



CP 1–Cathodic Protection Tester Course Manual

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CP 1–Cathodic Protection Tester Course Manual

What to do with this manual NOW

1. **READ MANUAL IMMEDIATELY.** Before attending the NACE CP 1–Cathodic Protection Tester course, please read the entire manual. Students who do not read the manual before the class may find the class much more difficult than they would otherwise. Focus (at the very least) on understanding Ohm’s Law, Series and Parallel Circuits, and Meter Operations.
2. **REVIEW THE OHM’S LAW TUTORIAL AND THE BASIC MATH SELF ASSESSMENT.** This information will also help prepare you for the CP 1–Cathodic Protection Tester course.
3. If you break the shrink wrap on this manual, but do not attend the class, **there will not be a registration refund.**
4. If, after reviewing the manual, you want to postpone your classroom date to give you more time to review more of the book, then please **contact NACE immediately** to ask about your options for transferring to another course. Transfers are time sensitive....if you think you may want to transfer, then please the manual as soon as you receive this book.

There are varying transfer fees that begin taking effect 35 days prior to each class.
5. **STUDY** Chapter 2 prior to arriving to class. Chapter 2 covers basic corrosion chemistry and basic corrosion theory.

Thank you. Please call or write to us with questions:

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SEE YOU IN CLASS!

ELECTRICAL FUNDAMENTALS –

Ohm's Law

By Buddy Hutson, Enron Corp.

This information is intended to assist students of the NACE Cathodic Protection Training and Certification Program prior to class attendance. Other students may also find this information useful as a starting point for understanding the fundamental principles underlying cathodic protection technology.

When you attend the NACE Cathodic Protection Tester course, one of the first things you will be taught is basic electricity. Whether your plans are to be an electrician, electronics technician or work in corrosion control, you will need to have a good working knowledge of basic electrical fundamentals. One of the things we have learned from cathodic protection courses taught through the years is that many students struggle with the math involved with some of the electrical fundamentals. With this in mind, we have put together a short introduction that will help you be better prepared when you come to the course. Please read this carefully, before coming to class. These concepts will be thoroughly reviewed at the beginning of class; however, students may have difficulty understanding cathodic protection practices that are demonstrated in class if they are not familiar with these fundamentals.

One of the most basic concepts of electrical fundamentals has to do with Ohm's Law. Back in 1828, George Simon Ohm discovered some facts involving voltage, current and resistance. Before we get into those facts that led to "Ohm's Law", let's look at the elements involved. Where do we find voltage, current and resistance? How about in your car, TV, flashlight, and even your pacemaker? Any time there is an active electrical circuit; these basic elements will be there. To make sure everyone knows what we are talking about here, let's define the three elements of Ohm's Law. Keep in mind that these terms will be expounded upon during the actual course. For simplicity sake, we will be talking about Direct Current (DC) throughout this discussion. During the actual course, we will get into (AC) Alternating Current as well. Keep in mind that batteries are DC and power from the wall socket in your home is AC.

VOLTAGE

Voltage can be defined as a difference of potential. Potential refers to the possibility of doing work. When we use a voltmeter to read across the terminals of a battery, we are reading the difference in potential between one terminal and the other. Voltage can be called an electromotive force, indicating the ability to do the work of forcing electrons to move. The symbol for voltage is the letter E and this comes from the term electromotive force. The unit of measure of voltage is the "**Volt**". In a gas system, voltage compares to pressure. Gas flows through a pipeline as a result of the pressure on the system.

Voltage	Difference of potential, electromotive force, ability to do work
Unit of measure	Volt
Symbol	E or V (This symbol will be used in the Ohms Law Formula)
Compares to	Pressure in a gas or liquid system

CURRENT

Current can be defined as the flow of electrons. When the difference of potential between two charges forces a third charge to move, the charge in motion is an electrical current. To produce current charge must be moved by a potential difference. The unit of measure for current is the “**Ampere**”. We often just say Amps. The symbol for current is the letter I. This comes from the term Intensity since current is a measure of how intense or concentrated the electron flow is. Current compares to gas flow in a gas system. The pressure causes the gas to flow in the pipe just as voltage caused electrons to flow in an electrical circuit.

Current	Flow of electrons
Unit of measure	Ampere
Symbol	I (This symbol will be used in the Ohms Law Formula)
Compares to	The flow of gas or liquid in a piping system

RESISTANCE

Resistance can be defined as the opposition to current flow. Depending on the atomic structure of a material, it may be termed a conductor, semi-conductor or an insulator. These terms are determined by how many free electrons are available to allow the flow of current when a difference of potential is applied across it. Conductors have many free electrons and therefore, current flows quite easily. Semi-conductors have less free electrons and provide more opposition to the flow of current. Insulators have very few free electrons and offer extremely high opposition. Practically speaking, extremely good insulators do not allow the flow of current. The measure of resistance is the “**Ohm**” (I suppose that George Simon Ohm didn't want to be forgotten). The symbol for the Ohm is the letter R from the word resistance. We also see the Greek letter Omega (Ω), used as well. In a gas or liquid piping system, resistance can be compared to the orifice effect or the restriction to the flow provided by the inside diameter of the pipe.

Resistance	Opposition to current flow
Unit of measure	Ohm often seen as the Greek letter Omega (Ω)
Symbol	R (This symbol will be used in the Ohms Law Formula)
Compares to	Orifice effect or the size restriction of inside pipe diameter



Stop here and answer a few questions without looking back at the text. If you can't answer the questions, I would suggest that you read the material again before proceeding.

1. Voltage can be defined as:
 - A. Electrodynamic force
 - B. Electropotential force
 - C. Electrochemical force
 - D. Electromotive force
2. Current is the
 - A. Build up of electrons
 - B. Flow of electrons
 - C. Division of electrons
 - D. Passing of electrons
3. Resistance is the _____ of/to current flow.
 - A. Opposite
 - B. Opposition
 - C. Result
 - D. Reverse
4. Voltage compares to _____ in a gas system.
 - A. Flow of gas
 - B. Restriction of gas flow
 - C. Pressure
 - D. Orifice effect
5. Current compares to _____ in a liquid piping system.
 - A. Orifice effect
 - B. Flow of product
 - C. Pressure pushing the product
 - D. Friction of the inside pipe wall
6. Resistance compares to _____ in a gas or liquid piping system.
 - A. Build up of pressure
 - B. Flow of product
 - C. Orifice effect
 - D. Pipe's outside diameter

Hopefully, you marked 1. (D), 2. (B), 3. (B), 4. (C), 5. (B), 6. (C)

OHM'S LAW

Now that we have defined the elements of "Ohm's Law" let's look at the discoveries that George made back in 1828. He found that, in a simple circuit like the one shown in Figure 1, when the voltage is **held constant**, the current and resistance will vary **inversely**. This means that when the current in the circuit goes up, the value of resistance decreases. Figure 2 shows this relationship.

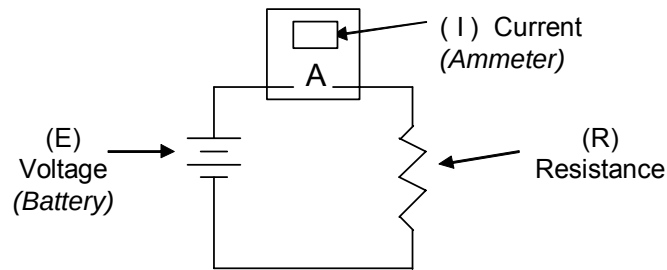


Figure 1. Simple Electrical Circuit

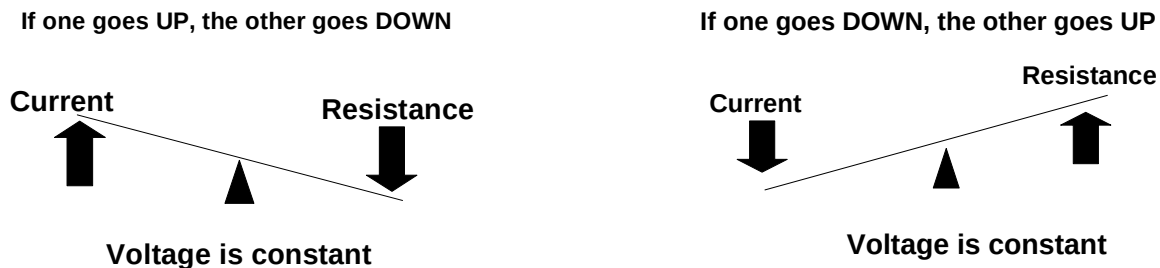


Figure 2. Relationship between Current and Resistance

The next thing that George observed was that when the **Resistance** is **held constant**, the **Voltage** and **Current** values are **directly proportional**. This simply means that if one increases the other increases and if one decreases the other decreases and at the same proportions. Figure 3 shows the relationship.

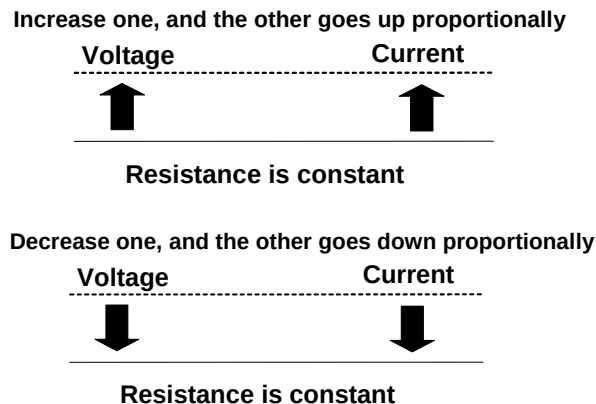


Figure 3. Relationship between Current and Voltage

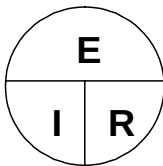
He established the fact that these relationships never change, so now they can be expressed by math. Thus, Ohm's Law became the formula **$E = IR$** or **Voltage equals Current multiplied by Resistance**. Let's see if the relationship holds true if we put in values. If we had a current of 2 Amps and a resistance of 10 Ohms, we would have $E = 2 \times 10$ or a Voltage equal to 20 Volts. If we used only half the current (1 Amp), now the voltage would be $E = 1 \times 10$ or 10 volts, also half of the first. This proves the second fact that voltage and current are directly proportional, current went down by 50% and the voltage went down by 50%.

The following are excerpts from the slide presentation I use when teaching Ohm's Law. This should help you understand how the basic formula can be changed with a little algebra for finding current and resistance.

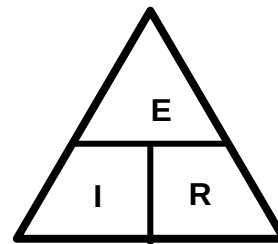
There is an easy way to remember the Ohm's Law Formula. It is called the Magic Circle or sometimes it's called the Magic Triangle.

Simply cover up the symbol of the factor that you are looking for, and the formula for calculating that factor is revealed by the position of the two remaining symbols.

Magic Circle Memory Aid 



OR

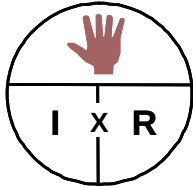


Ohm's Law Formulas

FINDING VOLTAGE

Using the Magic Circle

Cover the R to see the mathematical relationship between Voltage and Current



Ohm's Law Formula for finding Voltage

$$\text{Voltage} = \frac{(E)}{\text{Current}} \times \frac{(R)}{\text{Resistance}}$$

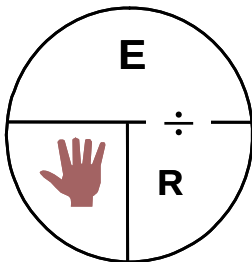
In other words, to find Voltage
Multiply the Current times the Resistance.

$$E = I \times R$$

FINDING CURRENT

Using the Magic Circle

Cover the I to see the mathematical relationship between Voltage and Resistance



Ohm's Law Formula for finding Current

$$\text{Current} = \frac{\frac{(I)}{\text{Current}}}{\frac{(E)}{\text{Voltage}} \div \frac{(R)}{\text{Resistance}}}$$

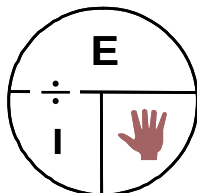
In other words, to find Current
Divide the Voltage by the Resistance.

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

FINDING RESISTANCE

Using the Magic Circle

Cover the R to see the mathematical relationship between Voltage and Current



Ohm's Law Formula for finding Resistance

$$\text{Resistance} = \frac{\frac{(R)}{\text{Resistance}}}{\frac{(E)}{\text{Voltage}} \div \frac{(I)}{\text{Current}}}$$

In other words, to find Resistance
Divide the Voltage by the Current.

$$R = \frac{E}{I} \quad \text{or} \quad I \overline{)E}$$

One important thing to note about Ohm's Law: in order to find an unknown value, you must know the two other values. The math is impossible to solve without at least two values.

This completes this short introduction to Ohm's Law. We look forward to seeing you in class!

P.S. If you need more information and do not plan to attend the new NACE CP 1–Cathodic Protection Tester Course, then here are some other options for learning more about cathodic protection:

1. For CP beginners, I recommend *Peabody's Pipeline Corrosion and Cathodic Protection*. It is available in the NACE Store on the NACE website at <http://www.nace.org/nace/index.asp>. It is also the reference book given to students in the NACE CP 1–Cathodic Protection Tester Course.
2. NACE has 1- and 2-day Cathodic Protection tutorials that are sponsored by NACE Areas and Sections. For additional information on the CP Tutorials, please email education@mail.nace.org.
3. If you have a technical question about CP, remember that you can use the NACE Corrosion Network list serve to post technical questions.
<http://www.nace.org/nace/content/discussion/NcnCorrosion.asp>
4. If you have a question about the NACE Cathodic Protection Training and Certification program, please email msd@mail.nace.org or visit the Education/Certification section of the NACE website.
5. Following are some other very good training programs that teach cathodic protection technology:
 - ❑ Kilgore College (Kilgore, Texas) offers a 2-year Associates degree program in corrosion technology with semester courses devoted to cathodic protection technology. (See <http://www.kilgore.edu/corrosion.asp>)
 - ❑ The Appalachian Underground Corrosion Short Course (AUCSC) is a week-long annual event that provides seminars and other topical presentations on cathodic protection. (See <http://www.aucsc.com/>)
 - ❑ The University of Oklahoma also sponsors a short course in conjunction with several NACE sections: go to <http://www.occe.ou.edu/engr/corrosion/>.



BASIC MATH SELF ASSESSMENT

The CP 1–Cathodic Protection Tester and CP 2–Cathodic Protection Technician courses involve the use of basic mathematics skills including addition, subtraction, division, fractions, algebra, balancing equations, conversions of units, percentages, and graphs. This test was developed to help CP 1–Cathodic Protection Tester and CP 2–Cathodic Protection Technician course students assess their skill in the mathematical concepts utilized in these courses.

The questions should be solved without the use of a calculator.

Solve the following questions. Write your answer in the space provided.

1. Write the answer in exponential form. $(8 \times 8 \times 8) =$ _____

2. Solve. $3^2 \cdot 3^3 =$ _____

3. Solve the following.

a. $1^{47} =$ _____

b. $2^2 =$ _____

c. $7^3 =$ _____

4. Write each fraction in decimal format.

a. $\frac{81}{100} =$ _____

b. $\frac{3}{10} =$ _____

c. $\frac{37}{50} =$ _____

5. Write each decimal as a fraction.

a. $0.4 =$ _____

b. $0.1 =$ _____

6. Solve for each of the given fraction problems. Reduce the fraction to the lowest terms.

a. $\frac{15}{10} + \frac{50}{50} = \underline{\hspace{2cm}}$

b. $\frac{35}{110} + \frac{21}{12} = \underline{\hspace{2cm}}$

c. $\frac{36}{78} - \frac{20}{78} = \underline{\hspace{2cm}}$

d. $\frac{2}{5} \times \frac{2}{5} = \underline{\hspace{2cm}}$

e. $\frac{4}{7} \times \frac{3}{4} = \underline{\hspace{2cm}}$

f. $\frac{4}{8} \times \frac{1}{2} = \underline{\hspace{2cm}}$

g. $\frac{10}{30} \div \frac{10}{50} = \underline{\hspace{2cm}}$

7. Solve for "x" in the following equations.

a. $x + 3 = 5$ $x = \underline{\hspace{2cm}}$

b. $-6 + x = 9$ $x = \underline{\hspace{2cm}}$

c. $10x = 130$ $x = \underline{\hspace{2cm}}$

8. Convert to the given units

a. 200 millivolts = Volts

b. 0.03 Volts = millivolts

c. 1,000 Amperes = kiloampere

d. 0.5 Amperes = milliamps

e. 0.7 megOhms = Ohms

9. Use Ohm's Law to answer the following questions.
- Given an electrical circuit with a driving voltage of 12 Volts and a resistance of 10 Ohms, how much current does the circuit produce?
 - A corrosion circuit produces 2 Amperes of current at a driving voltage of 1.6 Volts, what is the resistance of this circuit?
10. Use Ohm's Law to answer the following questions.
- Given: A 5 A/50 mV shunt has a voltage drop of 12 mV.

Find: What is the amount of current in this circuit?
 - Given: A 30 A/50 mV shunt has a voltage drop of 10 mV.

Find: What is the amount of current in this circuit?

BASIC MATH SELF ASSESSMENT

ANSWER KEY

1. $(8 \times 8 \times 8) = 8^3$

2. $3^2 \cdot 3^3 = 243$

3.

a. $1^{47} = 1$

b. $2^2 = 4$

c. $7^3 = 343$

4.

a. $\frac{81}{100} = .81$

b. $\frac{3}{10} = 0.3$

c. $\frac{37}{50} = 0.74$

5.

a. $0.4 = \frac{2}{5}$

b. $0.1 = \frac{1}{10}$

6.

a. $\frac{15}{10} + \frac{50}{50} = 2\frac{1}{2}$

b. $\frac{35}{110} + \frac{21}{12} = 2\frac{3}{44}$

c. $\frac{36}{78} - \frac{20}{78} = \frac{8}{39}$

d. $\frac{2}{5} \times \frac{2}{5} = \frac{4}{25}$

e. $\frac{4}{7} \times \frac{3}{4} = \frac{3}{7}$

f. $\frac{4}{8} \times \frac{1}{2} = \frac{1}{4}$

g. $\frac{10}{30} \div \frac{10}{50} = 1\frac{2}{3}$

7.

a. $x + 3 = 5$ **$x = 2$**

b. $-6 + x = 9$ **$x = 15$**

c. $10x = 130$ **$x = 13$**

8.

a. 200 millivolts = **0.2 Volts**

b. 0.03 Volts = **30 millivolts**

c. 1,000 Amperes = **1 kiloampere**

d. 0.5 amperes = **500 milliamps**

e. 0.7 megOhms = **700,000 Ohms**

9.

a. Given an electrical circuit with a driving voltage of 12 Volts and a resistance of 10 Ohms, how much current does the circuit produce?

1.2 Amperes

b. A corrosion circuit produces 2 Amperes of current at a driving voltage of 1.6 Volts, what is the resistance of this circuit?

0.8 Ohms

10. Shunt Calculations

- a. Given: A 5 A/50 mV shunt has a voltage drop of 12 mV.

Find: What is the amount of current in this circuit?

$$\frac{5 \text{ A}}{50 \text{ mV}} \times 12 \text{ mV} = 1.2 \text{ A}$$

- b. Given: A 30 A/50 mV shunt has a voltage drop of 10 mV.

Find: What is the amount of current in this circuit?

$$\frac{30 \text{ A}}{50 \text{ mV}} \times 10 \text{ mV} = 6 \text{ A}$$

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Cathodic Protection Levels	9
Groundbed Malfunctions	10
Galvanic and Impressed Current Groundbeds	10
Rectifiers.....	11
Routine Maintenance	11
Output Problems	12

Section 10

Appendices

Glossary of Terms

Ansuini, Frank J., James R. Dimond, “Factors Affecting the Accuracy of Reference Electrodes”, MP, 33, 11 (1994): pp. 14-17.

SP0169 “Control of External Corrosion on Underground or Submerged Metallic Piping Systems”

RP0285 “Corrosion Control of Underground Storage Tank Systems by Cathodic Protection”

SP0176 “Corrosion Control of Submerged Areas of Permanently Installed Steel Offshore Structures Associated with Petroleum Production”

SP0388 “Impressed Current Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks”

SP0177 “Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems”

SP0575 “Internal Cathodic Protection (CP) Systems in Oil-Treating Vessels”

RP0193 “External Cathodic Protection of On-Grade Metallic Storage Tank Bottoms”

RP0196 “Galvanic Anode Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks”

SP0290 “Impressed Current Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures”

SP0200 “Steel Cased Pipeline Practices”

TM0497 “Measurement Techniques Related to Criteria for Cathodic Protection on Underground or Submerged Metallic Piping Systems”

TM0101 “Measurement Techniques Related to Criteria for Cathodic Protection on Underground or Submerged Metallic Storage Tanks”

Section 11

Worksheets

CP Tester Practical Exam Reference Sheet

Instructions for Completing the ParSCORE™ Student Enrollment Score Sheet

1. Use a Number 2 (or dark lead) pencil.

2. Fill in **all** of the following information **and** the corresponding bubbles for each category:

- ✓ ID Number: Student ID, NACE ID or Temporary ID provided
- ✓ PHONE: Your phone number. **The last four digits of this number will be your password for accessing your grades on-line.** (for Privacy issues, you may choose a different four-digit number in this space)
- ✓ LAST NAME: Your last name (surname)
- ✓ FIRST NAME: Your first name (given name)
- ✓ M.I.: Middle initial (if applicable)
- ✓ TEST FORM: This is the version of the exam you are taking
- ✓ SUBJ SCORE: This is the version of the exam you are taking
- ✓ NAME: _____ (fill in your entire name)
- ✓ SUBJECT: _____ (fill in the type of exam you are taking, e.g., CIP Level 1)
- ✓ DATE: _____ (date you are taking exam)

3. The next section of the form (1 to 200) is for the answers to your exam questions.

- **All answers MUST be bubbled in on the ParSCORE™ Score Sheet .** Answers recorded on the actual exam will **NOT** be counted.
- If changing an answer on the ParSCORE™ sheet, be sure to **erase completely**.
- Bubble only **one** answer per question and do not fill in more answers than the exam contains.

ParSCORE™
STUDENT ENROLLMENT SHEET

→ PASSWORD

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EXAMINATION RESULTS POLICY AND PROCEDURES

It is NACE policy to not disclose student grades via the telephone, e-mail, or fax. Students will receive a grade letter, by regular mail or through a company representative, in approximately 6 to 8 weeks after the completion of the course. However, in most cases, within 7 to 10 business days following receipt of exams at NACE Headquarters, students may access their grades via the NACE Web site.

WEB Instructions for accessing student grades on-line:

Go to: **www.nace.org**

Choose: **Education**
 Grades
 Access Scores Online

Find your **Course ID Number** (Example 07C44222 or 42407002) in the drop down menu.

Type in your **Student ID or Temporary Student ID** (Example 123456 or 4240700217)*.

Type in your **4-digit Password** (the last four digits of the telephone number entered on your Scantron exam form)

Click on **Search**

Use the spaces provided below to document your access information:

STUDENT ID _____	COURSE CODE _____
PASSWORD (Only Four Digits) _____	

*Note that the Student ID number for NACE members will be the same as their NACE membership number unless a Temporary Student ID number is issued at the course. For those who register through NACE Headquarters, the Student ID will appear on their course confirmation form, student roster provided to the instructor, and/or students' name badges.

For In-House, Licensee, and Section-Registered courses, a Temporary ID number will be assigned at the course for the purposes of accessing scores online only.

For In-House courses, this information may not be posted until payment has been received from the hosting company.

Information regarding the current shipment status of grade letters is available upon the web upon completion of the course. Processing begins at the receipt of the paperwork at NACE headquarters. When the letters for the course are being processed, the "Status" column will indicate "Processing". Once the letters are mailed, the status will be updated to say "Mailed" and the date mailed will be entered in the last column. Courses are listed in date order. ***Grade letter shipment status can be found at the following link:***

<http://web.nace.org/Departments/Education/Grades/GradeStatus.aspx>

If you have not received your grade letter within 2-3 weeks after the posted "Mailed date" (6 weeks for International locations), or if you have trouble accessing your scores on-line, you may contact us at GradeQuestions@nace.org

NACE CORROSION NETWORK (NCN)

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

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

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

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

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

CP 1 – Cathodic Protection Tester Course Outline

DAY ONE	
	Introduction, Welcome, Overview
Chapter 1	Basic Electricity
DAY TWO	
Chapter 2	Basic Chemistry & Basic Corrosion Theory
Chapter 3	Underground Corrosion Control
Chapter 4	Safety
Chapter 5	Field Measurements
DAY THREE	
Chapter 5	Field Measurements (continued)
Chapter 6	Stray Current Interference
Chapter 7	Monitoring Cathodic Protection Effectiveness and Recordkeeping
	Introduction to Indoor Field Measurement Test Stations
	Indoor Field Measurement Test Station Practice
DAY FOUR	
	Outdoor Field Program (weather permitting)
DAY FIVE	
Chapter 8	Installing CP Components
Chapter 9	Troubleshooting
	Indoor Field Measurement Test Station Practice
	Course Review
DAY SIX	
	Written and Practical Examinations

Introduction

The Course

Corrosion is one of the most important problems encountered by the owners and operators of underground, offshore, submerged and other metallic structures exposed to an electrolyte. If corrosion is not controlled, it can lead to large costs in repairs or facility replacement. Even greater costs can be incurred from environmental damage, injuries and fatalities.

Corrosion control personnel must have a good basic understanding of corrosion mechanisms. They also need to know the various conditions under which corrosion can occur on underground facilities.

In this course, we will focus on the control of metallic corrosion by applying cathodic protection. This course was developed for cathodic protection field technicians, although this knowledge is also needed by corrosion engineering personnel.

Corrosion prevention can be better understood after acquiring a good understanding of corrosion itself. Corrosion is defined as the deterioration of a substance or its properties as a result of an undesirable reaction with the environment. This includes metals, plastics, wood, concrete, and virtually all other materials. Current estimates show that the cost of corrosion in the U.S. exceeds \$500 billion per year amounting to more than \$2,000 per person.

There are several forms of corrosion, such as erosion, fretting, nuclear, high temperature, and electrochemical. In this course we will study electrochemical corrosion because it is the most common form of corrosion that you will encounter.

Audience (Who Should Attend)

This course is directed toward those who are responsible for observing, recording or measuring the effectiveness of CP Systems including cathodic protection field personnel, technicians and those desiring certification as a NACE Cathodic Protection Tester.

Prerequisites

It is recommended that attendees have had at least six months of cathodic protection work experience and a High School diploma or GED.

Length

The course will begin on Sunday at 1:00 pm and concludes on Friday afternoon.

Reference Books

The primary reference for this course is *Peabody's Control of Pipeline Corrosion* by A. W. Peabody and will be furnished to each student.

EXPERIMENTS

Throughout the week, there will be experiments to help illustrate and reinforce principles discussed in the lecture sections.

CAUTION: Students should realize that these experiments are conducted under controlled conditions, field conditions will vary.

Field Training

On Wednesday, students will participate in a field training activity at a training site, weather permitting. The field training activity is designed to simulate actual field conditions that students may encounter on-the-job. Students will perform tests and collect data.

Quizzes and Examinations

There will be quizzes distributed during the week and reviewed in class by the instructors.

This course has both written and practical (hands-on) final examinations and the final examinations will be given on Friday.

The written final examination consists of 100 multiple-choice questions. The final written examination is open book and students may bring reference materials and notes into the examination room.

The practical examination is closed book.

A score of 70% or greater on both the written and practical examination(s) is required for successful completion of the course and to obtain certification. All questions are from the concepts discussed in this training manual.

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

Introduction

Corrosion and cathodic protection are electrochemical phenomena. Consequently, electrical instruments are used in some corrosion testing and we need to understand various electrical terms, laws, and circuits when working with cathodic protection. This knowledge is essential for anyone entering the field of cathodic protection technology. The more important concepts are discussed in this chapter.

Electrical Terms

Electrons

Electrons are particles that carry a negative charge. They also help hold matter together, a bit like the mortar in a brick wall.

Voltage

Voltage (joule/coulomb), or *potential*, is an electromotive force or a difference in potential expressed in Volts. Voltage is the energy that puts charges in motion. This force is measured in volts, millivolts, and microvolts. In corrosion work all three units are used. The following shows their relationship:

1,000 Volts	=	1 kilovolt
1.000 Volt	=	1000 millivolts
0.100 Volt	=	100 millivolts
0.010 Volt	=	10 millivolts
0.001 Volt	=	1 millivolt
0.000001 Volt	=	1 microvolt

Common symbols for voltage are:

emf	electromotive force - any voltage unit
E or e	voltage across a source of electrical energy (e.g. battery, pipe-to-soil potential)
V or v	voltage across a sink of electrical energy (e.g. resistor)

You will be concerned with voltage when making various measurements in cathodic protection work. Among these are pipe-to-soil potential measurements, voltage drops across shunts or along pipelines (a method of measuring current explained in Chapter 4), and the voltage output of a cathodic protection rectifier.

Current

Current is the flow of charges along a conducting path and is measured in amperes. Current is frequently abbreviated as amps, milliamps, or microamps. In corrosion work we use all three units. The following shows their relationship:

Ampere = the common unit of current = a flow rate of charge of 1 coulomb per second. One coulomb is the unit of charge carried by 6.24×10^{18} electron charges.

1,000 amperes	=	1 kiloampere
1.000 ampere	=	1000 milliamperes
0.100 ampere	=	100 milliamperes
0.010 ampere	=	10 milliamperes
0.001 ampere	=	1 milliampere
0.000001 ampere	=	1 microampere

Common symbols for current flow are:

I	any unit of current such as: amperage unit
A	Amperes or Amps
mA	milliamperes or milliamps
μ A	microamperes or microamps

Direct current flows constantly in one direction in a circuit. Alternating current regularly reverses direction of flow, commonly 100 or 120 times per second.

Resistance and Resistivity

Resistance is the opposition that charges encounter when moving through a material.

The ohm is the common unit of resistance measurement. It is the resistance of a conductor when a voltage of one volt produces a current flow of one ampere along the conductor. Resistance may also be measured in milliohms (0.001 Ohm) or in megohms (1,000,000 Ohms).

Common symbols for resistance are:

- R, r
- Ω (Greek letter *omega*)

Resistance is important in such matters as cathodic protection groundbeds, resistance of a structure to the electrolyte, and the linear resistance of a long structure such as a pipe or cable.

Resistivity is the resistance of a conductor of unit length and unit cross-sectional area.

The symbol used for resistivity is ρ (Greek letter rho).

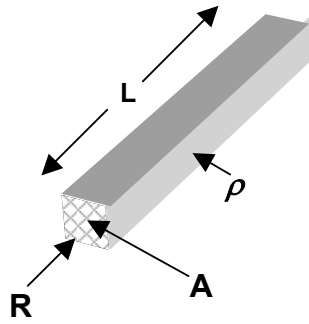
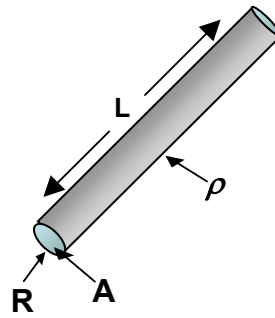
Resistivity is constant for a given material and is computed by the formula:

$$\rho = \frac{R \times A}{L}$$

where ρ = Resistivity in ohm-cm
 R = Resistance in Ohms
 A = Cross-sectional area in cm²
 L = Length in cm

If the resistivity of a material is known (see Table 1.1), the resistance of a conductor such as a cable or pipeline of known length and cross-sectional area can be calculated from:

$$R = \frac{\rho \times L}{A}$$

**Figure 1.1a****Figure 1.1b**

Crosssectional Area

$$A(\text{cm}^2) = h \times w$$

where: h = height (cm)

w = width (cm)

$$A(\text{cm}^2) = \pi r^2$$

where: r = radius (cm)

The terms are the same as in the above equation.

Resistance to current flow is lowest for:

- Low-resistivity (high-conductivity) media
- Short length for current flow
- Large area of current flow

Resistance will be greatest for:

- High-resistivity (low-conductivity) media
- Long path length for current flow
- Small cross-sectional area of current flow

Table 1.1 Typical Resistivity of Common Materials

Material	Resistivity ($\Omega\text{-cm}$)
Aluminum	2.69×10^{-6}
Carbon	3.50×10^{-3}
Copper	1.72×10^{-6}
Iron	9.80×10^{-6}
Steel	18.0×10^{-6}
Lead	2.20×10^{-5}
Magnesium	4.46×10^{-6}
Zinc	5.75×10^{-6}
Ice	5.75×10^8
Rubber	7.20×10^{16}
Water (tap)	3.00×10^3
Water (sea)	3.00×10^1
Soil (varies)	1.00×10^2 to 5×10^5

Scientific notation uses exponents where the multiplier 10 is raised to a power. For example,

$$1 \times 10^2 = 1 \times 10 \times 10 = 100$$

$$1 \times 10^{-2} = 1 \times .1 \times .1 = .01$$

The common unit of resistivity measurement for an electrolyte is ohm-centimeter. Electrolytes dealt with in corrosion and cathodic protection includes soils and liquids (water). Since electrolytes do not usually have fixed dimensions (the earth or a body of water, for example), resistivity is usually defined as the resistance between two parallel faces of a cube one cm on each side. Electrolyte resistivities vary greatly. Some electrolytes have resistivities as low as $30 \Omega\text{-cm}$ (seawater) and as high as $500,000 \Omega\text{-cm}$ (dry sand). Resistivity of an electrolyte is an important factor in evaluating the corrosivity of an environment and designing cathodic protection systems. Measurement of electrolyte resistivity is covered in Chapter 5.

Electrical Schematic Diagram Symbols

Resistor	
Ground	
Battery	
Connection	
Rectifier	
Switch	
Diode	

Electric Circuit

The *electric circuit* is the path followed by an electric current. See Figure 1.2. Examples of various circuits are shown in Figures 1.6, 1.7 and 1.8.

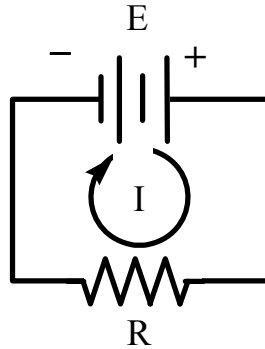


Figure 1.2 Basic DC Electrical Circuit

Electrical Laws

Electrical laws govern the relationships in electric circuits.

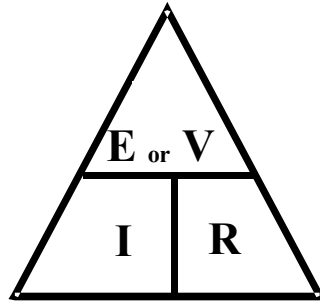
Ohm's Law

Ohm's Law is a relationship between the ratio of voltage and current to the resistance of a circuit. The law states that a voltage of 1 volt will create a current of 1 ampere in a circuit having a resistance of 1 Ohm. Ohm's Law can be expressed as follows:

where E or V	= Voltage (electromotive force)
I	= Current (amperes)
R	= Resistance (Ohms)

E or V	= IR
I	= E/R
R	= E/I

This can be graphically illustrated by the “Ohm’s Law Triangle”:



If two of the three variables are known, you can compute the third. If you have measured the voltage and current in a cathodic protection circuit, for example, you can easily calculate the circuit resistance. An easy way to use the Ohm’s Law triangle is to place your thumb over the quantity you are looking for. If you want to find resistance, as in the above example, place your thumb over the R and you can see that $R = E/I$. If you want voltage, placing the thumb over the E shows you that $E = I \times R$.

Note that the units used must be consistent: amperes, volts and Ohms. Amperes and millivolts or volts and milliamps cannot be mixed.

Consider the circuit in Figure 1.3. A battery is connected across a known resistance.

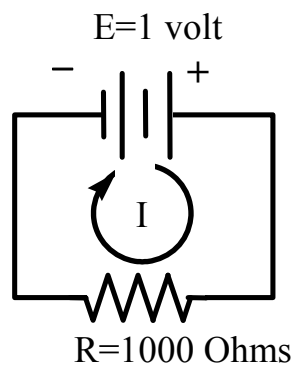


Figure 1.3 Current Through a Resistor

What is the current flow?

$$I = \frac{E}{R} = \frac{1.0 \text{ volt}}{1000 \text{ Ohms}} = 0.001 \text{ amps} = 1 \text{ milliamp}$$

Likewise, if we knew the current was 1 milliamp and the voltage was 1.0 volt, what is the resistance?

$$R = \frac{E}{I} = \frac{1.0 \text{ volt}}{0.001 \text{ amps}} = 1000 \text{ Ohms}$$

Note that we had to convert 1.0 milliamp to 0.001 amperes to use Ohm's Law since the voltage is in volts, not millivolts.

Ohm's Law plays an important role in your work and you need to be thoroughly familiar with it. Turn now to Group Exercise 1.1 at the end of this chapter and work through the calculations in the exercise.

Power

Power is the energy used by an electrical device. It is necessary to know the power required by a cathodic protection rectifier, for example, in order to size the alternating current supply circuit.

Power is measured in watts. The equations for power and the symbols used are:

$$P = EI$$

$$P = I^2R$$

where:

P = Power in watts

R = Resistance in Ohms

E = Voltage in volts

I = Current in amperes

Kirchhoff's Laws

Voltage Law

This law states that the sum of the source voltages around any closed loop of a circuit is equal to the sum of the voltage drops across the resistances in that loop.

For example, in Figure 1.4:

Source voltages = $12\text{V} + 12\text{V} = 24\text{V} = \text{IR drops } (8\text{V} + 8\text{V} + 8\text{V})$

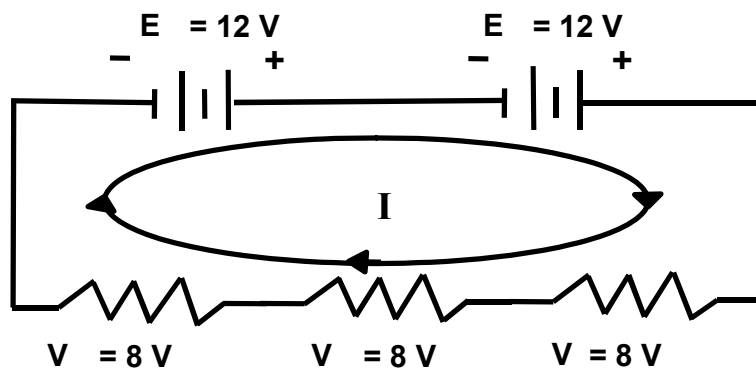


Figure 1.4 Kirchhoff's Voltage Law

The driving voltage in this circuit is a 24-volt battery. The voltage ($I \times R$ or IR) drop across each resistor is 8 volts. In this example, the three resistors are the same size. If the resistors were of different sizes, the sum of the voltage drops across them would still equal 24 volts. Voltage drops in an electrical circuit are like pressure drops along a length of pipeline. If the various pressure drops are added up, they will equal the total pressure drop across that length of pipeline.

Current Law

This law states that as much current flows away from a point as flows toward it. It is especially useful in analyzing parallel circuits and in tracing current flow in complex piping networks.

For example, in Figure 1.5:

Current in (6 A) = Current out (3 + 2 + 1 A)

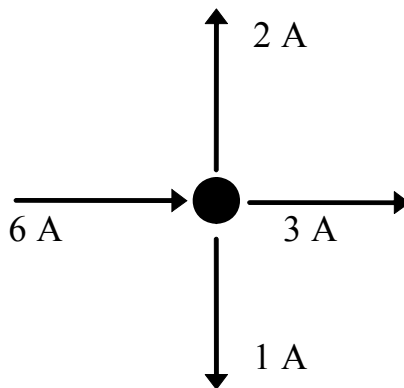


Figure 1.5 Kirchhoff's Current Law

Series Circuit

In a series circuit (Figure 1.6), the same current flows in an individual, consecutive, and continuous path from the source of voltage through the various loads and back to the source.

- The current is the same everywhere.
- The voltage drops may all be different depending on the value of each resistance, but the sum of the voltage drops (E_T) must add up to the voltage of the source (an example of Kirchhoff's Voltage Law).
- The total resistance (R_T) of a series circuit equals the sum of the individual resistances.

In cathodic protection work, we are concerned with series circuits, for example, in the length of cables running out to groundbeds. The longer the wire (a series circuit), the higher the resistance and the lower the current for a given voltage. The resistance between a single galvanic anode and a structure also represents a series circuit.

For example, consider the following circuit, where:

E_T = Total Voltage Across the Circuit

R_T = Total Resistance in the Circuit

I_T = Total Current in the Circuit

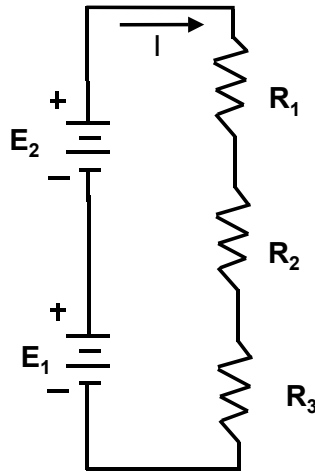


Figure 1.6 Series Circuit

Given $E_1 = 5 \text{ V}$
 $E_2 = 5 \text{ V}$
 $R_1 = 5 \Omega$
 $R_2 = 3 \Omega$
 $R_3 = 2 \Omega$

$$R_T = 5 \Omega + 3 \Omega + 2 \Omega = 10 \Omega$$

$$I_T = \frac{E}{R} = \frac{10 \text{ V}}{10 \Omega} = 1 \text{ A}$$

$I_1 = 1 \text{ A}$	$I_1 R_1 = 1 \text{ A} \times 5 \Omega = 5 \text{ V}$
$I_2 = 1 \text{ A}$	$I_2 R_2 = 1 \text{ A} \times 3 \Omega = 3 \text{ V}$
$I_3 = 1 \text{ A}$	$I_3 R_3 = 1 \text{ A} \times 2 \Omega = 2 \text{ V}$
$I_T = I_1 = I_2 = I_3 = 1 \text{ A}$	
$R_T = R_1 + R_2 + R_3 = 10 \Omega$	

Total IR Drop = $5+3+2 = 10 \text{ V}$
 OR

$$I_T R_T = 1 \text{ A} \times 10 \Omega = 10 \text{ V}$$

$$E_T = 10 \text{ V}$$

Note that Kirchhoff's Voltage Law is fulfilled.

Turn now to Group Exercise 1.2 for further practice with series circuits.

Parallel Circuit

In a parallel circuit (Figure 1.7), the current divides into a number of separate branches. Each branch may have a different resistance; thus, the value of the current in each branch may be different. Voltage drop across each element or source in the circuit is the same. If you can trace more than one path for current to flow through the circuit, you have a parallel circuit.

Galvanic anodes attached to a structure represent a parallel circuit. The same is true for impressed current anodes: the more anodes you add, the lower the resistance to the electrolyte and the more current you get.

For a parallel circuit:

- Voltage drop across each branch is the same and is equal to source voltage.
- Total current flowing into and out of the junction point of the branches equals the sum of branch currents (Kirchhoff's Current Law).
- Total (equivalent) resistance is equal to the reciprocal of the sum of the reciprocals of the individual resistances.
- The total (equivalent) resistance is always less than the smallest resistance in the circuit.

For example, consider the following circuit:

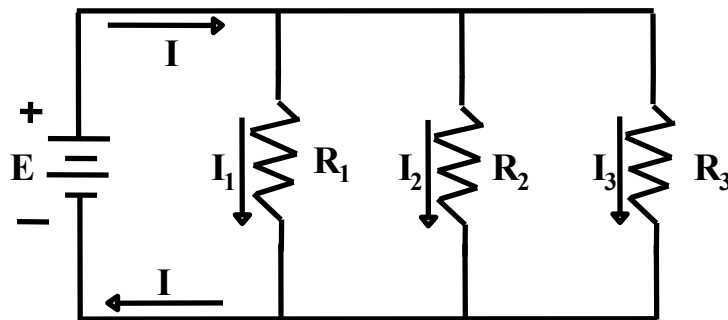


Figure 1.7 Parallel Circuit

$$I_T = I_1 + I_2 + I_3$$

$$E_T = I_1 R_1 = I_2 R_2 = I_3 R_3$$

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

$$I_1 = \frac{E_T}{R_1}$$

$$I_2 = \frac{E_T}{R_2}$$

$$I_3 = \frac{E_T}{R_3}$$

Given $E = 20 \text{ V}$
 $R_1 = 5 \Omega$
 $R_2 = 4 \Omega$
 $R_3 = 2 \Omega$

$$I_1 R_1 = E_T = 20 \text{ V} \quad I_1 = E_T / R_1 = 20 \text{ V} / 5 \Omega = 4 \text{ A}$$

$$I_2 R_2 = E_T = 20 \text{ V} \quad I_2 = E_T / R_2 = 20 \text{ V} / 4 \Omega = 5 \text{ A}$$

$$I_3 R_3 = E_T = 20 \text{ V} \quad I_3 = E_T / R_3 = 20 \text{ V} / 2 \Omega = 10 \text{ A}$$

$$I_T = 4 \text{ A} + 5 \text{ A} + 10 \text{ A} = 19 \text{ A}$$

Now consider the total circuit resistance:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} = \frac{1}{\frac{1}{5\Omega} + \frac{1}{4\Omega} + \frac{1}{2\Omega}}$$

$$R_T = \frac{1}{0.2 + 0.25 + 0.5} = \frac{1}{0.95} = 1.053 \Omega$$

$$I_T = \frac{20 V}{1.053 \Omega} = 19 A$$

If all the resistors in a parallel circuit are equal, the total resistance of the circuit is equal to one of the resistances divided by the number of resistors.

$$R_T = \frac{R}{N}$$

where:

R_T = Total resistance

R = Resistance of each resistor

N = Number of resistors

Turn now to Group Exercise 1.3 for further practice with parallel circuits.

Series-Parallel Circuit

A series-parallel circuit (Figure 1.8) combines the elements of both a series circuit and a parallel circuit. Very complex circuits can be reduced to a circuit consisting of series-parallel elements. This is important in the design of cathodic protection. The cable running out to the groundbed represents a series circuit, the groundbed itself a parallel circuit.

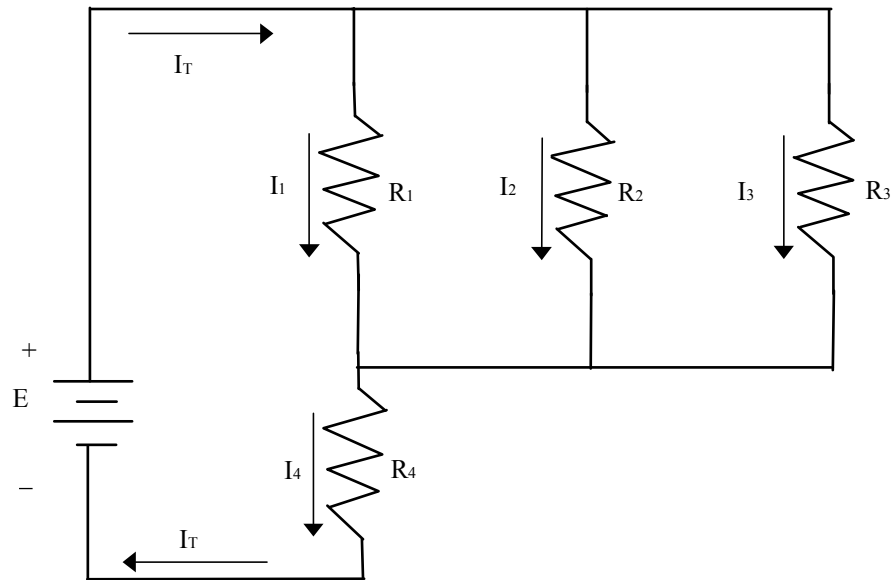


Figure 1.8 Series and Parallel Circuits Combined

Given $E = 20 \text{ V}$
 $R_1 = 5 \Omega$
 $R_2 = 4 \Omega$
 $R_3 = 2 \Omega$
 $R_4 = 0.95 \Omega$

First, reduce the parallel part of the circuit to a single resistance using the same formula as shown for Figure 1.7:

$$R_{1,2,3} = \frac{1}{\frac{1}{5 \Omega} + \frac{1}{4 \Omega} + \frac{1}{2 \Omega}} = \frac{1}{0.95} = 1.053 \Omega$$

We now have an equivalent series circuit of two resistors, 1.053Ω and 0.95Ω for a total resistance of 2.003Ω .

