



CP 2–Cathodic Protection Technician Course Manual

January 2010
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Basic Chemistry and Electrochemistry Review

Meter Operation Review

Glossary of Terms

“Factors Affecting the Accuracy of Reference Electrodes”, Frank Ansuini and James R. Dimond, Materials Performance, November, 1994 (NACE International, Houston, TX).

“A Guide to Understanding Electrode Readings”, Robert M. Park, Materials Performance, September, 2009 ((NACE International, Houston, TX).

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 Tank Systems”

TM0102 “Measurement of Protective Coating Electrical Conductance on Underground Pipelines”

MSDS Sheet for Copper Sulfate Pentahydrate



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.

[illegible]

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 2–Cathodic Protection Technician Course Outline

DAY ONE	
	Introduction, Welcome, Overview
Chapter 1	Corrosion Theory
DAY TWO	
Chapter 2	Cathodic Protection Fundamentals
Chapter 3	Cathodic Protection Systems
Chapter 4	DC Power Sources for Cathodic Protection
DAY THREE	
Chapter 4	DC Power Sources for Cathodic Protection (continued)
Chapter 5	Safety
Chapter 6	Field Measurements
	Introduction to Indoor Field Measurement Test Stations
	Indoor Field Measurement Test Station Practice
DAY FOUR	
	Outdoor Field Program (weather permitting)
Chapter 7	Stray Current and CP Interference
	Indoor Field Measurement Test Stations
DAY FIVE	
Chapter 8	Monitoring and Records
	Timed Practice with Indoor Field Measurement Test Stations
	Course Review
DAY SIX	
	Written and Practical Examinations



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.

The CP 2–Cathodic Protection Technician training course is the second course in the 4-level NACE Cathodic Protection Training and Certification Program. This course will focus of the topics of corrosion theory, cathodic protection principles and systems, advanced field testing and data collection.

Audience (Who Should Attend)

This course is designed for persons who either have a heavy engineering/scientific background and some working knowledge of cathodic protection, or who have extensive years of field experience with some technical background.

Prerequisites

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

Path 1:

- 3 years cathodic protection work experience
- High School diploma or GED
- CP 1–Cathodic Protection Tester certification or equivalent training

Path 2:

- 1 year cathodic protection work experience
- 4-year Physical Science or Engineering degree
- CP 1–Cathodic Protection Tester certification or equivalent training



Path 3:

- 2-year post high-school training from an approved Math or Science Technical or Trade School
- 2 years cathodic protection work experience
- CP 1–Cathodic Protection Tester certification or equivalent training

Length

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

Reference Books

Students have the option of selecting one of the following reference books: *Peabody's Control of Pipeline Corrosion, Second Edition* or *Pipeline Corrosion and Cathodic Protection, Third Edition*.

Experiments

Throughout the week there will be in-class experiments to help demonstrate 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

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.

Tests and Quizzes

Chapter quizzes will be distributed to students during the week and reviewed in class by the instructors.

The CP 2–Cathodic Protection Technician course has both written and practical (hands-on) final examinations. The final examinations will be given on Friday.



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

The final 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 presented 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.

Certification Application

Successful completion of both the written and practical examination and approval of the CP 2–Cathodic Protection Technician certification application is *required* before certification will be issued.



Cathodic Protection Certification Application
CP 2 - Cathodic Protection Technician
(Must be submitted to NACE Headquarters for certification to be processed)
Please Note – This Is **Not** A Class Or Exam Registration

NACE Member: ☐ Yes ☐ No Member # _____

Applicant's Name: _____

Home Address: _____

Company Name: _____

Company Address: _____

Country: _____ Zip/Postal Code: _____

Phone: Home _____ Business _____ Fax _____

E-mail: _____

SIGNATURE: _____ DATE: _____

PRINTED NAME: _____

REQUIREMENTS NECESSARY TO ACHIEVE CERTIFICATION

To achieve this certification, qualified individuals have two options (see each option for prerequisites):

CLASSROOM TRAINING - CP2 - Cathodic Protection Technician

or

EXAM ONLY OPTION - CP 2-Cathodic Protection Technician Exam Only

APPLICATION PROCEDURE

It is strongly recommended that Exam Only candidates submit a completed application for certification at least 60 days in advance so that work experience requirements and education prerequisites can be verified.

RECERTIFICATION REQUIREMENTS

Every three (3) years. Recertification requires a minimum of 2 years work experience in cathodic protection and 8 hours per year (24 hrs total) of professional development hours.

SUBMIT COMPLETED APPLICATION AND SIGNATURE PAGES TO:

**MAIL TO: NACE INTERNATIONAL
CERTIFICATION DEPARTMENT
1440 SOUTH CREEK DRIVE
HOUSTON, TX 77084**

OR FAX TO: 281-228-6311

If you have any questions, please contact Marie Newton in our Certification department at 281-228-6211 or by e-mail at marie.newton@nace.org.

