measurement Pipe Span**

Figure 6-5 shows the connections for measuring the resistance of a pipe span. As in the previous example, a voltmeter is connected to measure the voltage across the span. A current circuit is set up across the span with a battery and ammeter. When the current circuit is closed, the test current will flow through the span and cause the voltage across the span to change.

The general steps to conducting a 4-wire test are the following:

1. Take as-found voltage reading on the inside leads.

2. Induce test current on the outside leads and take a voltage reading on the inside leads with current flowing.

3. Calculate the calibration factor (K).

4. Calculate the current flow.

Rather than calculating the span resistance in ohms, it is simpler to determine a calibration factor (K factor) in units of amps per millivolt (A/mV) like we do with shunts. For example, assume that a test current of 10.8 amperes is connected across the span and changes the voltage across the span from 2.36 millivolts to 7.31 millivolts. The calibration factor will be:

$$K = \frac{I}{\Delta V}$$

$$K = \frac{10.8 \text{ A}}{7.31 \text{mV} - 2.36 \text{mV}} = 2.182 \frac{A}{mV}$$

After we have determined the K Factor, we can use this value to calculate the amount of current flowing on our pipeline. For example, when we started testing, we measured 2.36 mV across our span. Therefore, the amount of current flowing is:

$$A = K \times mV$$

$$A = 2.182 \frac{A}{mV} \times 2.36 \, mV = 5.15 \, A$$

When calibrating a pipe span, it is critical that there be two wires at each end of the span so that the voltage and current connections to the pipe are separate. Using the same test wire for voltage and current will create a significant voltage across the wire which will be included in the voltage measurement rendering it invalid.

Pipe spans used to measure current can be any length, but the resistance of the span needs to be high enough to allow measurement of the pipeline current with acceptable accuracy. A small amount of current flowing across a short span may not be measurable.

Measuring Current with an Ammeter

An ammeter can also be used to measure current. Most multimeters include an ammeter.

To measure current with an ammeter, you must break the circuit and install the ammeter in series within the circuit so that all the current to be measured flows though the ammeter.

Within the ammeter, the current is flowing through an internal shunt. The meter measures the voltage across the shunt and displays current.

The primary drawback of this method is that the circuit must be opened and the ammeter inserted in it.

An ammeter is used to measure current in circuits where a shunt has not been installed, such as galvanic anode beds or bonded electrical isolation devices. Figure 6-6 and Figure 6-7 show an ammeter being used to measure galvanic anode current and current across a bonded electrical isolation device.
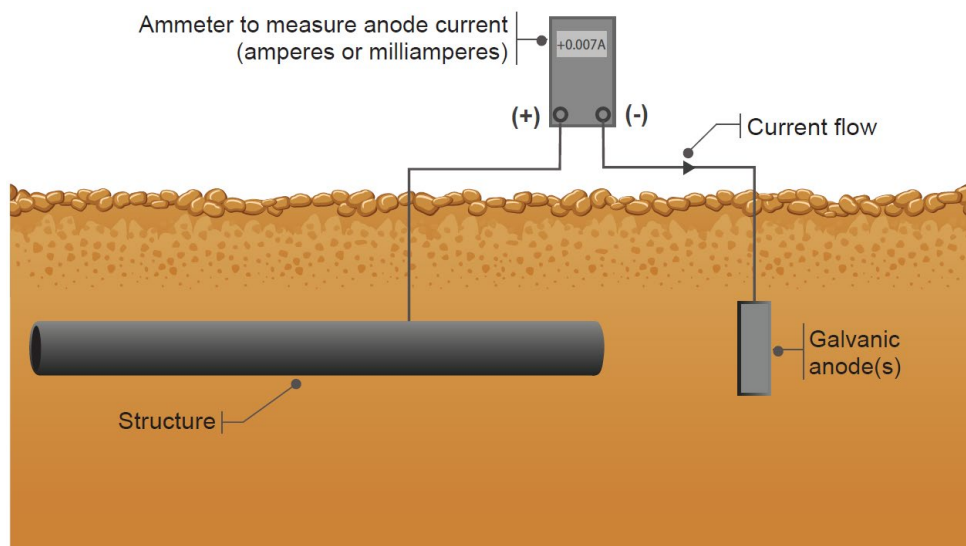

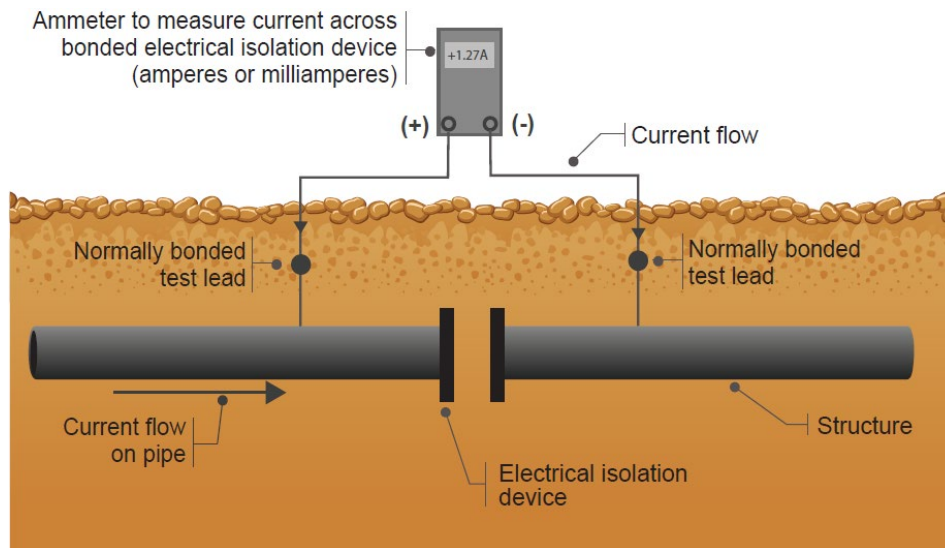**Figure 6-6: Measuring Current with Ammeter Across Galvanic Anode**

Figure 6-7: Measuring Current with an Ammeter Across Electrical Isolation Device

As with a shunt, the current direction through an ammeter is determined by the polarity of the measurement. Current flows from positive (+) to negative (-). If the measurement is positive, the current is flowing from the positive meter connection toward the negative meter connection.

Ammeters are also used to measure test current that is used for performing tests, like resistance tests.

Measuring CP Coupon Current with an Ammeter

Another common reading a corrosion technician takes is CP Coupon Current. The two most common methods to read coupon current are:

- Utilizing an Ammeter in series
- Utilizing a current shunt in series

If readings are going to be taken with an ammeter, it will need to be connected in series between the CP coupon and the structure (Figure 6-8). The bonding wire or switch within the Coupon Test Station will need to be in the open (disconnected) position during this. The meter is turned to the milliamp or microamp setting and then then current reading can be recorded for further analysis.

If readings are going to be taken with a current shunt, the current shunt needs to be installed in series between the CP coupon and the structure. Refer to the Calculating Current Through a Shunt Section on how to take a reading and calculate current through a shunt.

Figure 6-8: CP Coupon Current Reading

For more information on CP Coupon Test Stations, refer to NACE SP0104-2020.

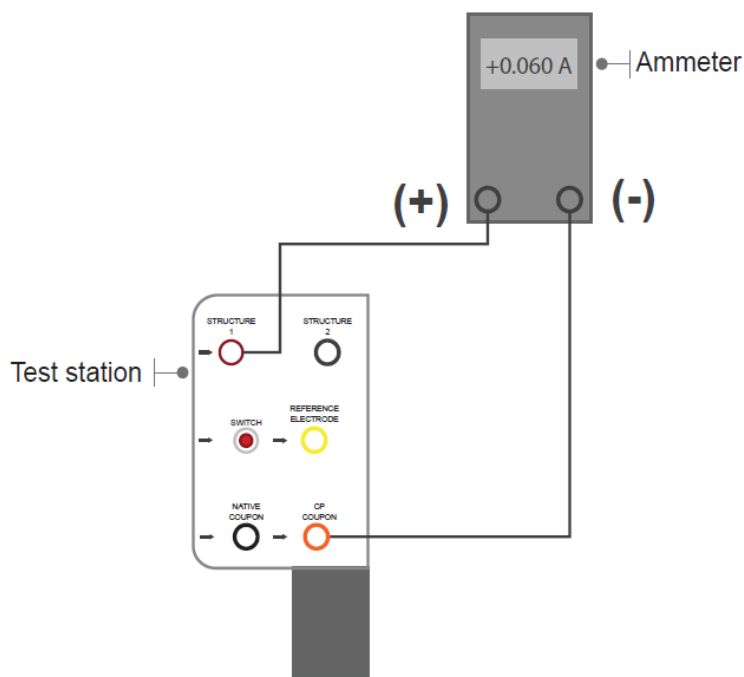## Clamp-On Ammeters

Another way to measure current flow on a conductor, such as a pipe or cable, is with a clamp-on ammeter. A clamp-on ammeter has a sensor in the form of a clip or clamp. When the sensor is placed around a conductor, the ammeter will indicate the current flow on it. Current quantity and direction will be indicated.

Small sensors are in the form of clips or "jaws." The clips are squeezed open and placed around the conductor. The clips are then released so that they close. The ammeter will then indicate the current flow on the conductor within the sensor. The sensor may be integrated into the ammeter or may be separate from the ammeter and connected to it with test leads. Sensors in the form of clips are available for use on conductors up to 6 inches in diameter.

Large sensors are in the form of 2- or 4-piece clamps that are assembled around the conductor. The assembled sensor is connected to the ammeter with test leads. The ammeter will then indicate the current flow on the conductor within the sensor. Large sensors are available for use on conductors up to 82 inches in diameter.

The sensors may be permanently installed around a buried or submerged pipeline and their test leads terminated in a test station so that current flow can be monitored.

It is important to note that clamp-on ammeters measure the net current within the sensor. If two conductors are placed within the sensor, the ammeter will indicate the sum of the current flow on the two conductors. For example, if the sensor is placed around both the positive and negative leads from a rectifier, the ammeter will indicate 0, since the current on the two cables is in opposite directions.

Figure 6-9 shows a clamp-on ammeter measuring current flow on a stainless-steel tubing line. In this example, the tubing line was installed across an isolating flange.

Figure 6-9: Clamp-On Ammeter Measuring Current on Stainless Steel Tubing

Chapter 7 – Resistance Measurements

INTRODUCTION

In Chapter 6, we learned about different methods for measuring current. In this chapter we are going to learn about measuring the other part of Ohm's Law: Resistance.

RESISTANCE MEASUREMENTS

Introduction to Resistance

The electrical resistance of an object is a measure of its opposition to the flow of electric current. In other words, resistance is what makes it hard for current (electrons) to flow within a circuit. It is typically expressed in units of ohms. Wires and pipes are examples of materials having resistance.