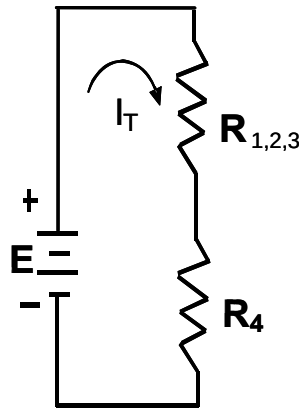


Figure 1.9

The total voltage, $E_T = 20 \text{ V}$

Total current flow $I_T = E_T/R_T = 20 \text{ V}/2.003 \Omega = 9.98 \text{ A}$

Next, calculate the voltage across the parallel part of the circuit. This is equal to the total voltage less the voltage drop across R_4 or $20 \text{ V} - (10 \text{ A} \times 0.95 \Omega) = 10.5 \text{ V}$. Calculating the currents through R_1 , R_2 , and R_3 is simply a matter of applying Ohm's Law:

$$I_1 = 10.5 \text{ V}/5 \Omega = 2.10 \text{ A}$$

$$I_2 = 10.5 \text{ V}/4 \Omega = 2.63 \text{ A}$$

$$I_3 = 10.5 \text{ V}/2 \Omega = 5.25 \text{ A}$$

$$I_T = 9.98 \text{ A}$$

Note that Kirchhoff's Current Law is fulfilled also. The currents entering Points A, B, and C equal those leaving these points.

Direct Current (DC)

Direct current flows in only one direction. Pure direct current is produced by a battery and appears as a straight line when viewed on an oscilloscope. See Figure 1.10. The circuits we have been discussing above are all based on direct current.

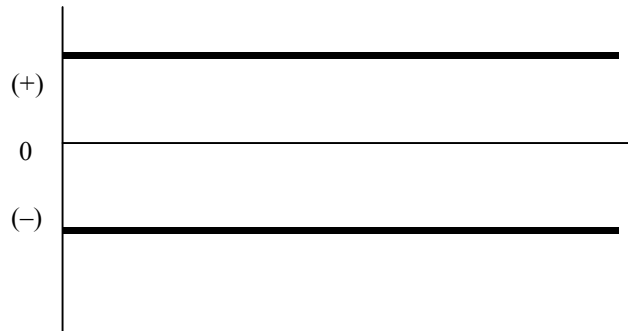


Figure 1.10 Pure Direct Current

Alternating Current (AC)

Alternating current, such as that which we have in our homes and buildings, reverses direction on a cyclic basis, most commonly 100 or 120 times a second. A full cycle is completed in a 50th or 60th of a second. The word hertz (hz) is used to represent a cycle, so AC is known as 50 hz or 60 hz current. Figure 1.11 shows a typical alternating current.

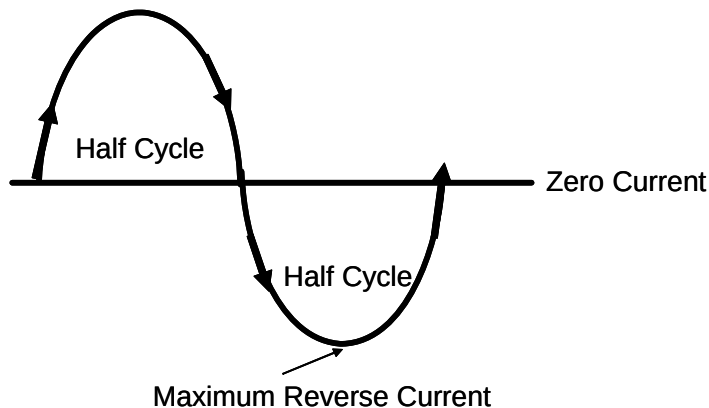


Figure 1.11 Typical Alternating Current

Alternating current can be turned into direct current through a rectifier. This is the function of cathodic protection rectifiers. The rectified DC still has some ripple in it, however, so it is not the pure DC that comes from a battery. Figure 1.12 shows a simple rectified AC.

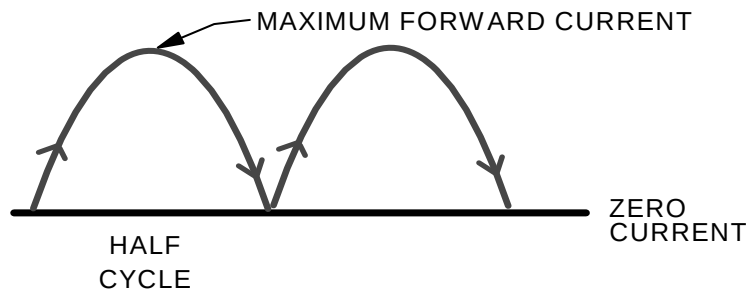


Figure 1.12 DC Produced by Rectifying AC

Knowledge of alternating current is important in understanding cathodic protection rectifiers. Some of the more important factors follow.

Transformers

Transformers may be used to increase or decrease voltage or to isolate an incoming voltage source from the outgoing voltage. The transformer has a laminated iron core as illustrated in Figure 1.13 that shows a transformer as part of a cathodic protection rectifier. There are two sets of windings on the core, the primary and the secondary. The primary winding is connected to the voltage source. The secondary winding is connected to the unit to which voltage is to be supplied.

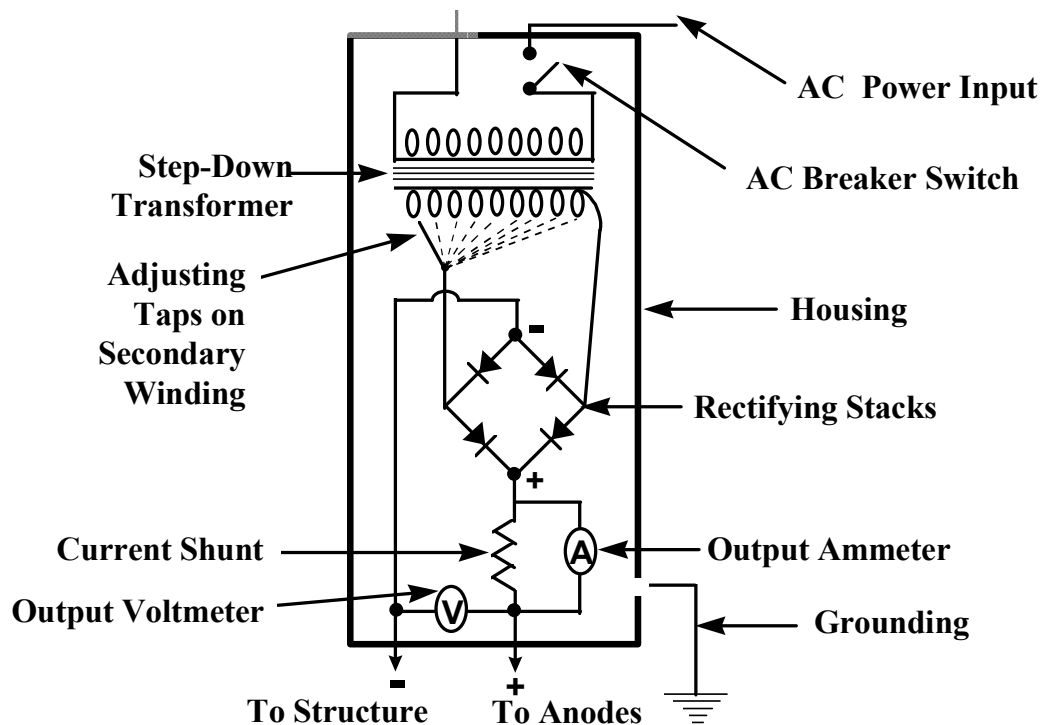


Figure 1.13 Typical Transformer Wiring in a Rectifier

An alternating magnetic field is established in the core from the voltage applied to the primary winding. This field induces voltage in the secondary winding. The ratio of the secondary voltage to the primary voltage is directly proportional to the ratio of the secondary turns to the primary turns. This ratio can be expressed as follows:

$$\frac{\text{PRIMARY VOLTAGE}}{\text{SECONDARY VOLTAGE}} = \frac{\text{NUMBER OF PRIMARY TURNS}}{\text{NUMBER OF SECONDARY TURNS}}$$

This exact relationship holds true under no load conditions. Losses in the core and laminations reduce the output voltage when under load.

In cathodic protection rectifiers, taps are located in the secondary wiring so that several voltage adjustments are possible.

Impedance

Impedance is the total opposition that a circuit presents to alternating current, similar to resistance in a direct current circuit. Impedance is equal to a complex ratio of AC voltage to AC current. Impedance also depends on the frequency and wave shape of the current. Impedance is measured in Ohms, as is DC resistance.

Meter Operation

General

The classification of a meter depends on the inner workings and the display of the meter. The inner workings of a meter may be either electromechanical movement or electronic. The display may be either analog or digital. Earlier instruments were constructed using an electromechanical movement with an analog display and are referred to as *analog meters*. These instruments have a needle that rotates across the meter face and indicates the reading on a scale.

Today, most instruments are electronic with digital displays and are referred to as *digital meters*. Hybrid meters that are electronic with analog displays (electronic amplifiers driving an electromechanical coil) are sometimes referred to as *electronic meters* (see Figure 1.14).

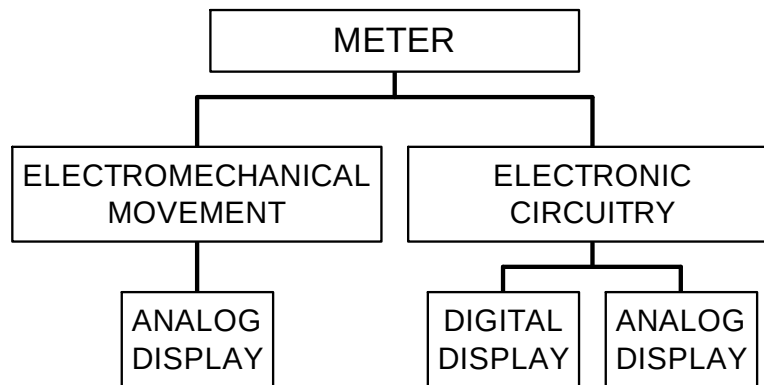


Figure 1.14 Meter Operation

Analog Meters

Basic Meter Movement

The basic movement of an analog meter is a stationary permanent magnet/moving coil system called a *D'Arsonval movement*. This is shown in Figure 1.15. The needle provides a continuous representation of the measurement, called an *analog* of the measurement value.

The D'Arsonval meter responds to a current flow through the moving coil. Electrical current is converted into a mechanical force, as indicated in the following steps:

1. Current from the external circuit flows through the coil and creates a magnetic field.
2. The coil rotates due to the reaction of its magnetic field with the magnetic field of the permanent magnet.
3. As the coil rotates, it works against a mechanical spring, causing tension in the spring.
4. The pointer comes to rest along the calibrated scale based on the balance in forces between the moving magnetic coil and the spring tension.
5. The reading on the scale represents the current flow through the coil from the external circuit. Note that the energy needed to operate the meter comes from the circuit itself.

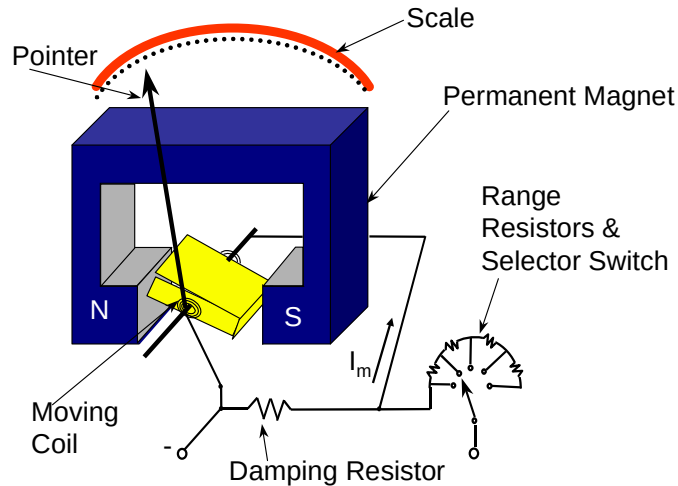


Figure 1.15 D'Arsonval Movement (Voltmeter)

Of the total current required to cause full-scale deflection, part of the current will flow through the moving coil and part through the damping resistor. The damping resistor is connected in parallel with the moving coil; its function is to reduce needle overswing and permit the needle to come to rest within a reasonable period of time.

The coil is delicate and can be destroyed easily if large currents flow through it; therefore, resistors are placed either in series or parallel to the meter movement to control the maximum current flow through the meter coil.

Whether an analog meter is used to measure voltage, current, or resistance, each of these measurements depend on the measurement of current flow. The meter measures current directly, and, by knowing one of the other variables, the third variable can be calculated by using Ohm's Law.

To obtain an upscale reading (needle moving to the right) current must enter the meter on the positive terminal. Remembering this will enable you to determine the direction of current flow in the circuit with which you are working.

Also, when using an analog meter, the reference electrode is connected to the positive terminal to obtain an upscale reading.

Voltmeters

Because the D'Arsonval meter responds to current flow through the coil, the current magnitude resulting in full-scale deflection of the meter can be determined. Also, the series resistance of the meter coil is known. The meter can be used to determine voltage by using Ohm's Law. The full-scale voltage is simply the full-scale current times the coil resistance. This is the smallest full-scale voltage range possible with the meter. Larger full-scale voltage ranges can be made available by switching resistors in series with the moving coil, which reduces the magnitude of voltage drop directly across the coil.

For low-voltage ranges, the circuit resistance becomes more sensitive and external resistances such as those associated with test leads and reference electrode-to-electrolyte contact may cause an error in the reading.

Voltmeter Ranges

The most common DC voltage scales on meters and their usage are as follows:

- 200 millivolts—Current shunt readings
- 2 Volts—Structure-to-electrolyte potentials
- 20 Volts—Structure-to-electrolyte potentials and rectifier voltage output
- 200 Volts—Rectifier voltage output
- 1000 Volts—Unknown voltage

WARNING – DO NOT TOUCH THE METAL PARTS OF THE TEST WIRES WHEN TAKING VOLTAGE READINGS.
--

Ammeters

If the meter is used as an ammeter, resistors are placed parallel to the moving coil to shunt a significant portion of the total current around the moving coil. The position of the range switch determines the value of the shunt resistance. The higher the current to be measured,

the smaller the shunt resistor must be to allow greater portions of the current to bypass the coil.

Current Range

The most common DC current scales on meters are as follows:

- 200 microamps
- 2 milliamps
- 20 milliamps
- 200 milliamps
- 2 amps
- 10 amps

Ohmmeters

If the current is measured and the driving voltage is known, the resistance of the circuit can be calculated by Ohm's Law. An ohmmeter measures the current flow caused by a known voltage source and indicates resistance on the scale or readout.

Ohmmeters find limited use in corrosion work. They can be useful for checking circuit continuity and for other testing in rectifiers or resistor panels, but they are not suitable for testing resistance between structures in an electrolyte (e.g., across an isolation joint, or casing to pipe). There are two reasons for this. First, when two structures are electrically isolated from each other by a fitting, there is a parallel resistance through the electrolyte. The ohmmeter cannot distinguish between the resistance of the fitting and the resistance through the electrolyte. More important, however, is the fact that there is nearly always a voltage difference between two isolated structures. This voltage affects the total voltage of the measuring circuit and creates appreciable errors. A high resistance may be indicated with the leads connected one way and a low resistance with the leads reversed.

WARNING – DO NOT TOUCH THE METAL PARTS OF THE TEST WIRES WHEN TAKING VOLTAGE READINGS.

Digital Meters

Basis of Operation

A digital meter is based on integrated microcircuit technology. The analog input is sampled over a specific period of time. The average input over this time is then converted to a digital value, a coded number, using an analog-to-digital (A-to-D) converter. For a digital multimeter (DMM), all measurements are converted to DC volts prior to the analog-to-digital conversion. The displayed value is not continuous but a sample of the input value measurements. However, the measurement is taken several times per second. The measured value is displayed as discrete digits; the digits do not require operator interpretation as the analog display does. If a voltage is changing, the numbers are also changing, and it may be difficult to read a specific value from the fluctuating members. Therefore, in areas with stray current, a digital meter may not be as useful as an analog meter.

Meter Hook Up

When current enters the meter on the positive terminal, a positive sign (+) is displayed. A negative sign (–) is displayed when current enters the meter on the negative terminal. Remembering this will enable you to determine the direction of current flow in the circuit with which you are working.

Also, when using a digital meter, the reference electrode is connected to the negative terminal to obtain the proper polarity reading.

Exercise 1.1: Ohm's Law

Write the 3 forms of Ohm's Law here

E =

I =

R =

Given:

A light bulb is designed for 120 V and has a resistance of 20 Ω .

How much current will flow through it? _____

How many watts will it take ($P = V \times I$)? _____

Given:

A corrosion circuit produces 2 A of current at a driving voltage of 1.6 V.

What is the resistance of this circuit? _____

Given:

A structure requires 100 mA for adequate cathodic protection and the total resistance is 1.5 Ω .

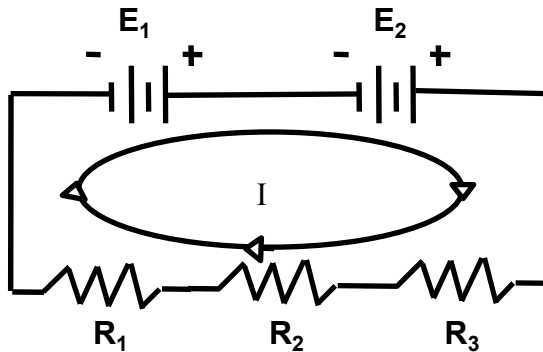
What is the required voltage for this circuit? _____

Given:

The driving voltage between the anodes and the structure of a cathodic protection system is 1 volt and the protective current is 100 mA.

What is the circuit resistance? _____

Exercise 1.2: Series Circuit



Given:

Power supply voltage $E_1 = 5\text{V}$, $E_2 = 5\text{V}$, $E_T = 10\text{V}$

Load resistance (R_1) = $1\ \Omega$

Load resistance (R_2) = $2\ \Omega$

Load resistance (R_3) = $1\ \Omega$

Calculate total resistance? _____

Calculate current? _____

Calculate voltage drop across R_1 ? _____

Calculate voltage drop across R_2 ? _____

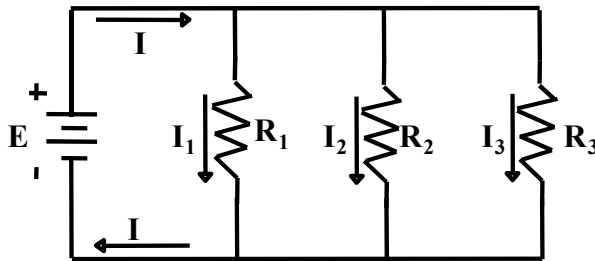
Calculate voltage drop across R_3 ? _____

Calculate the sum of the voltage drops? _____

Does the voltage drop sum = total power voltage? Y N

Is Kirchhoff's Voltage Law fulfilled? Y N

Exercise 1.3: Parallel Circuit



Given:

Power supply voltage (E) = 20 V

Load resistance (R_1) = 1 Ω

Load resistance (R_2) = 2 Ω

Current across load resistance (R_3) = 20 A

What is the total power voltage? _____

What is the voltage drop across R_1 ? _____

Calculate current through R_1 ? _____

What is the voltage drop across R_2 ? _____

Calculate current through R_2 ? _____

What is the voltage drop across R_3 ? _____

Calculate the resistance of R_3 ? _____

Calculate total current? _____

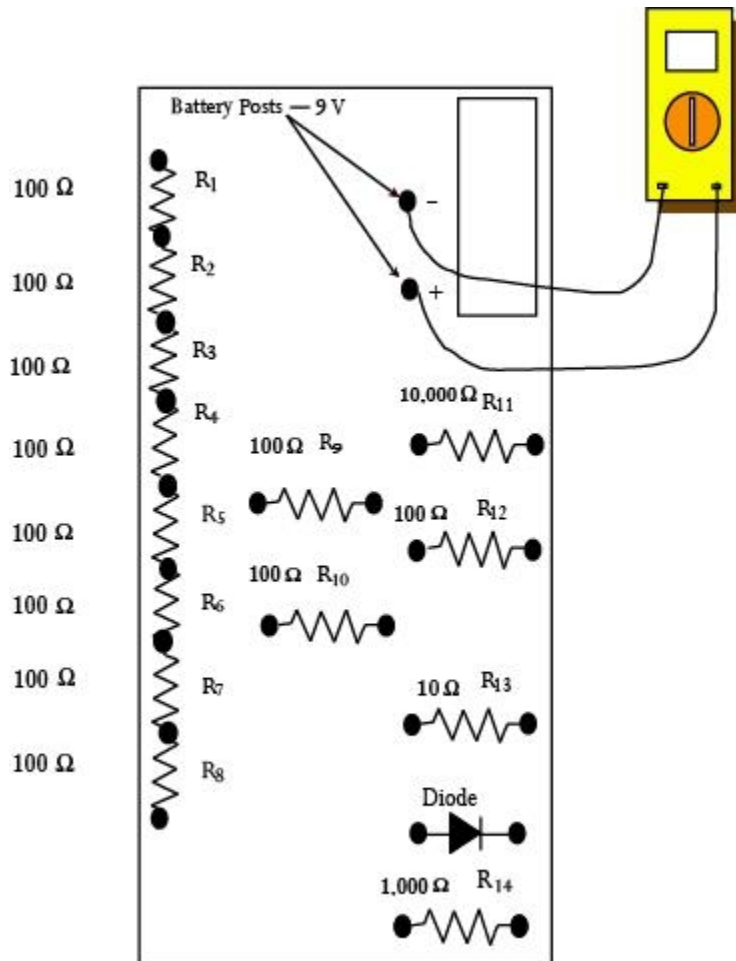
Calculate total resistance using Ohm's Law?

Calculate total resistance using the parallel circuit total resistance equation? _____

Using arrows, show the application of Kirchhoff's Current Law.

Exercise 1.4: Resistor and Instrument Lab

Simple measurements using the ammeter and voltmeter functions of a digital multimeter can be used to determine the characteristics and operating parameters of DC electrical circuits. The circuit board and digital multimeter contained in the experimental kits will be used for the following experiments. The circuit board layout is shown in below.



Record the data collected on the Exercise 1.4 Data Sheet provided.

- Step 1.** Using the voltmeter, measure the voltage of the battery. Does it equal the printed battery voltage? If not, why?
- Step 2.** Using the ohmmeter, measure the resistance of each resistor. Do the resistances equal those marked on the resistors? If not, why?
- Step 3.** Calculate the total resistance (R_T) of R_{12} , R_{13} and R_{14} .
- Step 4.** Wire the $1000\ \Omega$ (R_{14}), $100\ \Omega$ (R_{12}), and $10\ \Omega$ (R_{13}) resistors below the battery in series and measure the total resistance (R_T) with the ohmmeter. [DO NOT CONNECT BATTERY] Does your measurement equal your calculation in Step 3? If not, why?
- Step 5.** Using Ohm's Law and your measured values of E_T and R_T , calculate total current (I_T).
- Step 6.** With resistors still connected in series, connect the battery and the ammeter in series. [CAUTION: Make certain that the meter is set to mA scale before connecting battery.] Measure the total current (I_T). How does it compare with your calculated value?
- Step 7.** [SET METER TO VOLTS_{DC}] Measure the IR drop across each resistor and add them up and measure the source voltage. Does this sum equal the total measured voltage?

DIODE CHECK

Check the diode with the diode checking circuit. Measure the forward and reverse voltage and record if it is good, open circuit or shorted.

EXERCISE 1.4 DATA SHEET

STEP 1. RATED BATTERY VOLTAGE (E_T): _____ Volt(s)

BATTERY VOLTAGE (E_T): _____ Volt(s)

STEP 2. RESISTANCE MEASUREMENTS

	<u>Nominal</u>	<u>Measured</u>
R_{11}	10,000 Ω	_____
R_{14}	1,000 Ω	_____
R_{12}	100 Ω	_____
R_{13}	10 Ω	_____

SERIES CIRCUIT

STEP 3.

Calculated Total Resistance $R_T = R_{14} + R_{12} + R_{13} =$ _____ Ω

STEP 4.

Measured Total Resistance $R_T = R_{14} + R_{12} + R_{13} =$ _____ Ω

STEP 5.

Calculated Current (I_T) = $E_T / R_T =$: _____ A

STEP 6.

Measured Current (I_T)= _____ A

STEP 7. MEASURED VOLTAGE DROPS $V_{14} = :$ _____ Volt(s) across 1000 Ω resistor $V_{12} = :$ _____ Volt(s) across 100 Ω resistor $V_{13} = :$ _____ Volt(s) across 10 Ω resistorCalculated Total $V_T = :$ _____ VoltsMeasured Source Voltage (E_T): _____ Volts

DIODE CHECK

Decide diode status and insert readings in the appropriate line.

	FORWARD READING	REVERSE READING
Good	☐ _____	_____
Open	☐ _____	_____
Shorted	☐ _____	_____

Chapter 1 Appendix 1

Meter Fuses – Instructions for Replacement

Meter fuses need to be checked and replaced if you have confirmed that your meter leads are good (electrically continuous) and:

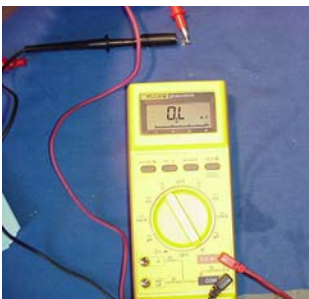
1. When setting the meter to volts D.C. and shorting the positive and negative leads together does not produce a zero (0.0) voltage; or
2. When setting the meter to measure resistance (ohms) and shorting the positive and negative leads together the meter continues to read “overload” (OL); or
3. When reading current (milliamps or amperes) direct and an amperage reading is not displayed or the amperage reading fluctuates.

To check fuses perform the following:

1. Remove screws and remove back cover. On some meters, the fuses can be found in the battery compartment.



2. Remove each fuse and test using another multi-meter using the ohm resistance scale. A good fuse will read a small resistance near zero (0.0). A bad fuse will read as over-load (OL) or an extremely high resistance. You may also be able to visually see into the fuse to confirm if the fuse element appears burnt, separated, or no longer intact.



“Bad Fuse”

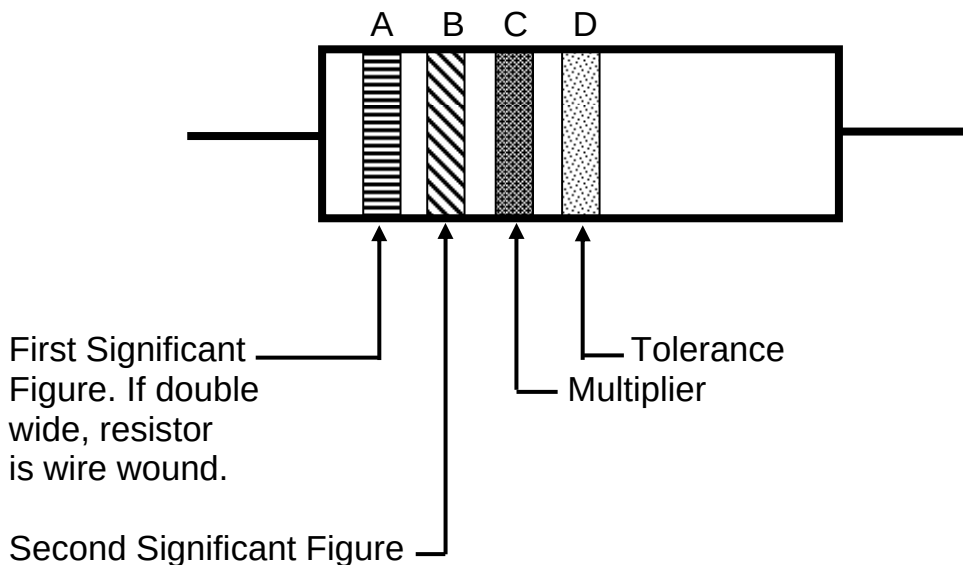


“Good Fuse”

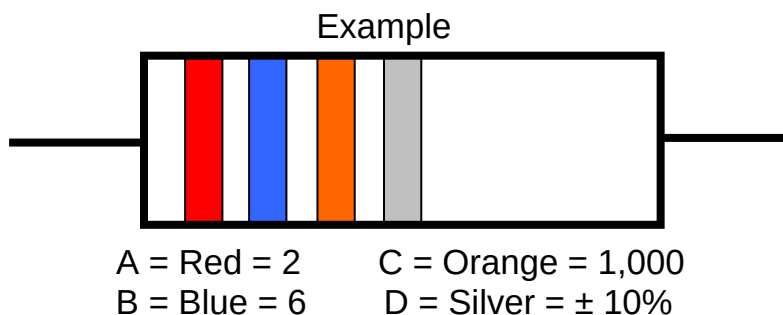
3. Replace the fuse with the proper rating. Replace meter cover. Check for proper operation as described above.

Chapter 1 Appendix 2

Color Code for Resistors



Values							
Band A		Band B		Band C		Band D	
Black	0	Black	0	Black	1	Silver	$\pm 10\%$
Brown	1	Brown	1	Brown	10	Gold	$\pm 5\%$
Red	2	Red	2	Red	100		
Orange	3	Orange	3	Orange	1,000		
Yellow	4	Yellow	4	Yellow	10,000		
Green	5	Green	5	Green	100,000		
Blue	6	Blue	6	Blue	1,000,000		
Violet	7	Violet	7				
Gray	8	Gray	8	Silver	0.01		
White	9	White	9	Gold	0.1		



Resistance Value = $26,000 \Omega \pm 10\%$, or between $23,400 \Omega$ and $28,600 \Omega$

Basic Chemistry

Corrosion is defined by NACE International as the deterioration of a material, usually a metal that results from a reaction with its environment.

Understanding corrosion and cathodic protection requires a basic knowledge of chemistry and electrochemistry. Electrochemistry is a branch of chemistry dealing with chemical changes that accompany the passage of an electric current, or a process in which a chemical reaction that produces an electric current. Pertinent terms and descriptions are given in this chapter.

Elements

All matter is made up of chemical elements. These elements are the building blocks of the physical world and are composed of atoms. As of 1998 there were 109 recognized elements, some of which have been found only as products of nuclear reactions and last for only very short periods.

Atoms

An atom consists of a nucleus and orbiting electrons. The nucleus is made up of positively charged particles called *protons* and neutral particles called *neutrons*. For any given atom, the number of protons equals the number of negatively charged electrons. Therefore, an atom has no net electrical charge. See Figure 2.1.

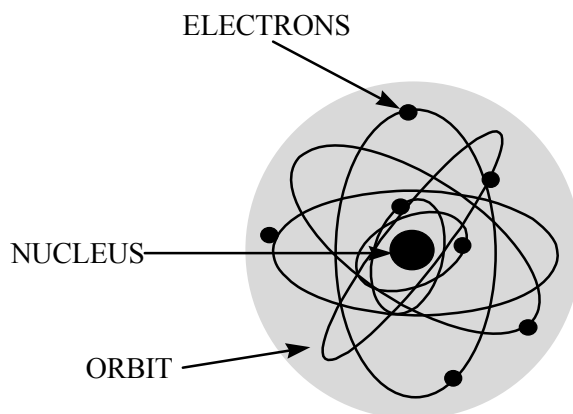


Figure 2.1 The Bohr Model of an Atom

Ions

Gaining or losing electrons can electrically charge atoms. Electrically charged atoms are referred to as *ions* and the charge on an atom is known as its valence state. An ion formed by the gaining of electrons is called an *anion* and is negatively charged because the number of electrons is greater than the number of protons. The loss of electrons yields a positively charged ion called a *cation*. For example, when sodium combines with chlorine an electron is transferred from sodium to chlorine, creating a positively charged sodium ion and a negatively charged chloride ion. The two ions, now of opposite charge, are electrostatically attracted to each other, forming a molecule. Ions allow for transfer of electrical charge in liquids.

Compounds (Molecules)

Molecules are composed of two or more atoms. A molecule is the smallest unit of a substance with the same specific chemical properties of that substance. For example, a single water molecule is composed of one oxygen and two hydrogen atoms as shown in Figure 2.2. Further splitting of this molecule would result in a substance with characteristics unlike water. The atoms of a molecule are held together by a force referred to as *chemical bonding*. It is this chemical bonding that defines many of the properties of a substance.

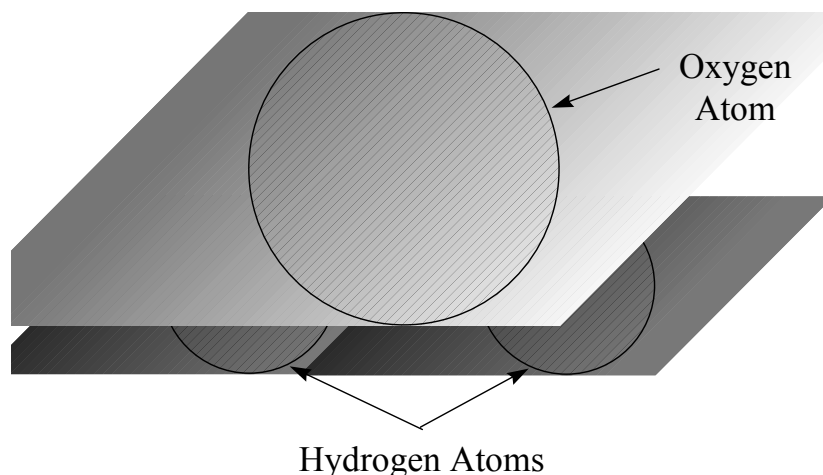


Figure 2.2 Water Molecule

Acidity and Alkalinity (pH)

When discussing an aqueous medium (including soil), the question often arises as to how acid or alkaline the solution is. This refers to whether there is an excess of hydrogen (H^+) or hydroxyl (OH^-) ions present.

When acids dissociate, the cation produced is the hydrogen ion, H^+ . A medium is said to be *acidic* when there is an excess of H^+ ions. The strength of an acid is a measure of the hydrogen ion concentration in an aqueous solution and is classified according to the pH scale. The definition of pH is the negative logarithm to the base 10 of the hydrogen ion concentration, or:

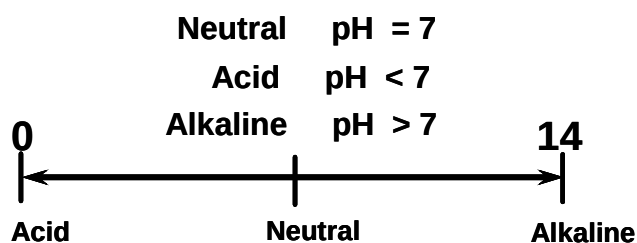
$$pH = -\log [H^+]$$

When an alkali dissociates, the anion produced is a hydroxyl ion, OH^- . A medium is said to be *alkaline* when an excess OH^- (hydroxyl) ions are present.

This concept is better understood if we look at pure water, H_2O . Pure water will ionize into equal parts of hydrogen ions (H^+) and hydroxyl ions (OH^-). The ionization constant for water is the square root of 10^{-14} . That equals 10^{-7} . This is the definition of a negative logarithm. Since water ionizes into equal parts of hydrogen and hydroxyl ions, 7 represents a neutral solution.

The pH scale is illustrated in Figure 2.3. The neutral point is 7. Acid solutions have a pH below 7 and alkaline, or basic, solutions have a pH

above 7. Since the pH scale is logarithmic, for each unit of pH the environment becomes ten times more acid or alkaline. A medium with a pH of 6, for example, is ten times more acid than one having a pH of 7.



$$\text{pH} = -\log [\text{H}^+]$$

Figure 2.3 Illustration of Acid and Alkaline pH

An understanding of pH is important in corrosion and cathodic protection work. For many metals, the rate of corrosion increases appreciably below a pH of about 4. Between 4 and 8 corrosion rate is fairly independent of pH. Above 8, the environment becomes passive and corrosion rates tend to decrease. This is shown in Figure 2.4, which is typical of the behavior of steel.

The corrosion rate of aluminum and lead, on the other hand, tends to increase in environments above a pH of about 8. This is because the protective oxide film on the surface of these metals is dissolved in most strong acids and alkalis and the metals corrode. Metals that corrode under low and high pH levels are termed *amphoteric* metals. Figure 2.4 illustrates this phenomenon.

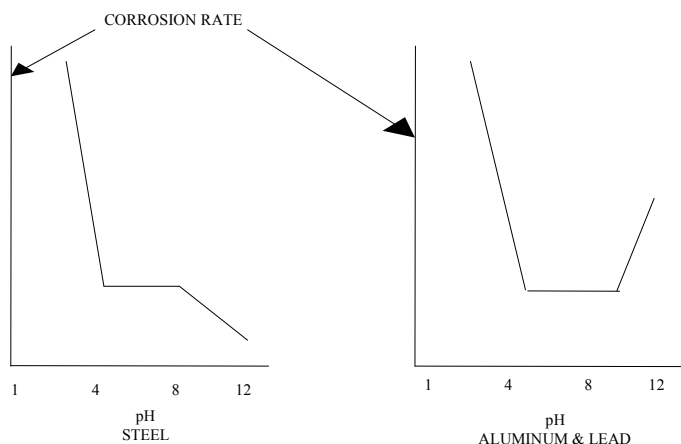


Figure 2.4 Effect of pH on the Rate of Corrosion

An understanding of the effect of pH is also important in the application of cathodic protection. The pH of the environment around the cathode (the protected structure) becomes more alkaline due to the production of hydroxyl ions or removal of hydrogen ions. This is important when working with amphoteric metals, as the corrosion of these metals can actually be accelerated under excessive cathodic protection due to the rise in pH around the structure.

Basic Electrochemistry

Electrochemistry is the division of chemistry that deals with the transfer of electric charge in chemical reactions. These chemical reactions are electrochemical reactions. One branch deals with solid state reactions that take place in semiconductors such as transistors and diodes. Corrosion and cathodic protection pertain to the branch of electrochemistry concerned with charge transfer in aqueous or other liquid environments.

Oxidation and Reduction

Oxidation

Oxidation is the term applied to the loss of one or more electrons from an atom or molecule, which then forms a positively charged ion. An oxidation reaction occurs any time electrons are given up by an atom or molecule. The atom or molecule decreases in negative charge.

For example, when a neutral iron atom (Fe) oxidizes, it may lose two or three electrons, producing positively charged iron ions (Fe^{++} or Fe^{+++}), as shown in Figure 2.5.

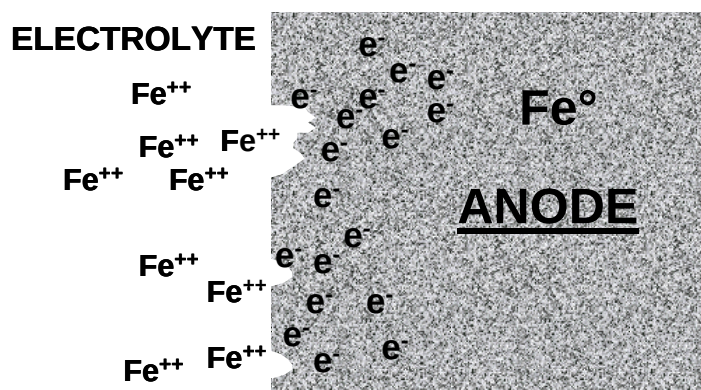
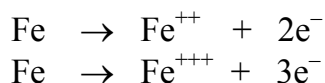


Figure 2.5 Anodic Process (half reaction)

The electrode or metallic site where oxidation occurs is called an *anode*.

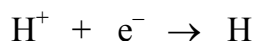
Note: The term oxidation is not necessarily associated with oxygen.

Reduction

Reduction is the term applied to the gain of one or more electrons to an atom or molecule, which then forms a negatively charged ion or neutral element.

A reduction reaction occurs any time that electrons are gained by an atom or molecule. The atom or molecule increases in negative charge.

For example, when a hydrogen ion (H^+) is reduced, it gains one electron, producing a neutral hydrogen atom (H).



The electrode or metallic site where reduction occurs is called a *cathode*. The process appears in Figure 2.6.

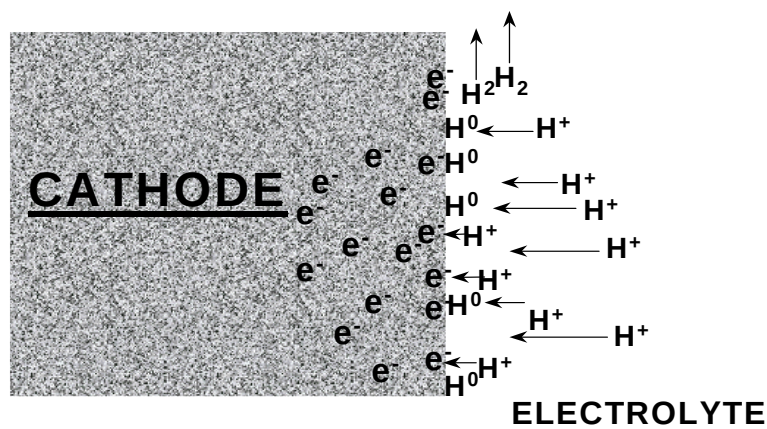
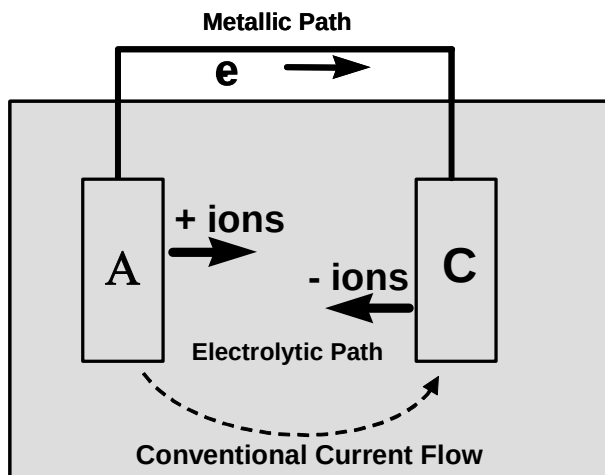


Figure 2.6 Cathodic Process (half reaction)

Electrochemical Circuits

The basic electrochemical corrosion cell is illustrated in Figure 2.7. The various parts of the basic cell are discussed following the figure.



**Figure 2.7 Basic Corrosion Cell –
An Electrochemical Circuit**

Electrolyte

The *electrolyte* is an ionized solution capable of conducting electricity.

Ionization

In addition to ions that may be produced in oxidation and reduction reactions, ions may be present in the electrolyte due to dissociation of ionized molecules. Cations are positively charged ions and anions are negatively charged ions). These ions are current-carrying charges. Therefore, electrolytes with higher ionization have greater conductivity.

Corrosion Cell

Corrosion is an electrochemical process involving the flow of electrons and ions. Metal loss (corrosion) occurs at the anode. No metal loss occurs at the cathode (the cathode is protected).

Electrochemical corrosion involves the transfer of electrons across metal/electrolyte interfaces. Corrosion occurs within a corrosion cell. A corrosion cell consists of four parts as illustrated in Figure 2.8.

- Anode
- Cathode
- Electrolyte
- Metallic Path

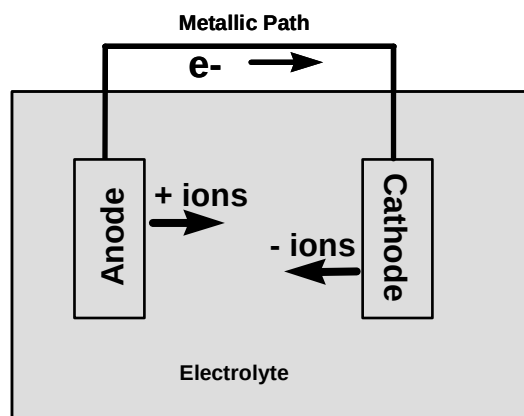


Figure 2.8 Corrosion Cell

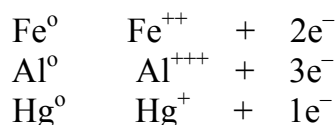
Anode Reactions

The chemical reaction that occurs at the anode, the anodic reaction, is an oxidation reaction. Corrosion is the result of the oxidation reaction in a corrosion cell. Oxidation is the loss of electrons as shown in the following reaction:



where n is the number of electrons involved.

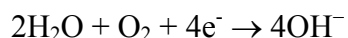
Other anode reactions:



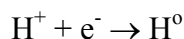
Cathode Reactions

The chemical reaction that occurs at the cathode, the cathodic reaction, is a reduction reaction. Reduction is the gain of electrons. The actual cathodic reaction that occurs will depend on the electrolyte. The following reactions are the two most common reduction reactions that occur at the surface of the cathode.

Oxygen Reduction—more common in neutral environments.



Hydrogen Ion Reduction—more common in acidic environments



Corrosion never occurs at the cathode of a corrosion cell.

The anode and the cathode can be on different metals or on the same metal as shown in Figure 2.9.

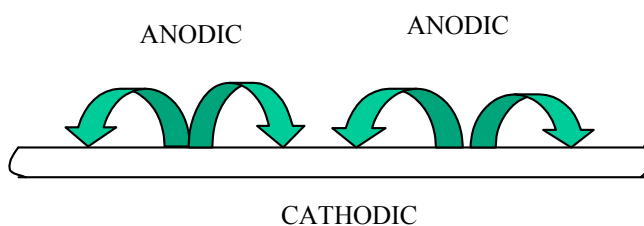


Figure 2.9 Typical Local Action Corrosion Cells on a Structure

External Circuit

The *external circuit* refers to those parts of an electrochemical circuit in which charge movement is electronic; that is, it involves the movement of electrons.

The electric current produced by oxidation and reduction flows through the electronic path by means of electron movement. The electrons produced in the oxidation reaction flow from the anode to the cathode to provide electrons for the reduction reaction to occur. This is shown in Figure 2.10.

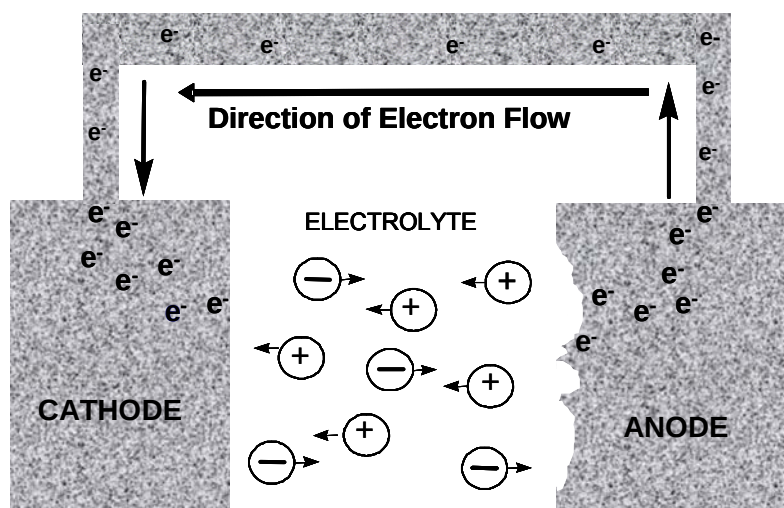


Figure 2.10 *Electron and Ion Flow*

Charge Transfer in the Electrolyte

Movement of charged ions is the mechanism for charge transfer through an electrolyte as opposed to the flow of electrons in a solid metal conductor. Positively charged ions (cations) move away from the anode and toward the cathode. (Note: the ions do not plate out on the cathode.) On the other hand, negatively charged ions (anions) move toward the anode and away from the cathode. This charge transfer is called *electrolytic current flow*. This charge transfer is shown in Figure 2.10.

Ions are relatively heavy and slow moving. Consequently, electrolytes have much higher resistivities than metals. This causes a phenomenon called polarization.

Conventional Current Flow

Figure 2.10 shows the actual electrochemical current flow that exists in a corrosion cell. In corrosion and cathodic protection work, *conventional current flow* is used. This is a flow of current in the direction of the positive ion transfer (so called positive current). The use of conventional current simplifies the understanding of corrosion cells and the use of cathodic protection.

Use of Voltmeters

An analysis of meter polarity connection and sign displayed allows the determination of the direction of conventional current flow.

Voltmeter Hook Up

When measuring voltage across an element of a circuit, the voltmeter is connected in parallel across the element. A parallel connection is made when the external circuit is not broken. For example, the voltmeter in Figure 2.11 is connected in parallel to Resistor B of the external circuit.