AFFIRMATION

I affirm that:

1. I understand that I am **solely** responsible for making sure that all necessary work experience documentation is complete and submitted in good order to NACE Headquarters.
2. I understand that if I knowingly provide, or cause to be provided, any false information in connection with my recognition under the NACE International Training and Certification Program, that it will be grounds for action against my understanding in the program.
3. I understand that the names of the categories within the NACE International Cathodic Protection Training and Certification Program are as follows:

Highest Level Successfully Completed	Category Name
CP 1	CP1-Cathodic Protection Tester
CP 2	CP2-Cathodic Protection Technician
CP 3	CP3-Cathodic Protection Technologist
CP 4	CP4-Cathodic Protection Specialist

4. NACE has a firm policy regarding the use of its logos and certification numbers and titles. The certification number and category title may be used only by NACE CP 1-Cathodic Protection Testers, NACE CP 2-Cathodic Protection Technicians, NACE CP 3-Cathodic Protection Technologists, and NACE CP 4-Cathodic Protection Specialists, and may not be used by any other persons.

All active CP card holders are permitted to use the term "NACE CP 1-Cathodic Protection Tester," "NACE CP 2-Cathodic Protection Technician," "NACE CP 3-Cathodic Protection Technologist," or "NACE CP 4-Cathodic Protection Specialist" (whichever level of recognition attained) and their certification number on business cards.

This example illustrates how this information can be used by a NACE CP 1-Cathodic Protection Tester.

John Smith
NACE CP 1-Cathodic Protection Tester, Cert. No. 9650
ACE Inspections, Inc., Knoxville, TN

NACE CP 1-Cathodic Protection Testers, NACE CP 2-Cathodic Protection Technicians, NACE CP 3-Cathodic Protection Technologists, and NACE CP 4-Cathodic Protection Specialists who are members in good standing of NACE International may display the NACE Logo for the purpose of identifying the individual as having achieved a NACE Certification.

I understand that violation of these rules will result in action against my standing in the program on the basis of violation of the NACE International Cathodic Protection Program Attestation.

5. I (re)affirm the NACE International Cathodic Protection Certification Program attestation and agree to abide by its provisions as long as I hold any level of recognition under the program.

Signed: _____

Date: _____

THIS DOCUMENT MUST BE SIGNED AND RETURNED WITH APPLICATION
RETAIN A COPY OF THIS DOCUMENT FOR YOUR RECORDS

ATTESTATION

I hereby:

- (1) Recognize and acknowledge that the proper control of cathodic protection can be critical to the safety and welfare of the general public and industrial facilities.
- (2) Recognize and acknowledge that the control of cathodic protection is obligatory to maximize conservation of our material resources, to reduce economic losses, and to protect the environment.
- (3) Recognize and acknowledge that the entire field of cathodic protection and its control encompasses the application of the knowledge and experience of many diverse disciplines and levels of technical competence which must often be consulted.
- (4) Recognize and acknowledge that only through continual association and cooperation with others in this field can the safest and most economical solutions be found to the many cathodic protection problems.
- (5) Recognize and acknowledge that the quality of my work reflects on the entire profession of corrosion control.

For these reasons I:

- (1) Agree to give first consideration in my cathodic protection work to public safety and welfare and to protection of the environment.
- (2) Agree to apply myself with diligence and responsibility to the cathodic protection work that lies within my area of competence.
- (3) Agree to pursue my work with fairness, honesty, integrity and courtesy, ever mindful of the best interests of the public, my employer, and of fellow workers.
- (4) Agree to not represent myself to be proficient or make recommendations in phases of cathodic protection work in which I am not qualified by knowledge and experience.
- (5) Agree to avoid and discourage untrue, sensational, exaggerated, and/or unwarranted statements regarding my work in oral presentations, written text, and/or advertising media.
- (6) Agree to treat as confidential my knowledge of the business affairs and/or technical process of clients, employers, or customers when their interests so require.
- (7) Agree to inform clients or employers of any business affiliations, interests, and/or connections which might influence my judgment.
- (8) Agree to uphold, foster and contribute to the achievement of the objectives of NACE International.

I understand that my failure to comply with these requirements could result in disciplinary action.

Signature: _____

Printed Name: _____

Date: _____

**THIS DOCUMENT MUST BE SIGNED AND RETURNED WITH APPLICATION
RETAIN A COPY OF THIS DOCUMENT FOR YOUR RECORDS**

NAME: _____

PLEASE CHECK APPROPRIATE BOX (choose only one):

☐

I AM APPLYING FOR CP 2 **CLASS & EXAM** SCHEDULED FOR:

(Please list city/dates of course you are planning to attend) _____



Click here for COURSE SCHEDULE

OR

☐

I AM APPLYING FOR CP 2 **EXAM ONLY** SCHEDULED FOR:

(Please list city and date of exam you are planning to attend) _____



Click here for EXAM ONLY SCHEDULE

REQUIREMENTS FOR Cathodic Protection Technician

Please provide the necessary **cathodic protection** work experience in accordance with the following requirements for acceptance in class or exam checked. Cathodic protection is defined as a technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

CP 2 CLASS & EXAM

3 years **cathodic protection** work experience **REQUIRED**

PLUS

High school diploma or GED **REQUIRED**

CP 1 Certification or equivalent training **REQUIRED**

OR

1 year of **cathodic protection** work experience **REQUIRED**

PLUS

4-year Physical Science or Engineering Degree **REQUIRED**

PLUS

CP 1 Certification or equivalent training **REQUIRED**

OR

2 years **cathodic protection** work experience **REQUIRED**

PLUS

2-year post-high school training from approved Math or Science Technical/Trade School **REQUIRED**