In corrosion control testing we may be interested in knowing the value of resistances like:

- The resistance across a wire, a reel of wire, a bond, a shunt, or a resistor
- The resistance across an electrical isolation device
- The resistance across a pipeline span
- The resistance between a pipeline and earth
- The resistance between an anode bed and earth

Measuring a Simple Resistance

Measuring the resistance across an object that has been temporarily isolated electrically is often referred to as a Simple Resistance measurement. This includes such items as resistors, current measurement shunts, stray current bond cables, instrument test leads, and reels of test wire.

These resistance measurements are simple applications of the basic electric circuit, as was discussed in Chapter 2. All that is needed for this measurement is a battery, a voltmeter, an ammeter, and test leads. Figure 7-1 shows the resistance measurement circuit based on the material contained in Chapter 2.
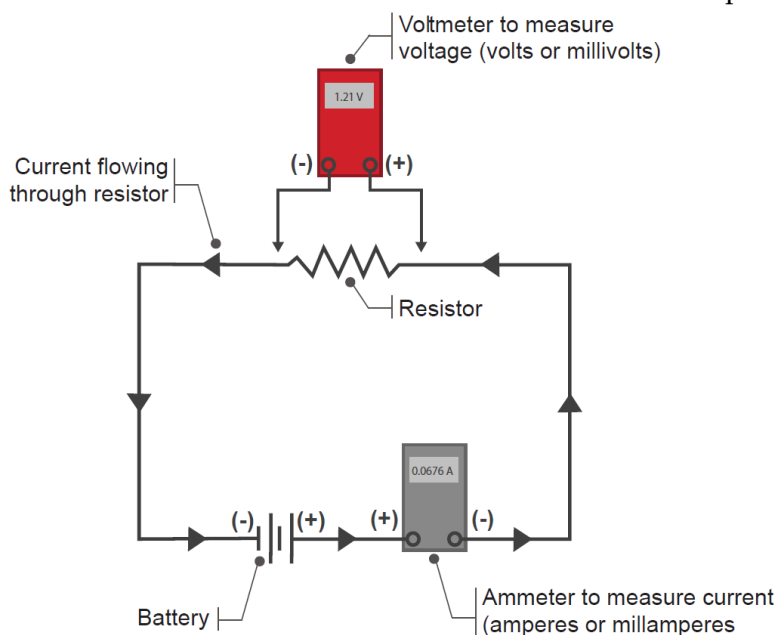

Figure 7-1: Measuring a Simple Resistance

To measure the resistance across an object, connect the multimeter as shown in Figure 7-1. Now apply Ohm's law where R = V/I. Remember to keep units in the same order by either converting the voltage reading to millivolts or converting the milliamps reading to amperes. Choosing the latter, the result is:

$$R = \frac{12.10 \text{ V}}{0.0676 \text{ A}} = 17.899 \text{ }\Omega$$

With typical test instruments, it is possible to accurately measure resistors ranging from a thousandth of an ohm (0.001 ohm) or less, up to tens of thousands of ohms (10,000 ohms).

Most multimeters have a built-in ohmmeter that can be used to measure simple resistances (Figure 7-2). These are especially useful for measuring the resistance of test leads and reels of wires.

Figure 7-2: Multimeter with Built In Ohmmeter

Delta Values in Resistance Tests

Before proceeding further, it is time to consider delta values and their use in Ohm's Law. The symbol Δ means "change in" and is normally read as delta. Delta is the On value minus the Off value.

For example, ΔV = V-On – V-Off and ΔI = I-On – I-Off. Delta calculations must include the polarities of the measurements.

In Figure 7-1, we caused a change in the voltage from 0 to 1.210 volts using a change in test current from 0 to 0.0676 A. So:

$$\Delta V = 1.210 \text{ V} - 0 \text{ V} = 1.210 \text{ V}$$

$$\Delta A = 0.0676 A - 0 \text{ A} = 0.0676 \text{ A}$$

When calculating resistance we need to use the Δ values, so Ohm's Law should be stated as R =ΔV/ΔI. In the example, V-Off and I-Off were both zero so considering the Δ was not necessary. However, in most cases in the field, V-Off will not be zero and ΔV must be used. In most cases when we use a test current, I-Off will be 0 since our test circuit is open and I-On = ΔI.

Resistance of Electrical Isolation Devices

An effective electrical isolation device must have a very high resistance through it. It might seem logical that by measuring the resistance across it we can determine if it is effective. The key difference here is that in the case of an installed device we cannot temporarily isolate the device electrically since the two sides of the device are in the earth, unlike with a simple resistance. If we connect as shown in Figure 7-1, there are two parallel paths for the test current to flow: through the device (the path we care about) and through the earth.

Figure 7-3 shows a set up using the simple resistance measuring circuit shown previously with some data as an example. The first thing you might notice is the voltmeter reads 0.19 V, with right hand side of isolating joint positive, before the current circuit is connected. The fact that the voltage across the device is not zero indicates that there is some resistance across it.
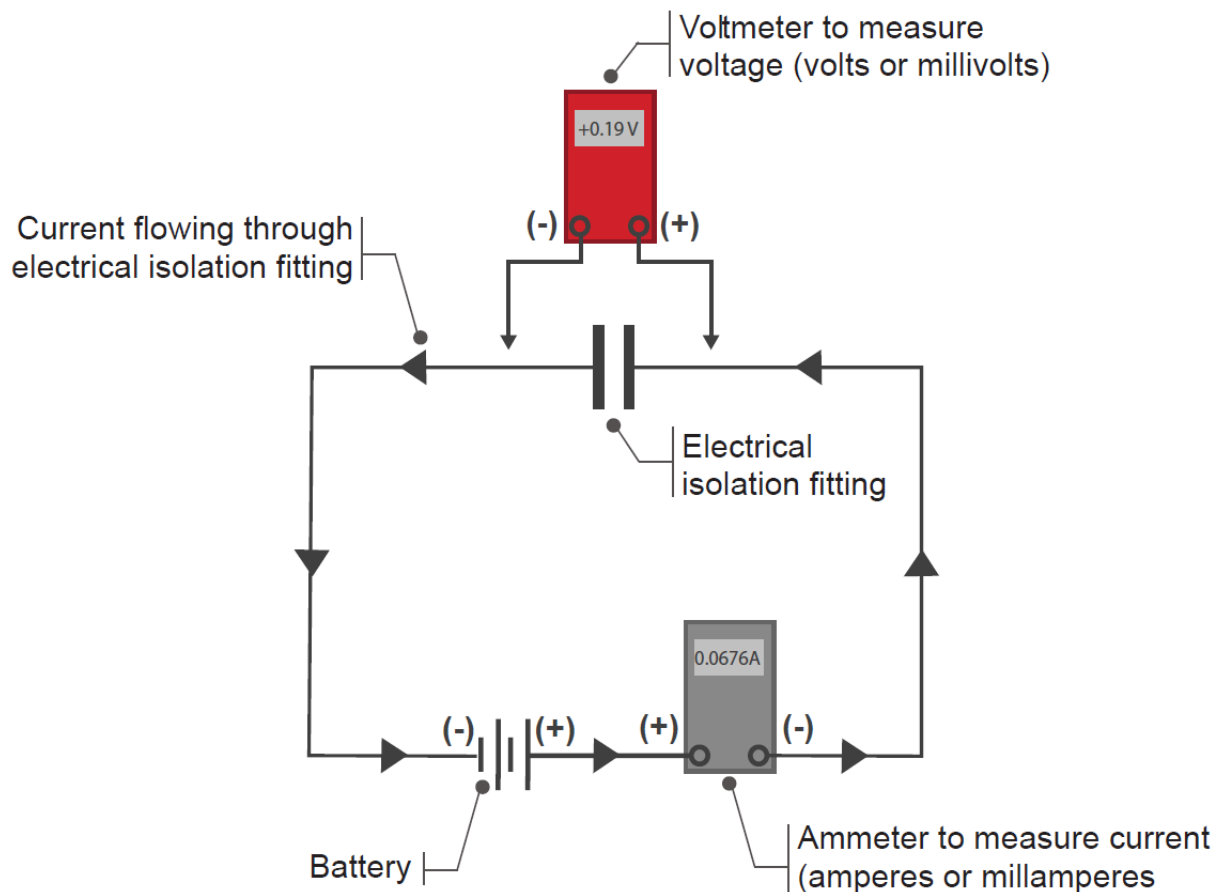
Figure 7-3: Measuring Resistance Across an Electrical Isolation Fitting

After the current circuit is closed, the ammeter reads 0.0676 amperes while the voltmeter reads 1.21 volts, with right hand side of isolating joint positive. To calculate the resistance:

$$R = \frac{\Delta V}{\Delta I}$$

$$R = \frac{1.21 \text{ V} - 0.19 \text{ V}}{0.0676 \text{ A} - 0 \text{ A}} = 15.089 \text{ } \Omega$$

But this not the resistance through the device. The resistance that has been calculated is that across a parallel resistance circuit, like was shown in Chapter 1. One of the parallel resistors is the electrical isolation device, the resistor we care about. The other parallel resistor is the resistance-to-earth of the pipe on one side of the device

plus the resistance-to-earth of the pipe on the other side of the device. All we know is that the resistance that was measured is less than the smaller of the two parallel resistance paths. Figure 7-4 demonstrates this.
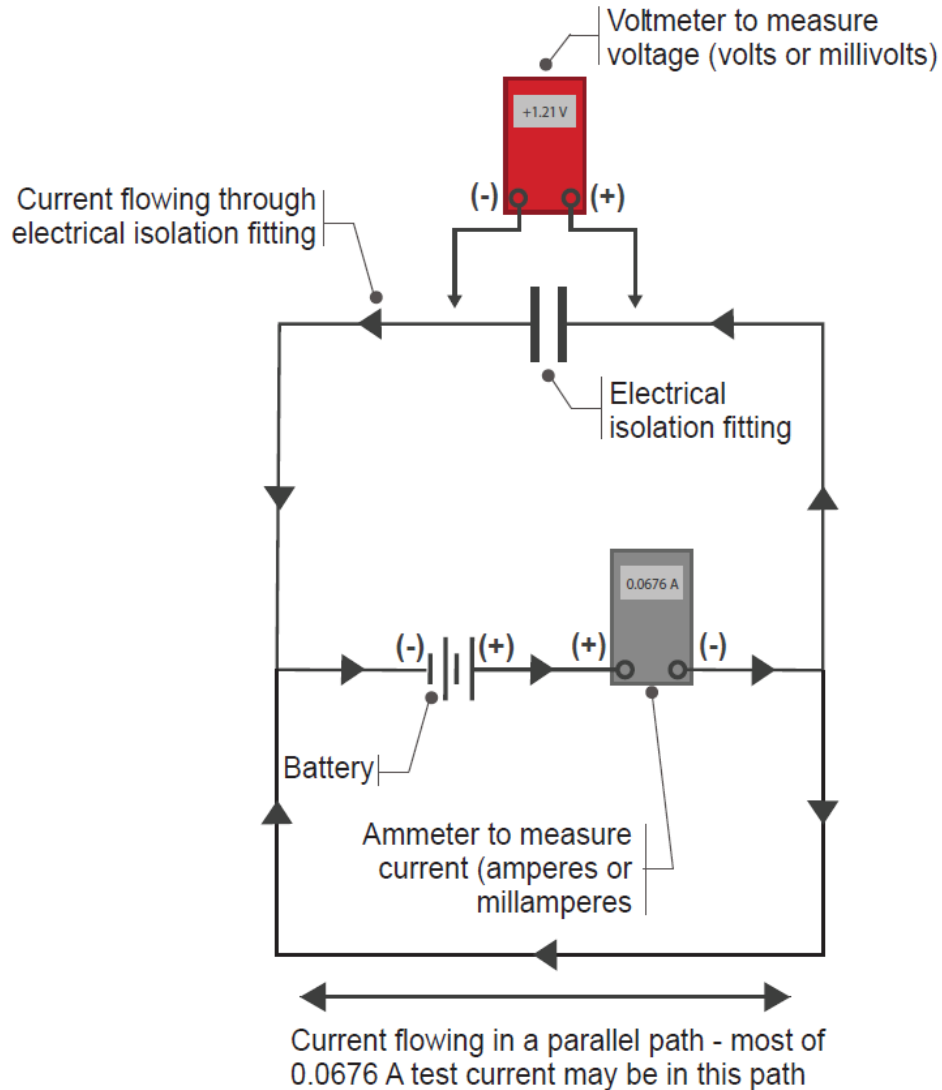