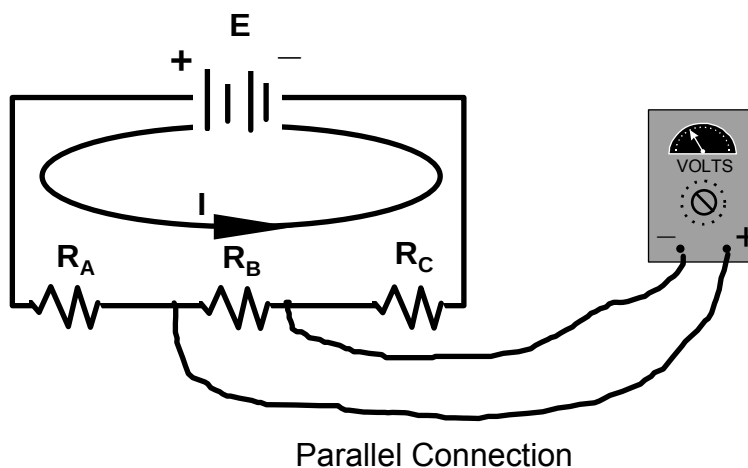


Figure 2.11 A Voltmeter Connection is a Parallel Connection

Current, I , of the external circuit does not flow through the voltmeter to complete the circuit, an indication the voltmeter is in parallel instead of in series with the circuit. All voltage measurements are made in parallel.

There are several voltage measurements commonly made in cathodic protection surveys:

- driving voltage of a galvanic anode system
- rectifier voltage output
- structure-to-electrolyte potential
- voltage drop across a pipe span
- voltage across a current shunt

A voltage measurement, like any measurement, should be taken with an anticipated value in mind including the magnitude, sign, and units to prevent mistakes in meter connections, misreading the meter, or overlooking problems with the system.

Polarity Sign

Most digital meters will display a negative sign for a negative reading and no sign for a positive reading. When a voltmeter is connected across a metallic element, such as a wire or pipeline with external current flow, the voltage display is positive when the positive terminal of the voltmeter is upstream of the current flow as illustrated in Figure 2.12.

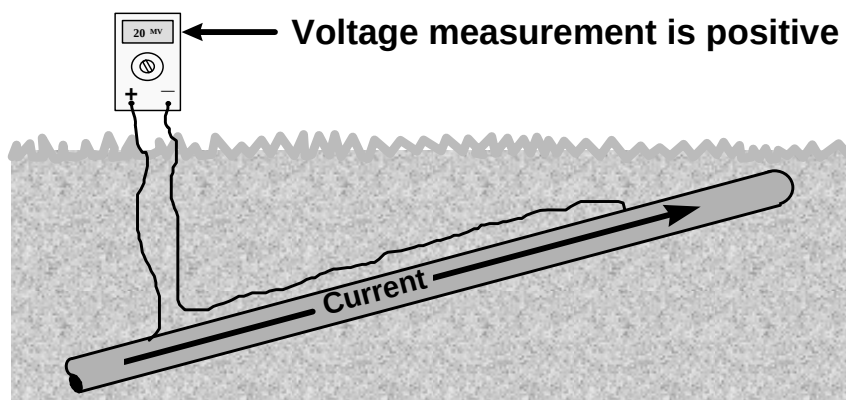


Figure 2.12 Current Direction

When measuring the voltage difference of dissimilar metals, the sign is positive when the positive terminal of the voltmeter is connected to the more noble metal as shown in Figure 2.13.

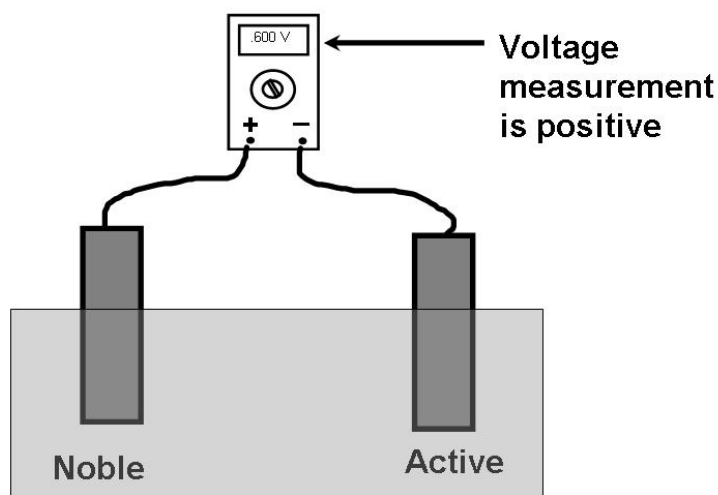


Figure 2.13 Voltage Measurement of a Noble Metal and an Active Metal Immersed in an Electrolyte

Sign Convention

For a positive reading on a digital display or a right hand deflection of the needle on an analog display, conventional current must flow into the positive (+) terminal. Since most instruments used today are digital with automatic polarity display, a surveyor may not be as concerned with the sign of the reading when connecting the voltmeter for the measurement. It is still important to pay attention to the connection of the instrument terminals and the expected sign in order to detect problems during a survey.

If a voltmeter is connected such that the positive terminal is connected to the more noble metal and the negative terminal to the more active metal, then the reading is positive. Current will flow from the active to the noble metal through the electrolyte and from the noble to the active metal through the metallic path. Therefore, the reading is positive because conventional current is flowing into the positive terminal of the voltmeter.

Structure-to-electrolyte readings are considered negative to the reference electrode. When using a digital voltmeter, the reference electrode is connected to the negative terminal. Connecting the reference electrode to the negative terminal produces a negative reading. On an analog meter, the needle will swing to the right when current enters the positive terminal. When using an analog meter with a center zero, if you connect the reference electrode to the negative terminal, the needle will swing to the left, indicating the negative reading. With a left hand zero instrument, you can still connect the reference electrode to the negative terminal, but it is

necessary to throw the reversing polarity switch. The meter will now read to the right, but the position of the switch will indicate that it is a negative reading.

Reference Electrodes (Half-Cells)

General

Reference electrodes, or half-cells, are important devices that permit measuring the potential of a metal surface exposed to an electrolyte. An example is a structure-to-soil potential measurement.

Structure-to-soil potentials are measured in reference to an electrode. What is often referred to as a structure-to-electrolyte potential is actually the potential measured between the structure and a reference electrode. The electrolyte itself has no potential value against which the potential of a structure can be measured independently of the potential of the reference electrode used. Therefore, before discussing how to measure potentials along a structure, we must discuss reference cells.

There are several potential benchmarks in common use, but all of them are related to a basic standard. In this standard one-half of the cell generating the potential to be measured is represented by a platinized electrode over which hydrogen gas is bubbled while immersed in a solution having a definite concentration of hydrogen ions. If it is arbitrarily agreed that the potential of the platinized electrode covered with hydrogen in its standard solution is zero on a scale of potentials, then the potentials of all the other metals in their appropriate solutions can be described in terms of this reference.

The standard hydrogen electrode half-cell is awkward to use in most circumstances in which potential measurements are to be made. Instead, other combinations of metal electrodes in solution with a specific concentration of ions are used. The reference cell must be stable and capable of producing reproducible data.

Copper-Copper Sulfate Electrode

Copper sulfate reference electrodes (CSE) are the most commonly used reference electrode for measuring potentials of underground structures and also for those exposed to fresh water. The electrode is composed of a copper rod, immersed in a saturated solution of copper sulfate, held in a

non-conducting cylinder with a porous plug at the bottom, as shown in Figures 2.14 and 2.15. The copper ions in the saturated solution prevent corrosion of the copper rod and stabilize the reference electrode. This electrode is portable.

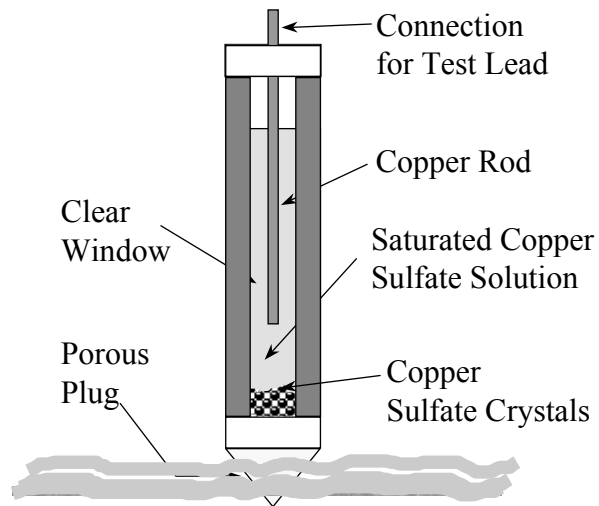


Figure 2.14 Copper-Copper Sulfate Reference Electrode in Contact with Earth



Figure 2.15 Portable Copper-Copper Sulfate Reference Electrodes

Use and Care of Copper Sulfate Reference Electrodes

- Keep clean.
- Keep the plastic/rubber cap on the porous plug when not in use.
- Periodically clean the porous plug to prevent clogging the pores.
- Keep free of contamination. Periodically replace copper sulfate and clean copper rod with a nonmetallic abrasive material; use silica sandpapers, for example, not an aluminum oxide paper to clean the rod. If the solution becomes cloudy, clean it out and replace with fresh copper sulfate solution. Be certain there are always undissolved crystals in the solution; this creates a super-saturated solution in which the copper will not corrode and thus will be stable. Perform maintenance after electrode has been used in a situation where contamination could have occurred (e.g., salt water). Chloride contamination changes the chemical reactions and the reference potential becomes a lower composite with the error being -20 mV at concentrations of 5 ppt and -95 mV at concentrations of 10 ppt.
- Keep a few spares on hand. Electrodes do get lost now and then and you need to have extras to continue your work.
- Keep one fresh electrode in the office or shop to be used to calibrate your field electrodes. Clean field electrodes if they are more than 5 mV different from your calibrating electrode.
- Correct for potential variations due to temperature and sunlight. Record the temperature when taking readings in the event temperature correction is needed. A temperature correction of 0.5 mV/ $^{\circ}$ F or 0.9 mV/ $^{\circ}$ C must be either added or subtracted when reference temperature is above or below ambient temperature, respectively.
- Shield the electrode from direct sunlight during measurements (e.g., place dark tape over clear strip on side of electrode). The potential of a reference electrode in the sun can decrease from 10 to 50 mV versus an electrode kept in the dark.

EXPERIMENT 2.1 and EXPERIMENT 2.2

Driving Force for Corrosion

By now we know that corrosion involves a process in which current flows from one metal surface, an anode, into the electrolyte and from the electrolyte onto a second metal surface, a cathode. The question now is “What causes the current to flow in the first place?”

Current flow is similar to water flow. Water will flow if there is a difference in elevation between the starting and ending flow points. See Figure 2.16.

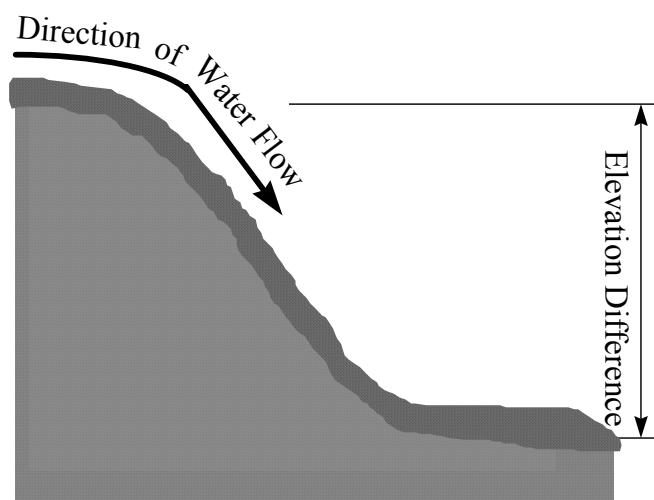


Figure 2.16 Elevation Difference Causes Water to Flow

Likewise, current will flow from one point to another if there is a voltage difference between the two points. This voltage difference may be generated by naturally occurring reactions or by stray current reactions as discussed in the section “Causes of Corrosion”. There must be a voltage difference between the anode and cathode of a corrosion cell for current to flow.

Corrosion Rate

Faraday's Law

The weight of any material deposited on the cathode (or liberated from the anode) is directly proportional to the quantity of electric charge passing through the circuit. Faraday's Law relates weight loss of metal in a corrosion cell with time and current flow. The law is expressed in the following formula:

$$Wt = KIT = \text{kg}$$

where

Wt = weight loss, kg
 K = electrochemical equivalent, kg/A-yr
 I = Amps
 T = years

The value of 'K' (in kg/A-yr and lb/A-yr) for some common metals is shown in Table 2.1.

Table 2.1 Consumption Rate (K) for Various Metals⁽¹⁾

Metal	Kg/A-yr	Lb/A-yr
Carbon	1.3	2.86
Aluminum	3.0	6.5
Magnesium	4.0	8.8
Iron/Steel	9.1	20.1
High Silicon/Chromium Iron	0.5	1.0
Nickel	9.6	21.2
Copper (Monovalent)	20.8	45.8
Zinc	10.7	23.6
Tin	19.4	42.8
Lead	33.9	74.7

⁽¹⁾Based on Table 2, Chapter 2, Basic Course Manual, Appalachian Underground Corrosion Short Course.

For example, if a steel bulkhead were discharging 875 mA over a period of four years, how much metal would be lost?

$$W_t = KIT = \text{kg}$$

K = From Table 2.1, the loss rate is 9.1 kg/A-yr

$$I = 875 \text{ mA} = 0.875 \text{ A}$$

T = The 4 year loss would therefore be:

$$9.1 \text{ kg/A-yr} \times 0.875 \text{ A} \times 4 \text{ years} = 31.9 \text{ kg} = 70.3 \text{ lb}$$

If the loss is occurring over the entire bulkhead, it will probably be insignificant. If, on the other hand, the bulkhead is coated and loss is taking place only at holidays, then several penetrations might occur in the short time of four years.

Faraday's Law is also very useful for determining the expected life of cathodic protection anodes. Knowing the anode material and expected output of an anode, you can calculate the life expectancy. These calculations are beyond the scope of this course but are covered in advanced cathodic protection courses.

Polarization

Polarization is the deviation from the open circuit potential of an electrode resulting from the passage of current. There are two major types of polarization.

The fundamentals of electricity, chemistry, and electrochemistry form the basis for an understanding of corrosion and cathodic protection.

As current flow continues over time, polarization occurs at both the anode and cathode. Polarization lowers the potential difference between the anode and cathode areas, causing a reduction in the corrosion current and the corrosion rate.

Depolarization is a condition that counters the effects of polarization. Depolarizers include:

- Dissolved oxygen
- Microbiological activity
- Water flow

Equilibrium is reached when there is a balance between polarizing and depolarizing effects. The potential difference and the corrosion current between the anode and cathode areas becomes steady. The rate of corrosion depends on this final current flow.

Factors That Affect the Corrosion Rate

Anode/Cathode Ratio

The relative area between the anode and cathode of a corrosion cell greatly affects the rate at which the anode corrodes. If the anodic area is small in relation to that of the cathode (a steel rivet in a copper plate, for example), the anode (steel rivet) will corrode rapidly. This is because the corrosion current is concentrated in a small area (large current density). Also, the large cathode may not polarize easily, thus maintaining a high rate of corrosion.

When a small cathode is connected to a large anode (copper rivet in a steel plate for example), the corrosion current density on the anode (steel) is much less than in the opposite case discussed above, and the anode corrodes more slowly. Polarization may play an important role here, too. The small cathode may polarize rapidly, reducing the rate of corrosion current flow.

Influence of the Environment

Moisture Content

Electrolytic corrosion requires the presence of moisture. A completely dry environment will not support this form of corrosion. A damp, well-aerated metal surface may undergo more rapid general corrosion than a surface that is totally immersed. An example of this is the splash zone on submerged steel piling. In this case, oxygen reduction is the primary cathode reaction and corrosion of steel is the anode reaction. The anodes and cathodes are close together and the corrosion is characterized as general metal loss.

In underground corrosion, high moisture content is generally associated with increased corrosion rates. However, total immersion (saturated soil) is not necessarily the most aggressive situation.

In general, clays are deficient in oxygen and in mixed soils the areas of a structure in contact with the clay become the anodes of an oxygen concentration cell. In such cells it is the difference in available oxygen between sand and clay areas in contact with a structure that produces the electrical energy that drives the corrosion process.

Conductivity

The amount of current through an electrolyte is affected by the ion content. The more ions, the greater the conductivity; the greater the conductivity, the more current for a given cell voltage; and the greater the current, the higher the rate of corrosion. Conductivity is equal to the reciprocal of resistivity. The unit of measurement is the Siemen-cm (mho-cm).

Conductivity or its reciprocal (resistivity) is an important parameter in the study of corrosion and its prevention. High conductivity itself does not indicate a corrosive environment; it only indicates an ability to support current flow.

Chemical Activity

It is the chemical activity of the electrolyte that provides the Redox (Oxidation-Reduction) reactions necessary to drive a corrosion cell. Some of the chemical species present in an electrolyte may assist in retarding or slowing chemical action by aiding the production of protective films. Carbonates, for example, may lead to the formation of a passive film on zinc; in such environments galvanized structures may undergo virtually no corrosion. If there are breaks in the galvanizing, however, the underlying steel at such breaks may corrode rapidly, as it will be at a more active potential than the zinc carbonate film. Passivation can also render zinc anodes ineffective.

Of particular interest is the pH, which expresses the hydrogen ion concentration in the electrolyte. The higher the concentration of hydrogen ions, the lower the pH. Hydrogen ions readily accept electrons when in contact with metals that are more electrochemically active than hydrogen. For example, magnesium, aluminum, zinc, iron, and lead are all more active than hydrogen. Other metals, such as copper, are less active (or more noble) than hydrogen. Thus, in an acid environment, metals more active than hydrogen will be corroded, and those more noble will not be corroded.

Highly alkaline environments, generally with a pH greater than 8, can cause accelerated corrosion on amphoteric metals such as aluminum and lead.

Causes of Corrosion

General

Nearly all of the corrosion you will encounter can be divided into one of two types—either a natural reaction or a stray current reaction. Naturally occurring corrosion takes place because of local action cells on the surface of the structure. These cells result from voltage differences caused by such factors as surface irregularities, mill scale, oxygen concentrations, differences in the electrolyte around the structure, and others. Stray current reactions occur when some source of current, external to the structure itself, causes corrosion on the structure.

Naturally Occurring Corrosion

Dissimilar Metals (Galvanic Corrosion)

The metal itself may be a source for the driving voltage of a corrosion cell. A difference in voltage may arise due to differences in the natural energy levels of different metals or composition variations formed during alloying.

Metals occur in nature in the form of various chemical compounds referred to as *ores*. After ore is mined, the metallic compound is removed from the rock-like ore and refined to produce a nearly pure state of the metal. Various processes—mechanical, chemical, and electrical—are employed to transform ores into useful metals. Regardless of the process, the metal absorbs energy during the transformation. The amount of energy required by a metal during the refining process determines the voltage or active state of the metal. The voltage is relatively high for such metals as magnesium, aluminum, and iron, and relatively low for such metals as copper and silver. A useful way of viewing metals in the order of their activity is shown in what is known as the *galvanic series*. This series is based on metals in seawater, but applies to metals in fresh water and underground. The series is shown in Table 2.2. The potentials shown are approximate since they vary somewhat depending on the environment. Potentials are shown vs. a copper-copper sulfate.

Table 2.2. Practical Galvanic Series

Metal	Volts vs Cu-CuSO₄
<i>Active or Anodic End</i>	
Magnesium	–1.60 to –1.75
Zinc	–1.10
Aluminum	–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
High Silicon Iron	–0.20
Carbon, Graphite	+0.30
<i>Noble or Cathodic End</i>	

When two different metals are connected, a voltage is generated between them. The more active metal (toward the anodic end) becomes the anode of the cell.

A classic example of a galvanic cell is the flashlight battery, shown in Figure 2.17. This consists of a zinc case enclosing an electrolyte and a carbon rod. From Table 2.2 you can see that the voltage difference between the two metals is about 1.4V (actually 1.5V in a battery) and that the zinc is the anode and the carbon is the cathode. This is a useful corrosion cell since the current produced can do work for us. Eventually the case will corrode through—we have all seen batteries in that condition.

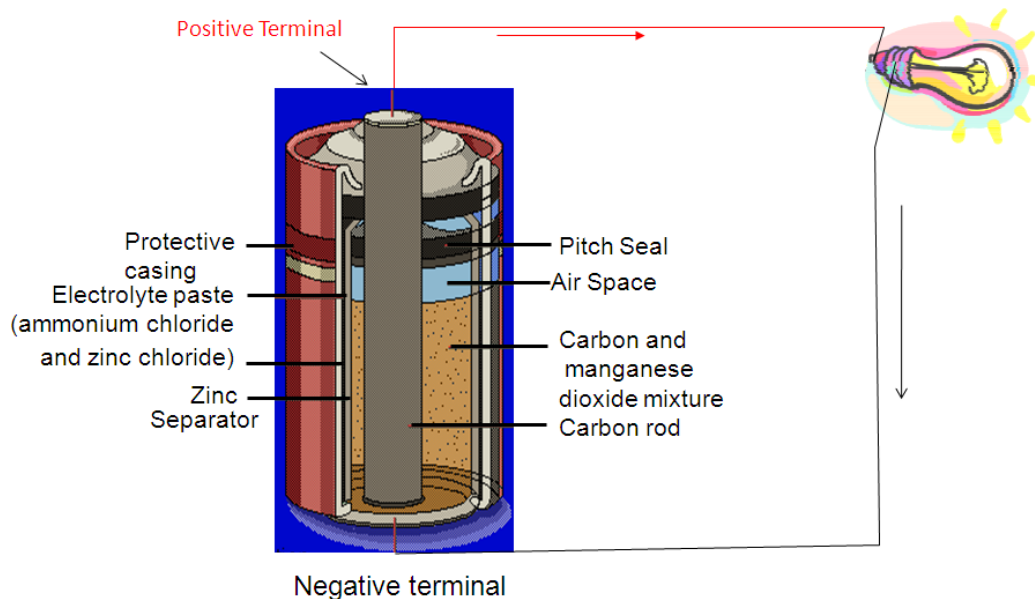


Figure 2.17 Flashlight Battery as an Example of a Galvanic Cell

EXPERIMENT 2.3

Alloying

In the alloying process, grain boundaries are formed. Similar to dissimilar metals, the grain boundary may be more active or more noble than the adjacent metal causing a voltage difference. Also, the more active metal used to make an alloy may corrode leaving behind the more noble metal. This is usually referred to as the active metal leaching from the alloy, such as zinc from brass (dezincification).

Mechanical Stresses

When a metal experiences mechanical stress, the more highly stressed area is usually the more active area and becomes the anode of the corrosion cell.

Temperature Differences in the Metal

If parts of a structure are at different temperatures, the higher temperature area is usually the more active area and becomes the anode of the corrosion cell.

Temperature Differences in the Electrolyte

For temperature differences in an electrolyte, the area of metal in the higher temperature is usually the more active area and becomes the anode of the corrosion cell.

Dissimilar Soils

Dissimilar soils, such as clay and sand, due to their differences in resistivity (reciprocal of conductivity) and oxygen content, may provide the driving force for corrosion. The metal in the vicinity of the lower resistivity soil is usually more active and is the anode.

Oxygen Concentration Cell

A metal exposed to different concentrations of oxygen may experience a difference in voltage. The metal in the vicinity of the higher concentration of oxygen will be more noble, or the cathode, because oxygen is a cathodic reactant.

Metal Ion Concentration Cell

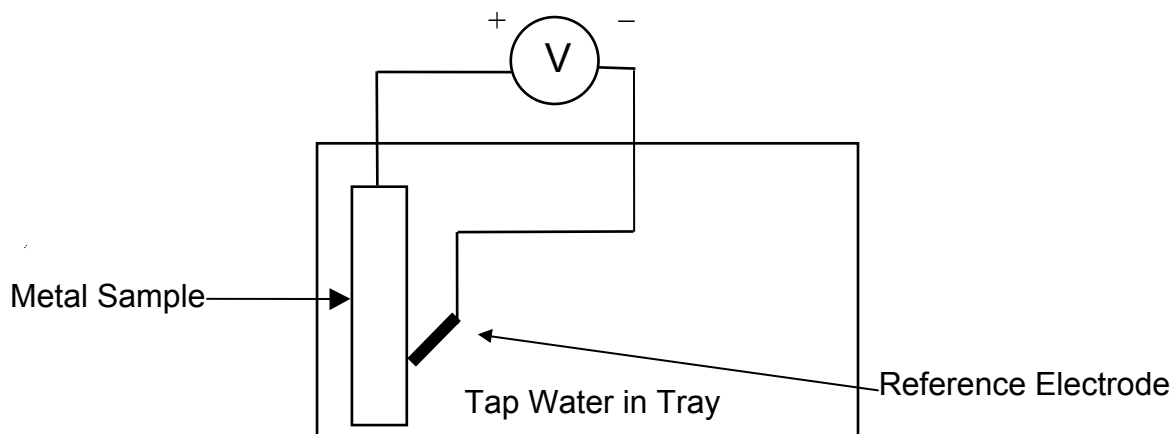
The higher the concentration of metal ions that are the same as the adjacent metal, the more the noble the metal becomes. For metal ions that are different from the adjacent metal, the effect may be difficult to determine. When a simple salt is present that does not contain a metal ion, the area of the metal in the higher concentration of salt is usually the anode.

Microbiological Influences

Microbiologically induced corrosion (MIC) is common. Various bacteria enter into redox type reactions. Some of these bacteria live only in environments free of oxygen. This class of bacteria is termed *anaerobic*. Other species thrive under aerated conditions and form acids. Although bacteria themselves do not attack metals, the metals become involved in the various redox reactions associated with the metabolism of the bacteria.

A particularly important example of MIC is sulfate reducing bacteria (SRB) which can accelerate corrosion of metal pipe in clay environments. In the overall cycle, the metal is oxidized and sulfur, normally present in soils as sulfate, is reduced to sulfide. The bacteria serve as an intermediary in this reaction. The presence of bacteria may significantly increase corrosion rates in environments that would otherwise be relatively benign.

Experiment 2.1–Metal Electrode Potentials in Tap Water



Experiment for Measuring Electrode Voltage (EMF) of Different Metals with Respect to a Copper/Copper Sulfate Reference Electrode

PROCEDURE

1. Place the copper, steel, zinc, and magnesium into the tray, making sure they do not touch each other.
2. Add 1-1/2 inch of tap water to the tray.
3. Set the meter to the V DC scale.
4. Connect the meter's negative lead to the reference electrode.
5. Connect the meter's positive lead to the metal being tested.
6. Place the reference electrode near the copper and record the copper's potential.
7. Place the reference electrode near the steel and record the steel's potential.
8. Place the reference electrode near the zinc and record the zinc's potential.

9. Place the reference electrode near the magnesium and record the magnesium's potential.

Results

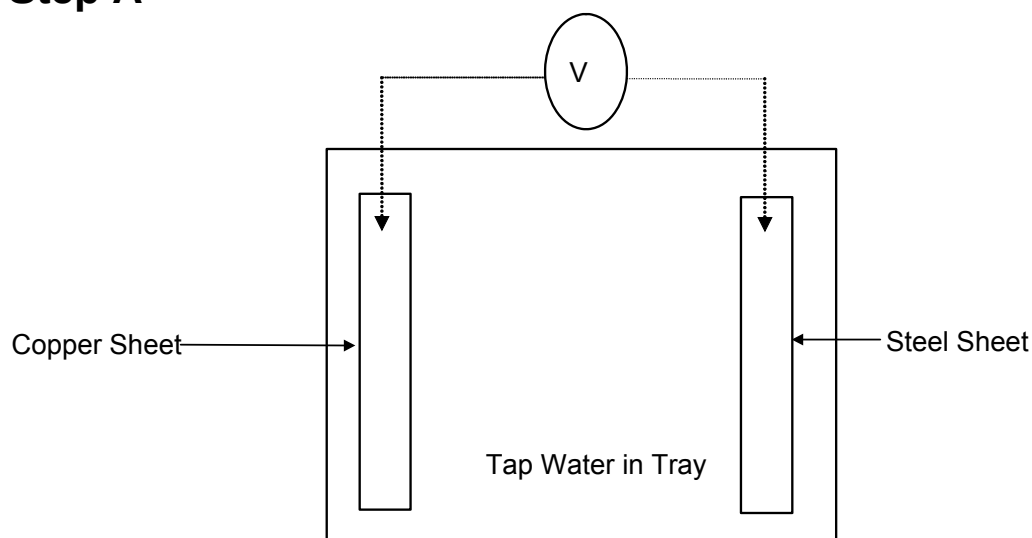
Metal	Reference Electrode Position	Approximate Potential mV/CSE	Actual Potential
Copper	Near Copper	-100	
Steel	Near Steel	-500	
Zinc	Near Zinc	-1000	
Magnesium	Near Magnesium	-1700	

Conclusions

1. Magnesium is more electronegative than copper, steel, or zinc.
2. Zinc is more electronegative than steel or copper.
3. Steel is more electronegative than copper.
4. Copper is more electropositive than steel, zinc, or magnesium.

Experiment 2.2–Corrosion-Cell

Step A



1. Place the copper and steel pieces at opposite ends of the tray.
2. Add 1-1/2 inch of tap water to the tray.
3. Set the meter to the V DC scale as shown on the next page.
4. Connect the meter to the metal samples as indicated below.

Results

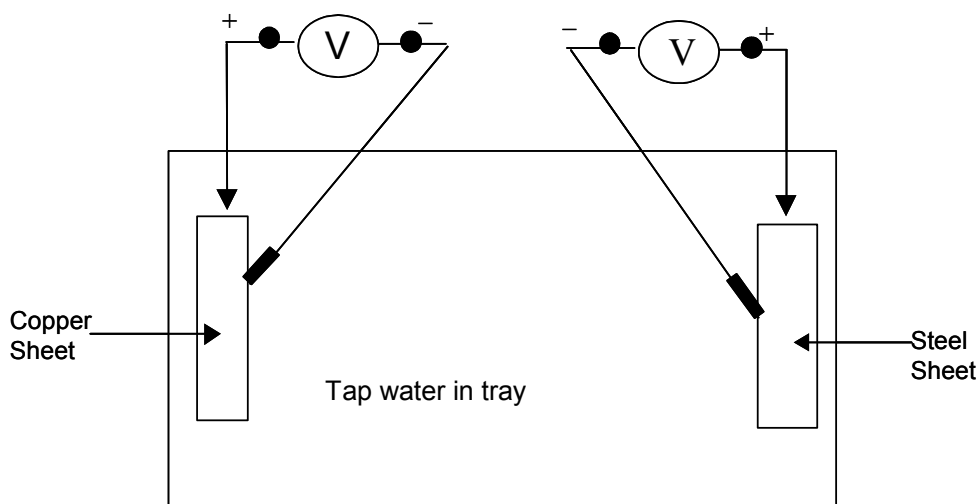
Meter Positive Lead	Meter Negative Lead	Approximate Potential mV	Actual Potential
Copper	Steel	+400	
Steel	Copper	−400	

Conclusions

1. The initial corrosion-cell potential is the difference between the open-circuit electrode potentials.
2. The more electronegative of the two electrodes is the anode; the more electropositive of the two cells is the cathode. The corrosion-cell potential can be estimated using the following expression:

$$\text{cell potential} = \text{potential}_{\text{cathode}} - \text{potential}_{\text{anode}}$$

Step B–Potential Measurement



1. Connect voltmeter positive lead to copper and connect negative lead to a copper-copper sulfate reference electrode.
2. Place reference electrode in the water at the copper/water interface.
3. Record the potential.
4. Repeat Steps B1 and B2 for the steel.

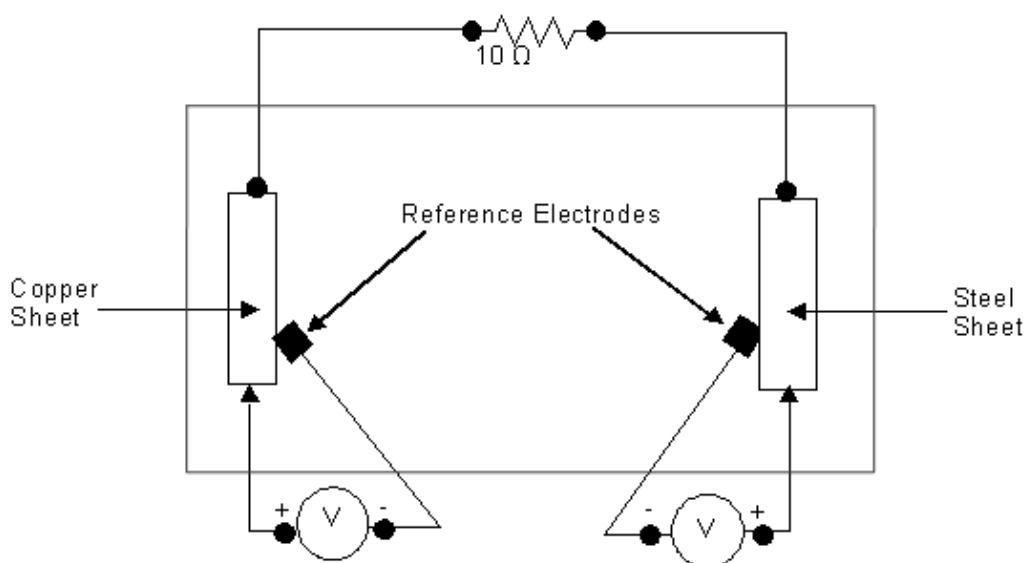
Results

Metal Sample	Potential
Copper	
Steel	

Conclusion

1. Steel is more electronegative than copper
2. The difference in potential between the steel and the copper is the same as measured in Step A.

Step C—Polarized Potential Measurement



1. Connect the steel to the copper through the 10-Ω resistor.
2. Repeat steps B1, B2 and B4.

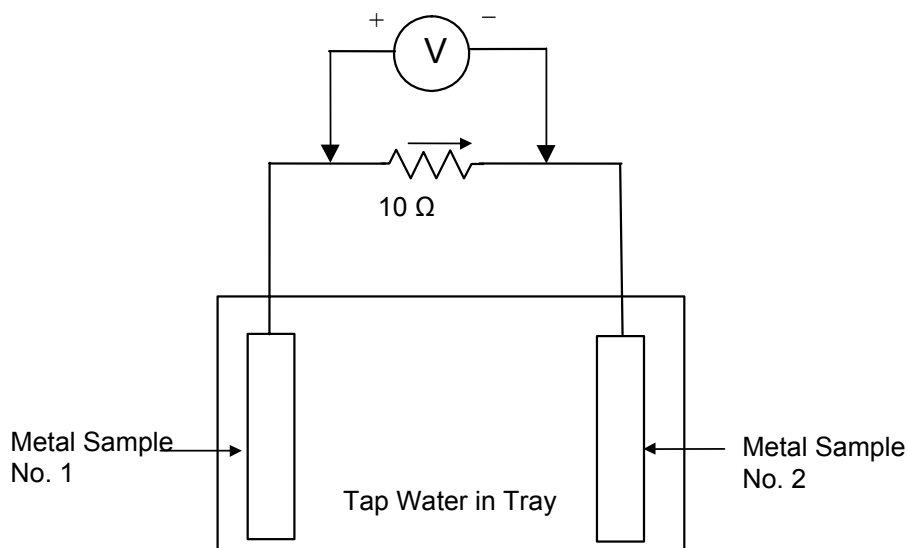
Results

Metal Sample	Potential
Copper	
Steel	

Conclusions

1. The copper sheet potential is more electronegative than in Part B.
2. The steel sheet potential is unchanged or less electronegative.

Step D Current Direction in the External Circuit in a Corrosion Cell



1. Connect the meter as indicated across a 10-Ω resistor between the two metals. See the figure on the next page.
2. Record the voltage drop across the resistor and note polarity.
3. Evaluate the direction of the current.
4. Repeat steps D1 to D3 for the other metal configurations shown in the table below.

Results

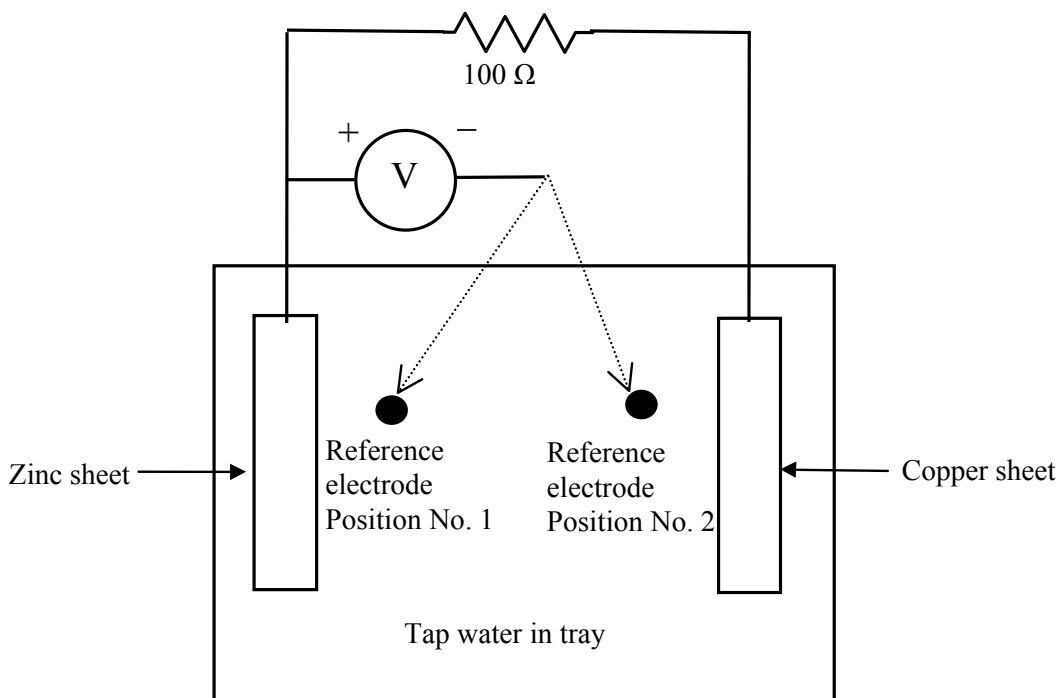
Meter Positive Lead	Meter Negative Lead	Measured Voltage Drop(mV)
Copper	Steel	
Steel	Copper	
Zinc	Steel	
Steel	Zinc	
Copper	Zinc	
Zinc	Copper	

Meter Positive Lead	Meter Negative Lead	Direction of Conventional Current in External Circuit			Which metal is the anode?
Copper	Steel		to		
Steel	Copper		to		
Zinc	Steel		to		
Steel	Zinc		to		
Copper	Zinc		to		
Zinc	Copper		to		

Conclusions

1. Conventional current in the external circuit is from the cathode to the anode.
2. The direction of current in the resistor emphasizes that the direction of conventional current is from the least electronegative (cathode) to the most electronegative active electrode in the external circuit. Thus, an Fe/Fe^{++} electrode can be either an anode or a cathode, depending on the other electrode to which it is connected.

Experiment 2.3 Current Direction in the Electrolyte in Corrosion Cells



Experiment for Measuring the Direction of Corrosion-Cell Currents in the Electrolyte

PROCEDURE

1. Place the zinc and copper at the sides of the tray.
2. Add 1-1/2 inch of tap water to the tray.
3. Set the meter to the V DC scale.
4. Connect the meter to the zinc and to the reference electrode as indicated in the figure.
5. Record the electrode potential with the reference electrode in the two positions indicated in the figure.
6. Evaluate the direction of current.

Results

Meter Positive Lead	Meter Negative Lead	Measured Potential (mV/CSE)
Zinc	Reference Position #1	
Zinc	Reference Position #2	

Conventional current will pass from the locations in the electrolyte that are more negative to the locations that are less negative, as indicated by potential readings at the reference electrode positions.

Conclusion

1. Conventional current in the electrolytic circuit is from the anode to the cathode.

Chapter 2 Appendix 1

Reference Cell Maintenance

Reference cells require attention if:

1. The solution is cloudy or appears contaminated; or
2. The copper rod is not bright and shiny; or
3. Copper sulfate crystals are not visible; or
4. When compared to a standard cell there is significant difference potential



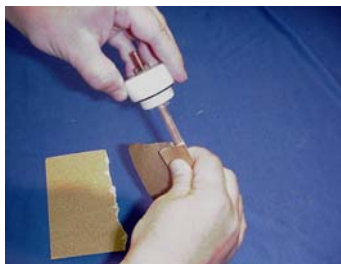
Contaminated Cells

To restore reference electrodes for proper operation perform the following steps:

1. Remove the reference cell tip, rod and end cap, and properly dispose of the fluid contained in the cell.



2. With non-metallic abrasive material (sandpaper), clean copper rod to a bright and shiny condition.



3. Re-assemble rod and end cap.

4. Pour in copper sulfate crystals to fill bottom of cell to a depth of $\frac{1}{2}$ to $\frac{3}{4}$ inch. Do not fill the cell beyond $\frac{1}{4}$ in volume.



5. Pour in distilled water or copper-sulfate solution (approved for reference cell use) to a point just below the manufactured threads in the cell body.



6. Assemble and screw in a reference cell tip that has been presoaked in distilled water.
7. Shake cell several times to mix cell solution with copper sulfate crystals.



8. Maintain fluid so that 95% of the cell is fluid filled.
9. Maintain cell so that copper sulfate crystals are always visible in the solution.

Chapter 2 Appendix 2

Conversions and Definitions

EMF	electromotive force – any voltage unit
E or e	any voltage unit
V or v	volts
mV or mv	millivolts
μ V or μ v	microvolts
I or i	any amperage unit
mA or ma	milliamperes or milliamps
μ A or μ a	microamperes or microamps
R, r or Ω	Resistance

1,000,000 volts	=	1 megavolt
1,000 volts	=	1 kilovolt
1.0 volt	=	1000 millivolts
0.100 volt	=	100 millivolts
0.010 volt	=	10 millivolts
0.001 volt	=	1 millivolt
0.000001 volt	=	1 microvolt

1,000,000 amperes	=	1 mega-ampere
1,000 amperes	=	1 kiloampere
1.0 ampere	=	1000 milliamperes
0.100 ampere	=	100 milliamperes
0.010 ampere	=	10 milliamperes
0.001 ampere	=	1 milliampere
0.000001 ampere	=	1 microampere

1,000,000 ohms	=	1 mega-ohm
1,000 ohms	=	1 kilo-ohm
1.0 ohms	=	1000 milliohms
0.100 ohm	=	100 milliohms
0.010 ohm	=	10 milliohms
0.001 ohm	=	1 milliohm
0.000001 ohm	=	1 micro-ohm

1 meter	=	100 cm
1 meter	=	1000 mm



Resistivity is constant for a given material and is computed by the formula:

$$\rho = \frac{R \times A}{L}$$

Where ρ , Resistivity in Ω -cm
R, Resistance in Ω
A, Cross-Sectional Area in cm^2
L, Length in cm

Using the Wenner method, the soil resistivity is determined by:

$$\rho = 2\pi aR$$

Where ρ , resistivity in ohm-cm
 π , pi, 3.14
a, the spacing of the pins (cm)
R, the resistance measured (Ω)
 ρ , resistivity (Ω -cm)
 π , pie (3.14)

OR

$$\rho = 191.5aR$$

Where ρ , resistivity in Ω -cm
a, the spacing of the pins (feet)
R, the resistance measured (Ω)
 ρ , resistivity (Ω -cm)

Ohm's Law

$$E = IR$$

$$I = E/R$$

$$R = E/I$$



Chapter 2 Appendix 3

U.S. Customary/Metric Conversion for Units of Measure Commonly Used in Corrosion-Related Publications

1 A/ft ²	= 10.76 A/m ²	1 inH ₂ O	= 249.1 Pa
1 acre	= 4,047 m ² = 0.4047 ha	1 knot	= 0.5144 m/s
1 A·h/lb	= 2.205 A·h/kg	1 ksi	= 6.895 MPa
1 bbl (oil, U.S.)	= 159 L = 0.159 m ³	1 lb	= 453.6 g = 0.4536 kg
1 bpd (oil)	= 159 L/d = 0.159 m ³ /d	1 lbf/ft ²	= 47.88 Pa
1 Btu	= 1,055 J	1 lb/ft ³	= 16.02 kg/m ³
1 Btu/ft ²	= 11,360 J/m ²	1 lb/100 gal (U.S.)	= 1.198 g/L
1 Btu/h	= 0.2931 W	1 lb/1,000 bbl	= 2.853 mg/L
1 Btu/h·ft ²	= 3.155 W/m ² (K-factor)	1 mA/in ²	= 0.155 mA/cm ²
1 Btu/h·ft ² ·°F	= 5.678 W/m ² ·K	1 mA/ft ²	= 10.76 mA/m ²
1 Btu-in/h·ft ² ·°F	= 0.1442 W/m·K	1 Mbpd (oil)	= 159 kL/d = 159 m ³ /d
1 cfm	= 28.32 L/min = 0.02832 m ³ /min = 40.78 m ³ /d	1 mile	= 1.609 km
1 cup	= 236.6 mL = 0.2366 L	1 square mile	= 2.590 km ²
1 cycle/s	= 1 Hz	1 mile (nautical)	= 1.852 km
1 ft	= 0.3048 m	1 mil	= 0.0254 mm = 25.4 μm
1 ft ²	= 0.0929 m ² = 929 cm ²	1 MMcfd	= 2.832 x 10 ⁴ m ³ /d
1 ft ³	= 0.02832 m ³ = 28.32 L	1 mph	= 1.609 km/h
1 ft·lbf (energy)	= 1.356 J	1 mpy	= 0.0254 mm/y = 25.4 μm/y
1 ft·lbf (torque)	= 1.356 N·m	1 oz	= 28.35 g
1 ft/s	= 0.3048 m/s	1 oz fluid (Imp.)	= 28.41 mL
1 gal (Imp.)	= 4.546 L = 0.004546 m ³	1 oz fluid (U.S.)	= 29.57 mL
1 gal (U.S.)	= 3.785 L = 0.003785 m ³	1 oz/ft ²	= 2.993 Pa
1 gal (U.S.)/min (gpm)	= 3.785 L/min = 0.2271 m ³ /h	1 oz/gal (U.S.)	= 7.49 g/L
1 gal/bag (U.S.)	= 89 mL/kg (water/cement ratio)	1 psi	= 0.006895 MPa = 6.895 kPa
1 grain	= 0.06480 g = 64.80 mg	1 qt (Imp.)	= 1.1365 L
1 grain/ft ³	= 2.288 g/m ³	1 qt (U.S.)	= 0.9464 L
1 grain/100 ft ³	= 22.88 mg/m ³	1 tablespoon (tbs)	= 14.79 mL
1 hp	= 0.7457 kW	1 teaspoon (tsp)	= 4.929 mL
1 microinch (μin)	= 0.0254 μm = 25.4 nm	1 ton (short)	= 907.2 kg
1 in	= 0.0254 m = 2.54 cm = 25.4 mm	1 U.S. bag cement	= 42.63 kg (94 lb)
1 in ²	= 6.452 cm ² = 645.2 mm ²	1 yd	= 0.9144 m
1 in ³	= 16.387 cm ³ = 0.01639 L	1 yd ²	= 0.8361 m ²
1 in·lbf (torque)	= 0.113 N·m	1 yd ³	= 0.7646 m ³
1 inHg	= 3.386 kPa		

Units Not To Be Used—Convert to SI Units

<u>Do Not Use</u>	<u>Value in SI Units</u>
angstrom (Å)	1 Å = 0.1 nm = 10 ⁻¹⁰ m
are (a)	1 a = 1 dam ² = 100 m ²
atmosphere, standard (atm)	1 atm = 101.325 kPa
atmosphere, technical (at)	1 at = 98.0665 kPa
bar	1 bar = 100 kPa
calorie (cal)	1 cal = 4.184 J
candle	1 candle = 1 cd
candlepower (cp)	1 cp = 1 cd
centipoise (cP)	1 cP = 0.001 Pa·s
centistokes (cSt)	1 cSt = 10 ⁻⁶ m ² /s
dyne (dyn)	1 dyn = 10 ⁻⁵ N
erg (erg)	1 erg = 10 ⁻⁷ J
fermi (fermi)	1 fermi = 1 fm = 10 ⁻¹⁵ m
gamma (γ)	1 γ = 1 nT = 10 ⁻⁹ T

Chapter 2 Appendix 3

Do Not Use

gauss (G)
gon, grad, grade (gon)
kilocalorie (kcal)
kilogram-force (kgf)
kilogram-force per square millimeter (kgf/mm²)
langley (cal/cm²)
maxwell (Mx)
metric carat
metric horsepower
micron
millibar (mbar)
millimeter of mercury (mmHg)
millimeter, centimeter, or meter of water (mmH₂O, etc.)
millimicron
mho
poise (P)
stokes (St)
torr (Torr)
 γ (mass)
 λ (volume)

Value in SI Units

1 G = 10^{-4} T
1 gon = $(\pi/200)$ rad
1 kcal = 4.184 kJ
1 kgf = 9.807 N
1 kgf/mm² = 9.807 MPa
1 cal/cm² = 41.84 kJ/m² = 4.184×10^4 J/m²
1 Mx = 10^{-8} Wb
1 carat = 200 mg = 2×10^{-4} kg
1 metric horsepower = 735.5 W
1 micron = 1 μ m = 10^{-6} m
1 mbar = 100 Pa
1 mmHg = 133.3 Pa = 0.1333 kPa
1 mmH₂O = 9.807 Pa, etc.
1 millimicron = 1 nm = 10^{-9} m
1 mho = 1 S
1 P = 0.1 Pa·s
1 St = 1 cm²/s = 10^{-4} m²/s
1 Torr = 133.3 Pa
1 γ = 1 μ g = 10^{-9} kg
1 λ = 1 mm³ = 1 μ L = 10^{-9} m³

Source: ASTM SI 10, "American National Standard for Use of the International System of Units (SI): The Modern Metric System" (West Conshohocken, PA: ASTM International, 2002).