PLUS

CP 1 Certification or equivalent training **REQUIRED**

CP 2 EXAM ONLY

3 years **cathodic protection** work experience **REQUIRED**

PLUS

High school diploma or GED **REQUIRED**

CP 2 class or equivalent training **RECOMMENDED**

OR

1 year of **cathodic protection** work experience **REQUIRED**

PLUS

4-year Physical Science or Engineering Degree **REQUIRED**

PLUS

CP 2 class **OR** equivalent training **RECOMMENDED**

OR

2 years **cathodic protection** work experience **REQUIRED**

PLUS

2-year post-high school training from approved Math or Science Technical/Trade School **REQUIRED**

PLUS

CP 2 class or equivalent training **RECOMMENDED**

Please provide the necessary **cathodic protection** work experience in accordance with above requirements for acceptance in class or exam checked.

S A M P L E

Form 1: Summary of **Cathodic Protection** Related Work Experience

Instructions: Make and use as many copies of this form as needed. Please provide all information requested. Forms must be printed legibly in black ink or typed. Illegible information can delay the application process. For assistance with this form, contact the Education Division at NACE International Headquarters.

Applicant Information:

Name: A. Sample Phone: 409/111-4321

Company: ZZZ Coating Inspection Inc. Fax: 409/111-1234

Address: 987 Gage Avenue

City: Millspec State/Province: TX

Zip/Postal Code: 77987 Country: USA

Please summarize below the information on each copy of Form 2, Individual Job Documentation. List your experience beginning with the most recent, followed by less recent experience.

From Month/Year	To Month/Year	Number of Months in this job	Job Title	Company Name
1/92	1/95	36	CP pipeline readings	ZZZ Gas Co.
12/89	12/91	24	Installer	AAA Tank Installers
12/87	12/89	24	Design Manager	ABC CP Design
/	/			
/	/			
/	/			
/	/			
/	/			
/	/			
/	/			

Applicant Affidavit: I understand that if I knowingly provide false information in connection with my recognition under this program, it will be grounds for disciplinary procedures.

Signed: XXX

Date: _____

Form 1: Summary of **Cathodic Protection** Related Work Experience

Instructions: Make and use as many copies of this form as needed. Please provide all information requested. Forms must be printed legibly in black ink or typed. Illegible information can delay the application process. For assistance with this form, contact the Education Division at NACE International Headquarters.

Applicant Information:

Name: _____ Phone: _____

Company: _____ Fax: _____

Address: _____

City: _____ State/Province: _____

Zip/Postal Code: _____ Country: _____

Please summarize below the information on each copy of Form 2, Individual Job Documentation. List your experience beginning with the most recent, followed by less recent experience.

From Month/Year	To Month/Year	Number of months in this job	Job Title	Company Name
/	/			
/	/			
/	/			
/	/			
/	/			
/	/			
/	/			
/	/			
/	/			
/	/			

Applicant Affidavit: I understand that if I knowingly provide false information in connection with my recognition under this program, it will be grounds for disciplinary procedures.

Signed: _____

Date: _____

Page ____ of ____

Job Information

E-mail: _____

Page ____ of ____

THIS SECTION MUST BE COMPLETED
Your application will be returned if this space is left blank

[illegible]

Signed: _____ Date: _____

Education and Training – CP Technician

NAME: _____

Please check applicable statement of qualification:

☐ 3 years **cathodic protection** work experience as documented in this application and hold a high school diploma or GED.

PLUS

CP Tester Certification or equivalent training as listed below (exam and course only) OR

CP Technician class or equivalent training as listed below (exam only)

OR

☐ 1 year **cathodic protection** work experience as documented on this application and a 4-year Physical Science or Engineering Degree (please complete information below and attach a copy of your degree)

PLUS

CP Tester Certification or equivalent training as listed below (exam and course only) OR

CP Technician class or equivalent training as listed below (exam only)

OR

☐ 2 years **cathodic protection** work experience as documented in this application and 2-year post high school training from approved Math or Science Technical/Trade School (please complete information below and attach copy of your diploma/certificate).

PLUS

CP Tester Certification or equivalent training as listed below (exam and course only) OR

CP Technician class or equivalent training as listed below (exam only)

EQUIVALENT TRAINING OR TRADE/TECHNICAL SCHOOL INFORMATION

Please list equivalent training OR trade/technical trade school information by providing name of school, course or training, company providing training, date of training, etc.

DEGREE INFORMATION

<u>Name of College or University</u>	<u>Degree Received</u>	<u>Date Awarded</u>	<u>Student ID Number</u>
_____	_____	_____	_____
_____	_____	_____	_____

QUALIFICATION REFERENCE

APPLICANT: Complete Items D.1, D.2, and D.3 then forward this form to the person you have listed in Item D.3. Ask this person to complete the remainder of the form and return it directly to NACE International.