Figure 7-4: Measuring Resistance Across an Isolating Fitting - Parallel Paths

The resistance measured tells us nothing about the effectiveness of the electrical isolation device. The purpose of this example is to demonstrate that measuring the resistance across an installed electrical isolation device is not a way to determine its effectiveness. There are other ways to test an electrical isolation device, such as the use of radio frequency insulation tester. Other methods will be discussed in the Intermediate Course.

Resistance-to-Earth of Pipelines and Anode Beds

Knowing the resistance-to-earth of a pipeline can help us evaluate its coating quality, determine its cathodic protection (CP) current requirements, and determine if it is electrically isolated. The higher the resistance-to-earth of a pipeline, the better the coating and the lower the CP current requirements. If the resistance-to-earth of a pipeline is unusually low, it may not be electrically isolated, and troubleshooting may be needed.

Knowing the resistance-to-earth of an anode bed can help us evaluate the anode bed. The lower the resistance-to-earth of an anode bed the better. If the resistance-to earth of an anode bed has increased from previous values, it may indicate depleted anodes or a cable break.

Measuring the resistance-to-earth of a pipeline or an anode bed can be done using the same test set up. Figure 7-5 shows a typical set up for measuring the resistance-to-earth of a structure.
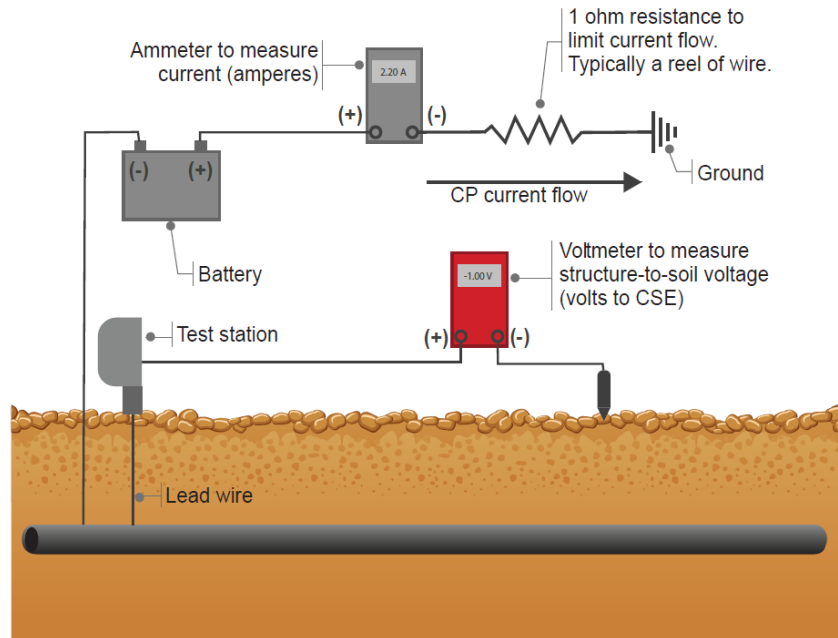

Figure 7-5: Measuring the Resistance-to-Earth of a Buried Structure

A current circuit and a voltage circuit are set up in Figure 7-5.

In the current circuit, a DC current source, such as a battery, is connected between the structure and an earth ground. The earth ground can be any metal that is in the earth. A low resistance ground works best. An ammeter is placed in the current circuit so that the test current can be measured.

In the voltage circuit, a voltmeter used to measure the structure-to-soil voltage to a reference electrode, like a CSE. When the current circuit is closed, current will flow through the earth between the structure and the ground, and the structure-to-soil voltage will change. The resistance-to-earth of the structure can be calculated using Ohm's Law.

When examining Figure 7-5, we see a test current of 2.2 amperes applied between a pipeline and a ground. The test current causes the pipe-to-soil voltage to change from -1.00 volts to -9.80 volts.

$$R = \frac{\Delta V}{\Delta I}$$

$$\Delta V = -9.80 \text{ V} - -1.00 \text{ V} = -8.80 \text{ V}$$

$$\Delta I = 2.20 \text{ A} - 0 \text{ A} = 2.20 \text{ A}$$

$$R = \frac{8.80 \text{V}}{2.20 \text{A}} = 4.00\Omega$$

Note that we have ignored the negative sign in ΔV when calculating the resistance since resistances are always positive.

Resistance of a Pipeline Span

Another resistance we may be interested in knowing is the resistance of a pipeline span. Since the primary purpose of knowing the resistance of a pipeline span is to calculate current, this was discussed in Chapter 6.

SOIL RESISTIVITY TESTING

Resistance versus Resistivity

Resistance is the opposition that current encounters when moving through a material, like a wire in a circuit. Resistivity is a property that quantifies how strongly a material with a cross-sectional area opposes the flow of electric current. For example, CP current leaves the anode and travels through the soil to collect onto the cathode. The soil's resistivity will impact how hard (high-resistivity) or how easy (low-resistivity) it is for that current to flow. Soil resistivity data can be used in the following ways:

- Help evaluate the corrosiveness of the environment
- Aid in the design process for CP systems
- Safety System designs for electrical shock hazard mitigation

There are many different test methods and testing equipment that can be utilized to gather and collect soil resistivity data. A few of the more common test methods are:

- Soil Box Method
- Measure the resistivity of soil samples removed from excavations or auger holes and placed in a specifically designed box
- Single Rod Method
- For rapid accumulation of spot soil resistivity data along an underground structure such as a pipeline, the single rod resistivity equipment can be used
- Four Pin Wenner Method
- This method, as opposed to soil box tests or single rod tests, has the advantage of permitting the measurement of mass soil resistivities to various depths without having to go below the surface

Soil resistivity, along with how to perform the three test methods, are covered in the Intermediate course.

Chapter 8 – Rectifier Basics

INTRODUCTION

A rectifier is a device that converts alternating current (AC) electricity from the power grid to direct current (DC) electricity for impressed current cathodic protection (CP).

This chapter will discuss the basic operation and monitoring of CP rectifiers including:

- Rectifier safety
- Rectifier components
- Types of rectifiers
- Periodic inspections of rectifiers
    - Preventive maintenance of rectifiers
    - Basic troubleshooting of rectifiers
- Interrupting rectifiers

RECTIFIER SAFETY

Before we proceed, let's discuss safety around CP rectifiers. Cathodic protection rectifiers can pose electrical shock and arc flash hazards. Many of the tasks associated within inspecting rectifiers require that the rectifier be energized in order to correctly test the unit. Use caution when working on live rectifiers and consider the following:

- Only qualified personnel should access CP rectifiers
    - Most companies have developed safety procedures for personnel accessing CP rectifiers
    - Qualified personnel accessing CP rectifiers must follow appropriate safety procedures. Not all personnel may be qualified to perform all the tasks described in this text.
- Always use insulated test leads
- Use caution when working on components behind the faceplate due to the increased risk of AC shock hazard

Most rectifiers are supplied with high voltage AC input. Voltages of 240VAC or greater are common. There is potential for this current to energize the rectifier cabinet and short to ground through whatever contacts the rectifier cabinet. Before touching the rectifier cabinet, you should always verify it is not energized and is safe to touch. This can be done by using a non-contact voltage detector or by measuring the rectifier case-to soil voltage with a voltmeter and a copper-copper sulfate electrode (CSE) reference cell. When measuring the rectifier case-to-soil voltage, the voltmeter connection to the case must be made with an insulated clip or probe. If the case-to-soil voltage is less than 15 VAC and it is safe to access. If AC potential is 15VAC or greater, that is a hazard that needs to be mitigated.[16] Stop work and do not touch the rectifier. Call the appropriate personnel to discuss the safety concern. For more information on AC potential hazards and safety concerns, refer to NACE SP0177.

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[16] (NACE International SP0177-2019)

RECTIFIER COMPONENTS

What is a Rectifier?

As stated previously, a rectifier is a device that converts AC electricity to DC electricity for impressed current cathodic protection.
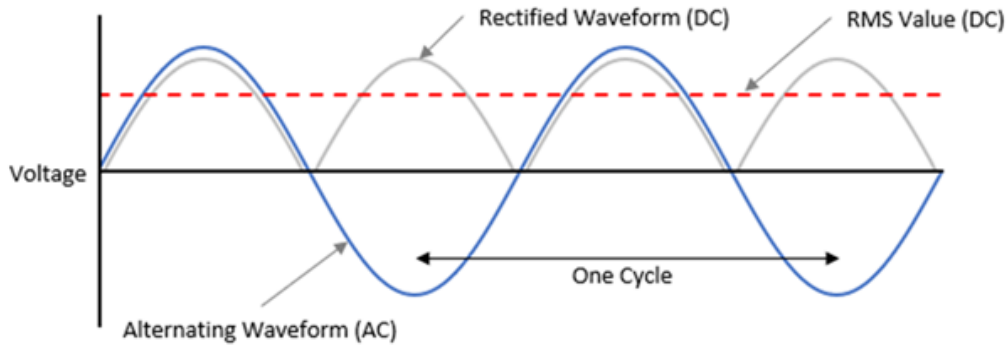

Figure 8-1: AC/DC Conversion

A rectifier forces whatever is connected to the positive terminal to corrode. With that said, the positive terminal of the rectifier is always connected to the anode bed. The negative terminal of the rectifier is connected to whatever needs to be protected. The structure (pipe) is always connected to the negative terminal (Figure 8-2). Connecting a rectifier with the opposite polarity will cause the structure to become the anode, causing it to corrode rapidly and could have catastrophic consequences if not corrected.