Materials Selection

Corrosion occurs as the result of a voltage differential between two components of a system. An anode and a cathode must be present. If a complex structure is constructed of materials that are near each other in the galvanic series, then there is reduced likelihood of potential differences. Construction using materials that are not close in the galvanic series (such as steel and copper) can create a corrosion cell. When mechanical considerations allow, always select materials that will exhibit little or no voltage differences when in contact with each other and a common electrolyte.

Nonmetallic materials also play an important role in corrosion control. However, nonmetallic materials will not be discussed in this course except for their use in electrical isolating devices.

Protective Coatings

Underground or Submerged Structures

General

Coatings are the first line of defense in many corrosion control programs. Unfortunately, coatings are not perfect and accelerated corrosion occurs at breaks (holidays) in a coating. Cathodic protection is used to prevent corrosion of the steel substrate at the holidays in the coating.

Coating also plays an important part in cathodic protection engineering. Although it is possible to protect a bare structure, if the structure is coated it is necessary to protect only the metal exposed at the holidays. This greatly reduces the size and cost of cathodic protection systems. Coating inspection is important because it is desirable to install the structure with the coating in the best possible condition. This will ensure that the cathodic protection system performs as designed.

Types of Mill Applied Underground Coatings

Exposure to Sunlight

Pipeline coatings designed for underground use generally do not have good resistance to ultra violet light. Consequently, lengthy storage of coated pipe in sunlight is to be avoided.

Bituminous Enamels

These coatings are formulated from coal tar pitch or natural asphalt and are reinforced with glass and a felt wrapper to provide additional mechanical strength and impact resistance. The exterior of the pipe is wrapped with kraft paper for protection during shipping and handling. These coatings have been in use since the early 1900's, but are being used less and less today because of toxicity and environmental concerns. Enamel-coated pipe must be handled carefully to prevent damage to the coating.

Extruded Polyolefin and Polyethylene

These coating systems consist of polyolefin or polyethylene extruded over a butyl or asphalt mastic adhesive. The coatings have high impact resistance and resist the development of holidays over time.

Tape Coatings

Most tape systems are cold applied. The system consists of a primer, a corrosion sealant inner layer, with a mechanical protective outer layer backing, usually polyethylene or polybutylene. There are also several multi-layer systems available. They must be shipped and handled with care to prevent damage and are prone to disbonding if the tape is not properly tensioned.

Fusion Bonded Epoxy

These coatings consist of a powdered resin electrostatically sprayed onto a pipe heated to 400°F to 500°F (204°C to 260°C). Typical thickness is 12 to 15 mils (0.304 mm to 0.381 mm). These coatings have good adhesion to steel and resist impact and abrasion damage well. Operating temperatures range from -40°F to 140°F (-40°C to 60°C). Long-term (10 to 15 years) moisture absorption can be a problem with these coatings, so cathodic protection current requirements may increase over time.

Two-Component Liquid Resin Coatings

These coatings consist of a liquid resin, usually an epoxy, and a curing agent. The two components are sprayed in the correct proportion onto the pipe, usually in one or two coats to achieve a final thickness of 12 to 16 mils (0.304 mm to 0.406 mm). These coatings are also resistant to impact and abrasion damage.

Girth Weld and Other Field Coatings

Welded joints, fittings, and other appurtenances must be coated in the field. Various materials are used for this procedure including heat shrink sleeves, hot- and cold-applied tapes, two-component liquid resins, coal tar mastics and fusion bonded epoxy. The field coating selected must be compatible with the adjacent coating and as durable as that on the structure itself.

Surface Preparation

Proper surface preparation is essential if the coating is to bond properly to the metal. Each type of field coating will have a specific surface preparation requirement that must be followed.

For all coatings, the surface must be clean and dry. Often this is accomplished with power tools but in some cases abrasive blasting and solvents is required.

Some coatings require a primer on the prepared surface prior to the application of the coating. Primer application must be done in accordance with the manufacturer's specifications and must be allowed to dry to the specified consistency before the outer coating is applied.

Application

Coatings may be hot or cold applied. The most common field coatings in use today are liquid epoxies, heat shrink sleeves and various types of tape. All coatings should be applied in accordance with the manufacturer's requirements.

Inspection Procedures

Initial Inspection

Surface preparation must be inspected to ensure adherence with the specifications. Environmental conditions such as temperature, humidity and dew point must be checked against the manufacturer or consultant's

specifications. This is to ensure the surface is being prepared and the coating is being applied in an atmosphere conducive to proper coating performance.

Maintenance Inspections

While detailed inspections need to be made by the proper level Certified NACE Coating Inspector, cathodic protection personnel may be called upon to make an inspection of exposed coating. This can be done visually, looking for signs of disbonding, damage, checking, cracking, chalking, and other deterioration.

The purpose of this inspection is to determine the condition of the coating to see if any reconditioning is required. If a poor coating is found, it may be necessary to excavate more of the pipe to see how far the deterioration exists.

Electrical Isolation

Electrical isolation devices may be used to separate different metals or other anodic and cathodic components of a corrosion cell. Insertion of dielectric material interrupts the electronic portion of the corrosion cell, thereby isolating the anode from the cathode.

Electrical isolation is also an important part in cathodic protection work and will be discussed in some detail in subsequent chapters.

Environmental Control

In aqueous environments, various chemicals may be introduced to the water or process stream to reduce its corrosivity to the exposed metal. Similar measures are used in pipelines carrying corrosive gasses or liquids.

There has been some application of environmental control to underground facilities, but success has been limited. Effective use of environmental control is basically limited to liquids in confined spaces such as piping, boilers, and tanks.

Inhibitors

Inhibitors are added to liquids to change the characteristics of the liquid or to form protective films on the surface of the metal. Some inhibitors form films on anodic or cathodic spots along the metal surface. Some,

such as those used in potable water systems, lay down a protective film over the entire metal surface.

Oxygen, which plays an important role in the corrosion reaction, may be controlled by the addition of oxygen scavengers. This is especially important in the treatment of boiler water.

Adjustment of pH

The pH of water affects its ability to precipitate out a protective scale. Control of pH is used to create a water that will not be aggressive to the metal piping and vessels it contacts.

Maintenance of Environmental Control

Inhibitors and other environmental control must be applied at the proper dosage and must be properly maintained. Corrosion prevention is dependent on the concentration of the chemicals in the liquid, and regular testing and chemical control must be initiated.

Cathodic Protection

This approach to control of corrosion using electrical current is limited to metals exposed to an electrolyte such as soil, water, and concrete. It does not work in the atmosphere.

Cathodic protection is often used in conjunction with other corrosion control methods including protective coatings and electrical isolation.

Theory

On a corroding surface, there are hundreds of local, or microscopic, corrosion cells. Figure 3.1 illustrates such a cell on the surface of a pipeline. There is a potential, or voltage, difference between the anode and cathodes of these cells; this potential difference drives the corrosion current.

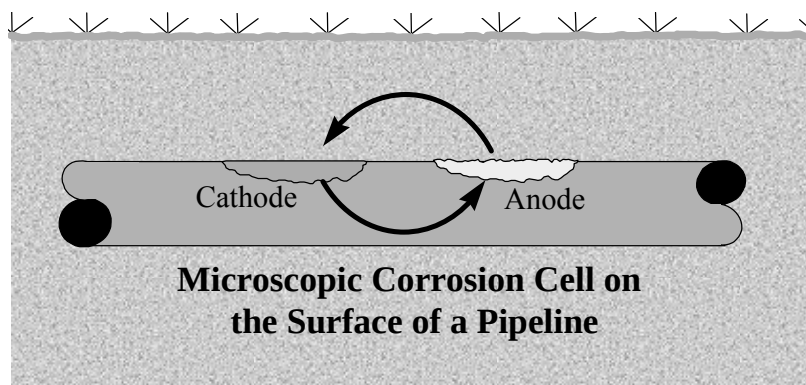


Figure 3.1 Microscopic Corrosion Cell

The concept of cathodic protection involves reducing the potential difference between local anodic and cathodic sites on a metal surface to zero, resulting in zero corrosion current flow. This can be accomplished by causing a current to flow onto the structure from an external anode which current polarizes the cathodic sites in an electronegative direction. As the potentials of the cathodic sites polarize toward the potentials of the anodic sites, corrosion current is reduced. When the potentials of all cathodic sites reach the open circuit potential of the most active anodic sites, the voltage difference between local anodes and cathodes is eliminated and corrosion ceases.

Cathodic protection does not actually eliminate corrosion. Instead, it transfers it from the structure to be protected to the cathodic protection anode(s). The structure is now the cathode of an intentional corrosion cell. Corrosion of the metal will cease once the applied cathodic protection

current equals or exceeds the corrosion current. This is illustrated in Figure 3.2.

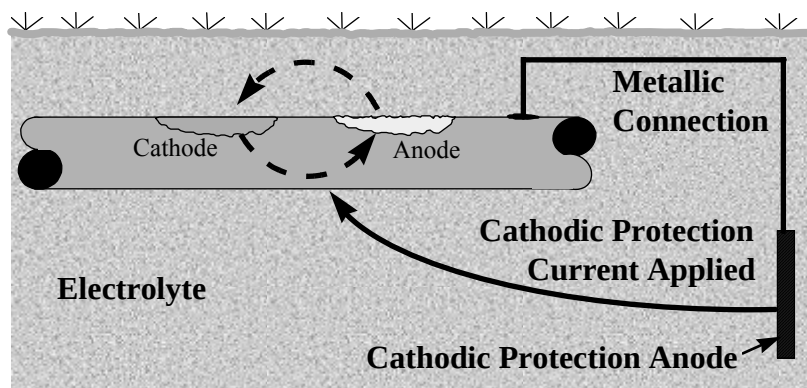


Figure 3.2 Cathodic Protection on a Structure

The cathodic protection current leaves the cathodic protection anode, enters the electrolyte, and passes as migrating ions through the electrolyte to the metal surface. At the point this current leaves the cathodic protection anode, an anodic reaction occurs. Where it is picked up on the protected surface, a cathodic reaction occurs. The current then flows to the metallic connection and returns to the anode. Note that in this discussion we are utilizing the concept of conventional current flow (see Chapter 2).

Definition

Cathodic protection is the cathodic polarization of all noble potential areas (cathodes) to the most active potential on the metal surface. Cathodic protection is achieved by making the structure the cathode of a direct current circuit. The flow of current in this circuit is adjusted to assure that the polarized potential is at least as active as the most active anode site on the structure.

Structures That Can be Cathodically Protected

Most metallic structures that are immersed or embedded in an electrolyte can be cathodically protected. Examples of structures where cathodic protection is employed include:

- underground or submerged steel, iron, aluminum, and prestressed concrete cylinder pipelines
- underground tanks and piping
- exterior bottoms (both primary and secondary) of above grade storage tanks.
- water tank interiors
- ship hulls
- ballast tanks
- docks
- sheet piling
- foundation piles on land and in the water
- bridge decks and substructures
- hot water storage tank interiors
- heat exchanger water boxes and tube sheets
- internal surfaces of oil heater treaters
- reinforcing steel in concrete
- lead or steel sheathed telephone and electrical cables.

Cautionary Note: It is possible to overprotect some materials such as prestressing wire, lead, and aluminum. High cathodic protection currents may cause hydrogen embrittlement in highly stressed steel and may actually increase corrosion of amphoteric metals such as aluminum and lead.

There are two methods of providing cathodic protection current to a structure:

- galvanic anode system
- impressed current system.

Galvanic Anode Systems

Galvanic (or sacrificial) cathodic protection makes practical use of dissimilar metal corrosion. It is important to note that there must be a substantial potential difference, or driving voltage, between a galvanic anode and the structure to be protected. The galvanic anode is connected to the structure it is protecting, either directly or through a test station so it can be monitored.

A typical galvanic cathodic protection system is shown in Figure 3.3.

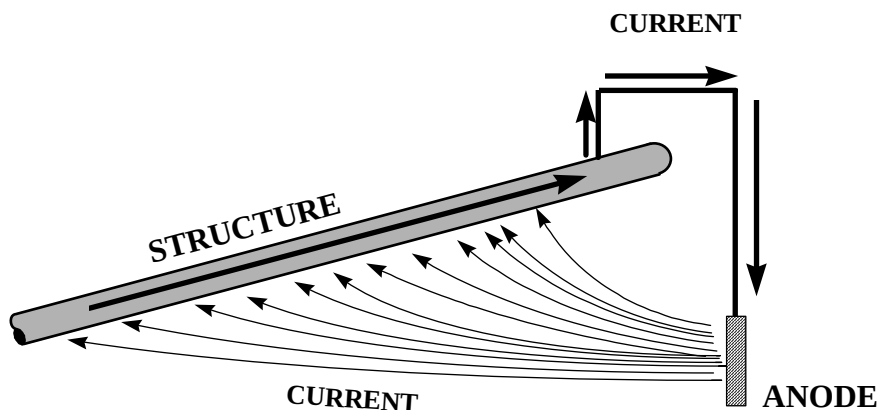


Figure 3.3 Typical Galvanic Anode Cathodic Protection

Anodes

There are several metals commonly used as galvanic anodes:

- aluminum
- magnesium
- zinc.

EXPERIMENT 3.1

Applications of Galvanic Anode Systems

The following are among the conditions where galvanic anodes are used:

- When a relatively small amount of current is required.
- Usually restricted to lower resistivity electrolytes.
- For local cathodic protection to provide current to a specific area on a structure. Some operators install galvanic anodes at each location where a leak is repaired rather than installing a complete cathodic protection system. Such practices may be encountered on bare metal or very poorly coated systems where complete cathodic protection may not be feasible because of cost.
- When additional current is needed at problem areas. Some structures with overall impressed current cathodic protection systems may have isolated points where additional current in relatively small amounts is needed. These requirements can be met with galvanic anodes. Typical applications include:
 - Poorly or incompletely coated buried valve installations
 - Shorted casings that cannot be cleared
 - Isolated sections where the coating has been badly damaged
 - Areas where electrical shielding impairs effective current distribution from remotely located impressed current systems
 - In cases of cathodic interference, if the conditions are suitable, galvanic anodes can be used at the discharge point on the foreign line to return interfering current.
- To provide protection to structures located near many other underground metallic structures where conditions make it difficult to install impressed current systems without creating stray current interference problems. Galvanic anodes can be an economical choice for a cathodic protection current source under such conditions.
- Galvanic anodes find extensive use in protecting the interior surface of heat exchanger water boxes and other vessels. They are used also within

oil heater-treater vessels, depending on the quality of the interior lining and the fluid chemistry and temperature.

- On offshore structures, large galvanic anodes may be used to protect the underwater components.

Advantages of Galvanic Anodes

- No external power source required.
- Low maintenance requirements.
- Small current output resulting in little or no stray current interference.
- Easy to install.
- Easy to add anodes in most cases.
- Provide uniform distribution of current.
- Minimum right-of-way/easement costs.

Limitations of Galvanic Anodes

- Low driving voltage/current output.
- Many anodes may be required for poorly coated structures.
- May be ineffective in high-resistivity environments.
- Higher cost per unit ampere than impressed current due to lower efficiency (self-consumption).
- May be difficult or expensive to replace spent anodes.

Component Parts of Galvanic Systems

Anodes

MAGNESIUM

Magnesium anodes are available in two alloys: a high-potential alloy having a nominal corrosion potential of -1.75 referenced to a copper-copper sulfate electrode and a low-potential alloy having a nominal corrosion potential of -1.55 V referenced to a copper-copper sulfate electrode. Magnesium is normally used in soils and fresh water.

ZINC

Zinc anodes are also commercially available in two alloys, one for use in soils and the other for seawater applications. Zinc may undergo rapid intergranular corrosion at temperatures above 120°F (49°C). At

temperatures above 130°F (54°C) and particularly in the presence of carbonates, zinc can passivate and the potential of the passive film can become more noble than steel, leading to corrosion of the steel.

ALUMINUM

Aluminum alloy anodes are used primarily in seawater applications and are produced in a variety of alloys, of which the mercury and indium alloys are the most common. The indium alloy has a slightly higher corrosion potential but is less efficient than the mercury-containing alloy. Aluminum is preferred for seawater applications because it has a much lower consumption rate than magnesium or zinc.

Aluminum anodes are not used in fresh water, except as impressed current anodes. They are not used underground.

An alloy of aluminum-zinc and indium is used as a sacrificial anode on reinforced concrete structures.

Aluminum anodes are commonly used in process vessels containing brine. At temperatures above 120° F (49° C), however, the current output may be reduced.

GALVANIC ANODE EFFICIENCY

The efficiency of a galvanic anode depends on the alloy of the anode and the environment in which it is installed. The consumption of any metal is directly proportional to the amount of current discharged from its surface. For galvanic anodes, part of this current discharge is due to the cathodic protection current provided to the structure and part is caused by local corrosion cells on its surface. Anode efficiency is the ratio of metal consumed producing useful cathodic protection current to the total metal consumed. Anode efficiency is generally about 50% for magnesium and 90% for zinc. Aluminum anode efficiencies are typically in the 90% range, but can vary dependent upon the type of anode selected and the environment to be installed.

Specifications of Galvanic Anode Systems

Size and Shapes

Galvanic anodes come in a variety of sizes and shapes. For seawater application aluminum anodes are often sized to fit the size of the structure. The ends of these anodes are equipped with welding tabs for electrical connection to the structure.

In soil environments, the shape and size of the anode depends more on resistivity of the soil, current requirement, and other conditions than on the size of the structure. These anodes are equipped with an insulated wire for the electrical connection. Spacing between the anode and structure is operator controlled. Another component required for a soil application anode is a chemical backfill.

Backfill

The chemical backfill used for galvanic anodes consists of 75% gypsum (CaSO_4), 20% bentonite clay, and 5% sodium sulfate. The chemical backfill surrounding magnesium and zinc anodes provides a uniform environment that reduces self-consumption of the anode. The chemical composition of the backfill is such that the anode functions more efficiently because the backfill reduces polarization of the anode. Also, the backfill swells upon getting wet, providing a tight fit with the surrounding soil and thus reducing the resistance of the anode to earth.

Galvanic anodes can be ordered bare or prepackaged with the chemical backfill. The plastic shipping bag around prepackaged anodes must be removed before installation. If anodes are not prepackaged with a special chemical backfill, field installation of the anode will require mixing the backfill on site and placing it around the anode.

Attachment to Structures

Galvanic anodes must be directly attached to the structure through a metallic conductor. This is achieved by one of the following methods:

- using insulated copper wire provided by the manufacturer and thermite welded or otherwise attached to the structure.

- as above with a test box installed between the anode and the structure. The test box may contain a resistor for control of current flow or a shunt to measure current output.
- as bracelets clamped around a pipe and connected to it with a welded pigtail connection.
- by means of a steel rod or strap cast in the anode and then welded to the structure.

If the galvanic anode wire has a hole in the insulation, the copper wire becomes part of the cathode circuit and receives cathodic protection current from the anode. For this reason, every effort should be made to avoid damage to the wire to minimize cathodic protection current loss to the anode wire.

Impressed Current Systems

An impressed current system consists of an external power source and anodes. The external power source forces current to flow from the anode to the structure through the electrolyte. The anodes used in an impressed current system are usually constructed of a relatively inert material. Exposed copper in the underground positive cable, splices or anode connections will corrode rapidly, therefore these components must be water tight. A typical installation is shown in Figure 3.4.

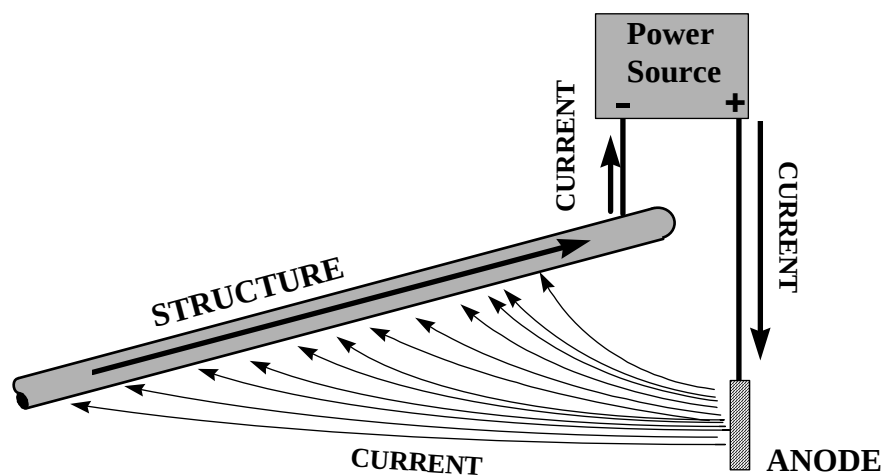


Figure 3.4 Typical Impressed Current Cathodic Protection

Anodes

Materials that have been used as impressed current anodes include:

- Graphite (carbon)
- High-silicon, chromium, cast iron
- Platinum-coated titanium and niobium
- Aluminum
- Magnetite
- Mixed metal oxide-coated titanium
- Conductive polymer
- Scrap iron or steel
- Lead silver

Power Sources

The power source for an impressed current system produces direct current (DC). Various power sources have been used with impressed current systems including:

- Rectifiers
- Solar (photovoltaic) cells
- Engine generators
- Wind-powered generators
- Thermoelectric cells

Where AC power is economically accessible, rectifiers have clear economic and operating advantages over other impressed current power sources.

Applications of Impressed Current Cathodic Protection

Typical uses of impressed current are:

- for large current requirements, particularly for bare or poorly coated structures
- in all electrolyte resistivities
- as an economical way of protecting structures having dissipated galvanic anodes
- to overcome stray current or cathodic interference problems
- for protection of large heat exchanger water boxes, oil heater-treaters, and other vessels
- for interiors of water storage tanks
- for exterior bottoms (both primary and secondary) of above ground storage tanks
- for underground storage tanks
- for underwater components of off shore structures

- for foundation piles and sheet piling, both underground and in the water.

Advantages of Impressed Current Systems

- Flexible with capability to handle a wide range of voltage and current outputs.
- Satisfy high current requirements with a single installation.
- Effective in protecting uncoated and poorly coated structures.
- Effective in high-resistivity environments.
- Less anode consumption than with galvanic anodes.

Limitations of Impressed Current Systems

- Higher inspection and maintenance cost than with galvanic anodes.
- Requires external power.
- Constant power supply cost.
- High risk of causing stray current interference.
- May cause overprotection resulting in:
 - coating damage
 - hydrogen embrittlement

Component Parts of Impressed Current Systems

Anodes

GRAPHITE (CARBON)

Graphite anodes installed underground with carbonaceous backfill function well. Graphite also exhibits excellent performance in chloride environments such as seawater. Where oxygen evolution takes place on the surface of a graphite anode, the graphite oxidizes to form carbon dioxide. Severe conditions of low pH and high sulfate concentration can increase the consumption rate.

Graphite anodes perform well in relatively dry soils.

HIGH SILICON IRON

Regular silicon iron consists of a very hard matrix, which has graphite flakes at the grain boundaries. The graphite produces an inherent weakness in the alloy. Adding chromium ties up free graphite as carbides and strengthens the alloy.

Silicon-chromium-iron anodes are brittle in comparison to graphite, but the hardness of the alloy makes the anode less susceptible to damage from abrasion or erosion. Installed underground with carbonaceous backfill, the anode performs similarly to graphite. When installed without backfill and where oxygen evolution is the predominant anodic reaction, the silicon-chromium-iron anodes perform better than graphite. In dry soil, the silicon dioxide film, which forms on the surface, introduces a high resistance that degrades performance.

PLATINUM

The two most common platinized anodes incorporate titanium and niobium substrates. The anodes were developed primarily for use in seawater and other chloride environments since both substrates form protective, dielectric, oxide layers when made anodic in the presence of chlorides. Platinized anodes are susceptible to premature failure by reactions with complexing ions, particularly in process applications.

Platinized anodes are economical only when operated at high current densities such as in seawater where there can be rapid migration of chlorides to the anode and products away from the anode. Where the predominant anodic reaction is the evolution of oxygen, higher driving voltages are needed. In terms of both the costs of the anode and the power required, it is therefore not usually economical for underground applications.

ALUMINUM

Aluminum anodes are used primarily in unheated water storage tanks. Because of the high consumption rate, the anode life is typically about one year. Ice damage in the winter makes annual replacement necessary, anyway, so the short life of the material can be tolerated. Aluminum anodes are also used because the corrosion products of the anode are colorless and non-toxic.

MAGNETITE

Magnetite is a form of iron oxide. These anodes are used in seawater, brackish water, fresh water, and high-resistivity soil.

MIXED METAL OXIDE

Mixed metal oxide anodes (also referred to as DSA for dimensionally stable anode) consist of electrocatalytic activated coatings on a titanium substrate. The metal oxide coating is highly conductive and demonstrates an extremely low weight loss. Mixed metal oxide anodes are extremely resistant to acid

attack even at a pH less than one. These anodes are available in rod, tube, or mesh form and are used in fresh water, salt water and underground environments, as well as embedded in concrete.

CONDUCTIVE POLYMER

This is a flexible wire-like anode that is used underground and also to protect reinforcing steel in concrete. For underground use, the anode can be obtained in a fabric tube containing carbonaceous backfill.

SCRAP METAL

Although not commonly used as an anode material because of its high consumption rate, scrap iron or steel can be employed. Abandoned steel piling and sections of old pipe have been used as impressed current anodes.

LEAD-SILVER

This material is used only in chloride environments. The most common application is seawater.

Backfill

For underground applications, impressed current anodes are almost always backfilled in a carbonaceous material. The backfill serves three purposes:

- reduces the anode-to-ground resistance.
- increases the current output capacity of the anode by extending the anode surface area.
- reduces the consumption of the anode since the backfill is conductive and when properly tamped becomes part of the anode and is consumed in addition to the anode.

Power Supply

RECTIFIERS

What is commonly referred to as a rectifier is actually a transformer-rectifier unit. It contains a step-down transformer, a means of adjusting the voltage, a rectifier to change AC to DC, and various controls and other components depending on its usage. Figure 3.5 shows a rectifier schematic.

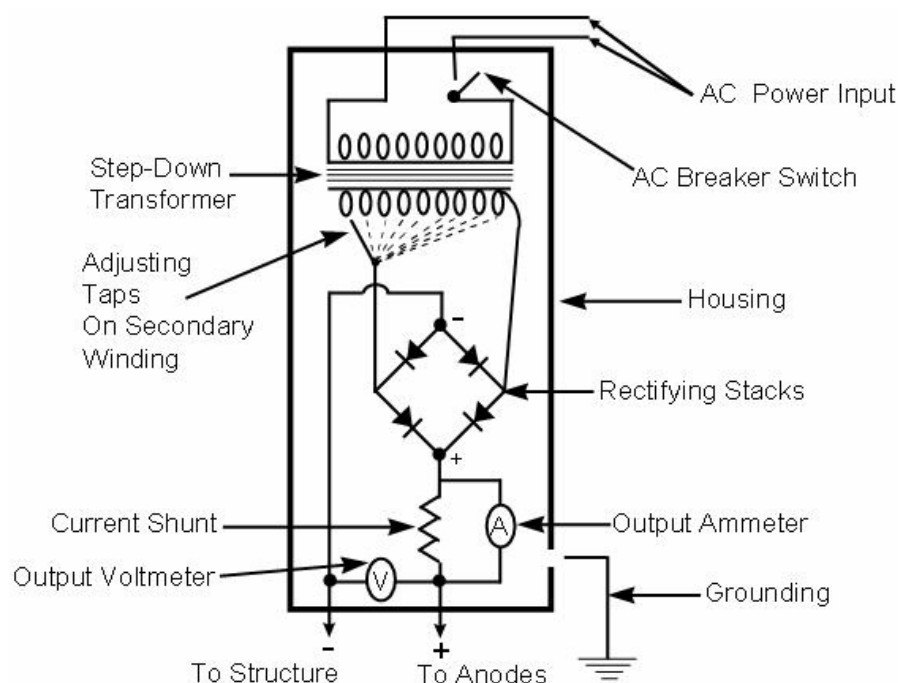


Figure 3.5 Cathodic Protection Rectifier Schematic

There are three basic types of rectifiers:

1. Constant voltage — the DC voltage at the terminals remains constant for all current outputs up to the rated maximum rectifier current.
2. Constant current — the current output remains constant over a wide range of circuit resistances up to the maximum rated output voltage.
3. Constant structure-to-electrolyte potential — the current and voltage output vary to maintain a pre-selected structure potential.

Where AC power is economically available, rectifiers have clear economic and operating advantages over other power sources.

SOLAR PANELS

Solar panels generate DC by a photovoltaic action with sunlight. The panels are combined with storage batteries to provide power during hours of darkness and on cloudy days.

ENGINE-GENERATOR UNITS

Engine-generator units may be used as a power source for impressed current systems. These units usually power standard rectifiers as shown in Figure 3.6.

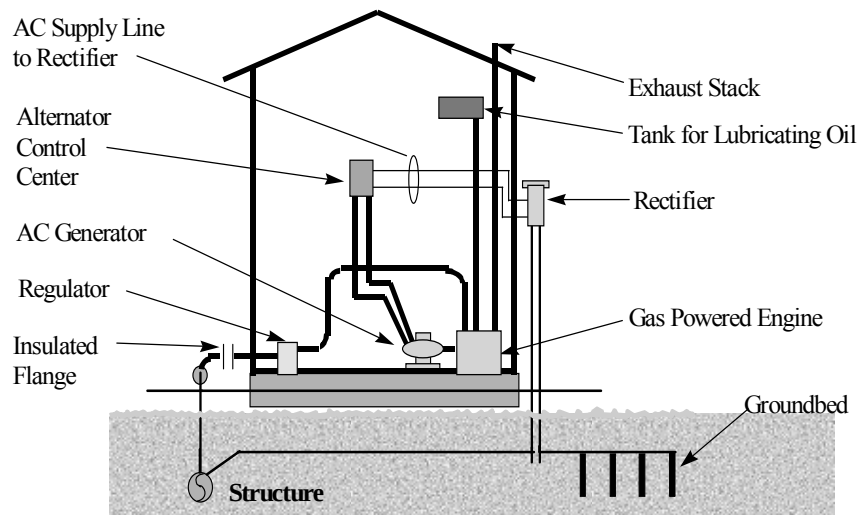


Figure 3.6 Engine-Generator Unit

WIND POWERED GENERATORS

Wind powered generators may be used in areas with prevailing winds of sufficient velocity. The generators also charge storage batteries so as to provide constant cathodic protection current.

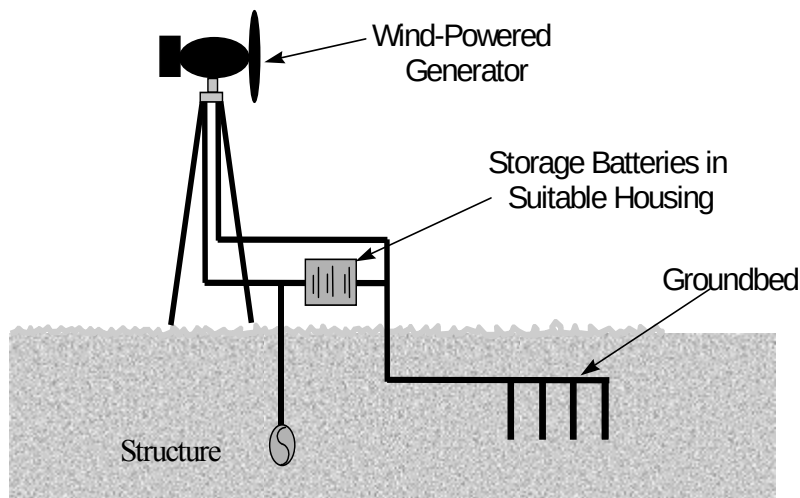


Figure 3.7 Wind Powered Generator Installation

THERMOELECTRIC GENERATORS

These units generate voltage by heating a junction of two dissimilar metals. They generate small currents, so are used in places having low current requirements.

Electrical Connections

All electrical connections used in impressed current cathodic protection systems (except the active anode surfaces) must be completely sealed with dielectric insulating materials.

EXPERIMENT 3.2

Factors Influencing Operation of Cathodic Protection

Many factors influence the operation of cathodic protection systems. Corrosion technicians must understand the effects of some of the more important factors.

Moisture Content of Soil

As moisture content increases to about 15%, soil resistivity decreases. Above about 15%, there is little change in resistivity. While low soil resistivity tends to increase electrochemical corrosion, it enhances cathodic protection by lowering the anode-to-earth resistance, thus allowing higher current output for a given voltage.

Coating

Coating reduces the amount of current required to protect a structure. Protecting a bare structure requires sufficient current to protect all the metal exposed to the electrolyte. On a coated structure, it is necessary to protect only the metal exposed at breaks, or holidays, in the coating. A well-coated structure may well have less than 1% of its surface exposed at holidays. As the coating ages, however, some deterioration may occur. Also, when protecting older coated structures, tests need to be made to determine coating quality.

Soil Texture

Clay and Silt

Tight soils may lead to gas blockage at the anodes causing increased resistance to ground. Blockage is caused by the inability of gasses generated at the anode to escape. This is of special concern in deep anode beds.

Tight soils may reduce depolarization effects on the structure. This helps to reduce protective current requirements.

Sand and Gravel

Porous soils permit rapid changes in moisture content. This may lead to cyclic wetting and drying of the soil, thus changing its resistivity. Such changes will

influence the cathodic protection circuit resistance. In some cases, constant current rectifiers are needed to maintain cathodic protection.

Oxygen can easily penetrate porous soils. Oxygen acts as a depolarizer, thus increasing current requirements.

Oxygen concentration cells may develop at points of contact between gravel and the structure. Cathodic protection current may not penetrate into the point of contact. As a result, it may be difficult to protect structures backfilled with or resting on gravel or crushed rock.

Glacial Till

Glacial till is similar to gravel and the concerns noted above apply also to this type of soil.

Temperature

Corrosion rates tend to increase with temperature. Consequently, in warmer electrolytes, current requirements will be higher than in cooler ones. Heat exchanger water boxes and oil heater-treater vessels are good examples of higher temperature environments. Gas pipelines downstream of a compressor station normally require a high current density for the increase in temperature caused by the compressed gas.

Increasing temperature acts to reduce polarization. This also increases current requirements.

As mentioned in the discussion of galvanic anode materials, elevated temperatures can affect the performance of aluminum and zinc anodes.

Oxygen Content

As oxygen levels increase, polarization tends to decrease. Thus, in oxygenated environments, high current requirements are to be expected.

Movement of Structure and Electrolyte

The relative movement between a protected structure and the electrolyte affects current requirement. As the relative velocity increases, so does the current requirement due to decreasing polarization.

Ship hulls are a good example of this phenomenon. At anchor, the current requirement for the hull is low. When under way, however, the current requirement increases. Here again, constant current rectifiers may be needed.

The same effect occurs in rapidly flowing water. Bridge piles in a rapidly flowing river will require more current than those in quiescent waters. Water flow through a heat exchanger water box will also affect the current requirement.

Make-up of the Electrolyte

The electrolyte itself can affect the performance of cathodic protection. Bacteria, especially sulfate reducing bacteria, have a depolarizing effect on the protected structures. It may be necessary to increase the level of cathodic protection in such electrolytes.

The fluid chemistry in oil heater-treaters affects anode performance. Carbon dioxide and hydrogen sulfide, for example, have a passivating effect on zinc.

Electrical Shielding

Metal

Metal components connected to a protected structure may prevent cathodic protection current from reaching a corroding surface. A shorted pipeline casing is an excellent example of metal shielding.

Figure 3.8 illustrates the effect of a shorted casing.

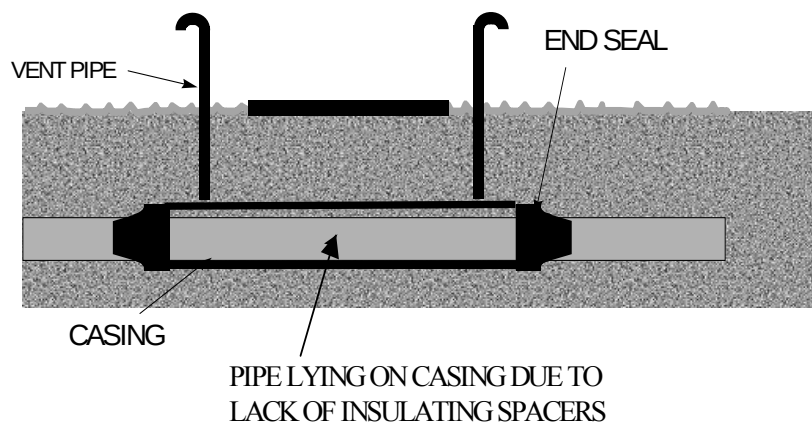


Figure 3.8 Cathodic Shielding Due to a Shorted Casing

Dielectric

If a sheet of plastic or other insulator is placed close to the surface of a cathodically protected structure, it may prevent adequate current from reaching a corroding surface. Disbonded coatings may have the same result.

Criteria for Cathodic Protection

Cathodic protection is a polarization phenomenon. As explained earlier in this chapter, cathodic protection involves reducing the potential difference between local anodic and cathodic sites on a metal surface to zero. This is accomplished by polarizing local cathode potentials to those of the local anodes.

Polarization of the cathodic sites to the open circuit potential of the anodic sites is the true criterion for eliminating corrosion. It is essentially impossible, however, to determine the open circuit potential of the most active anodic site. Because corrosion cells are usually microscopic and the measured potentials are mixed corrosion potentials, the initial measurements are most likely to be an average of corrosion potentials for several corrosion cells. Therefore, several surrogate criteria have been developed to assist meeting the true criterion. Various criteria are recommended by NACE International and other international standards organizations.

NACE International Recommended Criteria

General

There are several criteria recommended by NACE. These will be found in various standard practices (SP) or recommended practices (RP). The following discussion covers various metals in different environments. Pertinent recommended practices are also cited. When referring to these recommended practices, be certain to obtain the latest revision (the year of revision follows the RP number).

You will note that in many cases, the statement is made that voltage drops (IR drops) other than those across the structure-to-electrolyte boundary, must be considered for valid interpretation of the data. It is very important that you have a thorough understanding of this, since if IR drop is not considered, your data may indicate that the structure is protected when indeed it is not. This matter is discussed in the following section. After that, we will discuss criteria for various situations.

IR DROP

Since cathodic protection is a polarization phenomenon, the polarized potential of a structure must be measured to determine the level of protection. *Polarized potential* can be defined as the potential across the structure-to-electrolyte boundary (interface); this is the sum of the corrosion potential and the cathodic polarization.

Thus, the potential of interest is the polarized potential across the structure-to-electrolyte boundary. When a potential is measured, however, the result is the algebraic sum of all the voltage drops in the measuring circuit, as shown in Figure 3.9.

Resistances

Measuring Lead (+)
 Contact Lead (+)/Ref. Cell
 Reference Cell
 Contact Reference Cell
 to Electrolyte
 Electrolyte
 Polarization
 Structure
 Contact Test Lead/Structure
 Test Lead
 Contact Test/Measuring
 Lead
 Measuring Lead (-)
 Internal Meter

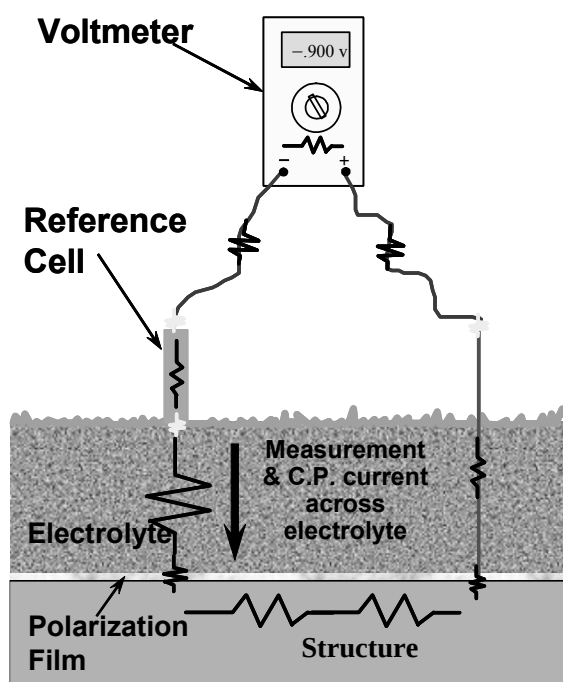


Figure 3.9 Voltage Drops in a Measuring Circuit

For a measured potential to represent the polarized potential across the structure-to-electrolyte interface, all other voltage drops in the measuring circuit must be negligible. Since voltage (or IR drop) is a product of current and resistance, voltage decreases when either current or resistance decreases. Current usually refers to the applied cathodic protection current; the measurement current (current required to operate the meter) or stray currents can be significant, however. The measurement circuit current is small if the input resistance of the meter is large. This is one reason why

meters having input resistances of millions of ohms are used in taking potential measurements.

Voltage drops are negligible in the measuring circuit under the following conditions:

- metallic paths — when lengths are short and/or area cross-sectional to current flow is large.
- contact between reference cell and electrolyte — when moist and/or large area contact is made.
- connection points — when good metal/metal contacts are made.
- internal circuit of the meter — when a high-input resistance meter (10 megohms, for example) is used.
- electrolyte — when resistivity and/or cathodic protection current density are low.

All the voltage drops in the measuring circuit are controllable except for the one through the electrolyte. The IR drop through the electrolyte can be reduced to nearly zero, however, by placing the reference electrode near the structure; it can be reduced to zero by interrupting the current flow.

In addition to attempting to make the IR drop negligible, another approach is to determine the magnitude of the IR drop, either through measurement or calculations, and adjust the measured potential by eliminating the IR drop.

IR drop will affect the accuracy of the data collected during cathodic protection testing. This is discussed further in Chapter 5, Field Measurements.

In the following discussion, the criteria noted are quoted from the referenced documents. In many cases, other criteria also apply. The 100-millivolt polarization criterion, for example, is applicable in many cases. It is imperative that you know the criteria specified for the structures you are testing. As noted earlier, there is no single, universal criterion for cathodic protection.

To understand the applicable criteria for the structures with which you are working, you need to read thoroughly the criteria section of each of the following referenced documents.

Underground or Submerged Iron and Steel

References

SP0169 Control of External Corrosion on Underground or Submerged Metallic Piping Systems

RP0285 Corrosion Control of Underground Storage Tank Systems by Cathodic Protection

RECOMMENDED CRITERIA

There are three criteria that apply: two involve a structure-to-soil potential of -850 mV in reference to a saturated copper-copper sulfate reference electrode (CSE), and one is a polarization shift of 100 mV.

The three criteria defined are:

- **A negative (cathodic) potential of at least 850 millivolts** with the cathodic protection applied. This potential is measured with respect to a saturated copper-copper sulfate reference electrode contacting the electrolyte. Voltage drops other than those across the structure-to-electrolyte boundary must be considered for valid interpretation of this voltage measurement.
- **A negative polarized potential of at least 850 millivolts** relative to a saturated copper-copper sulfate reference electrode.
- **A minimum of 100 millivolts of cathodic polarization** between the structure surface and a stable reference electrode contacting the electrolyte. The formation or decay of polarization can be measured to satisfy this criterion.

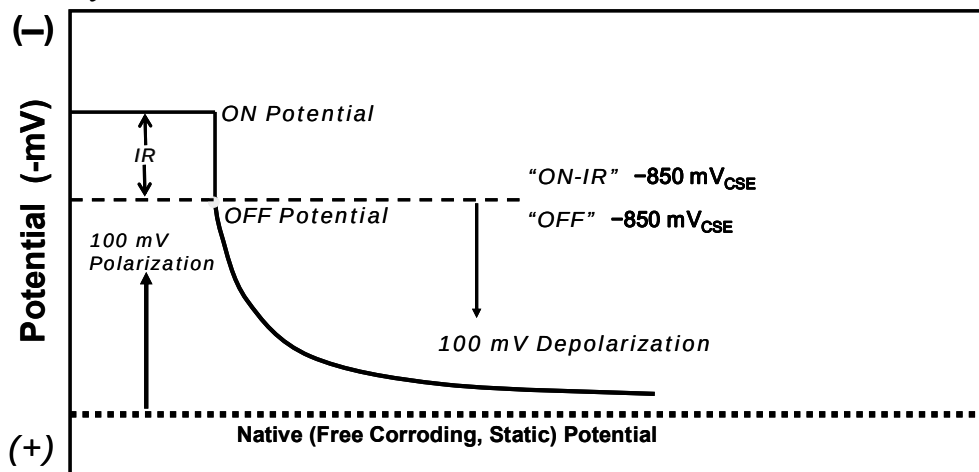


Figure 3.10 Structure-to-electrolyte Potentials

APPLICATION OF THESE CRITERIA

The first criterion, a potential of -850 mV obtained with current applied, is based on negligible IR drop or eliminating the IR drop from the measurement. The IR drop is usually negligible when the current density and/or the resistivity are low.

The second criterion, a polarized potential of -850 mV, is based on eliminating IR drop during the measurement. IR drop can be eliminated by either removing the resistance of the electrolyte or by shutting off the current. On a bare structure, if the potential is measured at the structure-to-electrolyte boundary, then the electrolyte is no longer in the measuring circuit and its resistance is nearly zero. If cathodic protection current is interrupted, then current is zero. Remember that polarization will dissipate when current is interrupted, and polarization is the measurement of interest. Therefore, when current is interrupted, the potential should be measured at “instant off,” which refers to the potential after IR drop is eliminated but before polarization begins to dissipate.

The 100-mV polarization criterion can be applied by either starting with the known corrosion potential (native or original “off” potential) or the polarized structure potential. Begin by momentarily interrupting the current flow to determine the “instant off” (polarized) potential. With current interrupted, watch the decay of the polarized potential. If the potential drops (becomes more positive) at least 100 mV, the criterion has been met. Likewise, if the “instant off” reading is at least 100mV more negative than the native reading, the criterion has been met.

You need to be aware that under some conditions such as the presence of sulfides, bacteria, elevated temperatures, and dissimilar metals, these criteria may not be sufficient. In well-aerated, well-drained soils, corrosion protection may be achieved at less negative potentials. Also, on bare or ineffectively coated pipelines, the measurement of a net protective current (current flow toward the pipeline at predetermined current discharge points) may be sufficient.

Your company probably has specific criteria for various situations. You need to know what criterion is to be used in your work and to understand that there are several criteria from which your design engineers have to choose.

Underground or Submerged Aluminum and Copper Piping

These metals are covered in SP0169. The 100 mV cathodic polarization criterion is used for both materials.

Aluminum is an amphoteric metal and can be damaged by excessive cathodic protection. A polarized potential more negative than -1200 mV should not be exceeded.

Dissimilar Metal Situations

SP0169 gives a criterion of a negative voltage to a stable reference electrode equal to that required for protection of the most anodic metal involved.

Offshore Platforms in Salt Water

SP0176 Corrosion Control of Steel Fixed Offshore Platforms Associated with Petroleum

A negative (cathodic) voltage of at least -0.800 volts measured between the platform surface and a silver-silver chloride (Ag-AgCl) electrode contacting the water. Normally this voltage should be measured with the protective current applied. This -0.800 criterion includes the voltage drop across the steel/water boundary, but does not include the voltage drop in the water.

There are other criteria and reference electrodes covered in this standard along with a lengthy discussion of testing techniques.

Interiors of Steel Water Storage Tanks

SP0388 Impressed Current Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks

A negative (cathodic) potential of at least 850 mV with the cathodic protection applied. This potential is measured with respect to a saturated copper-copper sulfate reference electrode contacting the electrolyte. Voltage drops other than those across the structure-to-electrolyte boundary must be considered for valid interpretation of this voltage measurement.