Qualification references may be submitted by the following, who have expertise in the **CATHODIC PROTECTION** field:

- Registered or chartered engineers
- Present and/or previous supervisor(s) of the applicant
- Present and/or previous professors/instructors of the applicant
- NACE International certificate holders. (For Corrosion Specialist and Specialty Area applicants, one Qualification Reference must hold a NACE Certificate at the level being applied for or higher, a P.E. registration, ICorr Professional Member or international equivalent.)

D.1 Applicant's full name: _____

D.2 Certification category applied for: _____

D.3 Name, title, address, and phone # of person who is familiar with the work experience of the applicant:

_____ Phone: _____

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D.4 I hold NACE Certification as a:

_____ Certified _____ No. _____

_____ I am a Registered engineer (or equivalent) _____

_____ State/Province: _____ Branch: _____ No: _____

Leave space blank if this section is not applicable

D.5 I have known the applicant for _____ years. What is/was the nature of the association?

Current Supervisor	_____	Previous Supervisor	_____
Current Client	_____	Previous Client	_____
Current Co-worker	_____	Previous Co-worker	_____
Current Professor/Instructor	_____	Previous Professor/Instructor	_____
Other	_____		

D.6 From personal knowledge, my assessment of the applicant's character and personal reputation is that it is

Excellent ☐ Average ☐ Below average ☐

D.7 From personal knowledge, I know that the applicant has been engaged in cathodic protection work for _____ years. (**"cathodic protection" is defined as a technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.**)

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Yes ☐ No ☐

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D.12 Additional remarks or amplifying information:

D.13 My signature below indicates that I have personal knowledge and expertise in the **CATHODIC PROTECTION** field upon which to evaluate the applicant's professional capabilities.

Signature: _____ Date: _____

Printed Name: _____

Return completed form to: NACE International, Certification Department, Attn Marie Newton, 1440 South Creek Drive, Houston, TX 77084-4906 USA

CP 2 – Cathodic Protection Technician must have:

CP Tester Certification or equivalent training **PLUS one** of the following:

1. 3 years CP work experience **PLUS** high school diploma or GED including algebra and logarithm training
2. 1 year CP work experience **PLUS** 4-year physical science or engineering degree
3. 2 years CP work experience **PLUS** 2-year post high school training from an approved math or science technical/trade school including algebra and logarithm training

CP 3 – Cathodic Protection Technologist must have:

CP Technician certification or equivalent training **PLUS one** of the following:

1. 8 years CP work experience with progressively increasing technical responsibilities **PLUS** high school diploma or GED **PLUS** algebra and logarithm training
2. 6 years CP work experience with progressively increasing technical responsibilities **PLUS** 2 years post high school training from an approved math or science technical/trade school including algebra and logarithm training
3. 3 years CP work experience with progressively increasing technical responsibilities **PLUS** 4 year physical science or engineering degree

CP 4 – Cathodic Protection Specialist must have:

CP Technologist certification or equivalent training **PLUS one** of the following:

1. 12 years CP work experience including 4 years in responsible charge **PLUS** 2 years post high school training in math or science from an approved technical/trade school
2. 6 years CP work experience including 4 years in responsible charge **PLUS** 4-year engineering or physical science degree
3. 4 years CP work experience in responsible charge **PLUS** a bachelors degree in engineering or physical sciences **PLUS** an advanced degree in engineering or physical science that required a qualification exam

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Leave space blank if this section is not applicable

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Current Supervisor	_____	Previous Supervisor	_____
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3. 2 years CP work experience **PLUS** 2-year post high school training from an approved math or science technical/trade school including algebra and logarithm training

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CP Technician certification or equivalent training **PLUS one** of the following:

1. 8 years CP work experience with progressively increasing technical responsibilities **PLUS** high school diploma or GED **PLUS** algebra and logarithm training
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_____ I am a Registered engineer (or equivalent) _____

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CP 3 – Cathodic Protection Technologist must have:

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3. 4 years CP work experience in responsible charge **PLUS** a bachelors degree in engineering or physical sciences **PLUS** an advanced degree in engineering or physical science that required a qualification exam

Qualification References

A qualification reference is a person who will vouch for your technical competence. Two Qualification References are required, four are recommended. You are asked to give the names of persons (unrelated to you and not more than one from your company) who have personal knowledge of your cathodic protection experience and abilities or of your teaching in a cathodic protection-related field. Acceptable references are registered engineers, present supervisor, present clients, previous supervisors, previous clients, professors and instructors, and NACE International Certificate holders of at least the same category for which you are applying.

NOTE: You are to send these individuals a Qualification Reference form (Item D), which they must complete and return directly to NACE International. This is your responsibility. You should follow up with these people to ensure that they correctly complete and return the Qualification Reference forms in a timely manner.

Name #1 _____
Name #2 _____
Name #3 _____
Name #4 _____

(Optional)

Please describe below any information which you wish to be considered by the Application Review Board (such as, but not limited to: education [college, trade school], publications on corrosion subjects, other technical papers or books that you have authored or co-authored, any patents you have obtained as a direct result of your efforts, etc.). You may attach a maximum of two, single sided pages of additional information if you desire. Attachments of more than two single-sided pages will not be reviewed.