Figure 8-2: Rectifier

A standard CP rectifier is a simple electrical device. The heart of the rectifier consists of the transformer and the rectifying element. These two components alone could provide the DC power required for a CP system. Other components, or accessories, are added to the unit to enhance its performance and provide safety functions.
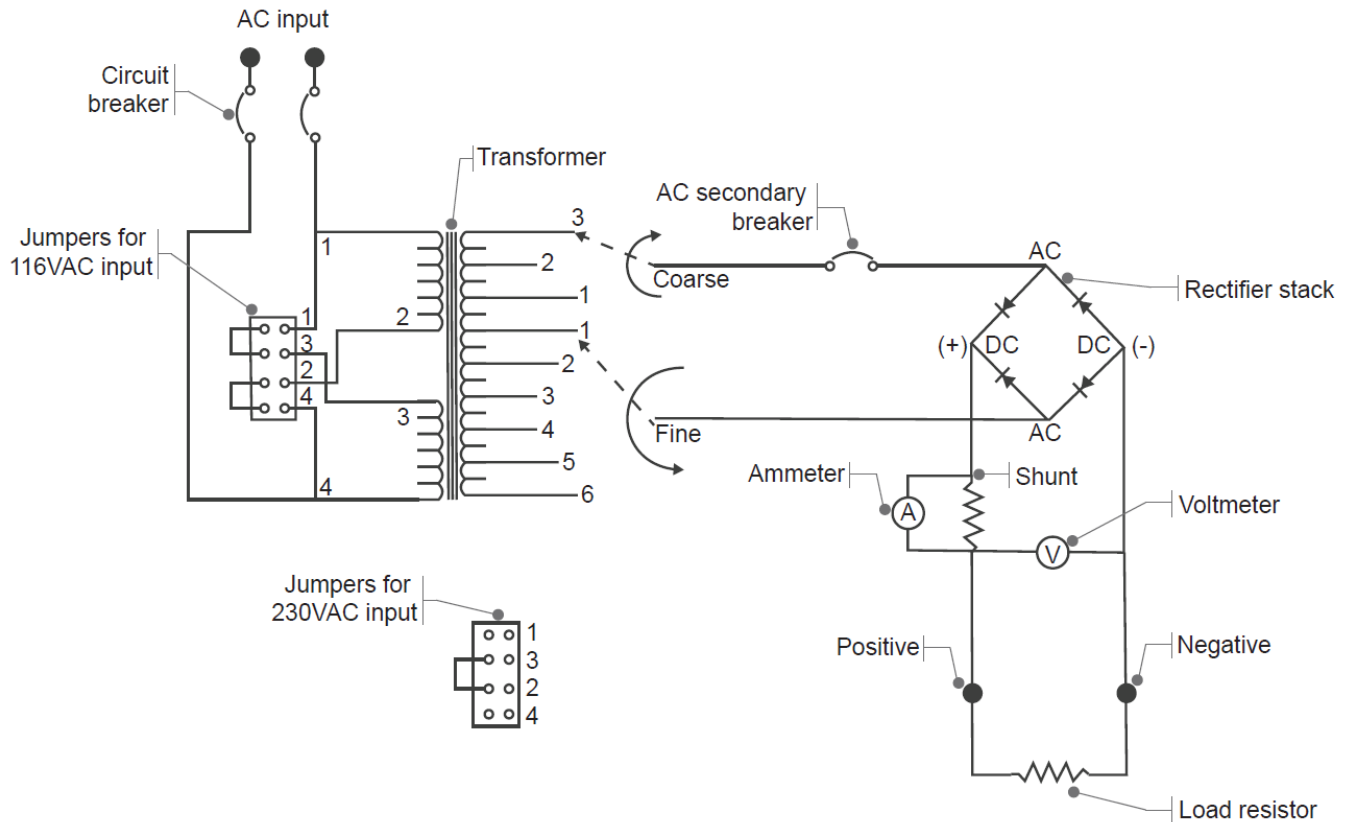
Figure 8-3: Standard Single-Phase Rectifier

Transformer

A transformer is a device used to step up (increase) a voltage, step down (decrease) a voltage, or to isolate a voltage from its source. In a rectifier, the transformer is used to step down the voltage from the power source to a suitable voltage for rectification. In most rectifiers, the voltage output of the rectifier is adjusted by changing the tap settings of the transformer (Figure 8-4).

Figure 8-4: Transformer

Rectifying Element

The rectifying element is an array of diodes that converts the AC into DC. A diode is an electronic component that allows current to flow only in one direction. By arranging multiple diodes in the proper configuration, the AC input is rectified into DC. The most common rectifying circuit is the single-phase bridge (Figure 8-5).
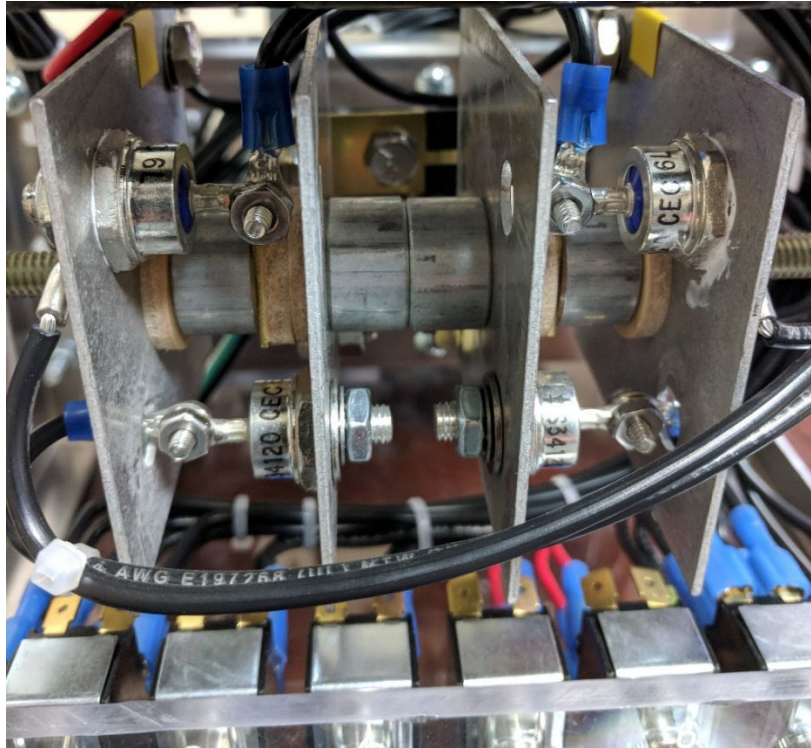

Figure 8-5: Diode Array

Most recently built rectifiers use silicon diodes. At one point in time, selenium bridges were the preferred rectifying element in CP rectifiers. Selenium bridges, while common in the 1960's and 1970's, have declined in usage in the industry. During those times, silicon devices were more susceptible to damage from spikes/surges, while selenium was more durable. The drawback is that selenium as a bridge, "ages" and declines in efficiency over time, while silicon bridges do not.

Some rectifying elements have multiple discreet diodes. For lower output rectifiers, one-piece silicon diode bridge rectifier modules can be used.

Circuit Breakers

The primary function of a circuit breaker is to provide overload protection for the circuit in which it is installed. In a rectifier, the built-in breaker also serves as the on/off switch for the unit.

In most rectifiers, turning off the built-in breaker will de-energize components on the rectifier panel; the output terminals, the shunt, fuse holders, and the transformer taps. It will not de-energize all components in the rectifier. To de-energize all components, an external disconnect must be used. It is good practice to have an external disconnect installed near the rectifier and to turn it off while performing any work on a rectifier.
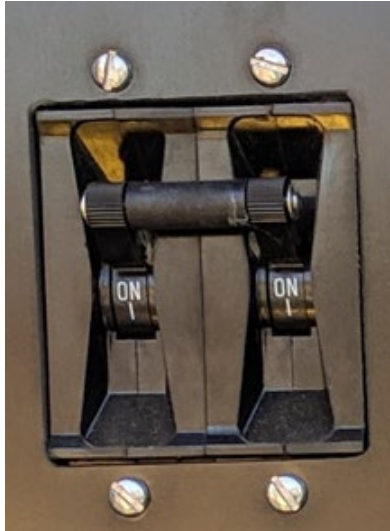

Figure 8-6: Rectifier Breaker

Shunts

Almost all rectifiers have shunts to allow a simple way to measure the DC current output. Not all rectifiers have the same shunt size, it is best practice to double check during each inspection. Calculating DC current output on a shunt was covered in Chapter 6.

Figure 8-7: Current Shunts

Accessory Equipment

Optional equipment (i.e., indicating meters, lightning arresters, fuses or breakers, efficiency filters, remote monitoring systems [RMUs], and communications filters) can also be supplied with the rectifier unit. Voltmeters and ammeters are commonly installed on the rectifier to facilitate the monitoring of its voltage and current output. Sometimes, only one meter is supplied which, by use of a selector switch, will read both volts and amperes. Built-in voltmeters and ammeters should not be considered accurate or reliable. Portable multimeters should be used to obtain accurate voltage and current output values.

Lightning arresters are normally installed on both the AC input and the DC output circuits of the rectifier. Lightning surges can enter the rectifier from both the AC and DC sides. Installation of lightning arresters will help prevent damage to the unit and its components due to these surges.

In addition to the main breaker, fuses or breakers can be installed in the positive and negative DC output circuits and the AC secondary circuit.

Efficiency filters can be added to some rectifying elements to improve the AC to DC conversion efficiency and save power costs.

Communications filters can be used to eliminate electronic noise/interference on electronic circuits and at the same time provide increased lightning protection to the DC circuits of the unit.

RMUs can be added to allow for remote inspection to ensure each unit is operating within its desired output. Using the manufacturer's software, commands can be sent to turn on/off and interrupt each unit.