American Water Works Association Standard D104 Automatically Controlled Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks” specifies -0850 to -1050 mV polarized to CSE.

Oil Heater-Treaters

SP0575 Internal Cathodic Protection Systems in Oil Treating Vessels

A minimum of -850 mV vs CSE (-800 mV vs a silver-silver chloride electrode (Ag-AgCl)). If, however, the fluid contains sulfides or hydrogen sulfide, a minimum potential of -950 mV (-900 vs Ag-AgCl) can be required.

Above Ground Storage Tanks

RP0193 External Cathodic Protection of On-Grade Metallic Storage Tank Bottoms

- A negative (cathodic) potential of at least 850 mV with the cathodic protection applied. This potential is measured with respect to a saturated copper-copper sulfate reference electrode contacting the electrolyte. Voltage drops other than those across the structure-to-electrolyte boundary must be considered for valid interpretation of this voltage measurement.
- A negative polarized potential of at least 850 mV relative to a saturated copper-copper sulfate reference electrode.
- A minimum of 100 mV of polarization.

Steel Reinforced Concrete

SP0290 Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Structures

The standard specifies the 100 mV polarization criterion plus two other, more complex criteria. These are 1) a potential at least as negative as that at the base of the Tafel slope on an E-Log I curve and 2) a polarized potential more negative than the statistical standard deviation of the native potentials. Discussion of these two latter criteria is beyond the scope of this course.

International Standard ISO 15589-1

Petroleum and Natural Gas Industries—Cathodic Protection of Pipeline Transportation Systems

Part 1 On-land pipelines

- Metal-to-electrolyte potential chosen for a corrosion rate less than 0.01 mm/yr (0.39 mils/yr)
 - Polarized potential more negative than $-850 \text{ mV}_{\text{CSE}}$
 - Limiting critical potential not more negative than $-1,200 \text{ mV}_{\text{CSE}}$
 - Anaerobic soils or sulfate-reducing bacteria (SRB) more negative than $-950 \text{ mV}_{\text{CSE}}$
 - High soil resistivity
 - $-750 \text{ mV}_{\text{CSE}}$ for $100 < \rho < 1,000 \Omega\text{-m}$
 - $-650 \text{ mV}_{\text{CSE}}$ for $\rho > 1,000 \Omega\text{-m}$
 - Cathodic polarization of 100 mV
- Precautions:
Avoid using 100 mV under conditions of high temperatures, SRB, interference current, equalizing current, telluric current, mixed metals or SCC conditions more positive than $-850 \text{ mV}_{\text{CSE}}$.

Canada

Canadian Standards Association Standard, Z662, Oil and Gas Pipeline Systems references CGA Recommended Practice OCC-1, For the Control of Corrosion on Buried or Submerged Metallic Piping Systems. The criteria are the same as in SP0169.

CSA Standard Z169 covers cathodic protection of aluminum.

Japan

Several documents list cathodic protection criteria, including:

- The Overseas Coastal Area Development Institute of Japan, “Corrosion Protection and Repair Manual for Port and Harbor Steel Structures.”
- Japanese Port Authority Association, Part 1, “Harbor Facility Technology Criteria and Discussion.”
- Japanese Water Piping Association, WSP-050, “Cathodic Protection Manual for Coated Steel Water Pipe.”

Australia

Australian Standards Institute Standard No. 2832 covers cathodic protection. It has three parts:

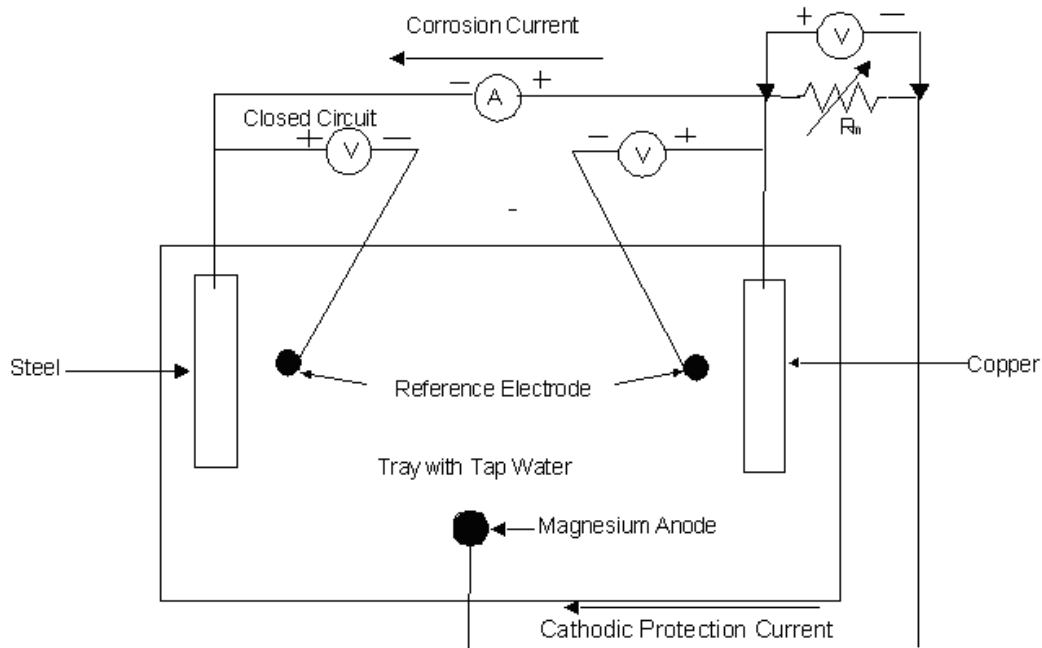
- Part 1 – Pipe, Cables and Ducts
- Part 2 – Compact Buried Structures
- Part 3 – Fixed Immersed Structures

Criteria for steel are the same as those in NACE standard SP0169.

Experiment 3.1–Demonstrate the Use of Cathodic Protection to Mitigate Local Action Cell Corrosion

NOTE: *Instructor will demonstrate this experiment.*

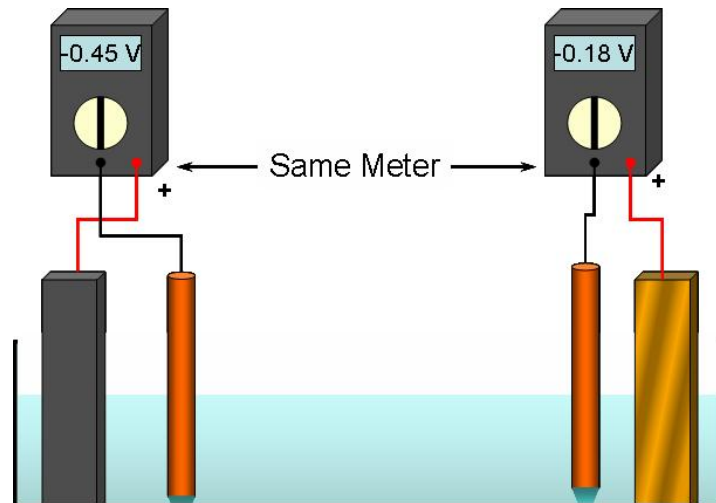
PROCEDURE



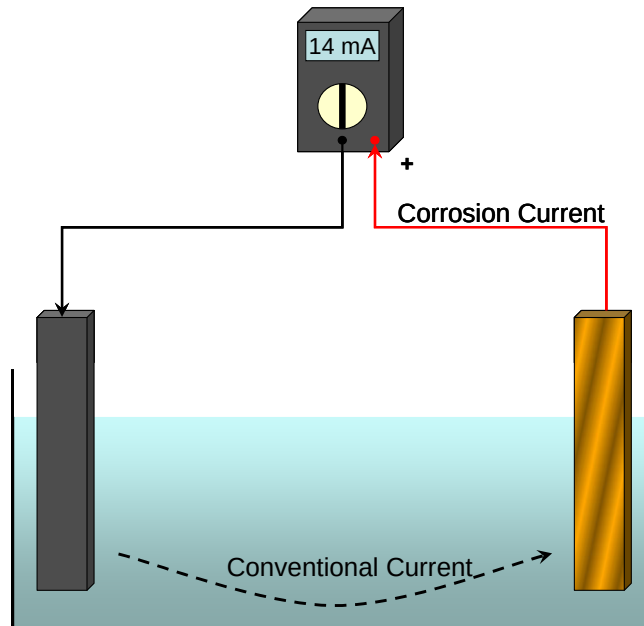
Experiment to Demonstrate Mitigation of Local Action Cell Corrosion with Cathodic Protection

Part A

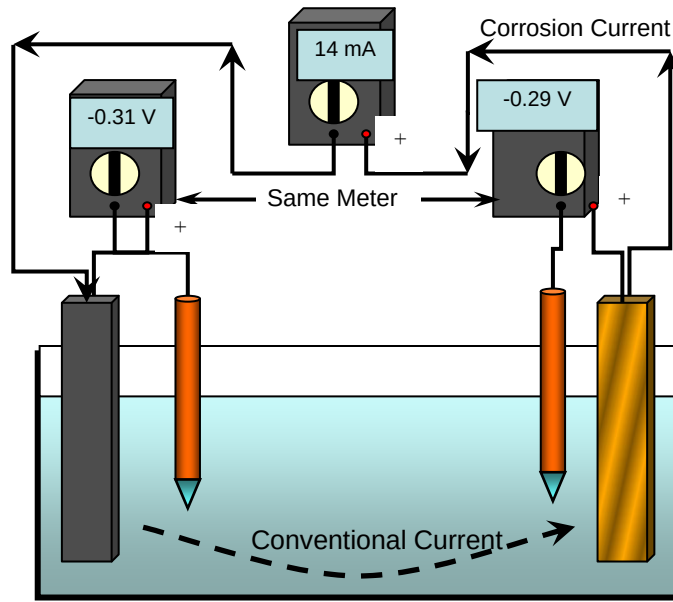
1. Insert steel and copper sheet in side of tray and 1-1/2 inches of fresh tap water.
2. Follow the following diagram.



3. Measure native potential of steel and copper.
4. Connect ammeter between copper and steel sheet and measure corrosion current (I_{corr}).
(A second meter from another kit can be used to obtain current flow (amperes) or a single meter can be relocated to obtain the information as shown.)

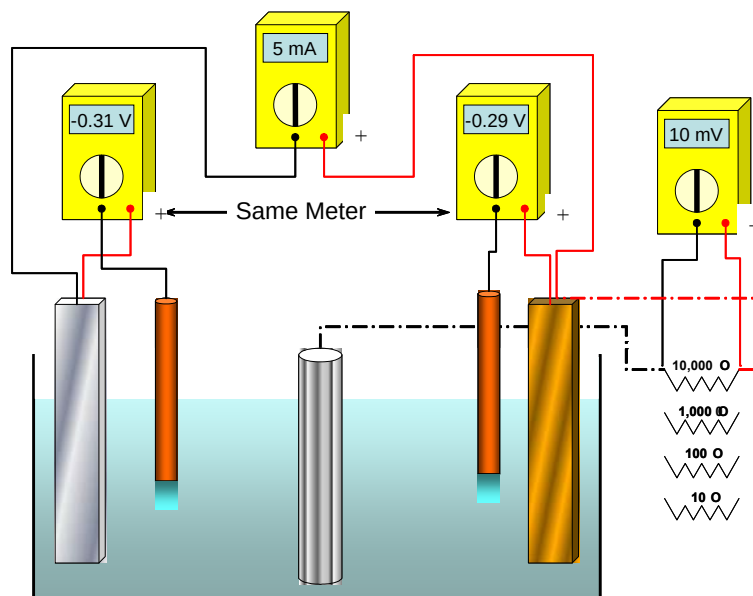


5. Measure polarized potentials of steel and copper.



Part B

1. Place magnesium anode in tray and connect to the copper sheet through a 10,000-ohm resistor.
2. Measure corrosion current (I_{corr}).
3. Determine the cathodic protection current ($I_{\text{c,p}}$) by calculating it from the voltage drop across the variable resistance.
4. Measure polarized potentials of steel and copper.



Part C

1. Repeat Part B using 100-ohm and 10-ohm resistors.

RESULTS

Circuit Conditions	E_{steel}	E_{copper}	Corrosion Current I_{corr} (mA)	CP Voltage Drop (V_r) Resistor	Calculated I_{cp}
Native (OC) (open circuit)			N/A	N/A	N/A
Polarized (Cu + Fe connected)				N/A	N/A
10,000 ohms					
1,000 ohms					
100 ohms					
10 ohms					

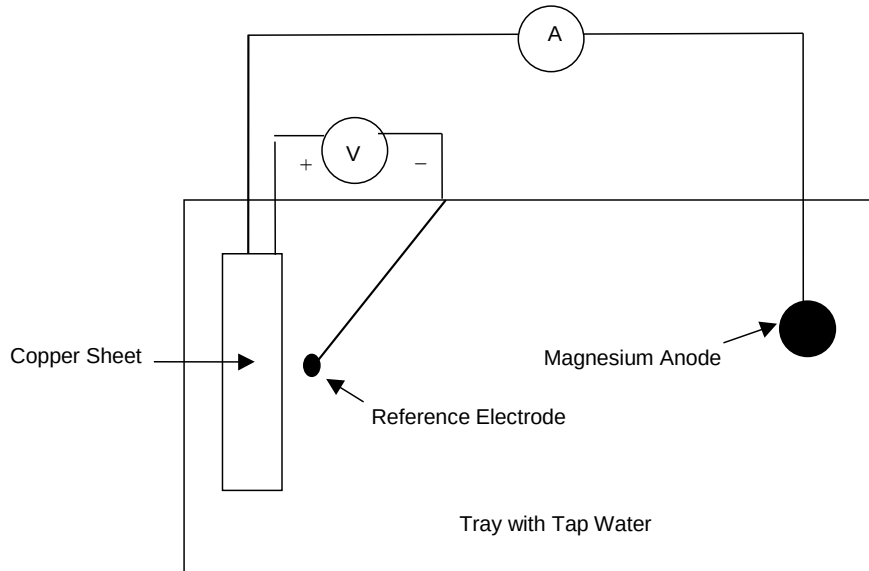
CONCLUSIONS

1. Corrosion current decreases as cathodic protection current increases.
2. Corrosion current decreases as polarized potential of cathode is made more electronegative.

Experiment 3.2 Demonstrate Change in Polarized Potential with Time

NOTE: Instructor will demonstrate this experiment.

PROCEDURE



Experiment to Demonstrate Change in Polarized Potential with Time

Part A

1. Place copper sheet in one end of tray and magnesium anode in opposite end.
2. Add 1-1/2 inches of tap water to the tray.
3. Connect anode to copper sheet as shown and measure initial cathodic protection current and polarized potential of the structure. (A second meter from another kit can be used to obtain current flow (amperes) or a single meter can be relocated to obtain the information.)

Part B

1. Re-measure the polarized potential of the structure at intervals until relatively stable.

Part C

1. Leave overnight.
2. Measure pH.
3. Disconnect anode and take depolarized readings.

RESULTS

Time	E_{copper} Cathodic Protection (mV)	Current (mA)
Instant of connection		

CONCLUSIONS

1. Polarized potential of the structure shifts electronegatively with time.
2. Cathodic protection current decreases with time.

Introduction

“Safety” is for your protection and that of your fellow worker. Although your company may take every precaution to keep you safe, your observations and actions on location will be the final determination as to whether you or someone else may be injured or killed. Safety may take some extra time but it cannot be compromised and must always be uppermost in your mind as you go about your work. No worker is required to work in unsafe conditions.

Some typical hazards that are encountered in cathodic protection testing or inspection are listed below. After a specific hazard assessment is completed for a particular job, the appropriate preventative measures must be determined to reduce higher risk and hazard exposure. This can be addressed by completing a Job Safety Analysis (JSA) that identifies each hazard and the preventative measures for each step of the project. The preventative measures are then incorporated into the job work procedure.

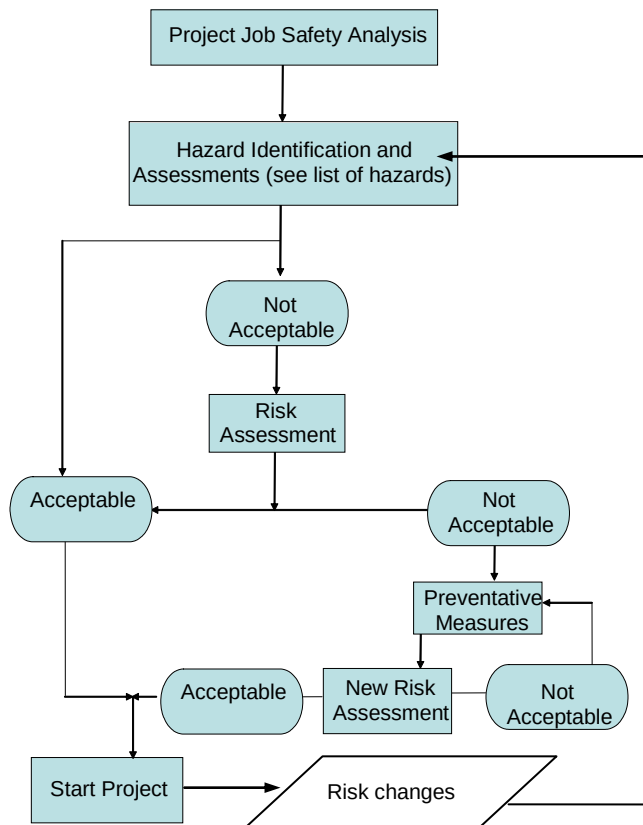


Figure 4.1 Safety Analysis Prior to Commencing Project

Some hazards that need to be considered include:

- Travel
 - Automobile or truck (highway or secondary roads)
 - All terrain vehicles (ATV)
 - Airplane
 - Helicopter
 - Boat
- Electrical
 - Rectifiers
 - Hazardous AC voltage on structures
- Environment
 - Atmospheric such as acid gases, H₂S
 - Soil and water pollutants
- Hazardous Materials
 - MSDS
- Trenches
 - Sloped or shored
- Reptiles, animals or insects
- Working at heights
 - Over land
 - Over water
- Working underwater
- Specific hazard(s) related to a project.

This is not intended to cover a complete safety program. The following safety hazards are those specifically related to cathodic protection and are not always in a standard safety program.

Electrical

Cathodic protection testers and technicians can become complacent with electricity as in many cases the voltage being measured is very low with a low source of energy. This is not the case when working on electrical equipment such as rectifiers and associated electrical equipment or structures in the vicinity of AC power lines.

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Electrical Equipment (Rectifiers)

Electrical Equipment (Rectifier) Case

Always assume that the electrical equipment or rectifier case may be poorly grounded and is inadvertently energized. This has happened! Before touching the case, either measure a case-to-ground voltage or use an instrument that detects AC voltage by a light that comes on when placed in close proximity. Do not touch the rectifier case while testing or in the first test do not extend your arms to bridge between the case and the ground probe. The case-to-ground voltage should be virtually 0 Volts_{AC}.

Remember it is the current through your body that kills. The values of current vary between the person and the length of exposure. The threshold of perception is generally agreed to be 1 mA. A current of 9 to 25 mA can cause lack of muscular control (let-go current) that makes it impossible to release and in fact it may cause the muscles to tighten¹. Research indicates the maximum safe current between an arm and a leg is 100 mA at 3 seconds². At a greater current, death may occur due to ventricular fibrillation of the heart.

Example:

If a person's resistance is 1000 Ω and contact is made with 120 V_{AC} then, using Ohm's Law ($I=E/R$), the current through the body is 120 mA, likely enough to be fatal. Note that rectifiers may be serviced with 240 V_{AC}, 480 V_{AC} or up to 600 Volts_{AC} thus the body current would increase proportionally.

Cathodic Protection (CP) Rectifiers

- CP rectifiers have exposed electrical AC and DC terminals on the panel of the rectifier. The voltage exposure varies with the rectifier rating and design. Do not make body contact with any electrical terminal when the rectifier is energized and protect yourself from this hazard.
- Take measurements with insulated meter probes intended for that purpose using a one-hand method while avoiding contact to the probe end. Never press a probe end and a terminal or wire between your fingers to make a contact.

¹ IEEE Std. 80, IEEE Guide for Safety in Substation Grounding, Institute of Electrical and Electronics Engineers

² L.P. Ferris, B.G. King, P.W. Spence, H.B. Williams, Effect of Electric Shock on the Heart, AIEE Trans., Vol. 55, pages 468-515 & 1263 May 1936 and IEEE Std 80.



- Turning off the circuit breaker in the rectifier will render the front of the panel safe but will not make the back or inside of the rectifier safe!
- The AC disconnect outside the rectifier must be OFF (locked out/tagged out) before the entire rectifier is safe to work on.
- Confirm that the AC power is off by testing as breaker contacts can fuse together thus making contact in the tripped position.
- Lock out and tag the rectifier breaker or AC disconnect after turning OFF when installing an interrupter, changing taps, replacing components, or installing and removing the rectifier. This is a good habit to form and is required by code in many areas.
- There is no testing that is required behind the panel with the rectifier energized with the exception of measuring the input AC supply voltage. This AC voltage measurement is only to be completed by persons properly trained and is only to be measured if the terminals are readily accessible at the side of the rectifier. Remember that even with the rectifier breaker OFF, AC line voltage still exists up to the rectifier circuit breaker.
- Remember to turn OFF, lock out and tag the AC disconnect when working on or removing rectifier components. No one else can then inadvertently turn the AC on before it is safe.

Lock Out / Tag Out

A lock out / tag out (LOTO) is intended to ensure that the power can not be turned on inadvertently while people are still working on the equipment. In addition it instills a safe work habit. As an example seat belts in vehicles were felt a nuisance at first but now one feels uneasy if it is not on when the vehicle is in motion. The same applies to a LOTO where if it becomes a habit to follow this procedure, you will feel uneasy if it is not in place making you more aware of the hazard.

In many jurisdictions it is required by regulation. There are some common rules that apply:

- The person that installs the LOTO must be the one to take it off
- If there is more than one person working on the equipment, then a group scissor-type lock is to be installed with each person's lock on it (Figure 5.1).
- The tag identifies the person, contact information, date and the equipment being locked out.

- The equipment is not to be re-energized until it has been inspected to make certain it is safe and all locks have been removed by the owner of the lock.



Figure 5.1 Group Scissor Lock Out / Tag Out (LOTO)

All cathodic protection personnel should carry a LOTO kit with them when in the field if they plan to work on rectifiers.

Electrical Hazardous Areas

Where there is a possibility of an explosive mixture of a hydrocarbon, the affected area will be designated as “hazardous” and electrical equipment must be contained in a sealed hazardous junction box. The CP technician must determine if he/she is qualified to work on electrical equipment in a hazardous area. Before electrical equipment is exposed in a hazardous area it must be turned off, locked out and tagged out to avoid the exposure of an arc that may act as a source of ignition.

Explosions or Ignitions

In addition to hazardous areas, many structures containing potentially explosive or combustible substances are cathodically protected. Under certain circumstances a cathodic protection system may have sufficient energy to ignite a combustible material or cause an explosion.

Whenever a current-carrying conductor is separated, depending upon the characteristics of the circuit, a spark may be generated. For example, a high-energy spark can occur on a cathodically protected pipeline carrying current back to the rectifier if the pipeline is cut or separated at a fitting. If a combustible atmosphere is present, an explosion can occur. To avoid this situation, an electrical bond must be temporarily installed around the location where a pipe section is to be cut or a flange is to be disconnected.

Another situation where a high-energy spark may be generated is when a cathodically protected structure is inadvertently or purposefully electrically connected to another metallic structure. At the moment the connection is made, a spark may occur. For example when a ship or barge containing a combustible material docks at a cathodically protected dock, the barge and the dock will usually make electrical contact through metallic hawsers or other components. To avoid a potentially disastrous situation, standard practice involves bonding the dock and the barge using two bonding wires prior to opening any hatch on the barge. Using this technique, if a spark occurs, it occurs at the location where the bond is attached and prior to release of any potentially explosive vapors. Another precaution is to turn off the cathodic protection rectifier(s) until the vessel is securely bonded to the dock.

Finally, any cathodic protection component that might generate an ignition spark should not be allowed within specific areas where explosive atmospheres may exist. Examples are within dikes around tanks containing combustible materials, facilities housing or encompassing propane, natural gas or combustible product pipeline components, gas or oil production platforms, etc.

Standard rectifiers and many types of lightning arresters are potential ignition sources. In special situations where a rectifier must be installed in an area where explosive atmospheres could exist, an oil-immersed rectifier with explosion-proof fittings, switches, and components must be employed. Care should be exercised to ensure that the explosion-proof design of the equipment meets the classification of the area and that the design is not defeated by improper installation.

Cathodic Protection Surveys

There is always a possibility of encountering hazardous potentials while conducting cathodic protection measurements. A number of precautions are suggested:



- Assume that the potential to be measured may be hazardous. Do not contact a measurement circuit until the potential is determined to be safe.
- If AC may be present, measure AC voltage first.
- Avoid measurements during thunderstorms since hazardous voltages may occur on structures as a result of even remote lightning strikes.
- Use caution when working near power transmission lines or, when measuring across isolating devices and polarization cells, use one-hand connection method with insulated test leads and clips.
- Consider the possible shock hazards from operating CP systems in water.

Induced AC Voltages

In cases where a structure or tracer wires parallel a high voltage AC (HVAC) power transmission circuit, significant AC potentials may be encountered. Hazardous AC potentials can occur on a structure as a result of induction, ground return currents, or faulted power circuits.

The AC voltage-to-ground of a structure should always be measured first if there is a possibility of hazardous potentials. Be careful not to make direct physical contact with the measurement circuit. Use a multimeter to measure AC potentials between the structure and a copper-copper sulfate reference electrode in contact with the earth or other low resistance ground. If an AC voltage in excess of 15 V is measured, the structure is considered hazardous; and steps must be undertaken to reduce the hazardous voltage level. If the potentials are determined to be less than 15 V_{ac}, no specific action is necessary; however, caution should be maintained as this voltage can change at any time with a change in power line load.

NACE SP0177, *Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems*, contains valuable AC safety information. You should become thoroughly familiar with this document especially Section 5, "Personnel Protection." NACE SP0177 is included in the Appendices section of the course manual.

A pipeline paralleling an HVAC transmission line can reach dangerous AC voltages when it is welded together on skids, but not backfilled. Special



safety precautions must be taken when working around such lines. The safety precautions may include temporary electrical grounding of the pipe, avoiding physical contact with the pipe and other grounded structures and avoiding physical contact across electrically isolating joints. Safety precautions are given in the NACE International slide show entitled "Some Safety Considerations During Construction Near Power Lines."

Always measure the AC voltage-to-ground voltage first before the DC structure-to-electrolyte potential or before touching the structure when in the vicinity of a power line.

Excavations

CP personnel often need to enter excavations. There are regulations on the back sloping requirements for different soil conditions in every jurisdiction otherwise shoring is required. A ready means of exiting the excavation must be in place (ladders). Backfill and materials must be kept back a meter or more from the edge of the excavation if not secured. Water is to be kept from entering the excavation.

A safety person is to be on the surface while the worker is in the excavation and must remain there until the worker comes out. No worker is required to work in conditions unsafe and can refuse to enter. Be aware that a person need not be completely buried to suffocate or have the heart receive a fatal shock.

Hazardous Material

During your work, you may encounter hazardous materials such as those listed below. Do not handle these materials unless you have the proper training or certification. These materials include the following:

- Solvents
- Acids used for cleaning metals
- Caustics used in polarization cells
- Chemicals used in reference electrodes.



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Material Safety Data Sheets (MSDS)

Material safety data sheets (MSDS) are available for every chemical and many pieces of equipment. These sheets provide information about the hazards associated with chemicals, dust, corrosion products, etc., and provides valuable information for first aid or medical personnel. Among products for which safety information is available are:

- Copper sulfate
- Impressed current and galvanic anodes
- Metallurgical and petroleum carbon backfill.

MSDS sheets must be available for review.

- As required by law, always have MSDS sheets readily available for any chemicals that may be used.
- Know, understand, and follow the information and procedures given.

Reaction Products

In an operating cathodic protection system a number of gases may be generated either at the anode surface or at the cathode surface. Among possible gases that may be encountered are oxygen, chlorine, carbon dioxide, carbon monoxide, and hydrogen. Some gases are potentially explosive. Asphyxiation can occur due to the displacement of oxygen by some of the other gases listed. Some gases are toxic when inhaled. Low pH (acid) environments can exist around anodes in deep groundbeds.

Due to the potential problems mentioned, caution should be exercised to avoid situations where gases generated by a cathodic protection system might be allowed to collect.

Other General Precautions

Other precautions not discussed above that must be considered include:

- Wear protective eyewear, gloves, shoes and other clothing.
- Avoid open flames.



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- Avoid causing electric sparks especially in areas that may contain a hydrocarbon.
- Know the handling/storage procedures for chemicals or other hazardous materials or equipment.
- Working at heights.
- Animals, reptiles and insects
- Vehicles: Drive defensively and be aware of hazard situations that could occur

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Portable Reference Electrodes

Copper-Copper Sulfate Reference Electrode

The copper-copper sulfate reference electrode consists of a copper rod immersed in a saturated copper sulfate solution. They are most commonly used for measuring potential of underground structures (soil) and also for those exposed to fresh water.

Silver-Silver Chloride Reference Electrode

Silver-silver chloride (Ag-AgCl) reference electrodes are used for measurements in seawater. The Ag-AgCl electrode is also used in concrete structures.

Calomel Reference Electrode

The saturated calomel reference electrode consists of mercury-mercurous chloride in a saturated potassium chloride solution. This is primarily a laboratory electrode.

Standard Hydrogen Reference Electrode (SHE)

The standard hydrogen reference electrode (SHE) is a laboratory reference electrode and is used to determine the potential of other reference electrodes that are better suited for field use.

Zinc Reference Electrode

Zinc is sometimes used as a reference electrode since the potential of zinc is relatively stable. Zinc is actually a pseudo-reference electrode since the potential of zinc can change as the environment changes.

For underground use, the zinc electrode is packaged in a cloth bag containing the same backfill as used around zinc anodes. In water, zinc electrodes are used bare.

Manganese Dioxide

The manganese dioxide electrode is also used in reinforced concrete structures.

Graphite Electrode

Graphite is a pseudo-reference electrode that is sometimes used in reinforced concrete structures.

Comparison of Potential Values of Typical Reference Electrodes vs. Copper-Copper Sulfate Reference Electrode

Relative electrode values are shown in Table 5.1.

Table 5.1 Relative Values of Typical Reference Electrodes to Copper-Copper Sulfate Reference Electrode

Electrode (Half-Cell) *	Potential (Volt)
Copper-Copper Sulfate	0.000
Silver-Silver Chloride (saturated)	−0.050
Saturated Calomel	−0.070
Hydrogen (SHE)	−0.320
Zinc	−1.100

**Electrode used under standard conditions (from SP0169)*

Stationary reference electrodes

A stationary copper-copper sulfate reference electrode is used for installation underground. These electrodes are used to reduce IR drop in potential measurements at inaccessible locations. Figure 5.1 shows a stationary CSE unit.

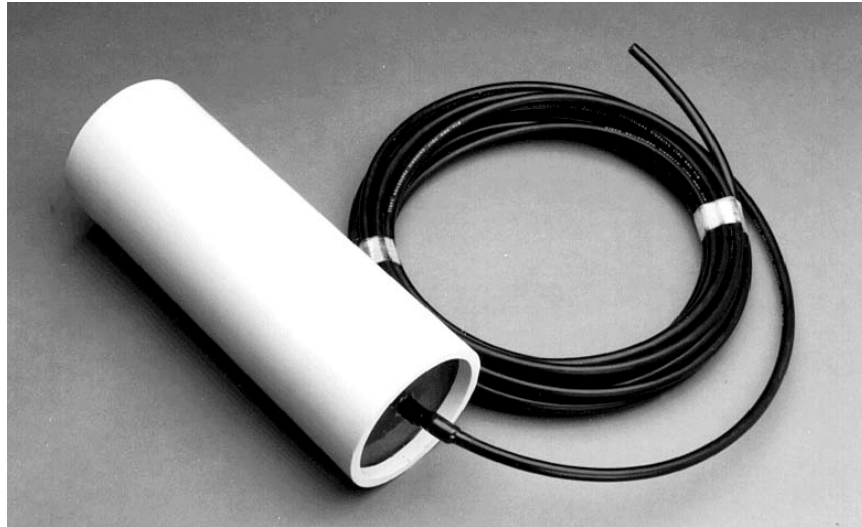


Figure 5.1 Stationary Reference Electrode

Stationary reference electrodes containing both zinc and Ag-AgCl units are used on offshore structures.

For oil heater-treaters, heat exchanger water boxes, and other vessels, reference electrodes can be installed through the vessel wall at strategic locations.

Similarly, embedded reference electrodes are installed in reinforced concrete structures. Various types of electrodes are used for this purpose.

Typical Applications

Structure-to-Electrolyte Potential

Basis of Measurement

A structure-to-electrolyte potential commonly is referred to as a structure-to-electrolyte or structure-to-soil potential. The definition of a structure-to-electrolyte potential is:

“The potential difference between the metallic surface of the structure and electrolyte that is measured with reference to an electrode in contact with the electrolyte.”

A structure-to-soil potential is a parallel measurement. The external circuit of this measurement is high, so a high-input resistance voltmeter is required for accurate measurement.

Location of reference electrode

To minimize the IR drop in the electrolyte, the reference electrode should be positioned as near to the structure as possible. When dealing with underground piping or tanks, the proper position of the electrode is over the center of the structure. There are times, however, when the electrode is purposely placed at some distance from the structure; this is discussed later under the section “Surface Potential Survey” and under “Remote Earth Determination”.

In water storage tanks, the electrode should be positioned as close to the wall of the tank as possible. The same is true for waterfront and offshore structures; the electrode should be as close to the piling as possible. In moving water, the electrode may swing about, so some structures are equipped with guide wires or perforated plastic ducts to restrict the movement of a portable electrode. (See Figure 5.2)



Figure 5.2 Reference Cell at Rim of AST

For on-grade storage tanks, data are frequently taken around the periphery of the tank. This may not yield accurate data about the potentials under the tank bottom, particularly if the anodes are in a ring around the tank. Stationary reference electrodes under the tank bottom yield the best data. (See Figure 5.3)

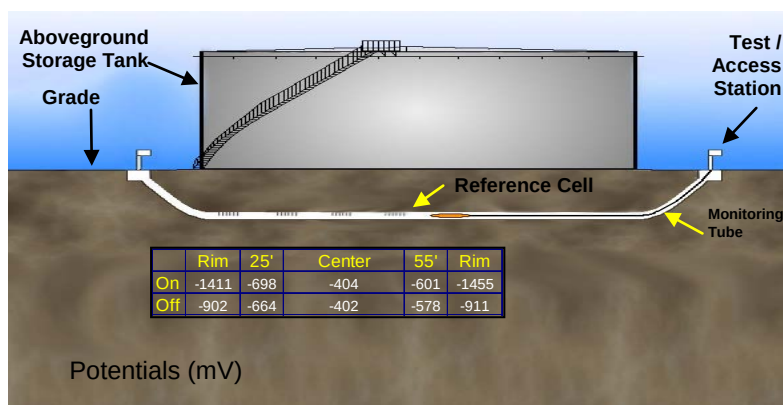


Figure 5.3 Reference Cell under AST

Close Interval Potential Survey

A series of structure-to-electrolyte potentials measured over the top of a pipeline may be helpful in determining variations in cathodic protection levels. A potential profile is performed to determine if adequate cathodic protection is achieved at all points along the structure. Figure 5.4 illustrates a pipe-to-soil potential profile. Note that the copper-copper sulfate reference electrode (half-cell or reference cell) is connected to the negative terminal of the meter.

In a close interval survey, the pipe-to-soil potential data are collected on a continuous basis. This is usually done by carrying a datalogger and wire-dispensing device equipped with distance measuring capability. Two reference electrodes, mounted at the end of short poles, are used, one in each hand. The wire is attached to a test station and the operator walks over the pipeline, making contact between the electrodes and the earth at closely spaced intervals. The operator records above grade appurtenances and other identifying items along the way so the location of the data can be pinpointed. Upon completion of the survey, the data are downloaded into a computer and often printed in graph form.

The survey is made over the line, so other personnel are assigned to locate and stake the line and provide other assistance.

When testing multiple pipelines that are bonded together, the survey data may represent an average of all the pipelines.

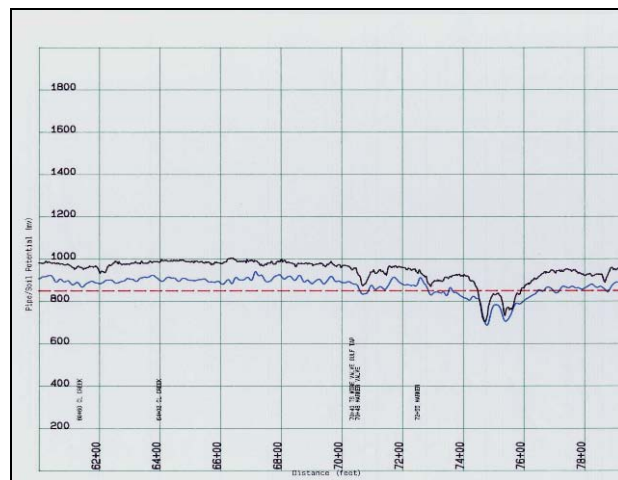
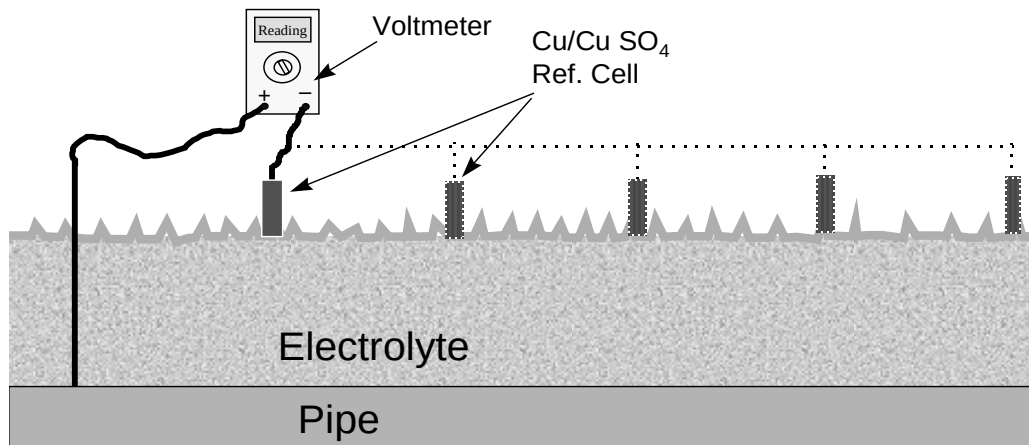


Figure 5.4 Pipe-to-Soil Potential Profile

Earth current flow and surface potential measurements

A series of potentials measured between two reference electrodes can indicate current flow and its direction in the earth, as shown in Figure 5.5. This type of measurement is sometimes used to determine if current is flowing toward or away from a structure. Direction of current flow is from the positive electrode to the negative electrode.

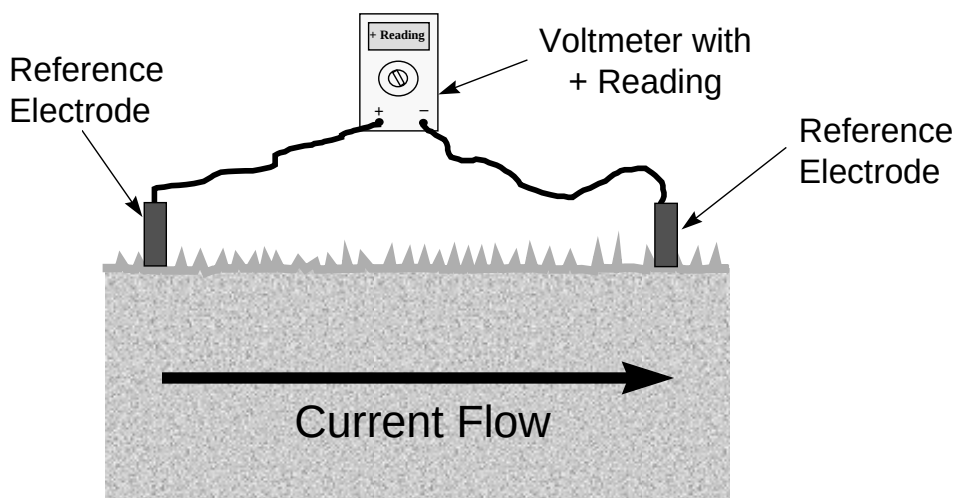


Figure 5.5 Potential Measurement Between Two Reference Electrodes

Voltage (IR) Drop in Potential Data

Accuracy of data is one of your most important responsibilities. Without accurate data, those responsible for your company's corrosion control program will not know how well the structures are protected.

Knowledge of voltage drops in the potential measuring in the potential circuit is critical to obtaining accurate data.

Recording Voltmeters

Recording voltmeters are used when a permanent record of data in graph form is desired or where it is desired to record voltage over a period of time. They are also used in stray current areas where voltages may fluctuate. The fluctuations are easily discernible on the chart. Recording voltmeters may display data on charts or may record data for later computer printout.

Data Loggers

Data loggers are computerized instruments by which data is taken by an integrated meter such as a voltmeter and the reading is then stored into a memory. “Alpha” characters can also be entered and saved into memory to identify the data recorded such as location, date and time in addition to overall survey information. Data loggers can be programmed to measure and save data on command or routinely over a period of time. Some of them are so small they can fit into a ground level test station. After use, data loggers are connected to a computer and the information is downloaded. The computer can also create graphs of data. Figure 5.6 shows a photo of a data logger.



Figure 5.6 Data Logger

X-Y Plotters

These instruments have two pens that record data on the X (horizontal) axis and the Y (vertical) axis. They are very useful in stray current areas where voltages are constantly varying. They are often used to make correlation curves between rail-to-pipe voltage and pipe-to-soil potentials in mass transit stray current work.

Strip Chart Recorders

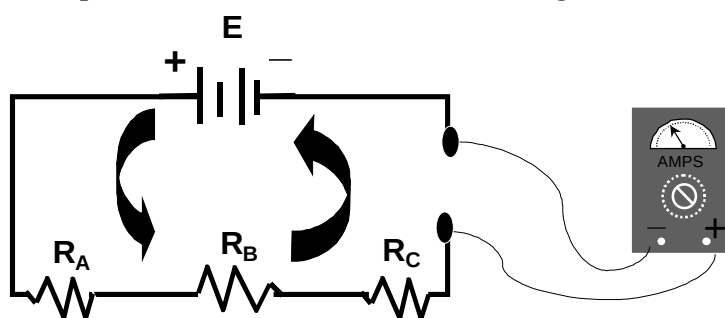
Strip chart recorders contain a roll of chart paper. A pen or stylus records voltage as the chart moves.

Measuring Current

One of three methods—an ammeter, a clamp on ammeter, or a current shunt can be used to obtain a current measurement.

Use of an Ammeter

When measuring current flow in an electrical circuit, the ammeter is connected in series with the circuit. A series connection is made when the circuit is broken and current flow of the external circuit must go through the meter to complete the circuit as illustrated in Figure 5.7.



Series Connection

Figure 5.7 Ammeter Connection

There are a wide variety of ammeters available today. The most important requirement of an ammeter for cathodic protection surveys is its internal resistance. The internal resistance of an ammeter should be low to prevent adding resistance to the external circuit, thus reducing the current of the external circuit. **Caution:** because of this low internal resistance, it is important not to set your multimeter on the ammeter when attempting to measure voltage. This can blow a fuse or damage the meter.

In practice, even the low internal resistance of an ammeter will affect current flow in a galvanic anode system. Therefore, current shunts are usually installed in the permanent circuit of a galvanic anode system (not in anodes connected directly to the structure, however). In fact, due to accuracy current shunts are favored over using an ammeter in most cases.

A current measurement using an ammeter requires more caution than voltage because the circuit has to be broken. Power of the external circuit should be de-energized before breaking the circuit and inserting an ammeter. If a circuit is broken with current flow and your hands act as the connectors, then your heart acts as a shunt for the external current flow. Work safely!

Current Direction and Polarity

If an ammeter is connected into an external circuit such that external current flow goes into the positive terminal of the meter, then the display is positive. If the display shows a negative sign, current is flowing into the negative terminal. Since the direction of current flow in cathodic protection work is as important as the magnitude, you should anticipate the direction of the current before connecting the meter into the circuit. Figure 5.8 depicts direction of current flow in an ammeter measurement. Current is flowing from the anode, through the soil, to the pipe, and then through the meter, back to the anode. Note that the current is entering the meter on the positive terminal, hence the positive reading on the meter display.

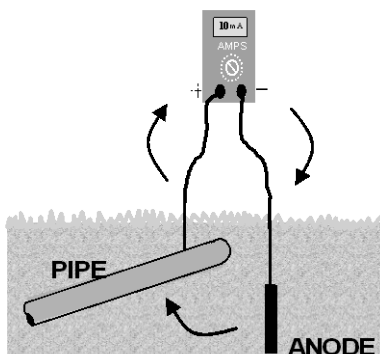


Figure 5.8 Direction of Current Flow in an Ammeter Measurement

Clamp-On Ammeters

The second method of measuring current is with a clamp-on ammeter, (See Figure 5.9). This device clamps around the metallic path through which the current is flowing and measures the magnetic field created by the current. Clamp-on instruments are available to measure both AC and DC.

Spring loaded clamp-on ammeters are more commonly used for wires and cables.



Figure 5.9 Clamp-On Ammeter

Clamp-on DC ammeters are available for pipes using special sensing hoops.

Shunts

This is the third method of measuring current. In using a shunt, you measure a voltage drop across a known resistance and calculate the current.

General

In practice, even the low internal resistance of an ammeter will affect current flow in a galvanic anode system. Therefore, current shunts are usually installed in the permanent circuit of a galvanic anode system, although not in distributed anodes connected directly to the structure. In fact, current shunts are favored over using an ammeter in most cases.

A current shunt is installed in series with the circuit the same as the ammeter. Current is obtained by measuring voltage across the current shunt and calculating current using Ohm's Law. Figure 5.10 illustrates a shunt measurement.

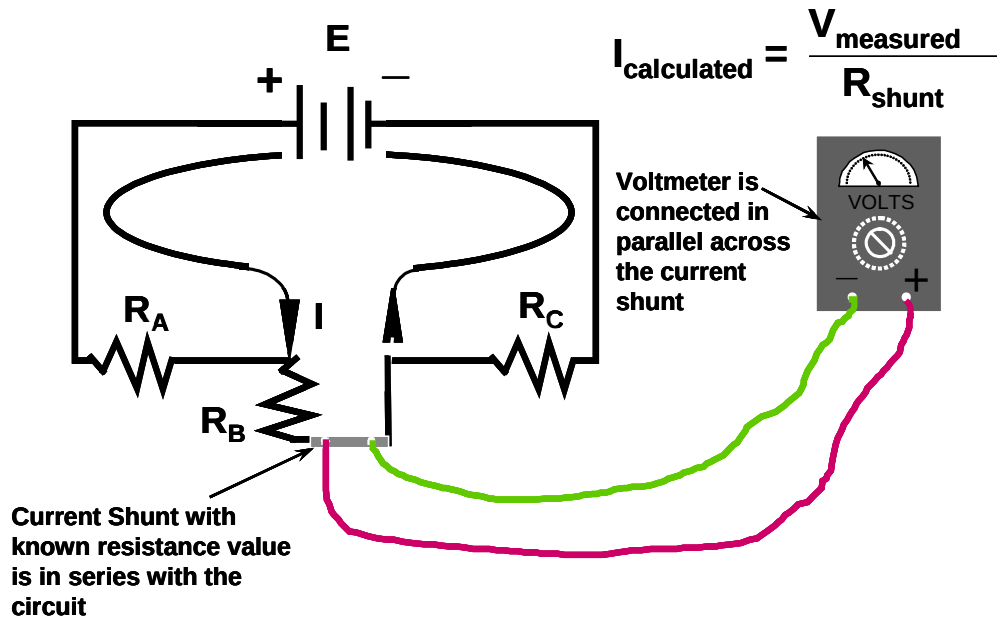


Figure 5.10 Shunt Measurement

Current Calculation

The resistance value of a current shunt may be given in ohms or amps/millivolts. If the resistance unit is ohms, use Ohm's Law, but do not forget to perform any conversion that may be necessary to maintain the units of the law (amps and volts or milliamps and millivolts).