MAKE A COPY OF ALL PAGES OF THIS APPLICATION FOR YOUR RECORDS

The 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 that consists of four parts:

- Anode
- Cathode
- Electrolyte
- Electronic/Metallic Path

The electrons generated by the formation of metallic ions at the anode pass through the electronic path to the surface of the cathodic areas immersed in the electrolyte. They restore the electrical balance of the system by reacting with positive ions in the electrolyte.

Referring to Figure 1.1, let us examine the process of corrosion for a single corrosion cell consisting of a single anode and a single cathode existing on the same metallic surface in water. The metal provides the anode, cathode, and electronic path of the corrosion cell. The water provides the electrolyte to complete the corrosion cell. The electrolyte has ionized so that hydrogen (H^+) and hydroxyl (OH^-) ions are present in small amounts (10^{-7}).

Metal ions leave the anodic surface going into the electrolyte, leaving behind electrons, which flow in the metallic path to the cathodic surface. At the cathodic surface, the electrons from the anode meet hydrogen ions from the solution. One hydrogen ion accepts one electron and is converted into a hydrogen atom. The hydrogen atom may combine with another hydrogen atom to form a molecule of hydrogen gas, which may either cling to the cathodic surface or be released as a bubble. In some cases, the hydrogen atom may enter the metal lattice and lead to hydrogen embrittlement (to be discussed under “Environmental Cracking”).

Single Corrosion Cell

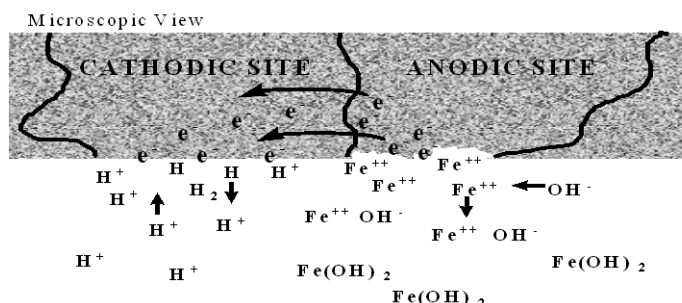


Figure 1.1 A Single Microscopic Corrosion Cell

Meanwhile, the metal ions combine with hydroxyl ions in the electrolyte to form metal hydroxide, or rust, which precipitates onto the metal surface.

As this process continues, oxidation (corrosion) of the metal occurs at the anodic surfaces and reduction of hydrogen ions occurs at the cathodes.

The graphite-zinc dry cell battery, as shown in Figure 1.2, often is used to illustrate the corrosion cell. As illustrated, zinc (anode) is electrically connected through an external load to carbon (cathode) in the presence of a corrosive electrolyte. When they are electrically connected, the corrosion cell is completed with the anodic reaction at the zinc and the cathodic reaction at the carbon electrode. The battery is depleted as the zinc is consumed.

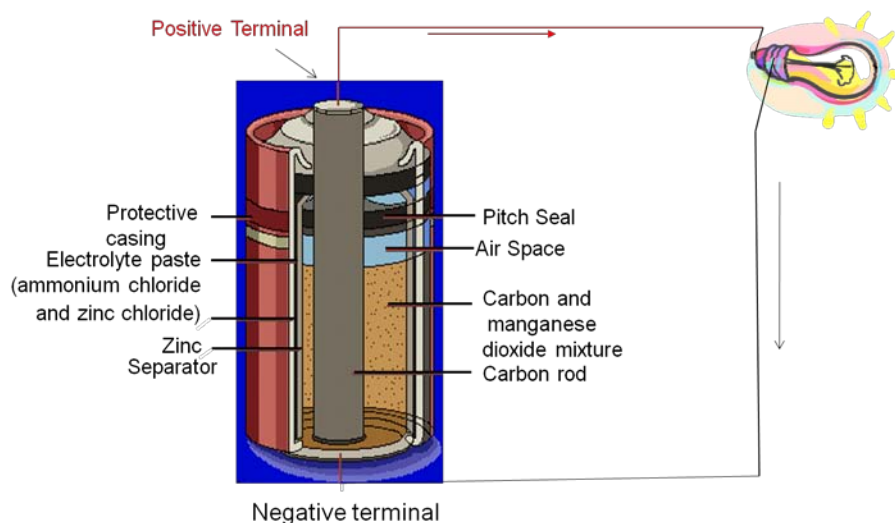


Figure 1.2 Graphite Zinc Battery

Remember: The term “oxidation” is not necessarily associated with oxygen.

Driving Force for Corrosion

Voltage

Corrosion involves a process in which electric charge 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?”

Voltage is the measure of the electrochemical difference between two electrodes in an electrolyte. A metal immersed in an electrolyte will begin to corrode and exhibit what is known as an electrode potential. The electrode potential represents the reversible work to move a unit charge from the electrode surface through the solution to the reference electrode. It is equal to the potential difference between two points for which 1 coulomb of electricity will do 1 joule of work in going from one point to another. The electrode potential is measured against a standard reference cell.

Metal

The metal itself may be a source for the driving voltage of a corrosion cell. A difference in voltage may arise due to variations in: grain structure of a metal, composition formed during alloying, temperature or deformation of a single metal surface developed during fabrication.