TYPES OF RECTIFIERS

Air Cooled Rectifiers

This type of rectifier and its components are enclosed in a steel enclosure with doors that provide access to the unit for testing and repairs. The bottom of the enclosure is usually constructed of steel screening to allow for the circulation of air. This type of unit can either be wall, pole, or pedestal mounted depending on the size and weight of the unit (Figure 8-8).
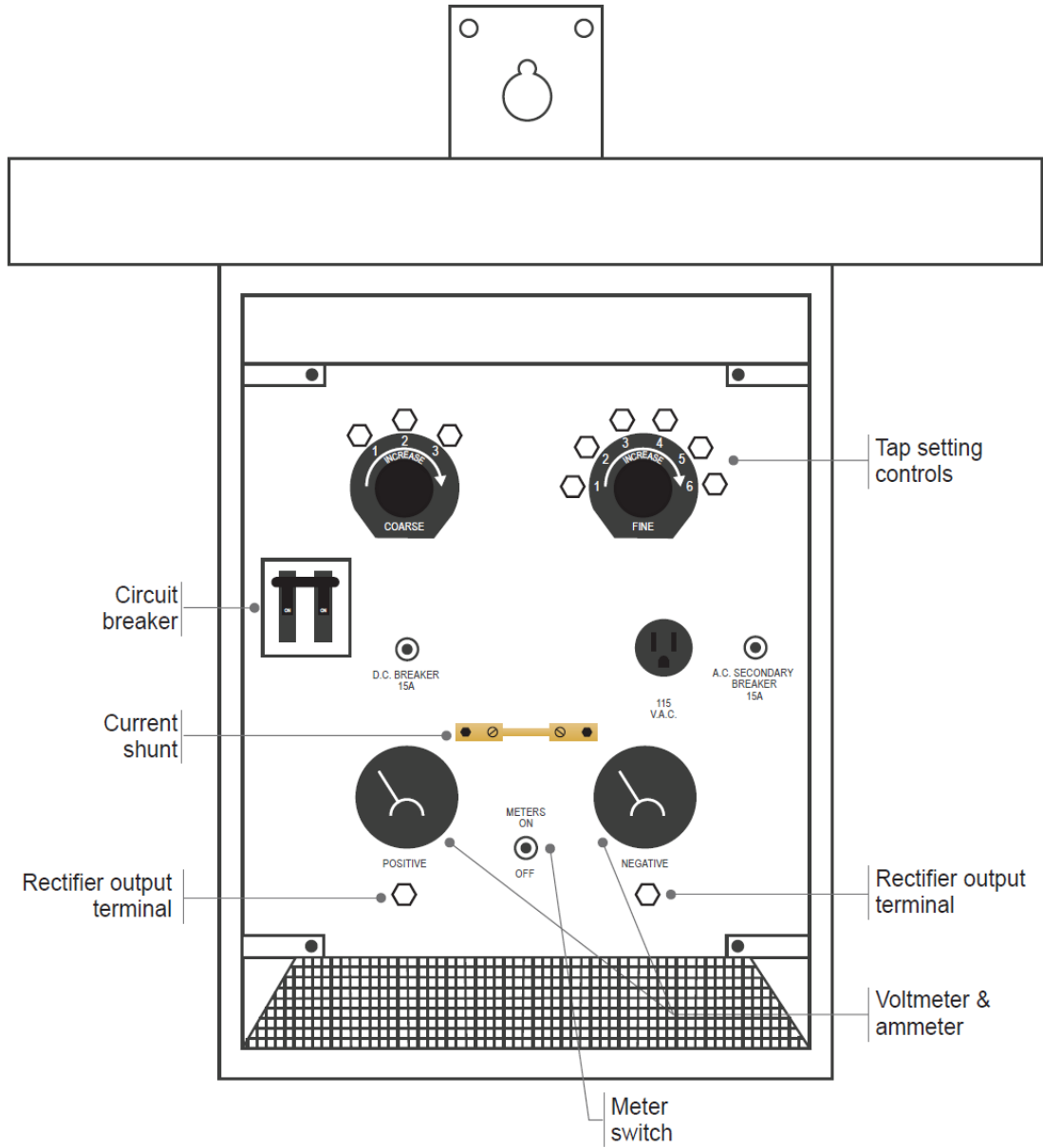
Figure 8-8: Typical Air-Cooled Rectifier

Oil Cooled Rectifiers

This type of rectifier is used in areas where dust, salt air, corrosive fumes, or excessive moisture may shorten the operating life of an air-cooled unit. The rectifier and its components are installed in a steel enclosure and are completely immersed in oil, isolating them from extreme environments. Oil cooled rectifiers are normally pedestal mounted due to their weight. See Figure 8-9 for a typical oil cooled rectifier detail.
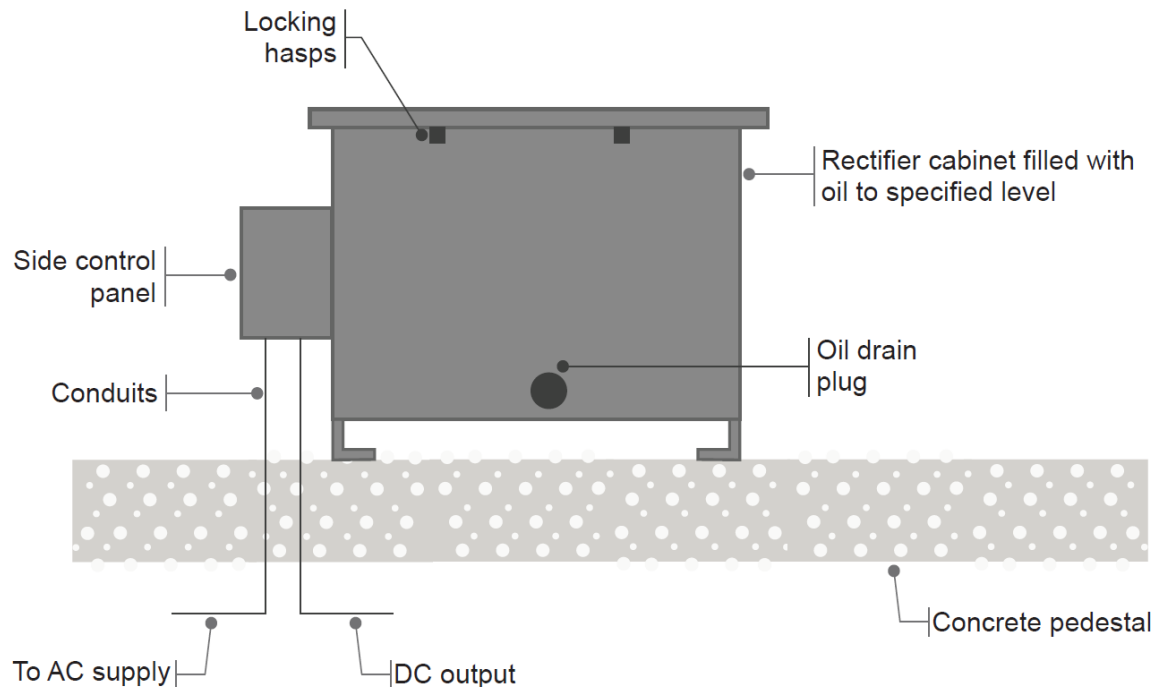

Figure 8-9: Typical Oil Cooled Rectifier

Explosion Proof Rectifiers

Modified oil cooled rectifiers are available with explosion proof fittings. These explosion proof rectifiers are suitable for use in areas where explosive or flammable vapors, liquids, or powders are present.

Constant Current Rectifiers

Constant current rectifiers have a special circuit that enables them to provide a nearly constant current output regardless of circuit resistance. This type of rectifier is used in applications where the circuit resistance changes drastically, and the output current would be exceeded with a normal rectifier. A rectifier having an anode bed installed along a coastline affected by tides is an example of a place a constant current rectifier might be used.

Automatic Potential Controlled Rectifiers

Automatic potential-controlled rectifiers monitor the structure-to-electrolyte potential and maintains it at a desired level. The use of this type of rectifier requires the use of stationary reference electrode and an additional test wire connection to the structure. Most units have a switch that allows them to be toggled between manual or potential control; if a unit is switched to manual, the current and voltage output is no longer affected by the structure-to-electrolyte potential. Automatic potential-controlled rectifiers are very useful in the control of corrosion on structures (i.e., water storage tanks or harbor structures) and for stray current caused by DC light rails.

PERIODIC RECTIFIER INSPECTIONS

Inspecting Rectifiers

To ensure proper operation, rectifiers must be inspected on a regular basis. Rectifiers that are subject to the Pipeline Hazardous Materials Safety Administration's (PHMSA) regulations must be inspected at least six times each year with no more than 2½ months between inspections to ensure the units are operating properly, per 49 CFR 192.465. Inspecting a rectifier at least every 2 months is a good practice even if it is not subject to any regulations.

A routine inspection of a rectifier should include measuring and recording the DC voltage and current output of the unit, at the very least. These values can be determined by reading the built-in voltmeter and ammeter, but it is more reliable to use a portable voltmeter. Inspections can also be completed by utilizing an RMU.

Remote Monitoring of Rectifiers

Rectifiers can also be fitted with RMUs. RMUs are devices that will measure the operating parameters of a rectifier and allow that information to be accessed remotely. These readings can be programmed to be taken and stored automatically to satisfy regulatory compliance requirements. RMUs are available in radio, satellite, and cellular communication configurations. Some systems allow the measurement data to be accessed through an internet web interface. Some systems will send notifications of rectifier operating anomalies by email or text messaging.

Approaching the Rectifier Case

Follow the operator's, or your company's, safety procedures before opening the rectifier. Before accessing a rectifier, perform a visual inspection of the rectifier:

1. Looking

    a. Look for unusual conditions in the case (i.e., loose wires, scorch marks, or holes).

    b. Look for insects, rodents, and other wildlife.

2. Smelling

    a. Stand downwind of the rectifier to try and detect any unusual smells of burned insulation or other materials.

        i. Selenium and other semiconductors smell like rotten eggs when burned.

3. Listening

    a. Listen around the rectifier for sounds of arcing, static, frying, or any sounds that may indicate an issue with the rectifier.

If your observations during this stage suggest it may not be safe to access the rectifier, contact your supervisor for guidance before proceeding.

Prior to Touching the Rectifier Case

Before touching the rectifier cabinet, you should always verify it is not energized and is safe to touch. You can complete the following to verify the rectifier is safe to touch.

1. Place a reference cell firmly in the soil near the rectifier.

    a. If a reference cell is unavailable, the rectifier cabinets grounding lug can be utilized in this step).

2. Connect the reference cell to the negative (-) or common terminal of the voltmeter and the other insulated lead to the positive (+) or hot terminal of the voltmeter.

    a. Always use insulated test leads when testing CP rectifiers.

3. Set the voltmeter to Volts AC.

4. Touch the positive (+) lead to an unpainted (bare metal) component on the rectifier cabinet.

5. If 15VAC or greater is identified, do not open/touch the rectifier cabinet.

    a. An industry standard hazardous level is 15VAC or greater.

    b. Under normal operating conditions, VAC should be near zero.

    c. An industry standard hazardous level is 15VAC or greater. If 15VAC or greater is identified, do not open/touch the rectifier cabinet. AC should be safely turned off at the circuit panel. Contact a supervisor before performing any additional troubleshooting or maintenance. Under normal operating conditions, VAC should be near zero.

Measuring Rectifier Voltage

The DC voltage output is determined by measuring the DC voltage between the rectifier output terminals with a voltmeter.