For example:

Given:

Shunt = 0.01Ω

Voltage across shunt = 50 mV

Calculate Current:

1. Convert units of voltage: 50 mV = .05 V
2. Calculate current using Ohm's Law $I = .05 \text{ V} / .01 \Omega = 5 \text{ A}$

If in the above example we wished to estimate the voltage drop for a known current, we would again apply Ohm's Law. To estimate the voltage drop for a current of 5 amps, simply solve Ohm's Law for voltage.

$$E = I \times R = 5 \text{ A} \times 0.01 \Omega = 0.05 \text{ V} = 50 \text{ mV}$$

An easier method for calculating current is to determine the amps/millivolt rating of the shunt. There are two values associated with the shunt, one in amps and the other in millivolts. Except for wire-type shunts, most shunts will have these values stamped on them. You can determine the amps/millivolt rating by dividing the amp value by the millivolt value. This calculation tells you how many amps are flowing per millivolt measured across the shunt. After you measure the millivolt drop across the shunt, multiply the millivolt drop by the amps/millivolt rating. This will give you the current flow through the shunt in amps.

For example,

Given:

Shunt data: 15 A/50 mV

Measured voltage drop: 28 mV

Determine shunt rating:

Rating = $15\text{A}/50\text{ mV} = 0.3\text{ A/mV}$

Calculate current:

Current = $0.3\text{ A/mV} \times 28\text{ mV} = 8.4\text{ A}$

For shunts that you test regularly, writing the amps/millivolt rating on the shunt will speed up your work considerably when taking data. You need only to multiply the rating by the millivolt drop to obtain the current.

Direction of Current Flow

You not only need to know the amount of current flowing through the shunt, but you also need to determine the direction of flow. This is done in the same manner as with voltmeters. Remember that when current enters the meter on the positive terminal, you will get a positive indication on a digital meter, and on an analog meter the needle will swing to the right. Remember also that the voltmeter is connected in parallel with the shunt. Consequently, the direction of current flow through the meter will be the same as that through the shunt.

Referring back to Figure 5.10, note that the positive lead from the meter is connected to the left terminal of the shunt and the negative lead to the right terminal. The figure shows an analog meter and note that the needle has swung to the right from the left hand zero position. This indicates that current flow is from left to right through the shunt.

Note also the battery and the direction of current flow around the circuit. Current is leaving the positive terminal of the battery and proceeding counter-clockwise around the circuit. Consequently, the current is flowing from left to right through the shunt.

Various types of shunts and their values are shown in Table 5.2. The shunt rating shown in the table is in amperes/millivolt.

Table 5.2 Shunt Types and Values

	Shunt Rating		Shunt Resistance	Shunt Factor
	Amps	mV	Ohms	A/mV
Holloway Type				
RS	5	50	.01	.1
SS	25	25	.001	1
SO	50	50	.001	1
SW or CP	1	50	.05	.02
SW or CP	2	50	.025	.04
SW or CP	3	50	.017	.06
SW or CP	4	50	.0125	.08
SW or CP	5	50	.01	.1
SW or CP	10	50	.005	.2
SW	15	50	.0033	.3
SW	20	50	.0025	.4
SW	25	50	.002	.5
SW	30	50	.0017	.6
SW	50	50	.001	1
SW	60	50	.0008	1.2
SW	75	50	0.00067	1.5
SW	100	50	.0005	2
J.B. Type				
Agra-Mesa	5	50	.01	.1
Cott or MCM				
Red (MCM)	2	200	.1	.01
Red (Cott)	.5	50	.1	.01
Yellow (MCM)	8	80	.01	.1
Orange (MCM)	25	25	.001	1

Typical Applications

There are several current measurements commonly made in cathodic protection surveys:

- Current output of a galvanic anode system
- Rectifier current output
- Test current for determining current requirement of a structure
- Current flow on a structure (this is a voltage measurement, and current is calculated)
- Current flow across a bond

Galvanic Anode Output

An ammeter can be inserted directly into the galvanic anode circuit. This is not difficult in a test station head where the anode and structure wires are connected by a shorting strap. In many test stations, however, the connection is made with a split bolt connector and then taped. Opening this connection takes time, and after testing, the connection must be made again.

As mentioned earlier, even the low resistance of the ammeter can cause the instrument to read a current lower than the actual anode output. Consequently, a shunt in the circuit is the preferred method of current measurement.

The voltmeter used for measuring current across the shunt in a galvanic anode installation needs to have a very low scale to measure small current outputs. Full scale deflections as low as 2 mV is sometimes necessary.

With a shunt in place, the measurement can be made without having to open the circuit. This not only saves time, but also yields a more accurate reading than that obtained with an ammeter.

Rectifier Current Output

Most rectifiers have a shunt on the panel. Usually the shunt rating data are stamped on the shunt. You can determine the rectifier current output by measuring the voltage drop across the shunt. The reading can then be compared with that shown on the rectifier ammeter. This serves as a check of the accuracy of the rectifier meter.

An ammeter can also be inserted into the rectifier circuit. Many rectifiers have large outputs, however, so it is necessary to be certain you have an ammeter capable of handling the current. There is also a safety hazard in working with higher currents. If you do test the output this way, be certain the rectifier is turned off when the circuit is opened and when it is closed again.

Current Requirement Tests

You may be asked to assist in making current requirement tests. In these tests, a current is impressed on a structure to be protected and the potential changes brought about by that current are measured. From the data, the amount of current required for protection can be determined.

The current in the test circuit can be determined by inserting an ammeter into the circuit or by the use of a shunt. Here again, if an ammeter is used, it must have sufficient capacity to handle the test current.

Current Flow on a Pipeline or Cable

A length of pipeline, cable, or similar long, thin metal structure can serve as a shunt. Line current measurement is useful in determining the distribution of current along a cathodically protected structure, solving stray current problems, and in locating areas of poor coating or perhaps a short.

In this section we will explore two techniques for determining current flow along such a structure:

- 2-wire test points
- 4-wire test points

Connections to the structure should be made by permanent test wires; probe rods are sometimes used on bare or poorly coated piping.

2-wire Line Current Test

Where 2-wire test points span a known length of a structure such as a pipeline and the diameter and wall thickness or the weight per foot are known, current flow across the span can be calculated. This is done by measuring the voltage drop across the span, determining the resistance of the span from a pipe table, and using Ohm's Law as you would with a shunt. Figure 5.11 shows the test setup. Table 5.3 provides some resistance values for common pipe sizes.

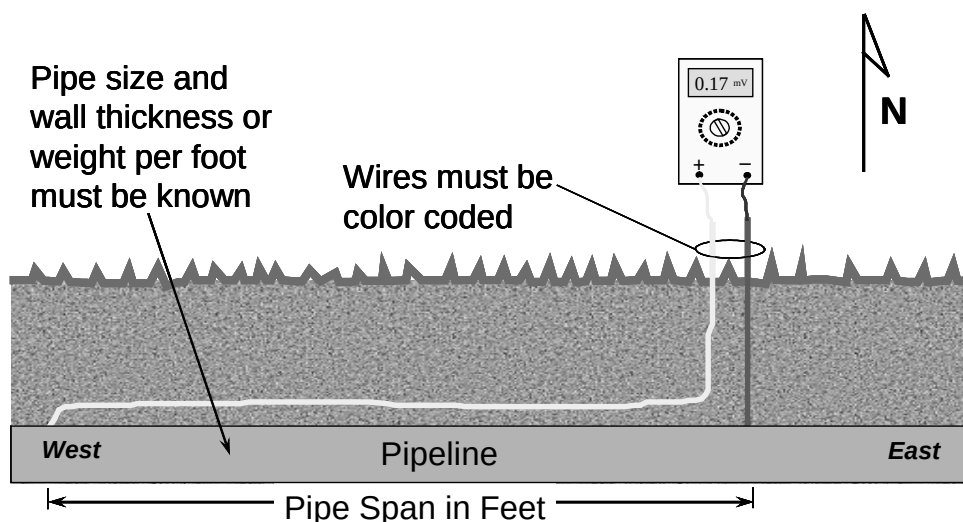


Figure 5.11 2-wire Line Current Test

Because the voltage drop across a pipe span is relatively small, with earlier instruments it was necessary to correct for the voltage drop in the test leads caused by the current drawn by the meter. However, with the high-input resistance meters available today, this correction is not necessary.

Using a high-input impedance meter, the procedure involves simply measuring the voltage drop between the test leads. For example, if the voltage drop across a 200-ft span of 30-in. (76.2 cm) pipe weighing 118.7 lbs./ft (176.65 kg/m) is 0.00017 V, then current flow is calculated as follows:

$$\begin{aligned}\text{Pipe resistance/ft} &= 2.44 \mu\Omega / \text{ft} \\ &= 0.00000244 \Omega / \text{ft}\end{aligned}$$

$$\begin{aligned}\text{Total resistance} &= 200 \text{ ft} \times 0.00000244 \Omega / \text{ft} \\ &= 0.000488 \Omega\end{aligned}$$

$$\text{Measured voltage drop} = 0.00017 \text{ V}$$

$$\begin{aligned}\text{Current (I)} &= E/R = 0.00017 \text{ V} / 0.000488 \Omega \\ &= 348 \text{ mA or } 0.348 \text{ A}\end{aligned}$$

Refer again to Figure 5.11. Note the meter is showing a positive indication. This means the current is entering the meter on the positive terminal. The positive terminal is connected to the west end of the span. Since the meter is in parallel with the span, current flow on the pipe is from west to east.

The accuracy of this test method depends greatly on accurate knowledge of the dimensions of the pipe. Should there be an odd-sized joint within the span, or some appurtenance such as a valve, the calculated resistance will not be correct. The 4-wire test method overcomes these difficulties.

Table 5.3 Table of Pipe Resistances**Steel Pipe Resistance*^(A)(B)**

Pipe Size in.	Outside Diameter		Wall Thickness		Weight		Resistance	
	in.	Cm	in.	cm	lb / ft	kg / m	μohms/ft	μohms/m
2	2.35	5.97	0.154	0.39	3.65	5.43	76.2	256.84
4	4.5	11.43	0.237	0.60	10.8	16.07	26.8	87.93
6	6.62	16.81	0.280	0.71	16.0	28.28	15.2	46.87
8	8.62	21.89	0.322	0.82	28.6	42.56	10.1	33.14
10	10.75	27.31	0.365	0.93	40.5	60.27	7.13	23.39
12	12.75	32.38	0.375	0.95	46.6	73.81	5.82	16.09
14	14.00	35.56	0.375	0.95	54.6	81.26	5.29	17.36
16	16.00	40.64	0.375	0.95	62.6	93.16	4.61	15.12
18	18.00	45.72	0.375	0.95	70.6	105.07	4.09	13.42
20	20.00	50.80	0.375	0.95	78.6	116.97	3.68	12.07
22	22.00	55.88	0.375	0.95	86.6	128.88	3.34	10.96
24	24.00	60.96	0.375	0.95	94.6	140.78	3.06	10.04
26	26.00	66.04	0.375	0.95	102.6	152.69	2.82	6.25
28	28.00	71.12	0.375	0.95	110.6	164.59	2.62	8.60
30	30.00	76.20	0.375	0.95	118.7	176.65	2.44	8.01
32	32.00	81.28	0.375	0.95	126.6	188.41	2.28	7.48
34	34.00	86.36	0.375	0.95	134.6	200.31	2.15	7.05
36	36.00	91.44	0.375	0.95	142.6	212.22	2.03	6.66

*Conversions: 1 in. = 2.54 cm

1 ft = 0.3048 m

(A) Based on steel density of 489 lbs/ft³ (7832 kg/m³) and steel resistivity of 18 microhm-cm.(B) $R = \frac{16.061}{\text{Weight per foot pipe, microhms}} \times \text{resistivity in microhm-cm} = \text{Resistance of 1 ft of}$

4-wire Line Current Test

A 4-wire current test station can be used to determine the line current even if the dimensions of the pipeline are unknown or there are anomalies within the test span. Figure 5.12 shows the set-up.

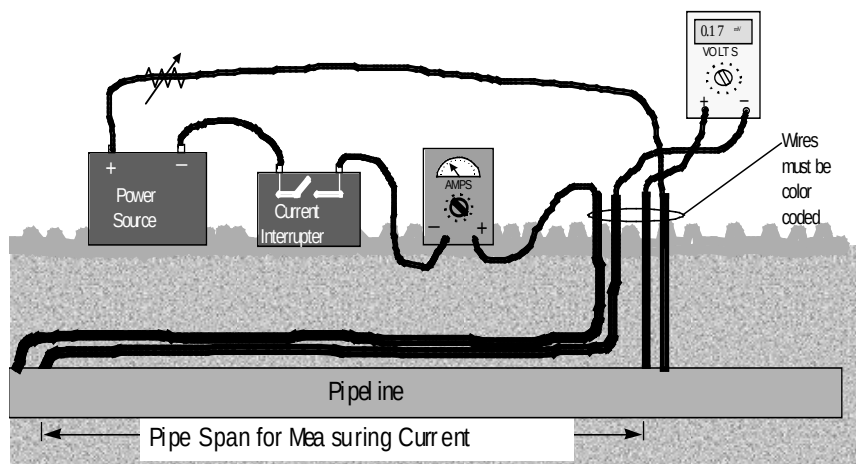


Figure 5.12 4-wire Line Current Test

The test procedure is as follows:

1. Calibrate the span by passing a known amount of battery current between the outside leads and measuring the change in voltage drop across the span (ΔE) using the inside leads. Divide the current flow in amperes (I) by the change in voltage drop in millivolts to express the calibration factor (K) in “amperes per millivolt.” The calibration factor is calculated as follows:

$$K = I / \Delta E = I / E \text{ with current applied} - E \text{ with no current applied}$$

Normally, if the pipeline operating temperature is stable, this can be done only once as the calibration factor may be recorded for subsequent tests at the same location. On pipelines where the temperature of the pipe changes considerably (with accompanying changes in resistance), more frequent calibration may be necessary.

2. Measure the voltage drop in millivolts across the measuring span (without the battery current) using the inside potential measurement leads. This voltage drop is due to normal pipeline current.
3. Calculate current flow by multiplying the calibration factor by the voltage drop measured above:

$$I (A) = K (A/mV) \times mV \text{ drop}$$

4. Note the sign of the voltage drop to determine the direction of current flow. If the voltage drop reading is positive, then the direction of current flow is from the positive to the negative terminal of the voltmeter. If the reading is negative, then the direction of current flow is from the negative to the positive terminal.

Based on Figure 5.12 if 10 A of battery current passes from the east to the west outside leads, resulting in voltage drop change (ΔE) of :

$$O_n = 5.08 \text{ mV}$$

$$O_{ff} = \underline{0.17} \text{ mV}$$

$$\Delta E = 4.91 \text{ mV}$$

Then the calibration factor will be:

$$K = \frac{10 \text{ A}}{4.91 \text{ mV}} \text{ or } \frac{10 \text{ A}}{5.08 - 0.17 \text{ mV}} = 2.04 \text{ A/mV}$$

Without test current applied, the voltage drop across the span between the inner leads is 0.17 mV. Therefore, current flow is:

$$I = K \times mV \text{ drop} = \frac{2.04 \text{ A} \times 0.17 \text{ mV}}{mV} = 0.347 \text{ A} = 347 \text{ mA}$$

Referring again to Figure 5.12, note that the positive lead of the digital meter is attached to the east inner lead. The meter indicates a positive display, showing that current is entering the meter on the positive terminal. Again, the meter is in parallel with the pipe span, so current flow on the pipe is from east to west.

Most digital meters will not read below 0.1 mV. If readings below 0.1 mV are anticipated, or if a zero reading is obtained during a test, a more sensitive meter must be used.

Bond Current

Resistance bonds (cables) are placed between structures to connect them for cathodic protection or to drain a stray current back to its source. Bonds usually have a shunt in them to permit measurement of the magnitude and direction of current flow. The procedure for reading these shunts is the same as discussed earlier in the section on “Shunts.”

Measuring Resistance

Typical Measurements

There are several types of resistance measurements made in corrosion control work. Among these are:

- across isolating fittings
- casing-to-pipe
- structure continuity
- structure-to-structure
- structure-to-anode
- structure-to-earth
- anode-to-earth.

In this course we will cover testing resistance across an isolating fitting and between a casing and a pipe. We will also cover measuring structure continuity and diode bias.

Measurements are made using Ohm's Law and sometimes by using an ohmmeter. These two methods are discussed below.

Using Ohm's Law

Using Ohm's Law is one of the best ways to determine resistance between structures buried or immersed in an electrolyte. This procedure has been discussed in relation to the 2-wire method of measuring current flow on a pipeline. It will be used again in measuring resistance across an isolating

fitting. Under this application, a known current and voltage are used and the resistance is calculated.

Using an Ohmmeter

An ohmmeter is the resistance meter in a multimeter. The meter determines resistance by providing a small current or voltage across an internal resistor and comparing its value to the external resistor. The test voltage of the meter is DC voltage and is suitable for metallic elements. This instrument is not suitable for electrochemical paths because the DC voltage causes polarization and a change in resistance.

Using an ohmmeter to check effectiveness of an isolation joint in service is not reliable because of the parallel resistance paths through the soil as illustrated in Figure 5.13.

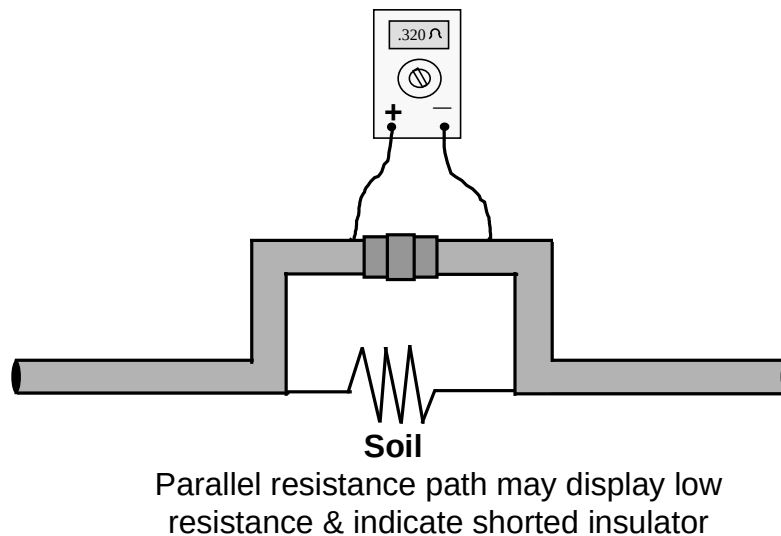


Figure 5.13 Isolation Joint Test Using an Ohmmeter

If an isolator is not in service and a parallel path does not exist, then an ohmmeter can be used for testing the fitting.

There are isolator checkers that are based on a high radio frequency and are more reliable for isolators in service.

Electrical Continuity

All parts of a structure receiving cathodic protection from a single source, galvanic anodes or impressed current, must have electrical (metal) continuity. Welded structures by nature of the fabrication have electrical continuity. If electrical continuity does not exist, bonds (cables) or some other means must be used to establish continuity.

Among items requiring bonds are:

- couplings and other compression fittings.
- screw joints
- bell and spigot joints
- lap joint flanges
- pile groups
- reinforcing steel in concrete.

Heat exchanger water boxes and tube sheets are often protected by anodes in the water box. The water box is connected to the exchanger shell through hinges and bolts. It is important that electrical continuity between the water box and the shell be maintained in order to protect the tube sheet.

Electrical Isolation

Purpose and Usage

The purpose of electrical isolation is to confine the protective current to the structure being protected. If, for example, a production well casing is being protected, and it is electrically connected to unprotected structures such as gathering or other pipe, building grounds, or other underground structures, some of the protective current will be lost to those structures. As another example, when galvanic anodes are used to protect well-coated piping or tanks, loss of current to other structures often means that the piping or tanks do not receive adequate current for protection.

Isolating fittings may also be used for stray current control. Isolation strategically placed in a piping network, for example, can increase the longitudinal resistance sufficiently to minimize the pick up of stray current.

In heat exchangers where the tube sheet is perhaps Monel metal and the water box is cast iron, it is often desirable to protect only the water box. This can be achieved by electrically isolating the water box from the shell.

There are times when it may not be desirable or even practical to isolate protected from unprotected structures. Examples are refineries, industrial plants, large tank farms, and similar complex facilities. There are many connections to the underground structures in such places and each would require a dielectric fitting. Maintenance of such a large number of fittings becomes prohibitive; also, one short circuit could cause loss of protection on a large number of structures.

Occasionally it is desirable to provide joint cathodic protection for a number of pipelines belonging to different companies, usually all running in the same right of way. In cases like this, the pipelines can be connected together and protected by a series of rectifiers, with each company assuming responsibility for a portion of the system.

Isolation (Insulating) Joints

Commercial fittings available for providing electrical isolation include:

- flanges
- couplings
- unions
- monolithic isolating pipe joints
- nonmetallic pipe and structural members
- swivels (meter sets).

Accidental Contacts

Some of the locations where electrical isolation can be compromised are:

- Crossing structures. Underground contacts made accidentally when one line crosses another. A good example is a copper water service line in contact with a steel gas line. Even though the gas line is coated, movement of the piping may eventually cause the copper line to wear through the coating and contact the steel.

- **Attachments.** Many attachments may be made to a protected structure. These include telemetering and other remote monitoring equipment, electrical valve operators, gauge lines, and the like. If these attachments bypass an isolating fitting, a short circuit will be created. You need to be alert for these attachments and other short circuits. If you find a structure that is not up to its protection criterion, a short circuit may be the cause. Watch for such shorts as you go about your daily routine.
- **Casings.** Casings need to be electrically isolated from carrier piping so as not to shield the carrier pipe from cathodic protection. A properly isolated casing is shown in Chapter 9. You may be called upon to assist in the installation of a casing. It is important that you help ensure proper isolation.
- **Grounds:** Additional problems may be associated with equipment grounds and safety bonding. Here again, it is essential to ensure that such grounds and bonds do not short-circuit any dielectric isolation.

Methods for testing an isolation fitting include:

- Measure the pipe-to-soil potential on each side of the isolation fitting with the reference electrode in a stationary position. If the difference in potential is approximately 100mV or greater, the isolation fitting is effective. If less than 100mV, further testing may be necessary.
- If the cathodic protection current can be interrupted “on” and “off” pipe-to-soil potentials can be recorded on each side of the isolation fitting with the reference cell in the same location. Similar “on” and “off” potentials on opposite sides of the fitting indicate a short. If the “on” potential was depressed on the side of the isolation away from the current drain, the fitting is effective.
- If there is no cathodic protection current to interrupt or if it is difficult to do so, a temporary current drain could be established and “on” and “off” readings recorded as described above.

Testing Resistance Between a Pipe and Casing

The procedure is the same as used to test the resistance across an isolating fitting. The test current is set up between the pipe wires and those on the casing. If the casing has only one wire, the vent is used as the other one.

Measuring Structure Continuity

There are several ways to measure structure continuity. We will discuss only the fixed cell, moving ground method. In this test, one reference electrode is placed at a fixed location and the positive lead from the multimeter is placed in contact with various parts of the structure. If essentially the same structure-to-electrolyte potential is read from each contact, continuity is indicated. It is possible that an isolated portion of the structure could have the same potential as the rest of the structure. If you suspect this is the case, other testing, beyond the scope of this course, will be required.

Continuity of pipelines, cables, and similar structures can also be tested by using a pipe or cable locator. These instruments are discussed later in this chapter.

Diode Bias

This is a multimeter operated in the diode bias mode. A functioning diode will typically display a meter value from 0.3 V to 0.9 V in the forward bias; positive lead to anode, negative lead to cathode. In the reverse bias condition, positive lead to cathode and negative lead to anode, a functioning diode will display “OL” (overload or out of limits).

For shorted diodes, the meter will display some low voltage value in both forward and reverse bias configuration. In the case of an open circuit diode, the meter will display “OL” in both forward and reverse bias.

To correctly verify diode operation, at least one lead must be disconnected from the circuit. Diodes cannot be properly checked while in the circuit or with power on.

Measuring Electrolyte Resistivity

Wenner Four-Pin Method

Most soil resistivity measurements are made by the four-pin Wenner method. This method is used to determine the resistivity of soil within an area. The Wenner procedure involves driving four metallic pins into the earth, in a straight line, equally spaced. The pin spacing is equal to the depth of investigation of the average soil resistivity, as shown in Figure 5.14. The average soil resistivity is a function of the voltage drop between the center pair of pins with current flowing between the two outside pins. After resistance is measured at a given spacing, then the spacing can be changed and resistance measured at the new spacing.

4-Pin (Wenner) Method

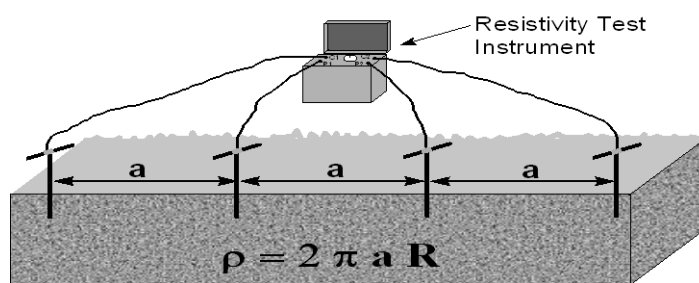


Figure 5.14 Four-Pin (Wenner) Method of Measuring Soil Resistivity

It is important that the pins are placed in a straight line and that they are equally spaced. Nearby metallic underground structures will create a false reading since they become part of the measured circuit. Consequently, the nearest pin should be at least 1.5 times the pin spacing from any underground metallic structures. Where this is not possible, the pins should be set at right angles to the underground structure.

The resistance, “R,” at each pin spacing “a”, is the resistance from ground level to a depth equal to the spacing of the pins.

Using the Wenner method, the soil resistivity, ρ (Greek letter *rho*), in ohm-centimeters is determined by:

$$\rho = 2 \pi a R = 6.28 \times a \times R$$

For “a” in centimeters and “R” in ohms

To obtain “ ρ ” in ohm-cm, if “a” is in feet and “R” is in ohms, the formula becomes:

$$\rho = 191.5 \times a \times R$$

You might be asked to collect data so that the resistivities of various layers of soil can be calculated. Figure 5.15 shows a typical layer situation.

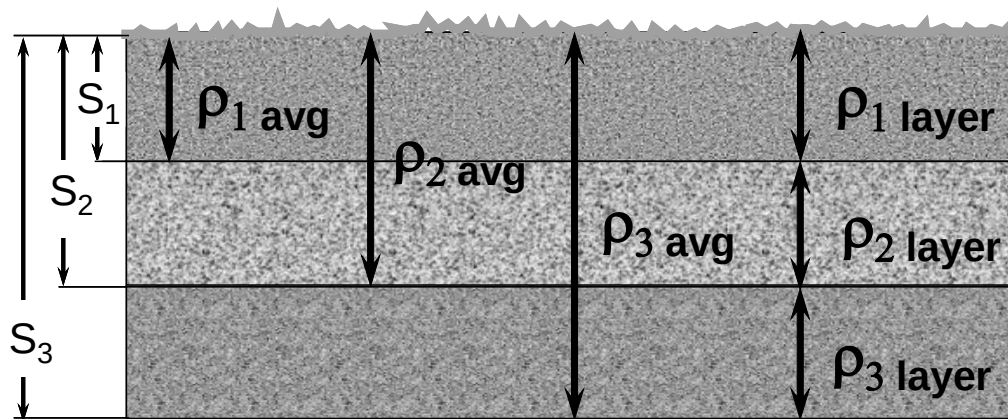


Figure 5.15 Average and Layer Resistivity

This measurement is done by taking a series of measurements at ever-widening pin spacings. It is important that the pin spacing be centered on a fixed point between the center two pins. This means moving all four pins out to wider spacings so that the center point of your measurement location is always centered between the two inside pins.

To ensure accuracy, it is good practice to take two sets of data, perpendicular to each other. This will help expose any anomalies in the soil layers.

Soil Box

The soil box method is used to measure the resistivity of an electrolyte that has been removed from its natural environment. The soil box method can also be used to measure resistivity of a liquid.

If a soil box is used for measuring resistivity of soil, the soil sample should be tamped in the box to simulate natural compaction and be flush with the top of the box. Because natural compaction and natural moisture content are not always accurately simulated, the test results may vary from in situ soil resistivity measurements.

A soil box consists of two plates at the end of the box for current flow and two pins in the center for voltage measurement as illustrated in Figure 5.16. If the cross-sectional area and linear distance between the voltage pins are equal, the calibration is a factor of 1 (other calibration factors may apply with different dimensions). Therefore, the measured resistance equals resistivity of the sample in ohm-cm. The soil box is connected to the resistivity test instrument in the same manner as in the Wenner method.

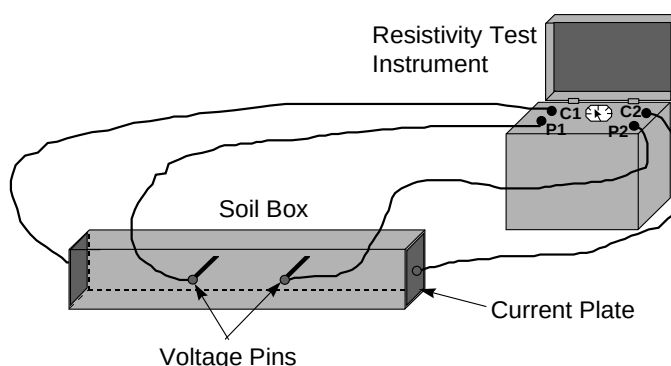


Figure 5.16 Resistivity Soil Box

If a soil box and resistivity meter are available, take time now to work with them; connect the instruments as shown in Figure 5.16. Fill the soil box with water and any available soil samples.

Resistivity Probe

This single-probe method is used to determine soil resistivity in the immediate vicinity of the tip of a probe driven into the ground to a depth of the desired measurement. This method is useful for:

- Rapid determination of local resistivity at intervals along a pipeline trench during construction (for later use during cathodic protection system design).
- Spot checks of soil or water resistivity.

The single-probe method is illustrated in Figure 5.17.

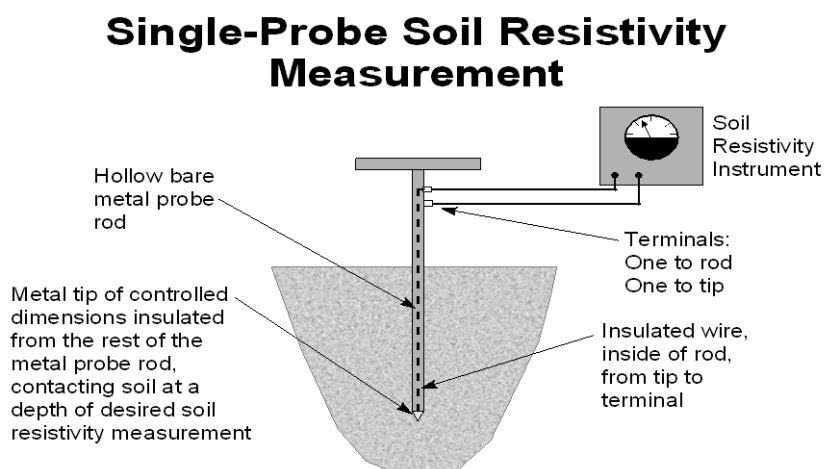


Figure 5.17 Single Probe Soil Resistivity Measurement

Measuring pH

Electrolyte pH can be measured in several ways. For liquids, pH (litmus) paper or a pH meter may be used. For soils, a pH meter may be used, or a filtrate may be made from distilled water and a soil sample and the pH measured with litmus paper, pH meter, or a pH test kits. Note that a pH meter uses a glass electrode with a rather fragile glass bulb on the bottom. Care must be taken when using these instruments not to break the electrode bulb.

Soil pH may also be measured using an antimony electrode and a copper-copper sulfate electrode. The antimony electrode consists of a slug of

antimony metal in the bottom of a nonmetallic tube. The slug is connected to a terminal on the top of the tube.

It is important to keep the antimony shiny and bright. Use fine non-metal bearing sand paper or emery cloth for cleaning. Do not use steel wool or other metallic abrasive since particles of metal may become embedded in the antimony and affect the reading.

The two cells are placed close together on the soil and connected to a voltmeter. It doesn't matter which cell is connected to which terminal of the meter since it is the potential between the two electrodes that is of interest. Take care not to get any copper sulfate on the antimony slug. There is a scale on the side of the antimony electrode that is calibrated in millivolts and pH. Once the potential is obtained, the pH can be determined from the scale.

Use of Pipe Locating Devices

During corrosion testing, it is often necessary to accurately determine the location of such buried items as a pipeline, conduit, or storage tank. Also, it is important to determine points of electrical continuity and discontinuity. A pipe and cable locator can be a great time saver for making such determinations.

Most locators include a transmitter and receiver. The transmitter is a source of radio frequency AC that is used to impress a signal on the structure. The receiver picks up the signal on the structure and provides it to the user as an amplifier sound. The sound of the signal, such as the frequency and rate of the pulse, can be controlled by the transmitter. The receiver controls the volume of the signal. The sound of the signal can be received through earphones or a speaker. In a noisy area earphones may be necessary. If your job requires constant use of a pipe locator, you may prefer the speaker type.

There are two types of pipe locators. Some locators contain both types in one unit:

- Conductive
- Inductive.

Conductive

The conductive locator uses either a radio or audio frequency AC signal that is connected to the structure by a direct wire.

The transmitter converts DC from dry cell batteries to AC by means of a vibrator circuit. This AC can then be passed through a transformer to give an output of several hundred volts, peak. This AC voltage is connected between ground and the structure to be traced. The AC signal will then flow through the earth to the structure and finally to the structure connection to complete the circuit.

When the receiver is near the structure, the AC field around the structure induces a voltage in the pickup coil. This voltage is amplified and produced as an audible signal heard by the user.

Figure 5.18 illustrates the principle of the conductive locator.

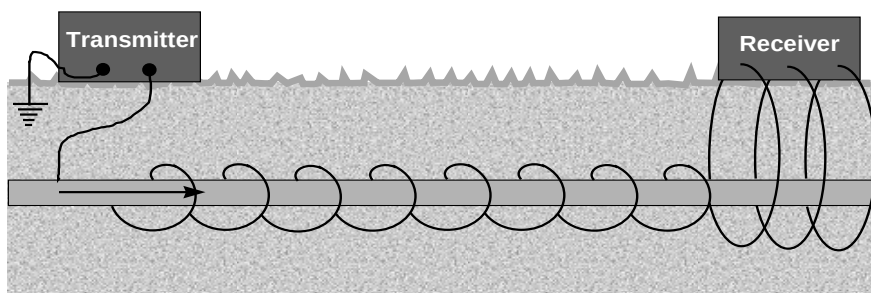


Figure 5.18 Conductive Pipe Locator Principle

Figure 5.19 shows an example of a conductive locator.

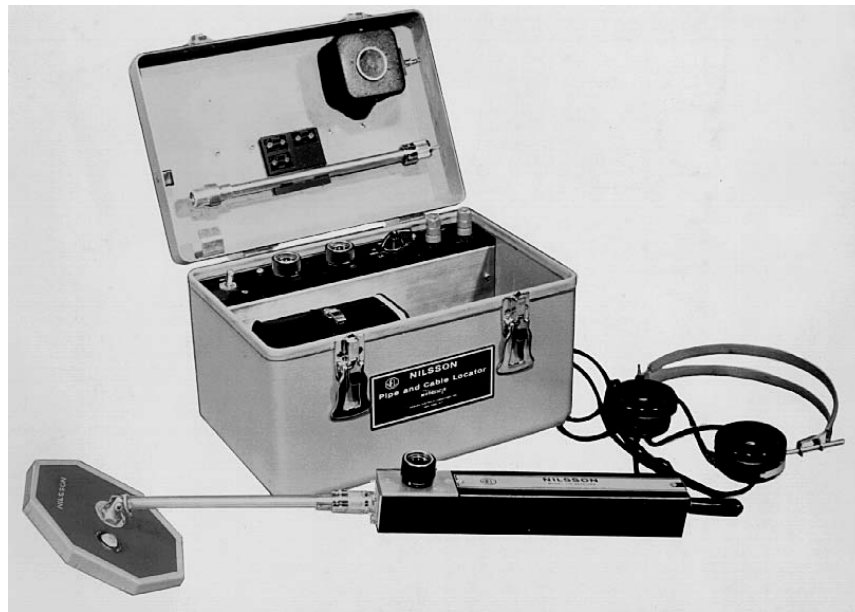


Figure 5.19 Example of a Conductive Pipe Locator

Inductive

An inductive locator uses a radio frequency AC signal, which is induced in the structure to be located by an induction coil that is part of the transmitter.

Inductive type locators permit the location of underground metallic structures where it is not feasible to attach a wire directly to the structure, as in the case of the conductive locator. This is accomplished by a coil in the transmitter that establishes a strong magnetic field that induces an AC current in the structure. The AC field surrounding the structure can then be detected in a manner similar to that described for the conductive locator. Figure 5.20 illustrates the principle of the inductive locator.

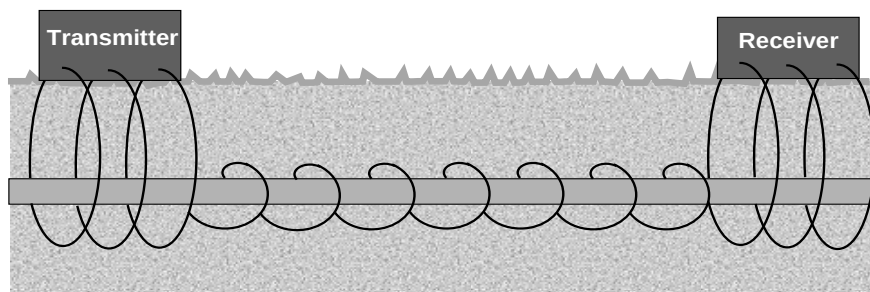


Figure 5.20 Inductive Pipe Locator Principle

Use of Current Interrupters

It is often desirable to determine the effect of a current source at various remote locations. To accomplish this, a current interrupter is inserted in the current source. An interrupter is a switch that is alternately turned on and off on a regular timed cycle by some mechanical or electronic means. A current interrupter is shown in Figure 5.21.



Figure 5.21 Current Interrupter

Coupon Measurements

Coupons are often used to check the effectiveness of cathodic protection. These are made of the same metal as the structure and are electrically connected to it. They are weighed prior to installation and then weighed periodically to determine if any weight loss has occurred. Corrosion is evidenced by weight loss.

Some test stations are equipped with a coupon so that structure-to-soil measurements can be made with essentially no IR drop. Some of these test stations have a stationary reference electrode built into them and some have a nonmetallic tube from grade to the coupon which a reference electrode can be lowered into.

Electric resistance probes are also used to monitor the effectiveness of cathodic protection. These can be placed underground, inside water storage tanks or other vessels, or on marine structures. An instrument is used to measure corrosion rate electrically. If the protection is effective, the corrosion rate is zero.

CHAPTER 6

Stray Current Interference

Definitions

Interference is any electrical disturbance on a metallic structure caused by a stray current. *Stray current* may be defined as current flowing on a structure that is not part of the intended electrical circuit. For corrosion to occur as the result of stray currents there must be an exchange of current between a metallic structure and an electrolytic environment.

Effects

Direct stray currents, as opposed to alternating stray currents, have the most pronounced effect on corrosion. Direct current (DC) flows continuously in one direction. Alternating current (AC60Hz commercial power) reverses direction 120 times per second. Although there are exceptions, alternating currents do not cause significant corrosion of common structural materials. AC current can be a significant safety hazard.

In accordance with Faraday's law, the weight of metal corroded is proportional to the amount of current being discharged from it into the electrolyte. Stray current corrosion is of serious concern because a large amount of current is usually involved. Whereas natural corrosion may generate milliamperes worth of current, stray current can involve hundreds of amperes. A current of 100 amperes (entirely reasonable with some rail transit systems) would destroy 910 kg (2,000 lbs.) of steel in one year. Consequently, when stray current is found, it is necessary to find the source and implement a solution.

Sources

Stray currents can be produced by any system conducting an electric current that has two or more points of contact with an electrolyte. These points of contact must have a voltage between them.

Typical sources of stray currents are:

1. Cathodic protection systems on underground or submerged structures (this is called interference) .
2. Electric powered mass transit systems (often called stray traction current) .
3. Welding where structure ground is at some distance from the welding electrodes.
4. Electric transmission lines (danger of induced AC).
5. High voltage DC (HVDC) transmission systems (mainly in monopolar operation).
6. Telluric currents (associated with sun spot activity and the earth's magnetic field).

Regardless of the source, currents flowing in an electrolyte produce voltage differences (gradients) in the electrolyte. If a voltage gradient is crossed by a metallic structure such as a pipe, cable, foundation pile, etc., current will be created on the structure. Where current is picked up, the structure is protected; corrosion occurs where the current leaves the metal and re-enters the electrolyte.

Types of Stray Current

Dynamic Stray Current

Dynamic stray currents vary in magnitude and often in direction. These currents can be manmade or natural in origin.

Manmade dynamic stray currents come from such sources as electrically-powered rail transit systems or mine railroads and arc welding operations.

Telluric currents are naturally-occurring dynamic stray currents that are caused by disturbances in the earth's magnetic field by sun spot activity. They are found most commonly on long pipelines in higher latitudes, but have also been seen in lower latitudes. How much, if any, corrosion is caused by telluric currents is still questioned, but they do create large variations in pipe-to-soil potential and current flow measurements.

Steady State Stray Current

Steady state or static stray currents maintain a constant magnitude and direction. Examples include cathodic protection interference and ground current from high voltage DC (HVDC) transmission line earth electrodes.

Identification of Stray Current

Dynamic Stray Current

Measurement Indications

Dynamic stray currents are manifested by fluctuations in structure-to-electrolyte potentials and, on pipelines, by variations in line current flow. If you encounter such fluctuations, you should suspect the presence of stray current. Additional testing is required to determine the extent of the fluctuations and the source of the stray current.

To determine the extent of the fluctuations, you need a recording instrument such as a strip chart recorder or datalogger. These instruments store or display the measurements over the test period so that the stray current activity can be evaluated. Figure 6.1 shows a typical recording of potentials produced by dynamic stray current.

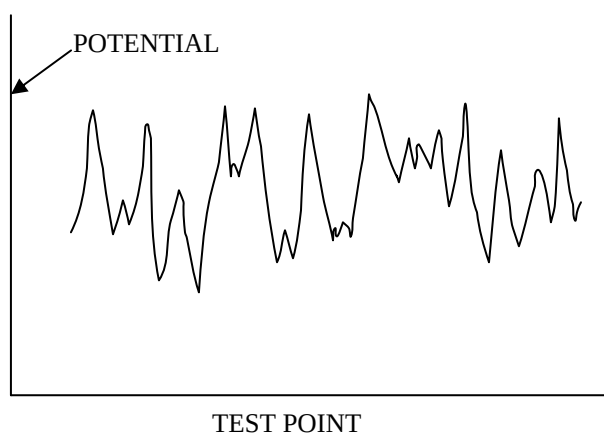


Figure 6.1 Recording of Dynamic Stray Currents

Proximity of Possible Sources

Even before you encounter fluctuating measurements, you may suspect that you are working in a stray current area. The presence of any of the sources listed above should lead you to suspect that you might encounter dynamic stray current.

Once you have located possible sources of stray current and have demonstrated its presence by measurements, it is necessary to determine precisely what the source is. This is done with a series of tests between the suspected source and the affected structure. Conducting these tests is, however, beyond the scope of this course.

Steady State Stray Current

Measurement Indications

Interference current can be recognized in several ways:

- Structure-to-electrolyte potential changes
- Changes in current flow on a pipeline
- Localized pitting near or immediately adjacent to a foreign structure
- Coating breakdown in a localized area near an anode bed or other source or stray current.

If you are making a routine survey and you find an area where the data have changed significantly from the preceding survey, you should suspect the possibility of steady state stray current. A data plot such as that shown in Figure 6.2 would indicate the presence of cathodic interference.

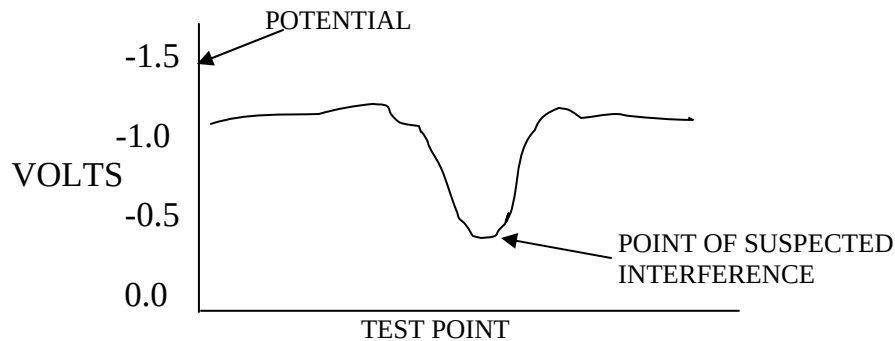


Figure 6.2 Pipe-to-Soil Data Plot Indicating Cathodic Interference

Location of Foreign Structures and Rectifiers

Here again, you may be able to spot possible interference problems just from looking around. If you notice a new pipeline crossing or a pipeline or tank farm under construction, for example, you will want to determine who the owner is and whether the structures have impressed-current cathodic protection. (Galvanic anodes seldom cause interference.)

As you drive about your territory, be alert for cathodic protection rectifiers. If you find one you haven't seen before, or find a new one replacing an old unit, the new rectifier may be a source of interference current.

When you are talking with colleagues from your own company and from other companies, you may find out that the output of an existing rectifier has been changed. If so, an interference problem may have been created somewhere on your structures.

Stray Current Corrosion Control

There are several ways to control stray current. Sometimes it is possible to relocate or remove the source of the current. Proposed structures might be rerouted to avoid a source. Among the most common methods are the installation of mitigation bonds and the use of cathodic protection.

Mitigation Bonds

Mitigation bonds, also called drain bonds or cables, provide a metallic path between the affected structure and the source of stray current. This permits the current to be drained through the cable back to the source rather than leaving the structure through an earth path.

A resistor may be incorporated in a bond to control the amount of stray current being drained. If dynamic currents are involved, a diode or reverse current switch may be needed to prevent reversal of current flow.

Mitigation bonds need to be maintained. If not kept in good working order, the affected structure may undergo serious corrosion. An important part of your work is to make regular inspections, which are required in various regulated industries, to insure that the bond is operative and is draining the proper amount of current.

Figure 6.3 shows the use of a mitigation bond to solve a stray current problem stemming from a rail transit system. Figure 6.4 illustrates a similar bond for mitigating cathodic interference.