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 used 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. The higher the energy, the more active the metal and the more tendency it has to corrode.

A typical cycle is illustrated by iron. The most common iron ore, hematite, is an oxide of iron (Fe_2O_3). The most common product of the corrosion of iron, rust, has the same chemical composition. The energy required to convert iron ore to metallic iron is “returned” when the iron corrodes to form the oxide.



Energy Cycle of Steel

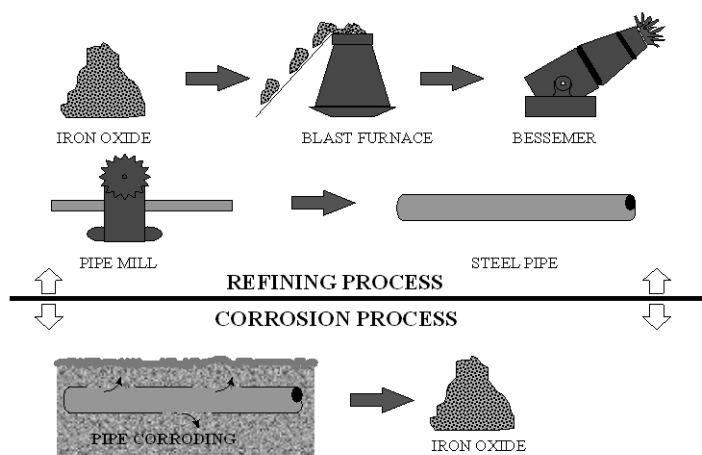


Figure 1.3 Refining Process of Steel

Figure 1.3 illustrates the refining and corrosion processes for iron and steel. Iron always is found in an oxidized state. It is mined from the ground as an ore. Energy is used to convert this iron oxide into iron and steel. It is loaded into a blast furnace where heat energy removes the oxygen and leaves elemental iron. It is then alloyed with other materials and loaded into a Bessemer furnace. Finally, it is rolled in a pipe mill, rod mill, etc., to form pipe, rebar, or structural shapes. When iron contacts an electrolyte, such as the earth or concrete, corrosion occurs. In the corrosion process, energy is lost and the iron combines with oxygen to form iron oxide. This corrosion product, rust, is identical to the iron oxide mined from the ground. Iron is considered thermodynamically unstable; given the right environment, iron will readily corrode to return to a lower energy state, such as rust.

Electromotive/Galvanic Series

The potential difference between metals exposed to solutions containing the respective ions at unit activity is represented in the standard emf series shown in Table 1.1. In this series, the metals are arranged from the most noble (e.g., gold) to the most active (e.g., magnesium).

Table 1.1 Partial Standard emf Series of Metals

Half-cell	Metal	Standard Electrode Potential E_o (volts) vs. SHE*
Au/Au ⁺⁺⁺	Gold	+1.498
Pt/Pt ⁺⁺	Platinum	+1.200
Cu/Cu ⁺⁺	Copper	+0.345
H ₂ /2H ⁺	Hydrogen	0.000
Pb/Pb ⁺⁺	Lead	-0.126
Ni/Ni ⁺⁺	Nickel	-0.250
Fe/Fe ⁺⁺	Iron	-0.440
Zn/Zn ⁺⁺	Zinc	-0.763
Al/Al ⁺⁺⁺	Aluminum	-1.662
Mg/Mg ⁺⁺	Magnesium	-2.363

*** Standard Hydrogen Electrode**

When two electrodes are placed in the electrolyte, electrochemical reactions will occur on each. If, for instance, one electrode is copper and the other is zinc, each will corrode and exhibit an electrode potential (as measured against a reference electrode). The potential between the two electrodes, also called the *electromotive force* (emf), is equal in sign and magnitude to the electrode potential of the anode less the electrode potential of the cathode. This emf or voltage between the two electrodes is the driving force for electrochemical corrosion. Note that the emf of a corrosion cell cannot necessarily be predicted from the standard emf series because (1) the emf series is produced under a standardized set of environmental conditions, and (2) metals polarize when connected together and this affects the voltage between them.

If a metallic path connects the two electrodes, the voltage difference will cause a current to flow between them (Figure 1.4). Current is the net transfer of electric charge per unit time.

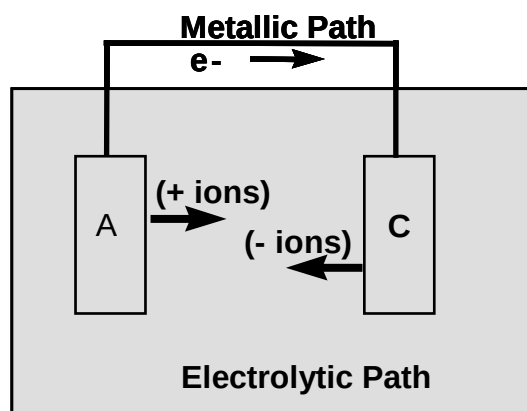


Figure 1.4 Charge Flow in an Electrochemical Corrosion Cell

When electrically interconnecting two different metals in a common electrolyte, the more active metal will tend to become the anode of the corrosion cell.