1. Select volts DC on the voltmeter.

2. Connect the voltmeter positive lead to the positive terminal (Figure 8-10).

3. Connect the voltmeter negative lead to the negative terminal (Figure 8-10).

If your voltmeter reads are set up in this fashion, your recorded voltage polarity should be positive; if all steps are taken correctly and if the rectifier is properly functioning. If the reading's polarity is negative, double check multimeter leads and rectifier components (Figure 8-10). If leads are placed correctly and measurement is still negative, turn off the rectifier, and contact a supervisor before performing troubleshooting or maintenance.
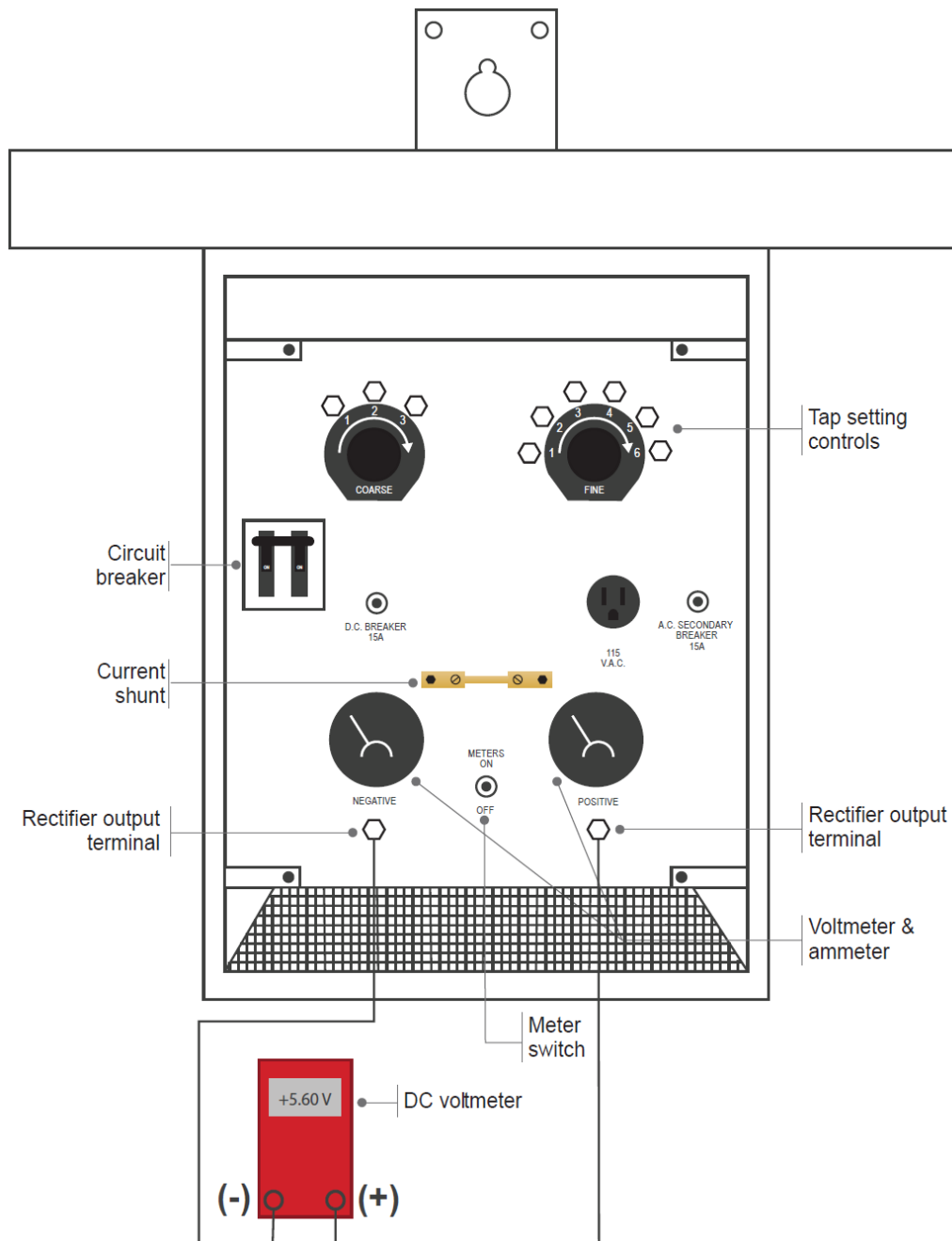
Figure 8-10: Measuring Rectifier Voltage

Measuring Rectifier Current

The DC current output is best determined by measuring the DC voltage across the rectifier shunt.

1. Select millivolts DC on the multimeter.

2. Connect the multimeter leads to each side of the shunt (Figure 8-11).

3. Confirm proper connection to the shunt.

4. Multiply the recorded millivolts by the shunt factor.

Use insulated clips or probes to avoid skin contact with the shunt.
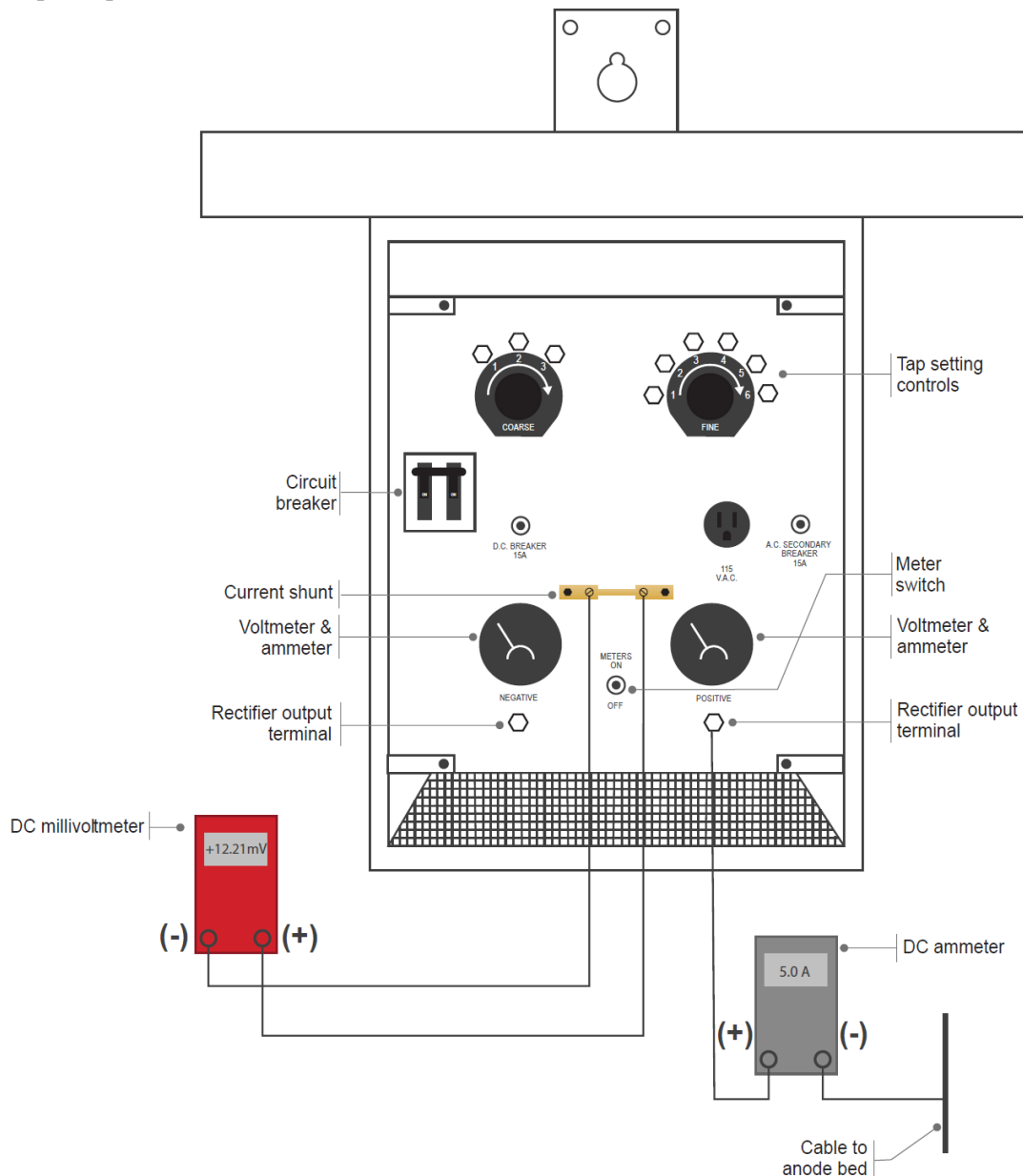
Figure 8-11: Measuring Rectifier Current

The rectifier current output can also be measured by inserting an ammeter in either the DC positive or negative cable. However, this requires that the rectifier be shut off, one of the cables disconnected, and the ammeter inserted in the circuit. The rectifier current output can also be measured by using a clamp-on ammeter, unless the positive and negative cables are run in the same conduit into the rectifier.

Using the rectifier shunt is the simplest and most accurate way to measure the current output of a rectifier. This was described in Chapter 6.

Preventive Maintenance

When inspecting a rectifier, if qualified, you should also:

- Remove insect and rodent nests and plug any holes through which insects or rodents can enter the rectifier
- Clean all ventilating screens in air-cooled units so that airflow will be completely unobstructed
- Remove excessive dirt and dust accumulations
- For oil cooled rectifiers, check the oil level and condition. The oil should be clear and nearly colorless. Failing oil is usually characterized by a murky or cloudy appearance with loss of transparency and should be replaced. Facilities are available for testing the oil and salvaging it by filtration where practical.
- Inspect all components, including lightning arresters, for signs of lightning damage – arc traces across insulators or panels, or discolored parts. If their appearance has been altered or if damage is suspected, the component should be replaced
- Replace all wires on which the insulation has been damaged
- Replace logbook if damaged or unreadable

Basic Troubleshooting

If a rectifier is found to be off, check to see if the cause is a blown fuse or a tripped circuit breaker. These are the two most common causes of rectifier malfunctions. If this is the case, resetting the breaker or replacing the fuse may be all that is required to restore the rectifier to operation.

If you cannot restore the rectifier to operation by resetting breakers or replacing fuses, notify appropriate personnel so that additional troubleshooting can be performed.

INTERRUPTING A RECTIFIER

When measuring structure-to-electrolyte voltages on an impressed current CP system it is common practice to cycle the rectifier on and off. This is commonly referred to as interrupting the rectifier and is done by installing a portable current interrupter in the rectifier. A current interrupter is an automated switch that opens and closes a circuit in the rectifier so that the DC current output is alternately on and off. Different ON and OFF cycles are used so they can be distinguished from each other. When testing a protected structure, the ON/OFF cycles are typically 3-seconds ON, 1-second OFF to prevent polarization loss on the structure.

Some RMUs include a current interrupter circuit that can be activated remotely.

If there are multiple rectifiers protecting a single structure, multiple synchronized interrupters are used so that they all turn on and off simultaneously. The interrupters can be synchronized by GPS. All RMU interrupters and most portable interrupters can be synchronized by GPS.

An interrupter can be installed in:

- The positive or negative DC output cable (preferred method)
- Across the Coarse or Fine setting

To install a current interrupter in the positive or negative DC output cable (Figure 8-12):

1. Shut the rectifier off and verify zero current and voltage output.
2. Remove the desired cable from the rectifier terminal.
3. Connect one side of the interrupter to rectifier terminal.
4. Connect the other side of the interrupter to the cable that was previously disconnected.
5. Turn the rectifier back on.