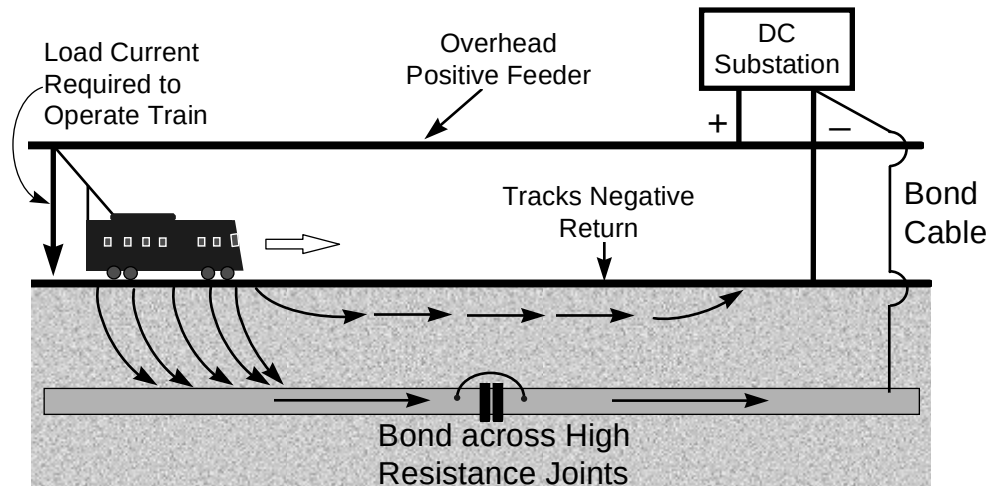


Figure 6.3 Mitigation Bond Used to Control Stray Current from a Rail Transit System

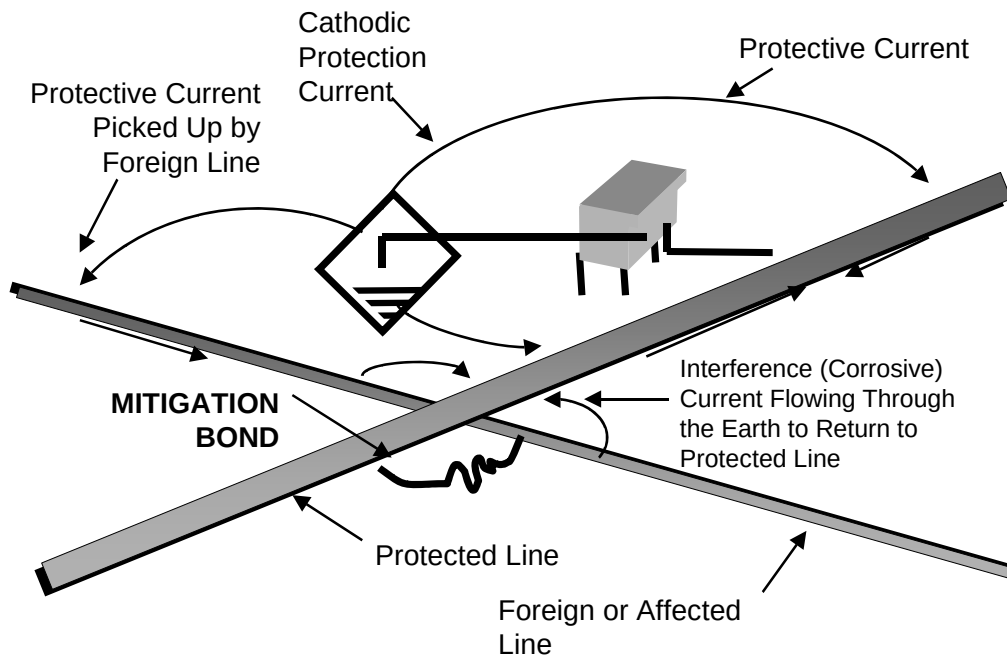


Figure 6.4 Mitigation Bond Used to Solve a Cathodic Interference Problem

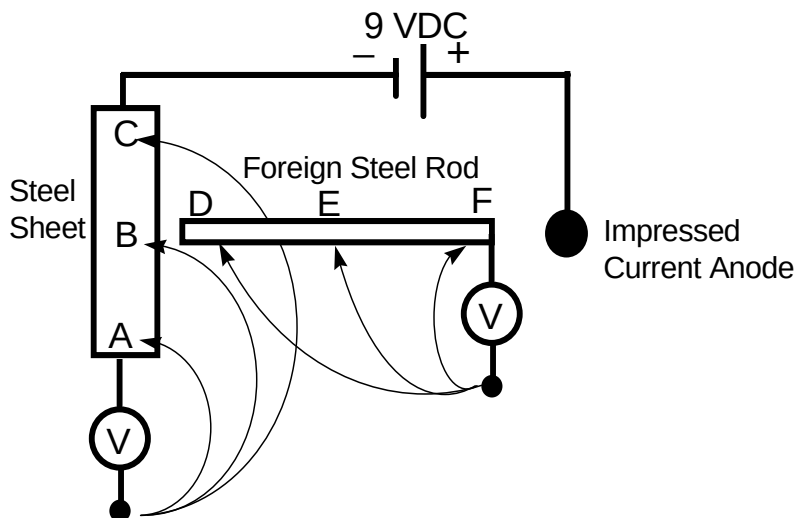
Mitigation with Cathodic Protection

Cathodic protection can sometimes be used to overcome stray current problems. This will work if the stray current is not so large that it cannot be overcome with the cathodic protection current. An advantage of using cathodic protection is that it avoids the use of bonds and the installation and maintenance problems that may accompany them.

Galvanic anodes may be used to overcome cathodic interference problems. Anodes are placed in the area of current discharge. The testing and design of such systems are, however, beyond the scope of this course.

EXPERIMENT 6.1

Experiment 6.1 — Demonstration of Cathodic Interference



Procedure

1. Set up the experiment as shown above without the steel rod (foreign structure).
2. Measure and record potentials on cathodically protected structure, the steel sheet, at positions A, B, and C.
3. Disconnect cathodic protection system.
4. Place the steel rod (foreign structure) in the water in the tray, as shown.
5. Measure and record potentials on the foreign structure at reference electrode positions D, E, and F.
6. Connect cathodic protection system.
7. Repeat Step 5.
8. Repeat Step 2.

Results

Experimental Step	Cathodically Protected Structure Potentials (mV)			Foreign Structure Potential (mV)		
	A	B	C	D	E	F
Step 2						
Step 5						
Step 7 & 8						

CONCLUSIONS

1. Stray current pickup and a negative potential shift on the foreign structure occurs at position F.
2. Stray current discharge and a positive potential shift on the foreign structure occurs at position D.
3. The potentials on the cathodically protected structure are altered by the presence of the foreign structure because the current distribution has been disturbed.

CHAPTER 7

Monitoring Cathodic Protection Effectiveness and Recordkeeping

Introduction

Field measurements represent a very important part of monitoring any corrosion control system. Although there are many remote monitoring systems in use today, it is still necessary to take field data to ensure that cathodic protection systems are operating properly and are providing adequate protection to the structure.

It is essential that clear, accurate data be taken. The data will be used to evaluate the effectiveness of cathodic protection, interference bonds, stray current control devices, and the like. If the data are not accurate and correct, the evaluation will be faulty and those responsible for the corrosion control program will be misled into thinking that systems are working properly when they may not be. This could lead to failures, leakage, fires, explosions, and other hazardous situations.

You must know how instruments work and what errors are possible. This means having a thorough understanding of the instruments you use and a knowledge of how the data should appear. It means taking the time in the field to review your data and make certain they are correct. Remember, if the data does not look right, they probably are not. Of course, unusual data may indicate a malfunction, and it is important that you recognize these situations, too.

Reasons for Monitoring

The most obvious reason to monitor cathodic protection is to make sure corrosion is under control. When a structure corrodes, leaks may occur, product may be lost, and structural damage may occur. There is also concern over public safety and environmental damage. For this reason, regulations have been enacted in many industries and countries to make sure structures containing hazardous products are adequately protected to reduce the risk to the public and the environment.

Monitoring Requirements

Although regulatory agencies have adopted standards set forth by NACE, International Standards Organization (ISO), Det Norske Veritas (DNV), etc. regarding corrosion control, many have gone a step further by specifying specific measurements and time intervals in which these measurements must be taken. The measurements not only include structure-to-electrolyte potentials, but other indirect methods of monitoring protection on a system in between potential surveys. Also, in the United States pipeline industry, efforts are being made by the U.S. Department of Transportation (DOT) to enact “Operator Pipeline Qualification” standards that will govern the required qualifications of personnel who are monitoring cathodic protection.

In the United States, a majority of facilities containing hazardous materials are regulated by agencies enforcing the Code of Federal Regulations (CFR). Corrosion control requirements can be found in these parts of the code:

- Natural Gas Pipelines – 49 CFR, Part 192, Subpart I
- Liquefied Natural Gas 49 CFR, Part 193, Subpart G
- Hazardous Liquids 49 CFR, Part 195, Subpart D
- Underground Storage Tanks 40 CFR, Part 280

Monitoring Cathodic Protection

To determine that a cathodic protection system is operating properly and protecting a structure from corrosion, the following data are recorded on a routine basis:

- Structure-to-electrolyte potential.
- Rectifier voltage and current outputs.
- Current output of galvanic anodes.
- Magnitude and direction of current through mitigation bonds.
- Resistance of groundbeds.
- Integrity of rectifiers, isolating joints, electrical bonds, and other physical features associated with the corrosion control system.

Measurement of structure-to-electrolyte potentials is the only method of determining when adequate cathodic protection is achieved. After a

potential survey has been conducted, however, other indirect measurements can be used to monitor a system before the next potential survey. For example, measuring current output of a rectifier does not provide any information about the protection level of a system. If an annual corrosion survey indicated that a well coated structure was adequately protected with 10 amps and after the survey the structure became electrically shorted to some large bare structure, would measuring 10 amps at the rectifier still represent adequate protection on the structure of interest? The answer is probably no. The only way current output can be used, as a measure of cathodic protection is if the system has remained unchanged since the potential survey was conducted. Therefore, all other measurements and tests that are done between potential surveys are based on the assumption that everything is the same as during the potential survey.

Other procedures for monitoring the effectiveness of cathodic protection, which may be conducted at specified intervals or as appropriate, include:

- Coupon test stations
- Electric resistance probe test stations
- Structure examination by excavation or divers
- Close interval potential surveys

Recordkeeping

Importance of Good Record Keeping

Documentation is the only way to follow the history of a system. The data you turn in become part of the company cathodic protection records. Consequently, you are an important part of the record keeping operation.

Technical

Accurate data is essential for detection of malfunctions in C.P. systems. Trends can be analyzed over extended time and plans can be made for maintenance and repair.

Legal

In the event of an accident or lawsuit, good records are essential to legal defense.

Data Sheets

Data sheets are extremely important. Data must be entered accurately and neatly. Obviously, it isn't always possible to keep neat data sheets, particularly when working in inclement weather or in adverse or dirty conditions. It may be necessary to copy the data onto fresh sheets after returning from the field.

Data sheets must be kept in such a way that someone else could go back on the same job, repeat your measurements, and obtain data in the same locations as you did. Remember that you may be assigned to do an annual inspection on an unfamiliar structure using only the data sheets of the person who was there before you.

Date, Time, and Weather

Date, time, and weather conditions should always be noted on data sheets.

Sketches

- Show layout of structure(s).
- Show location of measurements with polarity of measurement.
- Record name and serial numbers of all instruments used.

Site Conditions

Always indicate unusual site conditions.

Legibility

Data must be legible if it is to be of any value.

Computer Records and Spreadsheets

Nearly all corrosion records today are kept on computer databases. Usually these databases show the test points, date of last test, the measurement itself, whether or not the data meet the selected criterion, and when the next test is due. Printouts are then generated at the appropriate times for technicians to take into the field for the next scheduled tests. The latest data are then entered into the database. Spreadsheets can also be generated showing test points that do not meet criteria. These can be taken into the field for trouble shooting.

If you have been collecting data on a computer data logger, the data can be entered directly into a computer. Graphs and spreadsheets of data can be generated, or the data can be downloaded into the company computer system.

Large companies, particularly those with operations spread over a large area, are now using Internet access for corrosion control data. This makes it possible for all data in a technician's area to be available without having to have a large computer system in local offices.

Facility Maps and Work Documentation

Companies that operate underground plants, such as pipelines or cables, maintain atlas maps showing the location of structures, test points, cathodic protection installations, and many other data. The same is true of many large industrial plants, refineries, college campuses, and similar facilities.

You need to be familiar with what these maps show and be able to work with them in the field.

Documentation of your work is essential. Those responsible for updating facility maps will depend on your information to keep the maps current or to generate new maps. Consequently, as-built drawings of corrosion control installations must be accurate. Likewise, if you are involved with repairs of structures or corrosion control components, accurate information must be turned in. Accuracy in your work documentation is just as important as accuracy in your data sheets, as discussed above under “Data Sheets.”

Test Stations

General

The purpose of test stations is to provide access for the measurement of the effectiveness of a cathodic protection system. Test stations include those installed in association with:

- cased road crossings
- anodes
- stationary reference electrodes
- coupons
- dielectric isolation
- crossings with foreign structures
- measurement of current flow on a pipe or a cable system.

Location

Selection of locations for test stations is at the discretion of the design engineer. It is preferable to err on the side of more test stations rather than fewer test stations. When in doubt, install a test station.

All major buried isolating fittings should be provided with suitable test stations to permit measurements of effectiveness of isolation and to permit installation of control resistors.

Major crossings between underground structures will generally warrant installation of a test station.

Where electrical bonding of joints on ductile iron or mechanically joined steel is involved, frequent test stations permit testing of the bonding and/or the detection of broken bonds.

Environmental Factors

There are many situations where it would not be physically possible to make meaningful tests unless a suitable test station is installed at the time of construction—piping systems installed under concrete flooring, for example. Unless test facilities are provided at the time of construction, it is unlikely that they could be installed economically should they become necessary at a later date.

Other conditions such as restricted areas or hazardous locations may have unusual test station requirements.

Construction Notes

The structure and test lead wires should be clean, dry, and free of foreign materials at points of connection when the connections are made. Test lead wire connections to a structure must be installed to remain mechanically secure and electrically conductive.

All test lead wire attachments and all test lead wires should be coated with electrically insulating material. If the structure is coated, the insulating material should be compatible with the structure coating.

Conductors should be color-coded or otherwise permanently identified. Wire should be installed with slack. Damage to insulation should be avoided, and repairs should be made if damage occurs. Test leads should not be exposed to excessive heat or sunlight. Above ground test stations are preferred. If test stations are flush with the ground, adequate slack in the conductors should be provided within the test station to facilitate test connections.

Conductor connections at bonds to other structures or across isolating joints should be mechanically secure, electrically conductive, and suitably coated. Bond connections should be accessible for testing.

Types of Test Stations

Potential Measurement

Potential measurement test stations are used to monitor the effectiveness of cathodic protection, check for stray current effects, and, on unprotected or partially protected pipelines, to locate areas of active corrosion.

These test stations consist typically of two No. 12 AWG insulated wires, thermite-welded to the pipe. The test station head may be mounted on a post as shown in Figure 8.1 or it may be flush mounted as illustrated in Figure 8.2

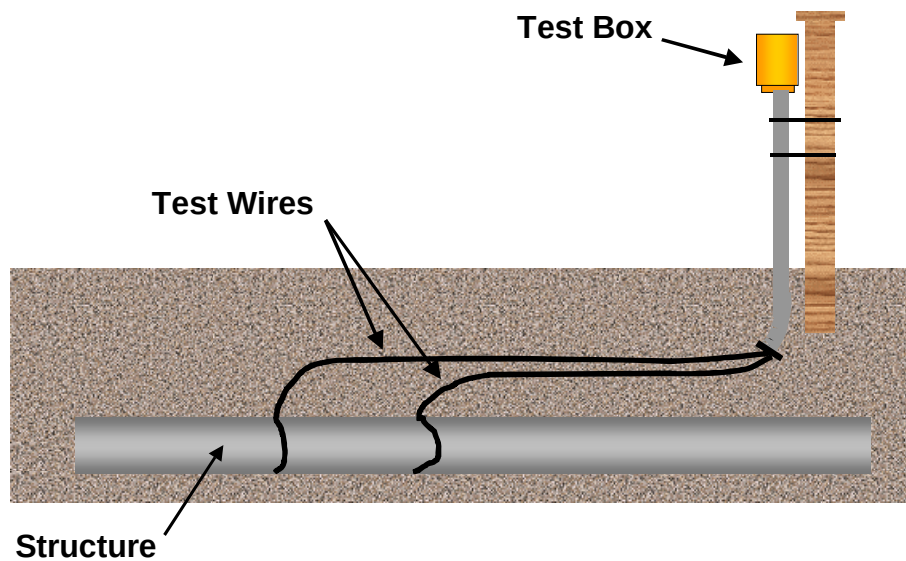


Figure 8.1 Typical Post Mounted Potential Measurement Test Station

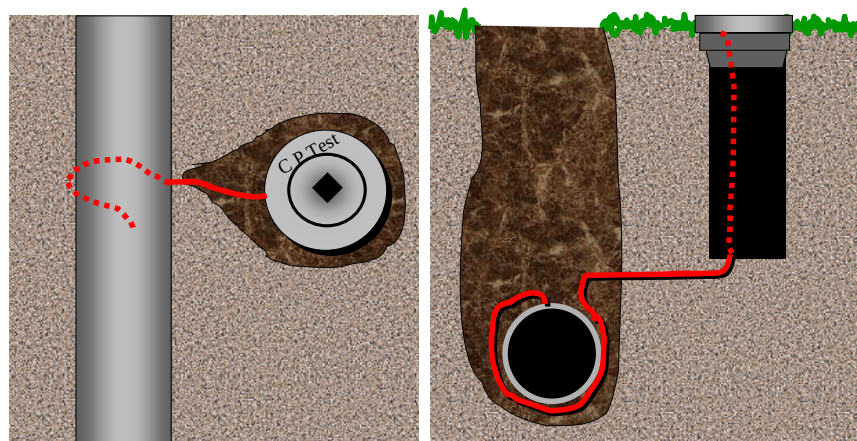


Figure 8.2 Typical Flush Mounted Potential Measurement Test Station

Post-mounted test stations are preferable to flush mounted ones because there is less chances of losing post-mounted units. In many distributions systems, however, it is difficult to use post-mounted test stations because of physical restrictions and lack of available places to put the post. Where flush mounted test stations are used; it is good practice to cast a concrete collar around the top of the station to minimize loss of the test point.

IR (Millivolt) Drop (Current Span)

These test stations are used to measure the magnitude and direction of current flow on a pipeline. This information is useful in monitoring the spread of cathodic protection, locating areas of bad coating on a pipeline, and for finding areas where short circuits may exist.

In this type of test station, the pipeline acts as a resistor; the magnitude of the current is determined by measuring the voltage (IR) drop across the span of the test wires. The direction of current is determined by the polarity of the voltage.

A typical IR drop station is shown in Figure 8.3.

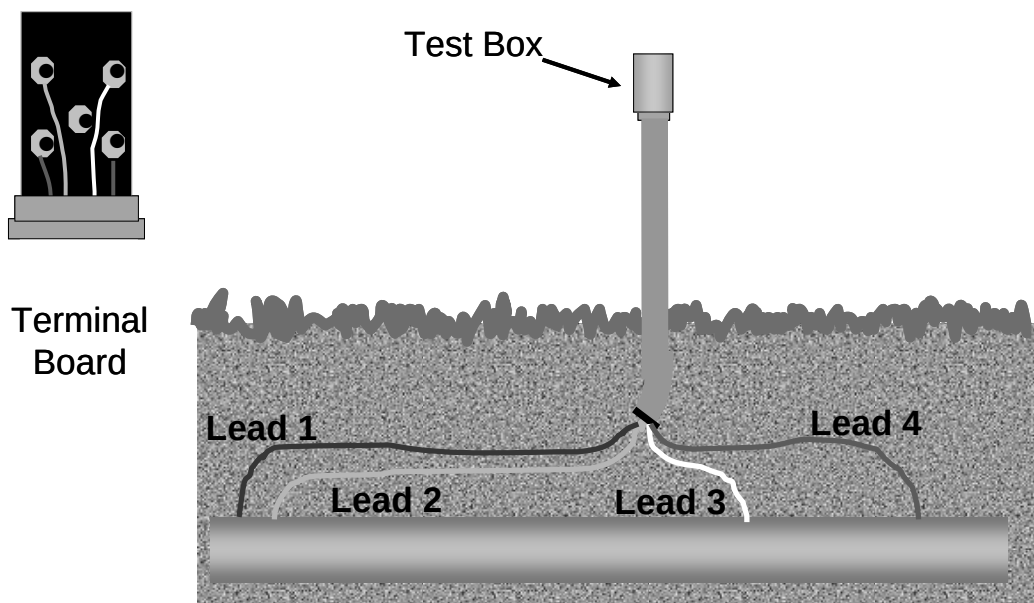


Figure 8.3 IR Drop Test Station

When installing this type of test station, it is important that the different color wires are placed on the pipe exactly as shown on the construction plans. This is because the wires are used for calibrating the station and also for measuring the current flow. If the wires are not installed as designed, erroneous reading will be obtained. Should one or more wires be installed differently from the designed color scheme, be certain the actual location of the wires is shown on as-built sketches.

Pipe Casing

The original intent of encased piping was for the casing to support dynamic loads caused by road traffic or trains to prevent harm to the pipe. Casings become an electrical shield of cathodic protection current when the casing and piping become electrically shorted, however. Sufficient inspection should be made to ensure that no metallic contacts exist or are likely to develop between the casing and carrier pipe.

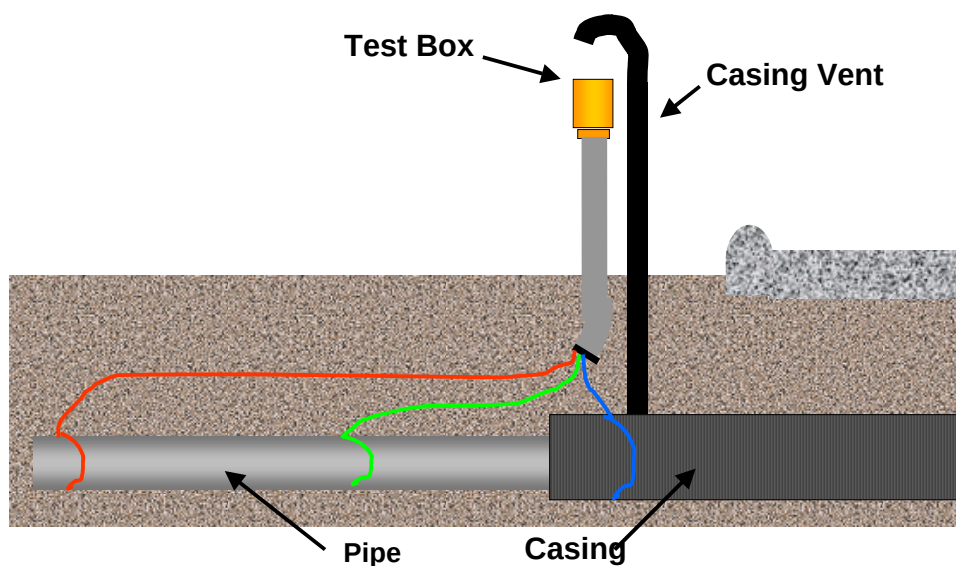


Figure 8.4 Casing Test Station

Note that different color wires are used on the pipe and the casing. Here again, it is essential that the color coding be exactly as shown on the design drawings.

Two wires may be used on the casing, or the casing vent may serve as one of the connections to the casing. The two connections to the casing and carrier pipe are necessary to make casing-to-pipe resistance tests.

Foreign Line Crossing

Underground structures such as pipelines or cables frequently cross each other or are in proximity to other facilities. Where one or both structures have cathodic protection, there may be an interaction between the two. This is called *cathodic interference*. To determine what effects are occurring and to provide a facility to mitigate any undesirable effects, a foreign line test station is installed. See Figure 8.5.

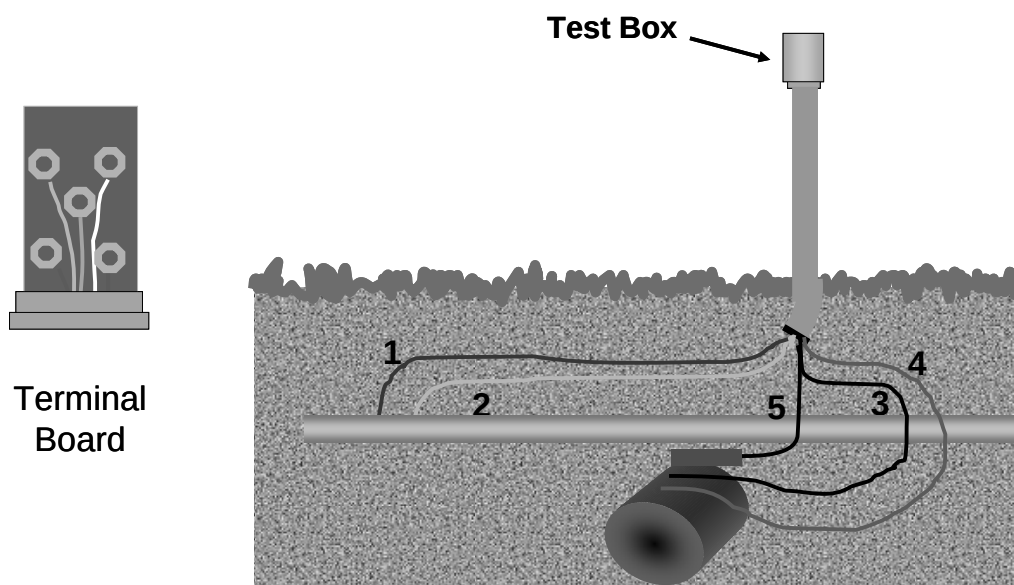


Figure 8.5 Foreign Line Crossing Test Station

A *foreign line* refers to any line other than the one with which you are concerned. It may be another line from your own company or it may belong to another company. When the foreign line belongs to another company, the wires attached to that line must be installed by representatives of that company.

Isolating Joint

All local and national codes should be followed in installing electrical isolators. Under no circumstances should an isolating device be installed where an explosive or combustible environment is present. Select locations where an electrical spark or discharge across the dielectric materials of the isolation device cannot produce ignition.

If an isolating joint must be installed in a area where the atmosphere or leakage of product could cause ignition if a spark occurred, a grounding cell or surge protector must be installed across the joint.

It is important to locate isolators so they will not be bypassed or short circuited by other connections or piping. Wherever possible locate isolating devices in an accessible place where repairs can be made.

Electrical isolators for piping systems come in a variety of types. These include flanges, couplings, and unions. Flanges may be double insulated or single insulated. Figures 8.6 to 8.8 show the construction of a number of different types of pipe isolation joints.

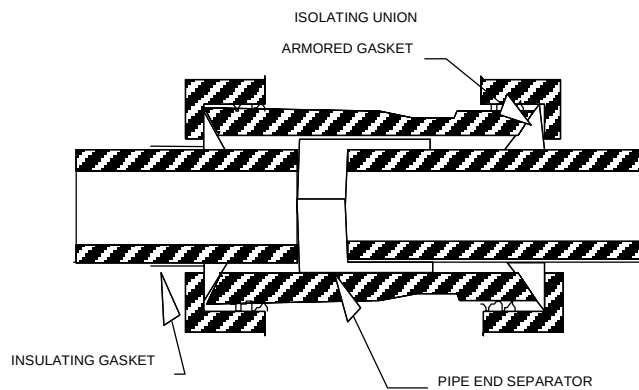


Figure 8.6 Isolating Coupling

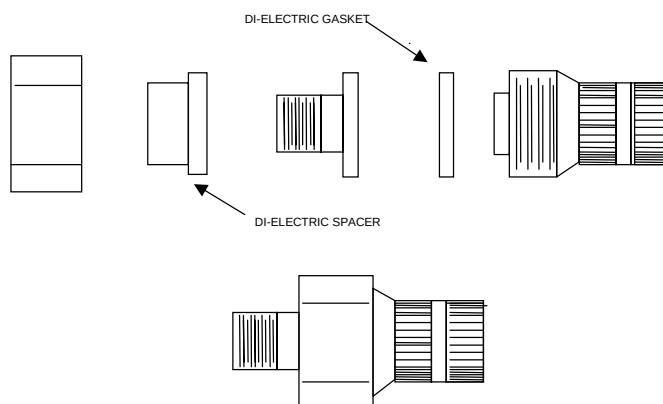


Figure 8.7 Isolating Union

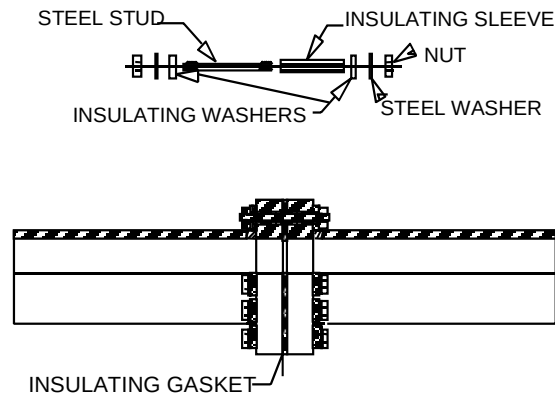


Figure 8.8 Isolating Flange

Other types of isolation devices include dielectric materials to maintain separation between pipelines and casings. In some situations, structural members are isolated from supports using sheet type dielectric material and insulating sleeves and washers. A properly isolated casing is shown in Figure 8.9.

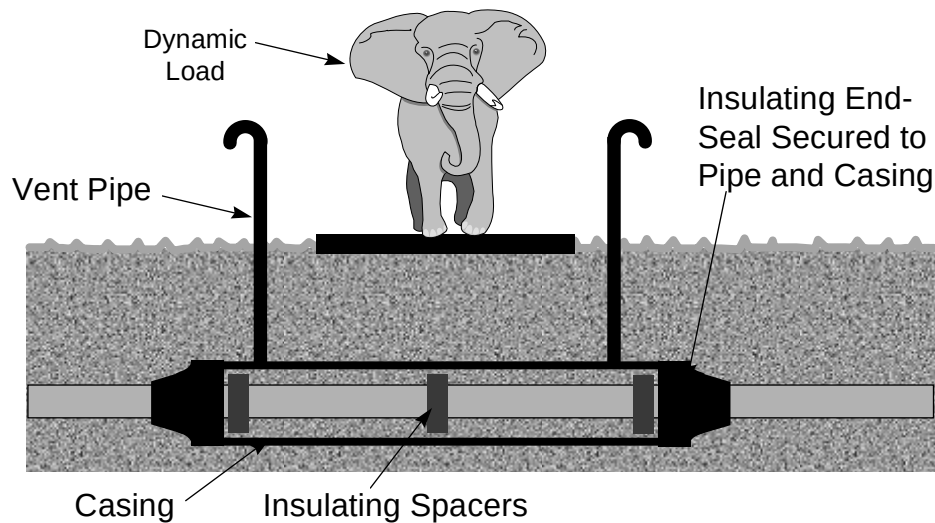
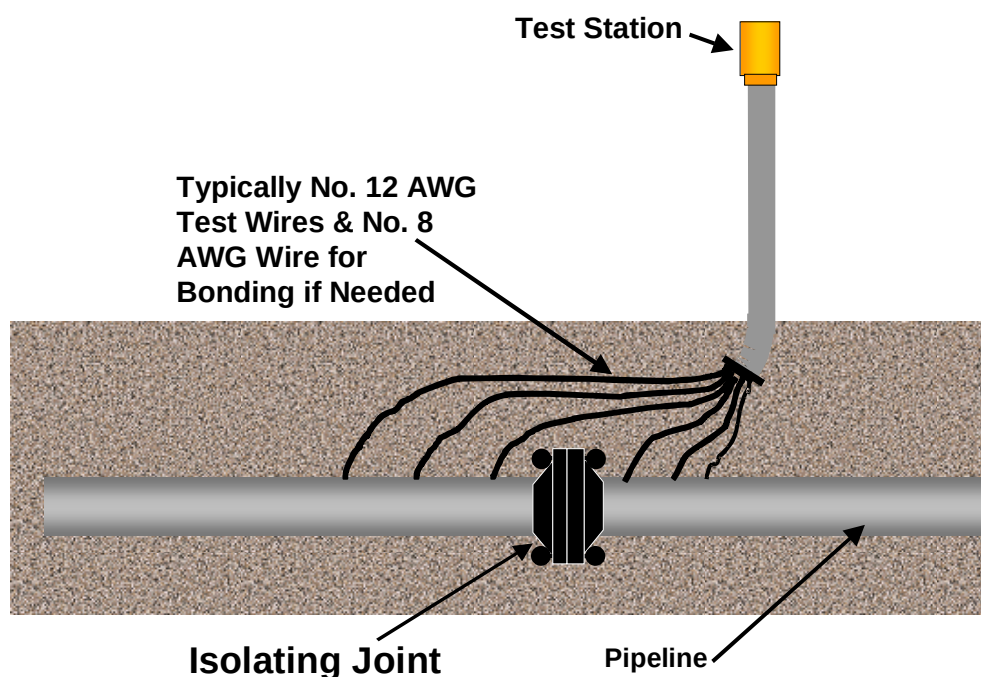


Figure 8.9 Properly Isolated Casing

Service conditions can vary greatly on different systems. In selecting an electrical isolating device, be certain that the materials of constructions meet the service requirements, both from the standpoint of temperature and mechanical properties.

Wherever possible, isolating joints should be installed above grade. Where one must be buried, a test station should be installed with wires on either side of the joint. The purpose of the test station is to enable one to determine the effectiveness of the joint.

A typical isolating joint test station is shown in Figure 8.10. Note that different colored wires are used on either side of the joint. This is important so that you can tell which side of the joint is being tested. As with other test stations containing wires of different colors, it is important that the wires are placed as shown on the design drawings.



**Figure 8.10 Isolation Joint Test Station
Mitigation Bond**

Coupons

Coupon test stations may contain one or both of two types of coupons—polarization coupons and electric resistance “smart” probes. Polarization coupons are made of the same material as the structure. They are located near the structure and connected to it through the test station head. One purpose is to allow for “instant off” potential measurements without having to interrupt the cathodic protection rectifier. Another is to measure the protective current density on a holiday of known size.

Electric resistance or so called “smart” coupons have a probe, again located near the structure and connected to it and to a test instrument receptacle in the test station head. The probe is wired in such a way that the instrument can measure the probe’s electrical resistance. If the probe corrodes, its resistance increases; the increase in resistance is measured by the instrument as a rate of corrosion in mils per year (mpy) [mm/year]. If the structure is adequately protected, the corrosion rate will be zero.

Coupon test stations are used mainly on pipelines. They should be installed so that the foot of the test station (containing the coupons) is within the pipeline backfill and at the depth of the bottom of the pipe. The tube of the test station should be about 6 inches (15 cm) from the side of the pipe to prevent shielding of cathodic protection current from the pipe. Backfill around the pipe carefully and compact the backfill thoroughly.

To provide a low resistance path up to a reference electrode that may be inserted in the tube, a low resistivity backfill is used within the tube. Often this is a mixture of sand and bentonite.

Figure 8.11 shows a coupon station.

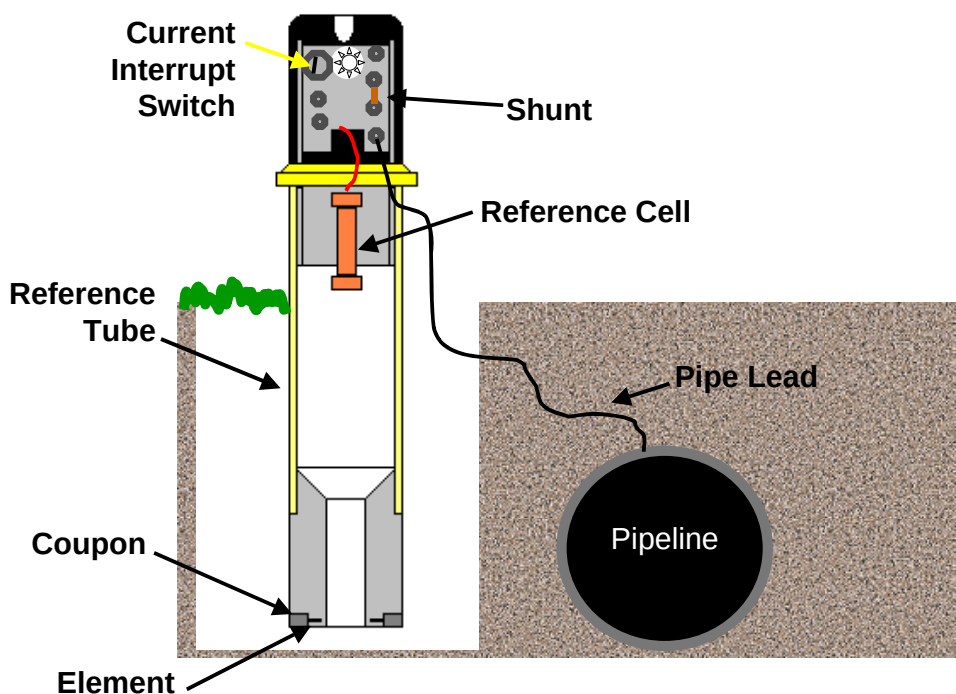


Figure 8.11 Typical Coupon Test Station

Electric resistance probes are also used in oil heater-treater and other vessels, water storage tanks, and on marine structures. Rate of corrosion is measured with the same instrument as discussed above.

Wire Attachment

General

The structure, test lead wires, or bond cables should be clean, dry, and free of foreign materials at points of connection when the connections are made. Connections to the structure must remain mechanically secure and electrically conductive.

Wire should be installed with slack. Damage to insulation should be avoided, and repairs should be made if damage occurs. Test leads should not be exposed to excessive heat or sunlight.

Thermite (Exothermic) Welding

The most common method of attaching wires and cables to a structure is by *exothermic welding*, also known as *thermite welding*. This process uses a graphite mold into which is poured a charge-containing mixture of copper alloy and magnesium starting powder as shown in Figure 8.12. The mixture is ignited with a flint gun, melts, and drops down, welding the wire to the structure.

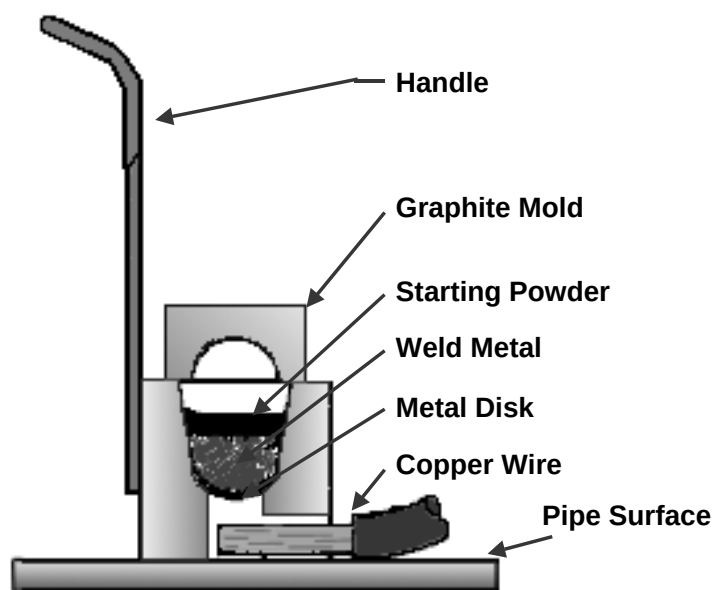


Figure 8.12 Thermite weld process

The manufacturer's literature specifies the proper size mold and charge for different size wires and structures. Different alloy charges are used for steel and cast/ductile iron structures.

Caution: Do not use larger than a 15-gram charge for carbon steel pressure pipe. Before thermite welding to *any* grade of steel, however, check your company's standards for the proper size charge. The heat affected zone around the weld can be hardened and may serve as a site for failure initiation. This is particularly true for high yield point steels.

After the weld has partially cooled, remove the welder and clean welding slag from the weld with a chipping hammer and wire brush. Check the security of the weld by tapping with a hammer. If the weld is not secure, or if the wire is burned partially through, remove the wire and make a new weld.

Thermite welding may be used for connections to above ground structures, too. There are welders for making connections to both horizontal and vertical surfaces. Cables requiring a larger charge size can be divided into a "crow-foot" with each end attached to the pipe with a 15-gram charge.

Be certain the mold and welding surface are thoroughly dry. Damp conditions will cause the molten metal to spatter, creating a safety hazard. Before using exothermic welding equipment, become familiar with the manufacturer's Material Safety Data Sheets (MSDS) and follow all of the manufacturer's recommended safety procedures.

While there are other methods of welding a wire to a structure, these may cause embrittlement of wire or structure. Brazing should not be used as the heat is too concentrated and may cause damage to both the wire and the structure.

Mechanical

Mechanical connections are used typically in places where flammable or explosive conditions preclude the use of thermite welding and also in places where connections are made above ground. Underground mechanical connections are usually made with a clamp and conductive epoxy.

Above ground connections may be made using lugs attached to the end of the wire or cable. The lugs can then be bolted to the structure.

Coating

All wire and cable attachments should be coated with electrically insulating material. If the structure is coated, the insulating material must be compatible with the coating on the structure. It is especially important to coat above ground connections where brass lugs are bolted to steel structures to prevent galvanic corrosion.

Galvanic (Sacrificial) Anodes

General

Galvanic anodes operate because of the galvanic (dissimilar metal) reaction between the anode and the structure. Hence the name, *galvanic anode*. These anodes are also called sacrificial because they may be thought of as sacrificing themselves to protect the structure.

It is important that galvanic anodes be installed according to construction specifications. Improperly installed anodes will very likely not function properly.

Prepackaged Anodes

Prepackaged anodes should be inspected to ensure that backfill material surrounds the anode. The white, powdery backfill within the package serves two purposes. It absorbs water, thus helping to keep the anode wet, permitting it to function properly. The backfill also absorbs corrosion products from the anode; this prevents the products from sticking to the anode and increasing its resistance to ground. Consequently, if the anode is not surrounded by the backfill, the anode may not function properly.

The cloth or cardboard package containing the anode backfill material should be intact. If the packaging container is torn or broken, the anode should not be used. Prepackaged anodes are supplied in waterproof containers; the container must be removed before installation. Prepackaged anodes should be kept dry during storage; also, they should not be pre-wetted or soaked prior to installation.

The lead wire must be securely connected to the anode and should be inspected to ensure that it is not damaged.

Galvanic anodes should be backfilled with compacted native soil, not sand, pea gravel, or other high resistance material. Anodes should be wet down after backfilling or left to absorb natural soil moisture. Care should be exercised so that lead wires and connections are not damaged during backfill operations. Lead wires should have sufficient slack in them to avoid strain.

Typical prepackaged anode installations are shown in Figures 8.13 and 8.14.

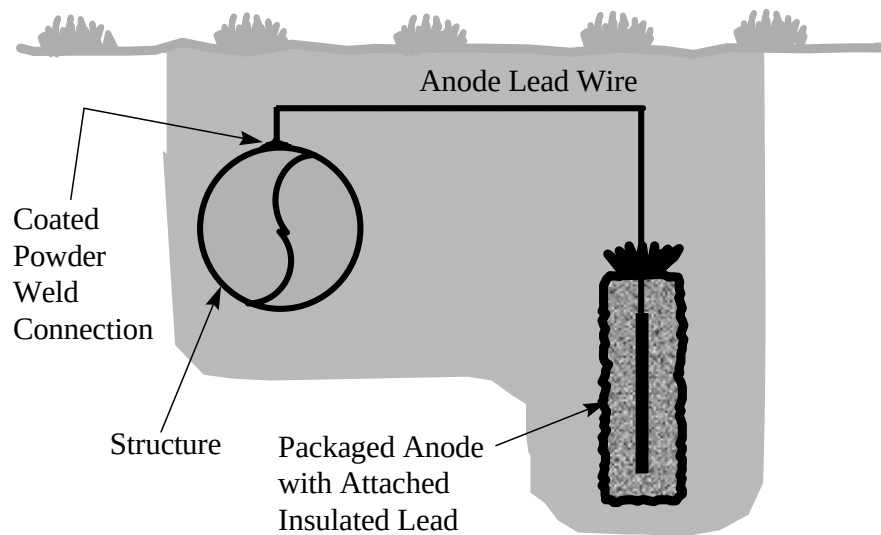


Figure 8.13 Single Prepackaged Vertical Anode

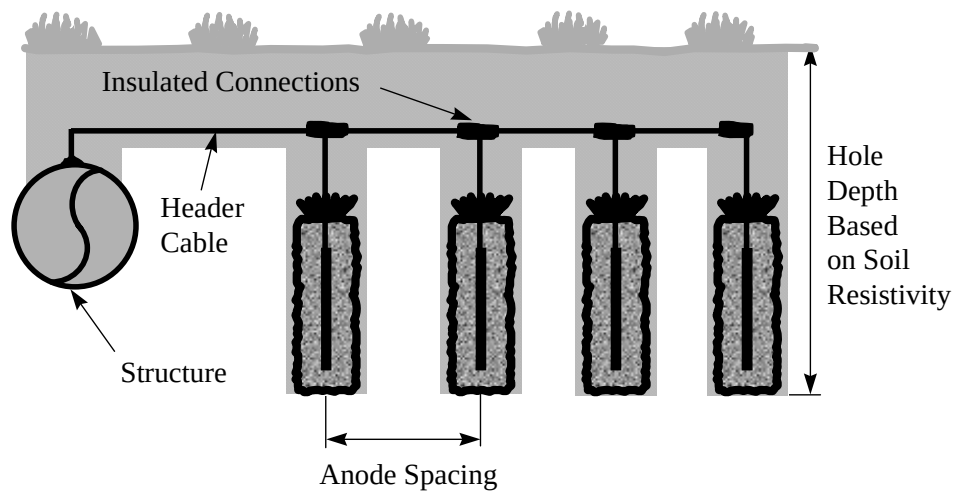


Figure 8.14 Multiple Prepackaged Vertical Anodes

Non Packaged Anodes

Non packaged anodes are used in water environments and occasionally in soil. The most common application in soil is for ribbon anodes. These are discussed below.

Underground anodes should still be installed in the special anode backfill that comes with prepackaged anodes. The installation should be made in such a way that the anode is centered in the special backfill; the special backfill should be compacted prior to backfilling with native soil.

Ribbon or Strip Anodes

Ribbon-type anodes can be trenched or plowed in, with or without special backfill as specified. These types of anodes are usually placed parallel to the section of pipeline to be protected. See Figure 8.15.

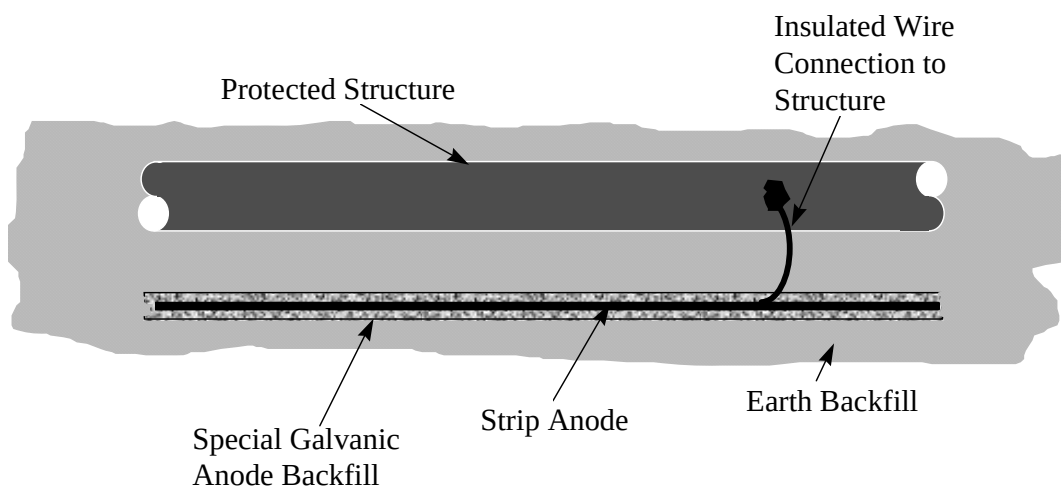


Figure 8.15 Ribbon or Strip Anodes

Bracelet Anodes

Bracelet anodes are used on offshore piping, river crossings, and other underwater environments. Where they are used, pipe coating beneath the anode should be free of holidays. Care should be taken to prevent damage to the coating when installing bracelet anodes. Be certain the anode pigtail is attached to the pipeline.

If concrete is used to cover the pipe, all coating and concrete must be removed from the anode surface. If reinforced concrete is used, there must be no metallic contact between anode and reinforcing mesh or between reinforcing mesh and pipe.

Figure 8.16 shows a typical bracelet anode installation.

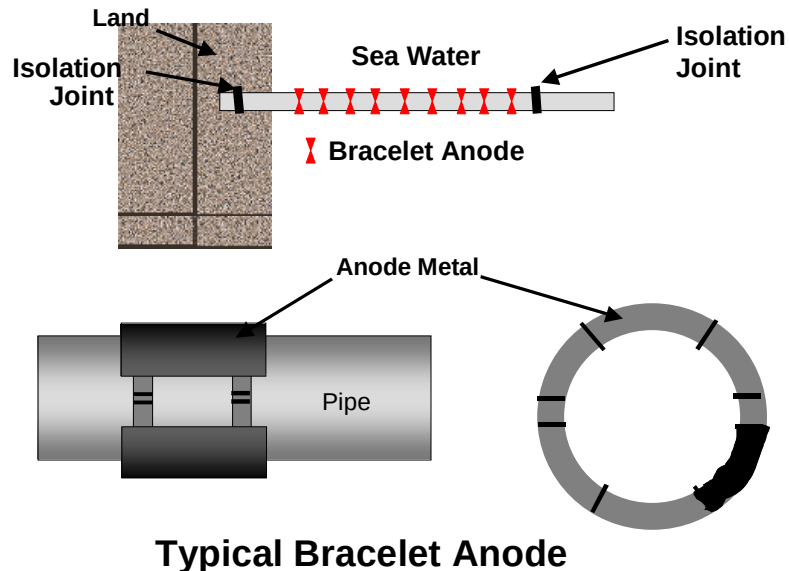


Figure 8.16 Bracelet Anode Installation for Underwater Piping

Offshore Anodes

Offshore anodes for use in salt water are usually made of an aluminum alloy and may weigh up to about 1,400 pounds each. The anodes are cast on a steel pipe core, which in turn is welded to the platform or other structure to be protected. Figure 8.17 shows a typical example.