The standard emf series is a means of organizing metals in order of their tendency to corrode. The standard emf series has its limitations, as stated above. A more useful method of ordering metals is the galvanic series. A galvanic series is based on the behavior of a metal in a particular electrolyte and the most common electrolyte used is seawater. Table 1.2 lists a partial practical galvanic series in seawater.

Table 1.2 Practical Galvanic Series in Seawater

Metal	Volts vs. Cu-CuSO₄	Volts vs. Ag-AgCl
	Active or Anodic End	Active or Anodic End
Magnesium	-1.60 to -1.75	-1.55 to -1.70
Zinc	-1.10	-1.05
Aluminum	-1.05	-1.00
Clean Carbon Steel	-0.50 to -0.80	-0.45 to -0.75
Rusted Carbon Steel	-0.30 to -0.50	-0.25 to -0.45
Cast/Ductile Iron	-0.50	-0.45
Lead	-0.50	-0.45
Steel in Concrete	-0.20	-0.15
Copper	-0.20	-0.15
High Silicon Iron	-0.20	-0.15
Carbon, Graphite	+0.30	+0.35
	Noble or Cathodic End	Noble or Cathodic End

Nernst Equation

The Nernst Equation expresses the exact electromotive force of a cell in terms of the activities of products and reactants of the cell.

$$E = E^{\circ} + \frac{RT}{nF} \ln \left(\frac{a_M^{+ne}}{a_M} \right) \quad \text{Eq. 1-1}$$

where:

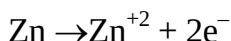
- E° = Standard state half-cell electrode potential
- E = Electrode potential in existing solution
- a_M^{+ne} = Activity of metal ions in solution
- a_M = Activity of the metal ($a_M = 1$ for pure metal)
- R = Universal gas constant = 8.31431 joules, $^{\circ}\text{K}^{-1}$, mole $^{-1}$
- T = Absolute temperature (K) = 298.2 $^{\circ}\text{K}$
- n = Number of electrons transferred
- F = Faraday's constant (96,500 C/equivalent)

This equation shows that the metal ion concentration in the electrolyte affects the potential of the electrode. Potentials of metals listed in various publications are based on a stated set of conditions. Standard conditions for pure metals in the emf series are based on one unit activity of metal ions in the electrolyte at 25 $^{\circ}\text{C}$ with no impurities in the metal or electrolyte and with reference to a standard hydrogen electrode.

The equation is often simplified by converting to logarithms to base 10 by multiplying by 2.303. Then the coefficient RT/F is often condensed to the value 0.0592 V, which is derived from $R=8.31431$ joules, $^{\circ}\text{K}^{-1}$ ·mole $^{-1}$, $T=298.2$ $^{\circ}\text{K}$, $F=96,500$ C/equivalent. The Nernst Equation then becomes:

$$E = E_0 + \frac{0.059}{n} \times \log \left(\frac{a_M^{+ne}}{a_M} \right) \quad \text{Eq. 1-2}$$

As an example, we will calculate the potential of zinc in a 0.01 molar zinc chloride solution at 25 $^{\circ}\text{C}$:



1. From Table 1.1, $E_0 = -0.763\text{V}$ vs. standard hydrogen electrode
2. $n = 2$ (see Table 1.3)



3. From a table of activity coefficients found in engineering handbooks, the activity coefficient for zinc chloride is 0.71 at a molar concentration of 0.01 and the activity of metal ions in solution [a_M^{+ne}] is equal to the activity constant times the molar concentration.
4. The activity of pure zinc, $a_M = 1$

$$E = -0.763 + \frac{0.059}{2} \times \log \left(\frac{0.71 \times 0.01}{1} \right)$$
$$\therefore E = -0.827 \text{ V}$$

Table 1.3 Valence of Common Metals

Metal	Valence
Aluminum	3
Copper	2
Iron	3
Iron	2
Lead	2
Zinc	2

Later in the course, various experiments will be conducted that involve the measurement of metal potentials with reference to a copper-copper sulfate reference electrode. Your results might be slightly different from the data in published tables because of differences in ion concentration between the table and the experiments. The higher the concentration of metal ions, the less active (or more noble) the metal.

Temperature Differences

In a temperature cell, the anode and cathode are of the same metal, but one is maintained at a higher temperature than the other by some external means. In most cases, the electrode at the higher temperature becomes the anode.

A gas transmission line emerging from a compressor station serves as an example. The just-compressed gas is hot and, as it travels down the line, the pipe loses heat by transfer to the surrounding soil (as well as losing some by expansion). The hot pipe near the compressor is the anode; the cooler pipe down the line is the cathode; the soil is the electrolyte; and the pipe itself is the connecting circuit. This is a particularly difficult type of corrosion cell because the high temperature just outside the compressor may damage the coating, so

that the part of the line that is the anode also is likely to have the poorest coating. See Figure 1.5.