To install a current interrupter on the coarse or fine setting (Figure 8-12):

1. Shut the rectifier off and verify zero AC voltage on tap settings, along with verifying zero DC current and voltage output.
2. Remove a tap connection by removing a tap bar or disconnecting a screwed tap connection.
3. Connect the two sides of the interrupter across the open tap connection.
4. Turn the rectifier back on.

   a. If the structure has induced AC on it the DC output may not go to zero when interrupting a transformer tap.

It is best practice when interrupting a rectifier to install the interrupter on the positive cable, this way when the interrupter is in the "open" (OFF) there is no path for induced AC along a structure to be rectified into DC.
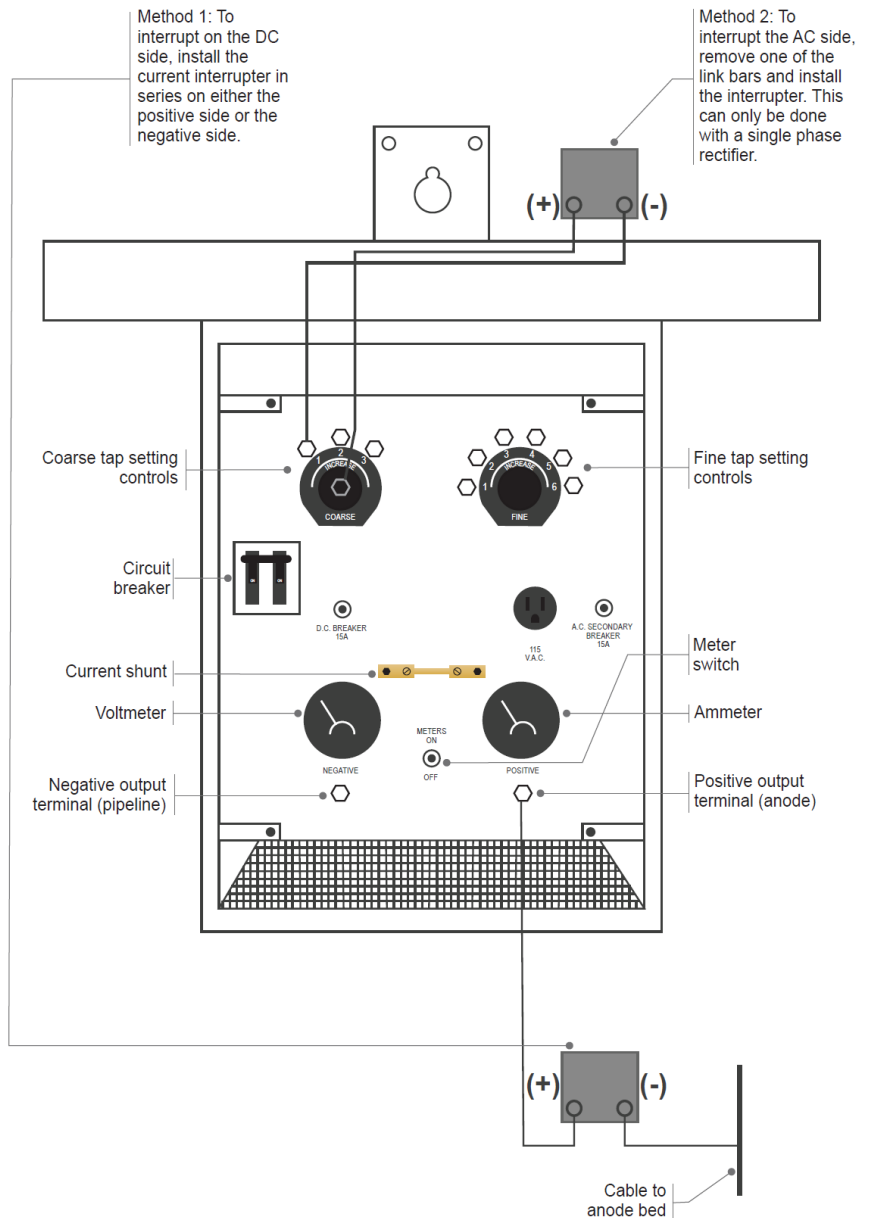

Figure 8-12: Interrupting a Rectifier

Chapter 9 – Atmospheric Corrosion

INTRODUCTION

Atmospheric corrosion has the same causes as any other type of corrosion. When the substrate is exposed to the environment, the metal reacts with the environment to degrade the metal. Like other corrosion reactions, it requires an anode, cathode, metallic pathway, and electrolyte. The metal already has the anode, cathode, and metallic pathway, so all that is needed to start corrosion is an electrolyte. The electrolyte can come into contact with the metal from precipitation, humidity in the air, nearby processes, or from a stationary water source like oceans, rivers, and lakes.

The speed of corrosion may be accelerated by the environment in which the metal resides. The amount of humidity and exposure to precipitation will increase the corrosion rate. Salts, like chlorides from road salt and the ocean, will accelerate corrosion. Other salts, like nitrates from fertilizer runoff, can accelerate corrosion. Pollution from nearby industrial processes can increase corrosion rates. ISO 12944-2 defines different atmospheres in relation to how aggressive the corrosion rate is. In order from least to most corrosive they are dry rural areas, rural areas, urban areas, marine/industrial, and marine with pollution.

Atmospheric corrosion can also be accelerated by temperature. Like most chemical reactions, corrosion speeds up with temperature; an 18°F increase in temperature will double the rate of reaction. However, real world corrosion rates are a function of not only temperature but humidity of the environment and wetness of the surface. As both humidity and liquid water on the surface tend to drop with increased temperature, the actual rate of corrosion increase with temperature tends to be much lower.

A much more complicated acceleration of corrosion is with concentration of oxygen. The more oxygen at the corrosion site, the faster the corrosion rate as rust is an oxide of a metal. Atmospheric oxygen levels stay relatively stable, so this effect is seen only in industrial process areas where there may be more or less oxygen than in the atmosphere.

Figure 9-1: Atmospheric Corrosion

IDENTIFYING COATING TYPE

Most above ground piping is coated with liquid coatings that cure to form a solid film that protects the steel beneath by being a barrier to water, being sacrificial (containing zinc to form cathodic protection), or both. Many above grade pipeline coating systems consist of multiple coats/layers, that each perform a unique function. The primer is in contact with the steel and provides adhesion and perhaps cathodic protection (CP). The middle coat is often a good water barrier. The top coat provides protection from the sun and has the aesthetic appearance that the owner wants.

With liquid applied coatings, it is not important to an atmospheric corrosion survey to identify what make and model of each individual layer is, or even the generic coating type. In general, most surveys have the surveyor just put "above grade coating" for each instance.

At transitions between below and above grade coating, the below grade coating may come above grade to provide extra mechanical protection; or there may be some sort of wrap. Refer to Chapter 4 for the identification of those coatings.
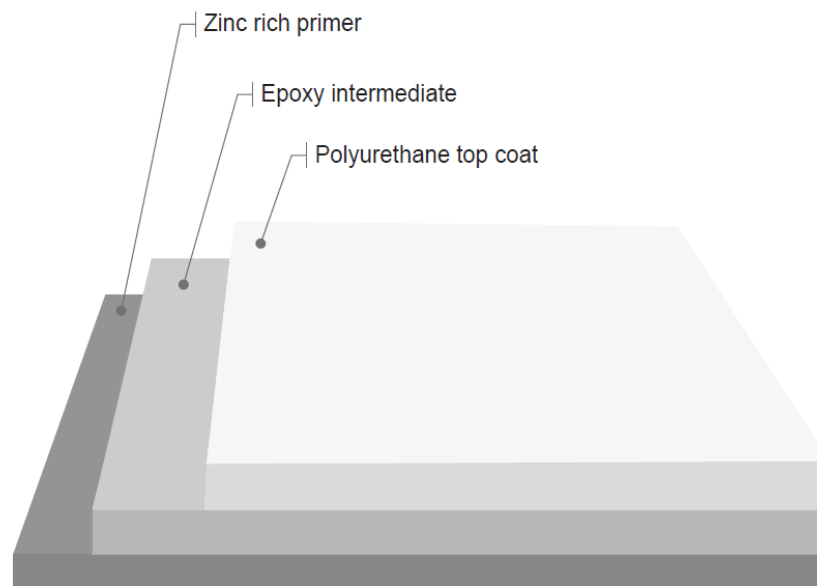
Figure 9-2: Atmospheric Coating System

ATMOSPHERIC CORROSION SURVEYS

It is wise to periodically inspect every asset for corrosion. This is not only to prevent failures, but to plan further work, evaluate coating performance, plan budgets, determine an asset's value prior to sale, and prioritize work. For pipelines covered under the Pipeline Hazardous Materials Safety Administration (PHMSA), inspections must be performed every three years, not to exceed 39 months, for onshore piping; and yearly, not to exceed 15 months, for offshore piping. Interstate piping is covered under 49 CFR 192 for natural gas and 49 CFR 195 for hazardous liquid pipelines. These regulations do not require that every instance of corrosion be addressed immediately. Corrosion that will not reduce the wall thickness to a level that would affect maximum operating pressure before the next scheduled inspection need not be addressed. This detail is outlined in 195.581 and 192.479.

This chapter is not a comprehensive instruction manual on pipeline integrity and should only be used for general information. A pipeline integrity professional needs to be involved with any corrosion decisions.

An atmospheric corrosion survey should be performed by qualified personnel who have specialized training, such as that provided by AMPP. Generally, it is the higher-level coating inspectors who perform surveys, or Basic Coating Inspectors (Level 1) who are overseen by higher level inspectors performing routine surveys on an established program. Often, operators hire a third party with experience in surveys to design and carry out a program. Corrosion surveys should pay special attention to areas that are prone to more aggressive corrosion like soil to air interfaces, under insulation, under disbonded coatings, under pipe supports, at deck and wall penetrations, and over water. CFR 192 and CFR 195 call out some of these areas specifically for special consideration.

An atmospheric corrosion survey program should be designed to break up assets into small pieces, which are individually rated for corrosion levels. Items such as valves, strainers, pumps, launchers and receivers, instrumentation, and pipe runs between elements should all be individually rated. Each item needs to have a unique name identifier. Items that have not already been named in the process drawings are often named as being upstream or downstream of the next named item.

It is important that the evaluation of corrosion level is consistent between surveys and between inspectors. For this reason, the program should have definitions and a rating system for corrosion level and descriptions. A good rating guide for corrosion is SSPC Vis. 2, Standard Method of Evaluating Degree of Rusting on Painted Steel Surfaces.