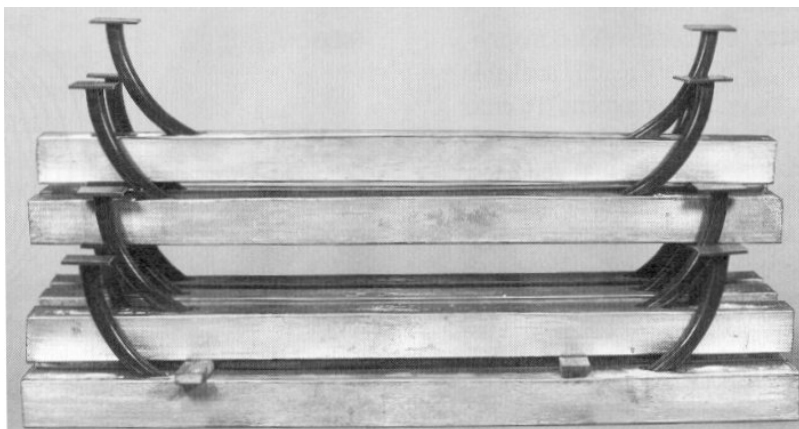


Figure 8.17 Aluminum Alloy Anodes for Offshore Structures

Hanging anodes, usually of aluminum alloy, may be used to protect piping on a wharf or similar structure. When hanging anodes are used, it is necessary to connect a lead wire between the anode eyebolt core and the structure.

In fresh water, zinc and magnesium anodes are frequently used. These anodes also find some use in salt water. They are also used on ship hulls and in ballast tanks and condenser water boxes as described below. The anodes may be cast on steel mounting strips or provided with a drilled hole for mounting on a stud bolt.

Impressed Current Groundbeds

General

Impressed current cathodic protection systems provide protection in a manner similar to galvanic anodes. The difference is that in an impressed current system, the current is supplied by an external source rather than by the galvanic action between the anode and the structure.

The groundbed and rectifier must be installed according to construction specifications. This is very important since premature failure can occur if proper installation procedures and precautions are not followed.

Impressed current anodes may be installed in either surface groundbed configurations or a deep anode configuration. Installation techniques are discussed below.

Handling and Inspection of Anodes and Cable

Impressed current anodes should be inspected for conformance to specifications concerning correct anode material and size, length of lead wire, and end cap, if used. Care should be exercised to avoid cracking or damaging anodes during handling and installation.

Lead wire should be carefully inspected to detect defects in insulation. Care should be taken to avoid damaging the insulation on the wire. Defects in the lead wire must be repaired, or the anode must be rejected.

Anode backfill material should conform to specifications. The backfill used around impressed current anodes is a carbonaceous material called coke breeze. It serves two purposes. First, it enlarges the size of the anode, thus reducing the anode-to-ground resistance. Second, it provides a uniform environment around the anode; this greatly increases anode life since most of the current flows electronically from the anode into the backfill, thus reducing electrolytic action on the anode. What electrolytic flow does occur causes relatively uniform corrosion of the anode rather than the localized action that can occur if the anode is backfilled in soil.

Coke breeze backfill can be tamped around a bare anode or anodes may be purchased prepackaged in backfill as shown in Figure 8.18.

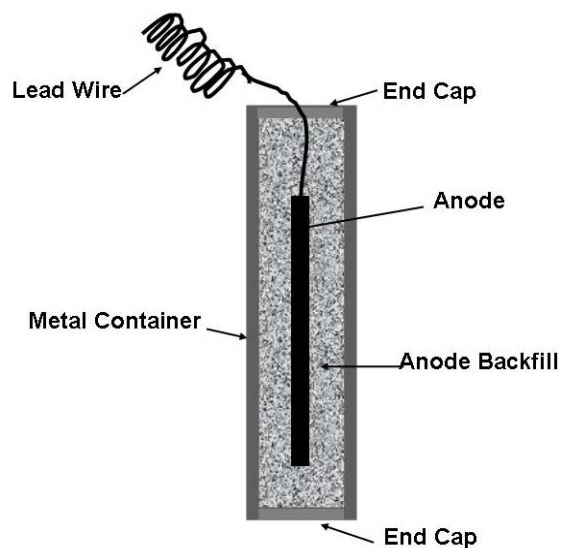


Figure 8.18 Prepackaged Impressed Current Anode

The conductor (negative lead wire) to the structure should be correctly connected. Conductor connections to the rectifier must be mechanically secure and electrically conductive. Before the power source is energized, it must be verified that the negative conductor is connected to the structure to be protected and the positive conductor is connected to the anodes. After the direct current power source is energized, appropriate measurements should be made to verify that the connections are correct.

Underground splices on the header cable (positive lead wire) to the groundbed should be kept to a minimum. Connections between header cable and conductors from anodes should be mechanically secure and electrically conductive. If buried or submerged, these connections must be sealed to prevent moisture penetration such that electrical isolation from the environment is ensured.

Care must be taken when installing direct burial cable to the anodes (positive lead wire) to avoid damaging insulation. Sufficient slack should be left to prevent strain on all wires. Backfill material around the cable should be free of rocks and foreign matter that might damage the wire insulation when wire is installed in the trench. Cable can also be installed by plowing if proper precautions are taken.

If insulation integrity on the buried or submerged header cable (positive lead wire), including splices, is not maintained, the cable will fail from electrolytic corrosion.

Surface Groundbed Configurations

General

Surface groundbeds are those where the anodes are installed either vertically or horizontally at a depth of typically five to fifteen feet below the surface. The anodes are usually connected to a header cable, which in turn is connected to the positive terminal of the rectifier.

Surface groundbeds are of either point or distributed configuration. Either vertical or horizontal anodes may be used in each. Each configuration is discussed below.

Vertical Anode Installation

Auger to the depth indicated on the plans. This is important as the design is based on the resistivity of the soil and the depth of the water table.

If you are installing bare anodes, place and thoroughly tamp the designed amount of coke breeze in the bottom of the hole. Lower in the anode using support ropes--do not lower the anode by the lead wire. Center the anode in the hole and thoroughly tamp layers of coke breeze backfill to the specified level above the top of the anode. Tamp native soil above the coke breeze to the level of the bottom of the header cable trench. Be very careful not to damage the anode lead wire insulation.

A similar procedure is used for prepackaged anodes. Although there is coke breeze within the canister, designs often call for coke breeze to be installed under, around, and over the canister.

A typical vertical anode installation is shown below in Figure 8.19.

Typical Vertical Anode Installation

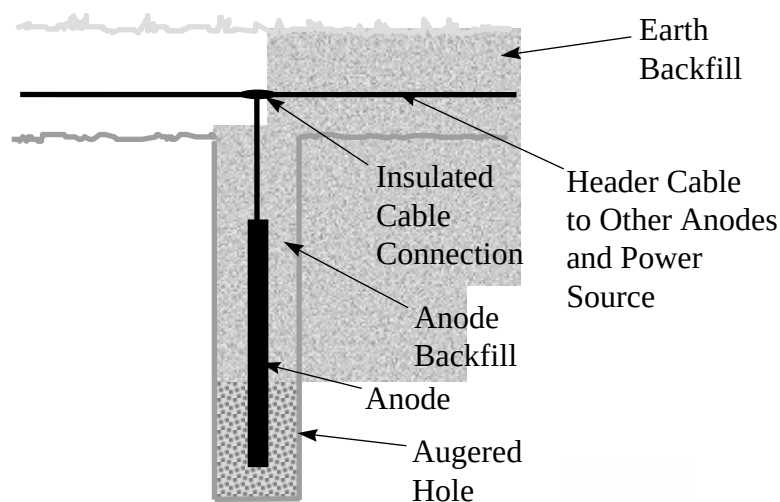


Figure 8.19 Vertical Impressed Current Anode

Horizontal Anode Installation

The first step in a horizontal installation is the installation of the anodes. This is done in a manner similar to that for a vertical anode installation. The anode installation depends on the spacing of the anodes. If the spacing is more than 10 feet, it is usually best to excavate a separate hole for each anode. With closer spacing, it is usually more economical to dig one long trench for both the header cable and the anodes.

Bare or prepackaged anodes may be used. They are installed, using coke breeze backfill, in a manner similar to that explained above for vertical anodes. Again, be certain to follow the design drawings and specifications during the installation.

Figure 8.20 illustrates a typical horizontal installation.

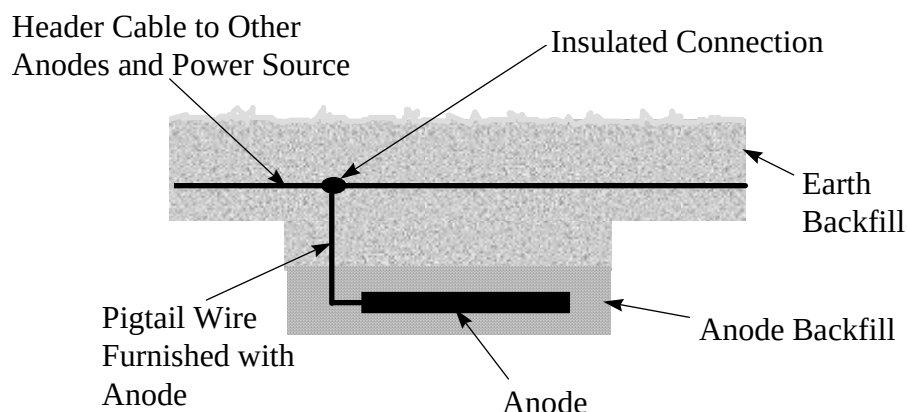


Figure 8.20 Horizontal Impressed Current Anode

Header Cable Installation

The header cable trench is usually dug by a backhoe or trencher to the specified depth in accordance with local code. Lay the header cable in the trench, again being very careful not to damage the cable insulation. Leave slack in all wiring. When long lengths of header cable are required such as, for example, in a surface distributed anode installation, the cable may be plowed in. When plowing in cable, be very careful not to damage the insulation.

Splice each anode lead wire to the header cable and carefully insulate the splice. The splice is the most critical part of the installation and must be done properly. Complete the installation by backfilling the header cable trench.

The cable should be laid on about three inches of sand or select backfill, and after all splicing is done, covered with about the same amount. Avoid getting any stones, debris, or other objects that might damage the cable into the backfill. Native soil is usually used to finish backfilling the trench.

If there is a concern over damage to the cable from future excavations, lay a plastic warning tape and perhaps a wooden plank about a foot over the cable. This precaution is especially important with surface distributed anode systems where there may be an extensive amount of cable in the ground.

Surface Remote Groundbed Configuration

In a remote groundbed, the anodes are placed in one location and the current flows from them to the protected structure. This configuration is typically used on transmission pipelines or in other places where there are few other structures that might be affected by the current.

A typical surface point installation is illustrated in Figure 8.21.

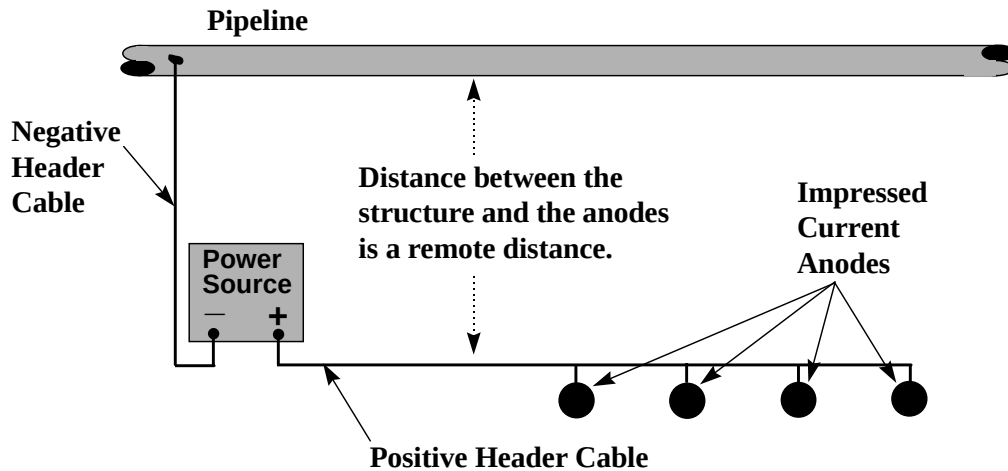


Figure 8.21 Surface Remote Groundbed Configuration

Distributed Anode Configuration

The distributed configuration is frequently used in complex areas to provide good current distribution and to minimize effects on other structures. A surface distributed groundbed is shown in Figure 8.22. Figure 8.23 illustrates a distributed impressed current bed protecting piling under a wharf.

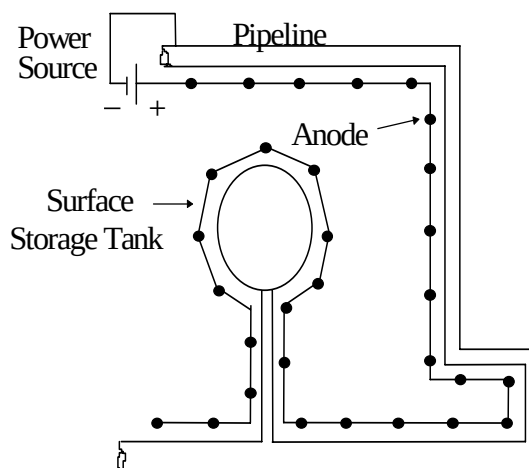


Figure 8.22 Surface Distributed Anode Groundbed Configuration

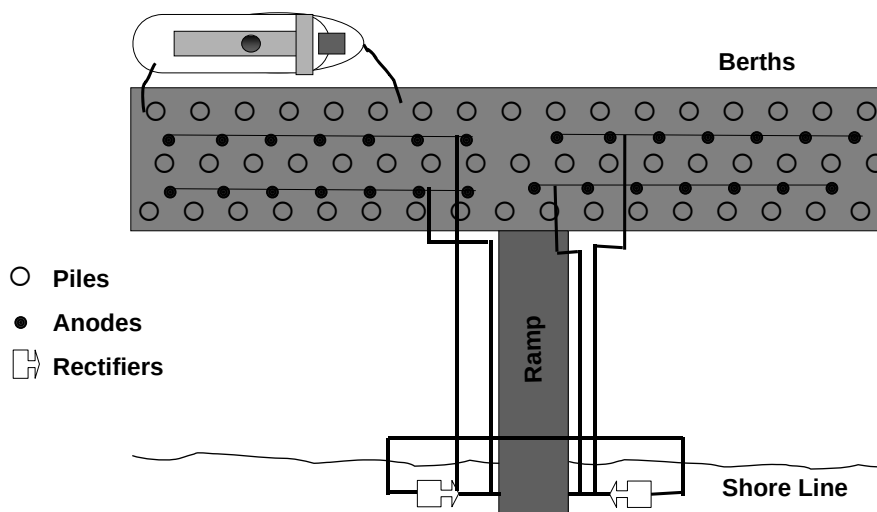


Figure 8.23 Distributed Anode Groundbed Protecting Wharf Piling

Deep Anode Groundbed Configuration

Deep anode installations are those where the anodes are installed in the bottom of a drilled hole. The general layout is shown in Figure 8.24.

The installation is begun by drilling a hole of the specified depth and diameter. An electrical log is frequently made of the hole to determine areas of lowest resistivity. This is done by measuring the resistance between a metal bar or anode lowered down the hole and some low resistance ground. The log helps to determine the desired locations for the anodes.

Anodes may be attached to a support pipe or in the case of light weight materials (e.g. MMO), may be lowered down the hole by the anode leads. Anodes usually have a centering device on them to keep them centered in the hole. These should not be made of nonmetallic material.

A slotted PVC vent tube is installed down to the bottom of the hole to vent off any gasses than may be generated by the electrolytic action of the anodes. This is important since accumulation of gas can increase the resistance of the anodes to ground.

The length of the hole containing the anodes is then filled with a fine coke breeze backfill. The backfill and anodes constitute what is known as the active column or anode area. The hole above the coke breeze may be filled with native soil, gravel, or simply left open.

The installation is completed by a length of surface casing (which may have been installed at the beginning of the drilling) with a cap on it. The vent pipe terminates in a screened cap.

The anode lead wires are led to a junction box and each lead is secured to a separate terminal. Each terminal is connected to the positive bus bar through a shunt so the individual anode outputs can be read. Be certain to mark each anode lead from bottom to top so that each can be identified in the junction box. A cable is then run from the positive bus bar to the positive terminal in the rectifier.

All deep anode groundbeds must be permitted, installed and completed in accordance with state and local codes.

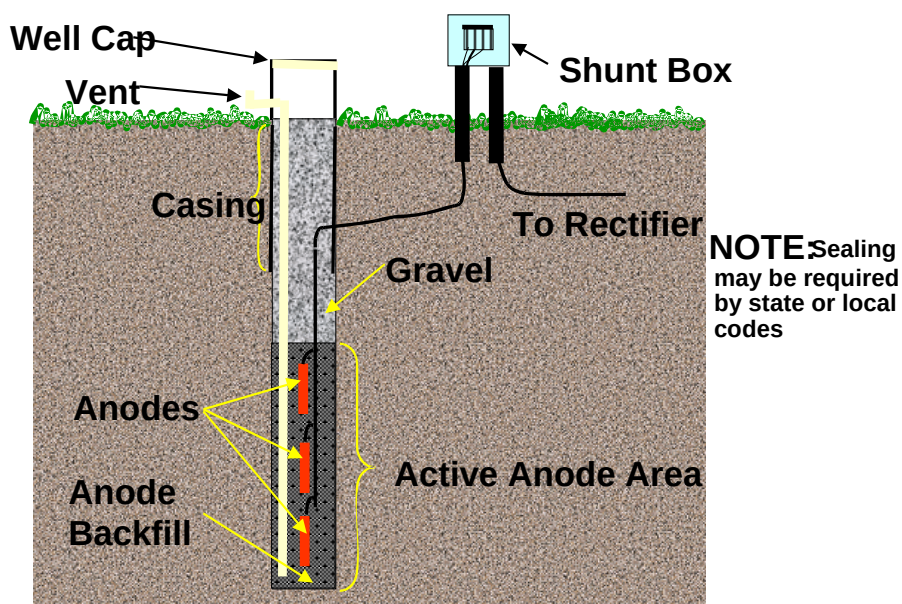


Figure 8.24 Deep Anode Installation

Negative Circuit

The *negative* or *return circuit* is the cabling from the structure to the rectifier. Be certain to follow the design specifications and drawings during installation.

Some cathodic protection designs have more than one negative circuit. This usually occurs when two or more facilities are being protected by a single rectifier. In order to control the current flowing to each structure, negative cables may be run to a junction box in which resistors can be placed. Follow wiring diagrams carefully to ensure the negative circuits are connected to the correct terminals in the junction box.

Be careful not to damage the insulation on the negative cable. Damage to the insulation is not as critical as it is on the positive cable, because the negative cable is on the cathodic side of the circuit. Still, precautions need to be taken in handling the negative cable.

The connection between the negative cable and the structure can be made by thermite welding or by a mechanical connection. Refer to the section on “Wire Attachment” for procedures and precautions.

Negative cables may be fairly heavy, ranging typically from No. 6 AWG to No. 2/0 AWG or larger. This size wire is too large to connect to a pipeline

with a single thermite weld. (Remember, a 15 gram charge is the largest that can be used on a steel pressure pipeline.) The strands of the cable may be crow-footed and welded using the correct size charge. In some cases, a lug can be welded to the pipe or other structure and the cable connected to the lug by exothermic welding or a mechanical connector.

Be certain to coat the negative connection in the same manner as test wires and other connections are coated.

Installation of Rectifiers or Other Power Sources

General

The rectifier or other power source should be inspected to ensure that internal connections are mechanically secure and that no damage is apparent. Rating of the direct current power source should comply with construction specifications. Care should be exercised in handling and installing.

Rectifiers or other power sources should be installed so that the possibility of being damaged or vandalized is minimized.

Wiring to rectifiers must comply with local and national electrical codes and the requirements of the utility supplying power. An external disconnect switch on AC wiring should be provided. The rectifier case must be properly grounded.

On thermoelectric generators, a reverse current device should be installed to prevent galvanic action between anode bed and structure if the flame is extinguished.

Rectifiers

General

What is commonly referred to as a *rectifier* is really a *transformer/rectifier unit*. The transformer reduces incoming AC voltage down to the operating voltage of the cathodic protection system. The rectifier changes the incoming alternating current to direct current for cathodic protection.



Some rectifiers don't have transformers, but utilize solid state circuitry to reduce the incoming power. These are called *switchmode rectifiers*.

AC Power and Wiring

AC wiring should be done by a licensed electrician. A fused switch box should be installed ahead of the rectifier so power to the entire unit can be turned off before any work is done on the rectifier.

Input voltage may vary from 480 volts to 115 volts. Both single phase and three phase power is used, depending on rectifier requirements and available power. Again, the AC wiring needs to be in the hands of a qualified electrician. As an inspector, however, you will want to be sure the unit is connected to the specified input voltage.

DC Output

Anode Circuit (Positive Circuit)

The portion of this circuit within the electrolyte has been discussed in detail previously in the sections on various types of groundbeds. At the rectifier, the anode cable is connected to the POSITIVE terminal, and the structure is connected to the NEGATIVE terminal. Be certain that this connection is made to the proper terminal. **Connecting a rectifier backward with the structure cable connected to the rectifier positive terminal will lead to rapid corrosion of the structure!**

Above ground wiring should be installed in conduit. Where explosion-proof installation is required, it is essential that all seals and other safety equipment be properly installed. In such cases, it may be well to have the above ground DC wiring done by a licensed electrician.

Negative Circuit

The *return* or *negative circuit* is the cabling from the structure to the rectifier.

The underground or underwater portion of this wiring has been discussed under "Impressed Current Groundbeds, Negative Circuit." The above ground portion is run, usually in conduit, to the rectifier negative terminal. Follow all of the precautions mentioned previously under "Anode Circuit" with regard to proper connection and installation.



Introduction

In this course we have been teaching you various techniques used to monitor cathodic protection. As previously discussed, monitoring is essential to ensure the continued proper performance of cathodic protection.

From time to time you will encounter problems with the cathodic protection you are monitoring. Many of these problems can be solved by some basic troubleshooting techniques when structure-to-electrolyte potential measurements indicate inadequate protection or when some other malfunction occurs.

Electrical Isolation

General

A single metallic contact (called a “short circuit” or “short”) can destroy the effectiveness of an entire cathodic protection system. The entire structure that is accidentally shorted to the protected facility becomes part of the system to be protected. The severity of the problem is determined by the relative structure-to-electrolyte potentials and the surface area of the shorted structure especially if it is at a less electronegative potential. If the shorted structure is a large bare unprotected structure then the potentials of the protected structure may not meet the criterion. If they are both protected structures, they become dependent on each other to maintain the respective cathodic protection systems.

Isolating Joint Shorts

The facility that is intended to be isolated may become shorted by a failure of the insulating material in the isolating joint or by a metallic bypass around the isolating joint. Testing of isolating joints is similar to casing isolation tests.

Where a pipeline appurtenance on each side of an underground isolating joint does not exist, at least two (2) test wires should be attached to each side of the underground isolation to allow testing and possible stray current mitigation. If contact to only one side is available some tests can be completed but stray current control by means of a bond could not be achieved in this case.

The tests that can be conducted include an “isolation checker”, structure-to-electrolyte potentials, interrupted structure-to-electrolyte potentials and a signal or noise trace.

Testing Above Grade Isolating Flange/Unions

Depending on the instrument, an “isolation checker” is specifically built to test either a below grade or an above grade isolation device (See Figure 9.1). For above grade isolation devices, the isolation checker probes are placed in contact with each side of the flange or union. A functioning electrical isolation device will show a full-scale deflection while an electrically shorted device will show a deflection toward zero on the scale. An audible “beep” will sound when the instrument is turned on and will increase when a short is detected. This instrument can also be used to test for a shorted isolating bolt or stud if it has double insulation.



Figure 9.1 Isolation Checker

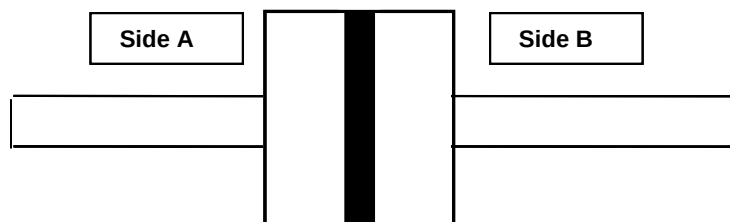
If the electrical isolating device is buried and test wires exist on both sides of it, an underground “isolation checker” may be used. This instrument is similar to the above grade isolation checker but is designed to be used only with an underground isolating fitting.

Note that these testers only check the effectiveness of the particular joint under test and are particularly useful to confirm which isolating joint is shorted in a header or where several are required to isolate a structure. The probes must be placed across the isolation but as close as possible together.

Structure-to-Electrolyte Potential for Isolation Testing

One can test the effectiveness of an isolating fitting using structure to electrolyte potentials. Placing the reference electrode in one location and not moving the electrode, a structure potential can be measured from each side of the fitting. If the structure potentials are identical or nearly identical, the possibility exists that the isolating fitting is shorted but more testing will be required to confirm it. If there is an appreciable difference in structure potentials from one side of the fitting to the other, the two sides of the fitting are electrically isolated.

Example



Flange Side	Isolated	Short Suspected
A	$-1.560 \text{ V}_{\text{CSE}}$	$-0.875 \text{ V}_{\text{CSE}}$
B	$-0.950 \text{ V}_{\text{CSE}}$	$-0.874 \text{ V}_{\text{CSE}}$

Interrupted Structure-to-Electrolyte Potential to Test Isolation

Using a current interrupter installed in the nearest CP current source, the protective current can be cycled “on” and “off”. Measuring an “on” and “off” structure to electrolyte potential on each side of the isolating device can determine if the device is functioning or not. With a functioning electrical isolating device, the side with the current source that is interrupted will have a more negative “on” potential than the “off” potential and the two values will be cycling on the same timing as the current interrupter. On the opposite side of the isolating device, the “on”

and “off” potentials will be nearly the same and sometimes, the “off” potential will be more negative than the “on” potential.

If the isolating device is shorted, the “on” and “off” potentials will be the same on each side of the isolating device and the potentials on both sides will be changing on the same timing cycle as the current interrupter.

Example

Flange Side	Isolated		Shorted	
	ON	OFF	ON	OFF
A	$-1.560 V_{cse}$	$-0.950 V_{cse}$	$-0.875 V_{cse}$	$-0.750 V_{cse}$
B	$-0.950 V_{cse}$	$-0.948 V_{cse}$	$-0.875 V_{cse}$	$-0.750 V_{cse}$

Current Profile

In a pipeline system, it may be possible to locate a short by tracing current flow. In a distribution system, where metallic service lines are electrically continuous with the mains, a failed isolating fitting at the meter will cause a short circuit. Cathodic protection current lost to other structures through this short will return to the main on the service line. Using a clamp-on ammeter, service lines in the affected area can be tested. Alternately current attenuation equipment can be used to measure current at different points. A shorted insulation at the end of a service or short section of pipe will be indicated by an unusually large current in this pipe (Figure 9.2).

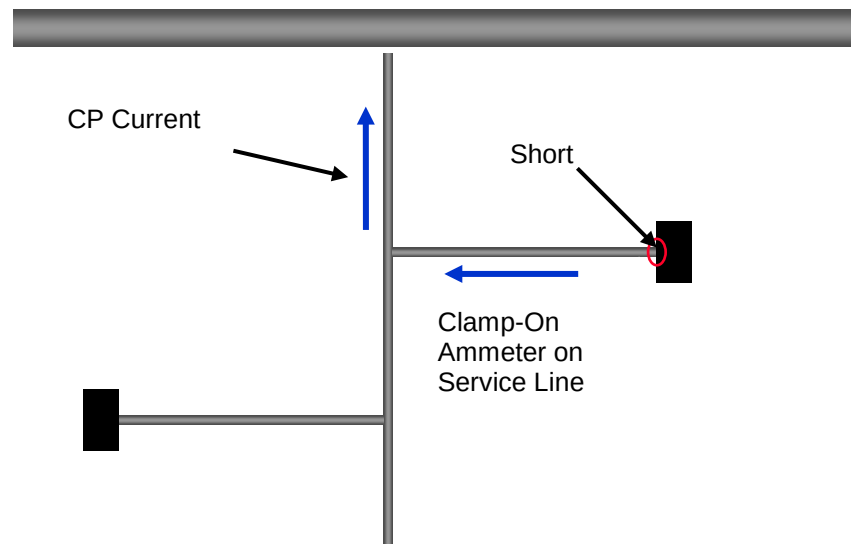


Figure 9.2 Locating a Short Through Current Flow

If a sudden increase in current occurs on either side of a pipeline crossing, an underground contact may be indicated (Figure 9.3).

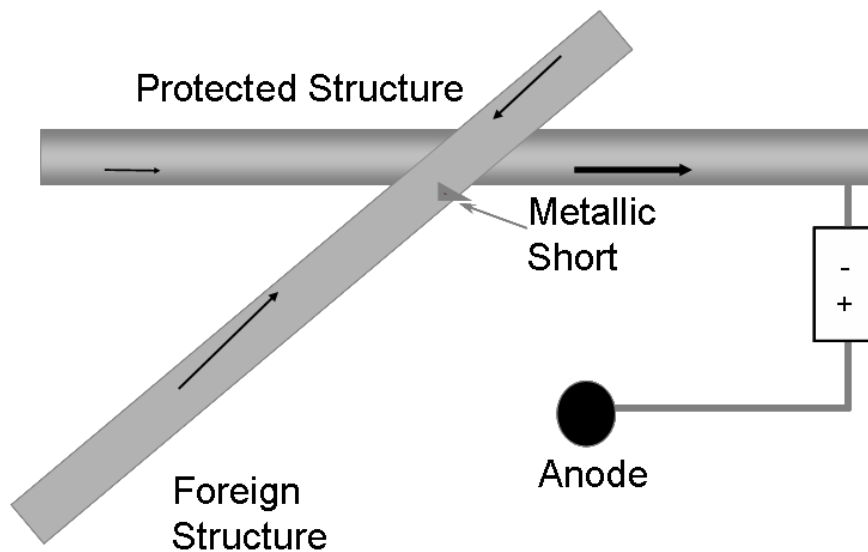


Figure 9.3 Pipeline Current at an Underground Contact

Tone Generator

Audio tone pipe locators are very useful for finding shorted isolating fittings or underground contacts. The transmitter creates a low frequency signal that is carried to the pipe through test wires. The signal creates an electromagnetic field around the pipe. The receiver picks up this field. The signal will travel only along electrically continuous paths.

Use caution when connecting and disconnecting this type of locators as high voltages may be involved. Also, do not use this type locator in an explosive atmosphere as a spark might cause ignition.

The transmitter is connected between the pipeline and a suitable ground such as a steel post, probe bar, etc. If a service line is shorted, the signal will travel up the line and across the isolating fitting. If an underground contact exists, the signal will generally be lost on the pipeline under test at this point and will be found on some other structure, often running at an angle from the pipeline. Figure 9.3 shows a typical situation.

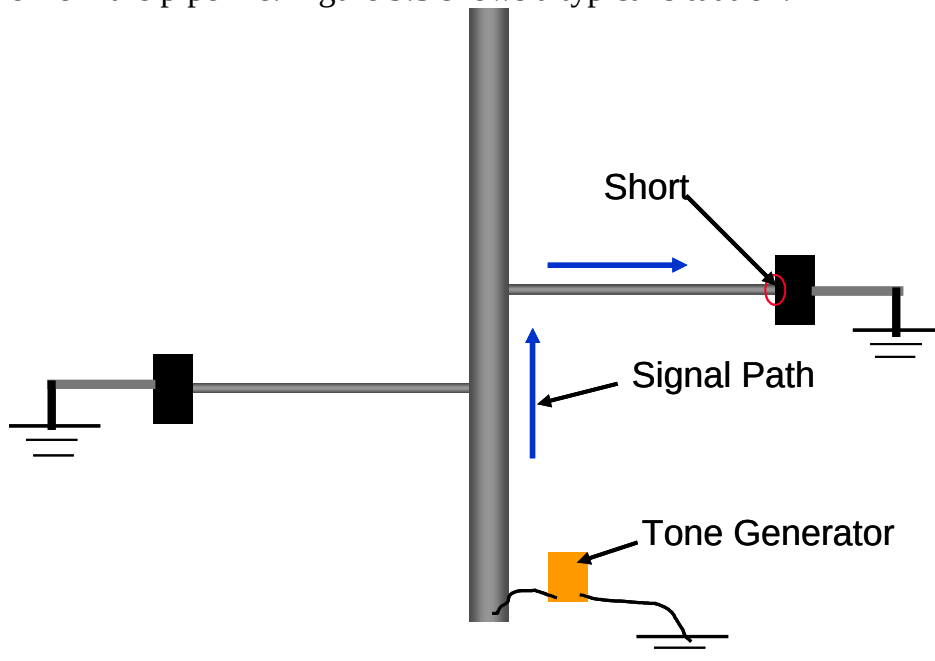


Figure 9.4 Using Audio Tone Locator to Find Shorts

Casing Shorts

Road and railroad casings must be electrically isolated from the carrier pipe to allow cathodic protection of the pipeline inside the casing and to avoid an unnecessary large current drain on the cathodic protection system. If the casing is shorted the casing will “intercept” the majority of the cathodic protection current intended for the pipeline inside and thus reduce the effectiveness of protection on the pipeline. Unfortunately the potential of the pipe inside the casing is not reflected in a structure-to-electrolyte potential taken at the ground surface. That is, the potential at the surface may indicate that the pipe is meeting a criterion when in fact it is not.

A casing may experience either a “metallic short” or an “electrolytic couple”. A “metallic short” is a metal-to-metal contact between the casing and the carrier pipe. Such a short will usually cause an electropositive shift in the pipe-to-electrolyte potential along the pipeline in the area of the casing. This means that the potential will become less electronegative through the casing area, for example, from $-950 \text{ mV}_{\text{CSE}}$ on the pipeline away from the casing to $-750 \text{ mV}_{\text{CSE}}$ at the casing. The electropositive shift is especially pronounced if the casing is bare. Discovery of such a change in the usual pipe-to-electrolyte potentials should lead you to suspect a shorted casing as a possible cause. If a metallic short exists, the structure potentials to a copper-copper sulfate electrode will be essentially the same from the pipe and the casing test wires however they may coincidentally be the same. Thus more than one test should be conducted to confirm a short.

An “electrolytic couple” occurs when a low resistance electrolyte such as water or mud gets into the annular space between the casing and the carrier pipe, the pipe-to-electrolyte potential of the casing may shift with the application of current. If the casing is isolated the shift on the casing will not be as great as that of the pipeline and there will still be a potential difference between the pipe and the casing.

Structure-to-Electrolyte Potential Survey

A simple way of testing for a metallic short is to measure the pipe-to-soil potential on the pipe and the casing with the reference electrode remaining in the same location. This requires test wires on the pipeline and casing or if no wires on the casing, the vent can be used (Figure 9.5).

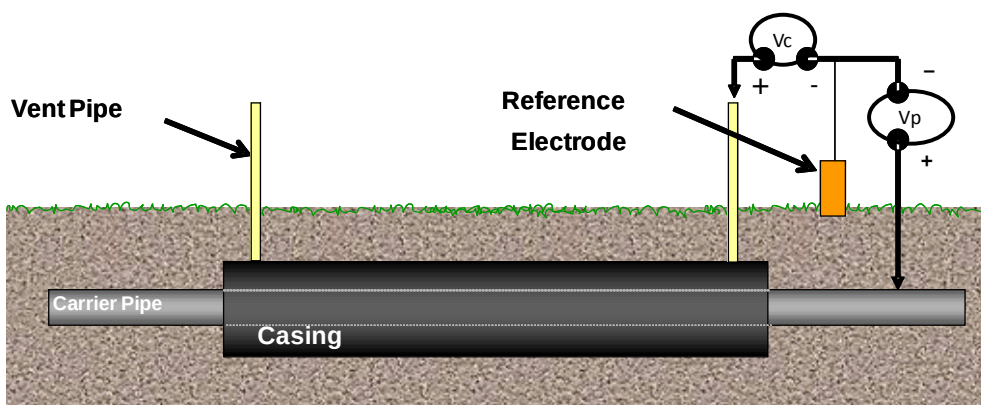


Figure 9.5 Measuring the Pipe-to-Electrolyte and Casing-to-Electrolyte Potential using the same Reference Electrode Location

There should be a difference of 100 mV or more between the pipe-to-soil potentials of the casing and the pipeline, or if not, another casing test must be conducted (see also NACE SP0200).

Example

	Short Suspected	Isolated
Casing	-0.900 V _{CSE}	-0.750 V _{CSE}
Pipe	-0.900 V _{CSE}	-0.910 V _{CSE}

Interrupted Structure-to-Electrolyte Potential Survey

This test involves either interrupting the nearest cathodic protection source or applying additional interrupted current to the pipeline to cause a change in the pipe-to-electrolyte potential. Measure the “on” and “off” structure-to-electrolyte potentials from both the casing and carrier pipes. If the casing potentials cycle in unison with the carrier pipe potentials and the “on” potentials on the pipe and the casing are the same and the “off” potentials on the pipe and the casing are the same, then the casing and carrier pipe are likely electrically shorted. If the casing potentials are shifting in the opposite direction to that of the pipe or are shifting only slightly between the “on” and “off” compared to those on the pipe, then the two structures would not be shorted. Again, the reference electrode should be located near the end of the casing pipe and must not be moved during these sets of measurements.

Example

	Shorted		Isolated	
	ON	OFF	ON	OFF
Casing	-1.56 V _{CSE}	-1.00 V _{CSE}	-1.00 V _{CSE}	-1.00 V _{CSE}
Pipe	-1.56 V _{CSE}	-1.00 V _{CSE}	-1.56 V _{CSE}	-1.00 V _{CSE}

Care should be taken during the interpretation of this data. If the CP current source is in close proximity to the casing, it is possible for the casing potentials to shift between the “on” and “off” cycle as a result of being in the anodic gradient of the CP source.

Other Casing Surveys

A complete description of the various casing tests is given in NACE SP-0200. If there is any doubt about the conclusion with the tests completed, additional tests need to be conducted.

An ohmmeter cannot be used to test the resistance between a pipe and a casing, first due to the parallel path through the soil and secondly due to the voltage between the pipe and the casing interfering with the ohmmeter circuit. In the first case the resistance between the pipe and the casing through the soil can be very low. If the pipe and casing are isolated then the voltage between them will either aid or oppose the ohmmeter voltage and when connected one way will indicate a high resistance and when the leads are reversed a low resistance will be indicated.

Cathodic Protection Levels

There are several factors that can affect the level of cathodic protection. The following are possible problems that should be investigated to determine a loss of cathodic protection.

- Reduced cathodic protection current.
 - The structure-to-electrolyte potentials will vary in proportion to the current applied.
- Groundbed malfunctions.
 - The groundbed resistance will increase as the anodes fail until the rated voltage output of the rectifier can no longer provide the needed current.
- Broken continuity bonds.
 - A faulty bond will isolate a portion of the structure intended for cathodic protection.
- Shorted isolation.
 - If a shorted isolation connects a structure with a less electronegative potential, the potential of the structure being protected will also become less electronegative.
- Underground contact to a foreign structure
 - An underground contact will have the same effect as a shorted isolation.
- Shorted casing
 - A shorted casing will cause a high current drain on the system that will result in a more electronegative potential in addition to shielding the pipe inside as discussed above.
- Stray current interference
 - Stray current will cause the potential to become more electronegative at the point of current pick up and less electronegative at the point of discharge. Note that the

interfering source must be interrupted to properly assess interference.

- Inaccurate measurements.
 - A high resistance contact between the reference electrode and the soil, contaminated reference electrodes, high structure contact resistance, cracked wires or faulty meters will all contribute to inaccurate measurements.

These problems are discussed in more detail in other parts of this manual.

Groundbed Malfunctions

Galvanic and Impressed Current Groundbeds

Anode Deterioration

Anode deterioration leads to reduced anode size. As the anode size diminishes, the resistance of the anode to the electrolyte increases. As the resistance increases, the current output for a given voltage drops. If you find you must increase rectifier voltage from time to time to maintain the desired current, anode deterioration may be the cause.

Improper Backfill

Anode backfill must be thoroughly tamped in layers around the anodes so that the backfill is in good contact with the anode. This permits electronic transfer of current from the anode to the backfill, extending the anode life. If anodes have not been backfilled properly, the backfill will not fully serve its purpose and deterioration of the anode itself will be accelerated. This will lead to increased anode-to-earth resistance and decreased anode life.

Cable Breaks

Cable breaks may be caused by third party damage from excavation or from discharge of current from positive cables. If a splice has been poorly insulated or if the wire is exposed at breaks in the insulation, rapid

deterioration of the wire will ensue. Such cable breaks are indicated if there is a sudden reduction in the rectifier current output.

A break can occur in the negative cable, too. When this happens, the rectifier current usually drops to zero. If the cable comes loose from the structure, but remains close to it, the rectifier output current may drop, but not to zero. This is caused by the fact that the current is returning to the negative cable through the electrolyte. Note that if this happens, accelerated corrosion of the structure will occur at the point of discharge.

Gas Venting Problems

This is a common problem in deep groundbeds and in tightly packed soils. It occurs because gas (e.g., oxygen or chlorine) generated by the anodic reaction cannot permeate away from the anode. The gas increases the anode to earth resistance, thus reducing the rectifier current output.

Drying of Soil

In times of drought or very low soil moisture content, soil resistivity increases appreciably. This will cause an increase in the groundbed resistance to earth. Higher voltage settings will be necessary to produce the desired current.

Before making major changes in the voltage output, however, check the level of cathodic protection on the structure. In high soil resistivities, less current is required for protection than in soils of low resistivity. You may be able to maintain protection, therefore, with less current during dry periods than otherwise.

Rectifiers

Routine Maintenance

Many problems with rectifiers can be prevented by regular maintenance. The primary objective of a good rectifier maintenance program is the prevention of failures and prompt repair when failures do occur. For energy pipelines, regular monitoring is required by code.

If certain basic observations are undertaken each time a routine rectifier reading is to be made, many potential failures can be avoided. The following list of observations can lead to early detection of a potential problem.



- Listen for unusual noises.
- Look for signs of heat (discoloration).
- Look for vent obstructions.
- Look for significant output changes.
- Smell for unusual odors (examples: rotten egg–selenium failure, ozone–insulation failure, burning–insulation failure).
- Feel for unusual heat. (Turn off power before touching live components.)

At least once each year (usually at the time of the annual corrosion survey), rectifiers should be thoroughly and systematically inspected. Special attention should be given to the following items:

- Clean and tighten all current-carrying connections.
- Clean all vent screens and remove any obstructions.
- Remove any insect or animal nests and plug entry points.
- Check indicating meters for accuracy by comparing with calibrated portable instruments.
- Replace any wire with cracked or deteriorated insulation.
- Check all protective devices (circuit breakers, fuses, or lightning arrestors) for evidence of damage.
- Carefully inspect for evidence of excessive heating.
- For oil immersed units, check color and level of oil. Change oil if rectifier components cannot be seen beneath the oil.

Output Problems

A good maintenance program can often detect potential rectifier failures before they occur allowing scheduled repair before an actual outage. Even with the best of maintenance programs, however, failures do occur. Often basic step-by-step troubleshooting techniques can determine the cause of the outage. For the following discussions, only standard single-phase, manual adjustment type rectifiers are considered.

When checking rectifier outputs on a routine basis, there are four basic cases of symptoms requiring investigation: zero current and voltage outputs, zero current output with unchanged output voltage, significant current change with unchanged voltage, or significant changes in both voltage and current outputs.

Zero Current and Voltage Outputs:

For the case of zero output for both current and voltage, either there is no input power to the unit or an open circuit within the rectifier is indicated. First, determine if input AC voltage is present. If not, the problem is external to the rectifier. If AC voltage is present at the input terminals, an open circuit exists within the rectifier. However, the open circuit may be due to a tripped circuit breaker at the rectifier input.

The component causing the open circuit can be located by realizing that the rectifier voltage must exist across the open circuit element. If it is determined that the input circuit breaker has tripped, a high current or overload has occurred. This high current could have been a temporary problem, perhaps due to a lightning surge, or a permanent short circuit. The best method of proceeding is to reduce the voltage output tap to a low level and reset the circuit breaker. If the circuit breaker does not trip again, the problem was probably temporary and full output voltage can be restored. If the circuit breaker does trip, a permanent short circuit is indicated.

To determine if the short circuit is external to the rectifier, disconnect one of the DC output connection leads and reset the breaker. If the short circuit is external to the rectifier, the circuit breaker will not trip. If the short circuit is internal to the rectifier, the circuit breaker will again trip. If the problem appears to be in the rectifier, a qualified person should be contacted to diagnose and repair it or it should be returned to a rectifier manufacturer for repair.

The sequence in Figure 9.9 describes a short in the rectifier.

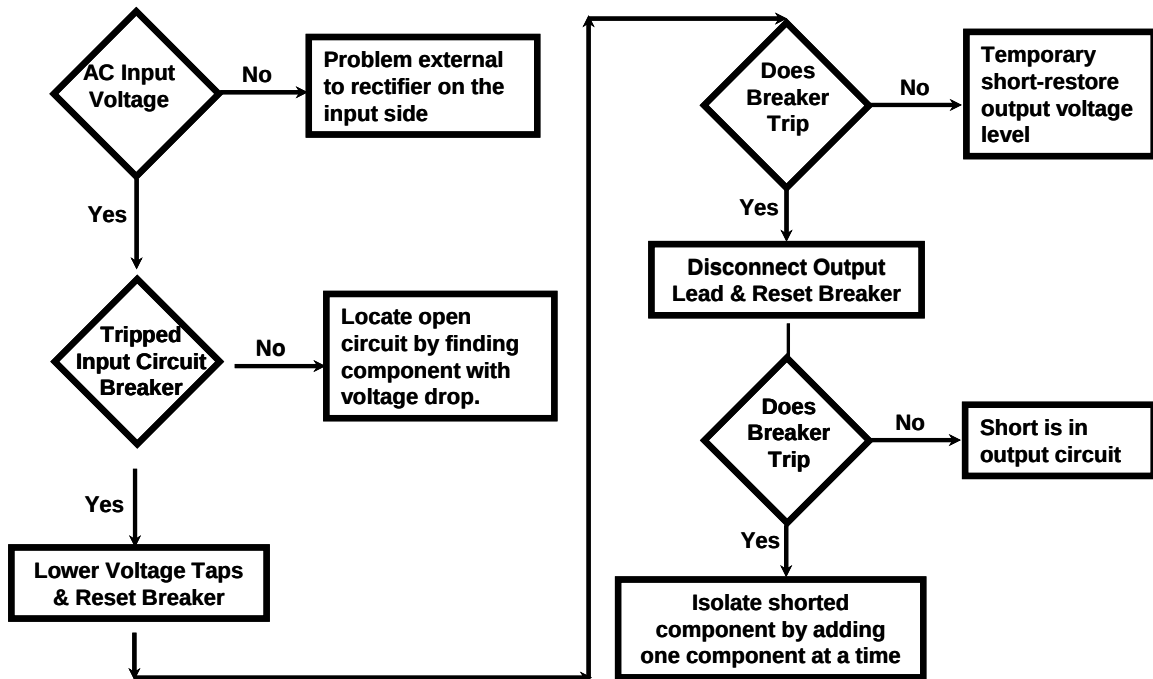


Figure 9.9 Short in a Rectifier

Zero Current Output with Unchanged Voltage Output

If the DC voltage output of the rectifier is relatively unchanged but the current output is zero, an open output circuit is indicated. This could be caused by:

- Open fuse in the output circuit
- An open positive or negative lead wire
- A failed groundbed.

If an open fuse in the output circuit is found, a short exists (or has existed) in the output circuit.

Significant Current Change with Unchanged Voltage

If the DC current output significantly changes with no change in the output voltage, the output circuit resistance has changed. If the current output has significantly increased, a lower circuit resistance is indicated. This could be due to system additions, shorts to other underground structures, or major coating damage. If the current output significantly decreased, a higher circuit resistance is indicated. Some of the possible causes might include installation of inline isolators, groundbed deterioration, discontinuity due to disconnection of system component, or gas blockage. Seasonal variations in

soil conditions, such as drying or frost, can also increase the current resistance.

Significant Changes in Both Voltage and Current Outputs

Sometimes both the voltage and current outputs will decrease significantly. If the voltage and current outputs are approximately one-half of the normal values, the most probable cause is partial failure of the rectifier stacks ("half waving"). If the rectifier stacks are found to be operating properly, the transformer should be investigated for possible winding-to-winding shorts.