Table 9-1: SSPC Vis. 2 Rust Grade

Rust Grade	Percent of Surface Rusted	Photographic Standard		
		Spot	General	Pinpoint
10	Less than or equal to 0.01 percent		None	
9	Greater than 0.01 percent to 0.03 percent	9-S	9-G	9-P
8	Greater than 0.03 percent to 0.1	8-S	8-G	8-P
7	Greater than 0.1 to 0.3 percent	7-S	7-G	7-P
6	Greater than 0.3 percent to 1 percent	6-S	6-G	6-P
5	Greater than 1 percent to 3 percent	5-S	5-G	5-P
4	Greater than 3 percent to 10 percent	4-S	4-G	4-P
3	Greater than 10 percent to 16 percent	3-S	3-G	3-P
2	Greater than 16 percent to 33 percent	2-S	2-G	2-P
1	Greater than 33 percent to 50 percent	1-S	1-G	1-P
0	Greater than 50 percent		None	

Table 9-1 shows 11 rust grades and three types of corrosion: spot, general, and pinpoint. Spot corrosion is where the bulk of the rusting is concentrated in a few localized areas. General corrosion is where the corrosion is uniformly spread out. Pinpoint rusting, sometimes called pitting, is where the corrosion is limited to one localized area. SSPC Vis 2 contains pictures for 27 different levels/types of corrosion.
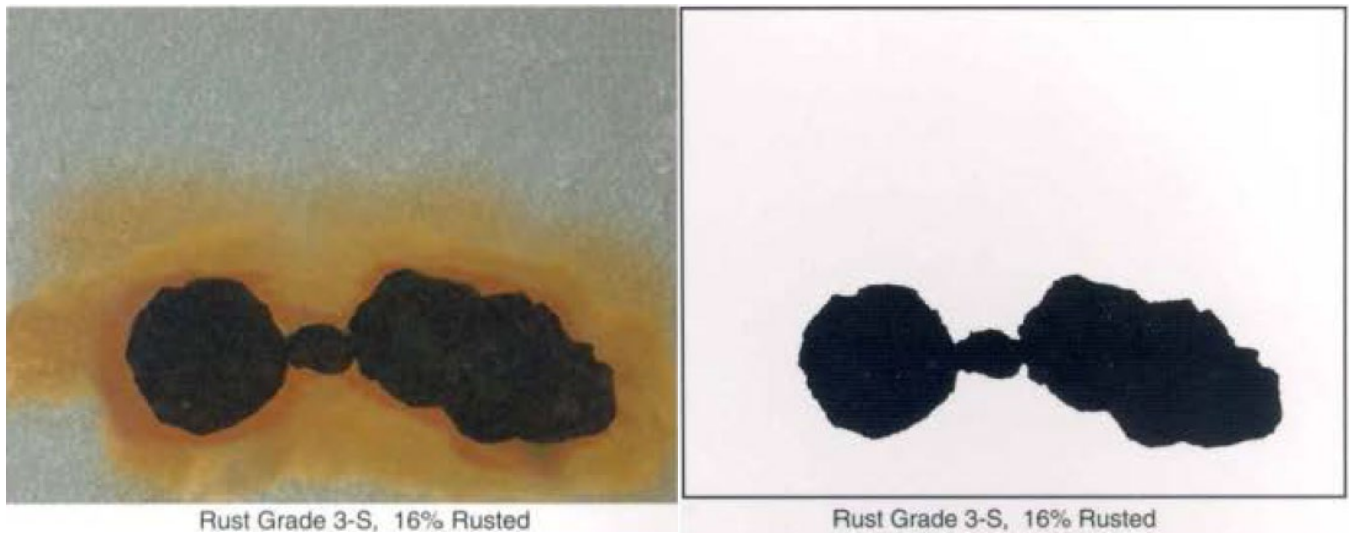
Figure 9-3: Rust Grade 3-S Picture (Left) and Drawing (Right)

Corrosion surveys can contain massive amounts of data including photographs of each item, often from multiple angles. Therefore, databases are often used to store and archive the data. There are many prepackaged databases commercially available for storage, management, sorting, and reporting the data. An operator may purchase the software used to store the data, but more and more often the data is stored on the cloud with an internet-based interface for the operator, where the operator would pay a yearly fee.

Atmospheric corrosion is costly. The rate of corrosion is dependent on many factors, such as materials of construction, environment, and corrosion protection used. The primary corrosion protection method are protective coatings, which can protect using chemical and or barrier techniques. It is important to comprehend the level of corrosion and the condition of the coating system on an asset. Performing corrosion surveys is the only way to get that kind of understanding. By understanding the causes and utilizing the corrosion prevention tools available, an operator can minimize the life cycle cost of any asset.

COATING FAILURE TYPES

There are multiple coating failure types. It can be beneficial to report the frequency and type of coating failures along with the corrosion size/grade/type.

Delamination

Delamination is where a coating loses adhesion to the steel or to another layer of coating and starts to come apart.

Figure 9-4: Coating Delamination to Substrate

Blisters

Blisters are areas where the paint has lost adhesion but has not come completely off the steel or the previous layer of paint. When evaluating blisters, record the size and frequency of them. ASTM D714 lists common ways to evaluate blisters. Blisters may be filled with water, air, or solvent. Blisters are usually caused by surface contamination or solvent entrapment.
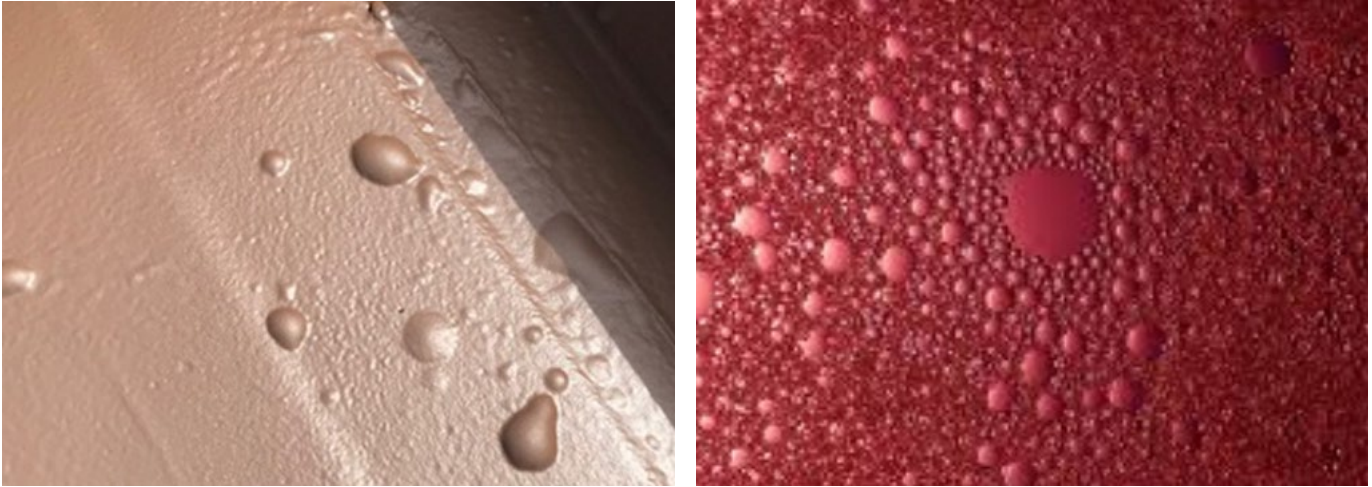

Figure 9-5: Blisters

Mechanical Coating Damage

Mechanical coating damage is where impact/abrasion/gouging from a foreign object has damaged the coating.

Figure 9-6: Mechanical Damage

Wrinkling

Wrinkling is where the coating gets a "wrinkled" appearance but does not expose any bare steel. Wrinkling is caused by internal stresses in the coating and can be caused by age and improper coating selection.

Figure 9-7: Wrinkling

Cracking

Cracking is where the coating splits exposing the substrate. This is not to be confused with checking where the coating has breaks, but they do not extend to the substrate. The easy way to differentiate between checking and cracking is that cracking will usually have rust bleeding from the cracks. Cracking can be caused by many different factors: coating selection, thickness, incompatibility between coats, age, mechanical stress, and more.
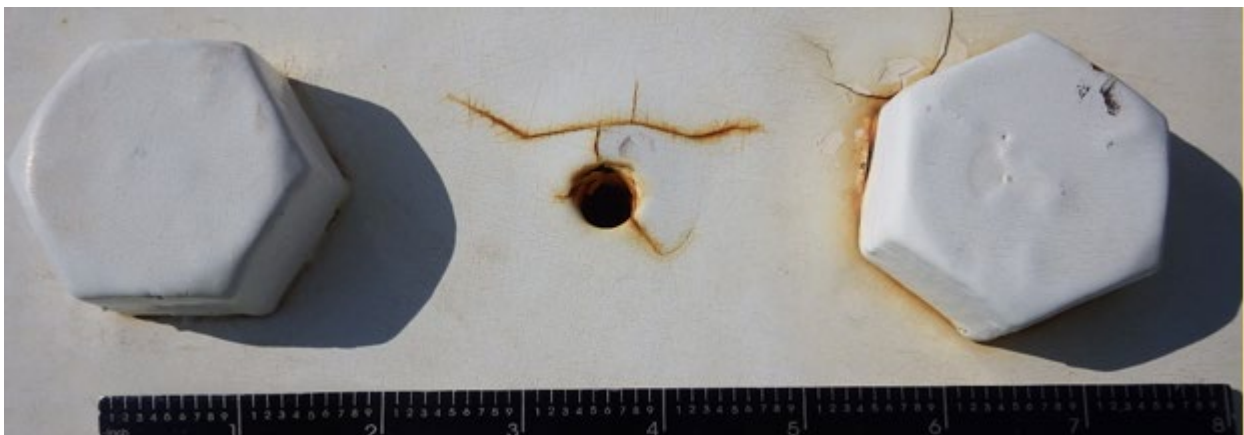

Figure 9-8: Cracks

Chalking

Chalking is when the coating is damaged by ultraviolet light from the sun. This removes thickness slowly over time.

Figure 9-9: Chalking

Pinholes

Pinholes are when small, round defects penetrate to the steel. There is not always rust bleed. Pinholes are caused by incorrect thickness, air entrapment, solvent issues, and more.
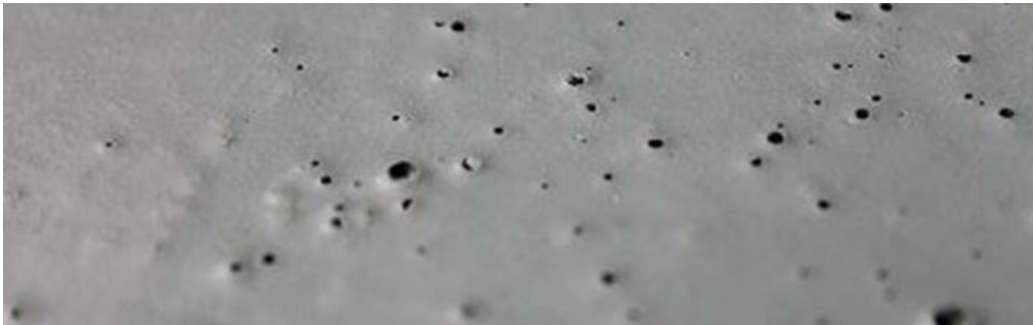

Figure 9-10: Pinholes

Runs, Sags, Curtains, Drips

The terms runs, sags, drips, and curtains are used interchangeably. They are caused by coating that is too thick, or the wrong formulation for the application.

Figure 9-11: Runs, Sags, Curtains, Drips

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