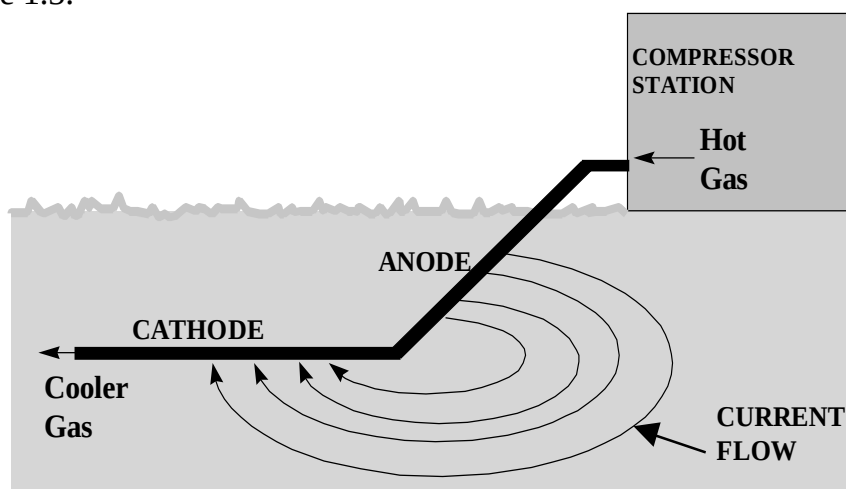


Figure 1.5 Temperature Difference Along a Metal Structure

Oil and gas well casings also experience similar corrosion cell attack. The pipe casing deep below the surface is at a higher temperature than the pipe near the surface and thus becomes the anode. (This is a natural phenomenon—temperature increases with depth.) The cooler pipe near the surface and the surface piping make up the cathode. The soil is the electrolyte and the pipe is the connection. Note that this cell operates in the same direction as the oxygen cell that will be discussed later in this chapter. Both tend to concentrate the corrosion on the deeper portion of the casing.

Effects of Alloying

During the process of alloying, the grain boundaries can become enriched or depleted of specific alloying elements. These differences in alloy composition may cause intergranular corrosion. Another common corrosion problem found in some alloys involves selective leaching, corroding of the more active alloying element in the solid matrix, such as zinc leaching from brass alloys or iron leaching from cast iron.

Metal Fabrication

During the fabrication of structures, metals may experience variations in stress. Highly stressed areas of a metal will tend to be at higher energy levels, thus more active than less stressed areas. Also, improper welding procedures may be responsible for corrosion due to incompatibility of welding rods or sensitizing of the adjacent metal.

Electrolyte

Corrosion cells may form because of differences in the electrolyte. For example, when a single metal structure spans an electrolyte made up of different types of soils, different chemical substances, different concentrations of the same substance, or temperature variations, the structure may experience voltage differences (see Figure 1.6). Another example of this is a reinforced concrete bridge deck where the top layer of reinforcing steel is exposed to salt contamination. A macro corrosion cell develops between the top rebar in salt-containing concrete and the bottom rebar layer in uncontaminated concrete.

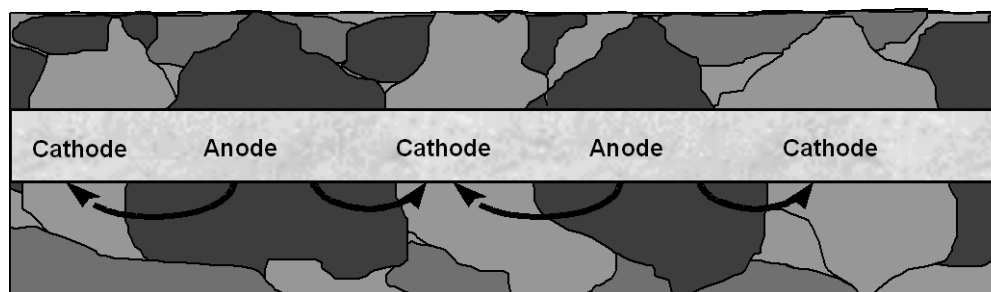


Figure 1.6 Corrosion Cells in Dissimilar Soils

If one electrolyte is a dilute salt solution and another is a concentrated salt solution, a concentration cell may form. This takes place because one of the factors determining an electrode potential is the electrolyte concentration. A similar cell is formed when the two electrolytes contain entirely different dissolved substances.

Concentration Cells

Concentration cells are responsible for much of the corrosion that takes place in soils. Pipelines, for example, pass through different soils on their way across the land. Oil and gas well casings penetrate various strata of different compositions. In every case of different soils in contact with a single piece of metal, a concentration cell is possible. This is particularly true for bare or poorly coated pipe.

In many cases in naturally occurring soils, that portion of pipe lying in the more conductive soil is the anode; that in the less conductive soil is the cathode. Moist soils themselves act as the electrolyte (in this case, a compound electrolyte) and the pipe itself is the connecting circuit between the anode and cathode sites. The current flows from the anodic area to the soil, through the soil and from it to the cathodic area, then along the pipe to the anodic area, as shown in Figure 1.7.

Types of Concentration Cells

When a simple salt is involved, and is not a salt of the metal that makes up the electrodes, the electrode in the higher concentrated solution may be the anode, as shown in Figure 1.7. When the electrolyte contains a salt that is of the metal and no other salts are present, then the metal surface in the dilute solution usually is the anode.

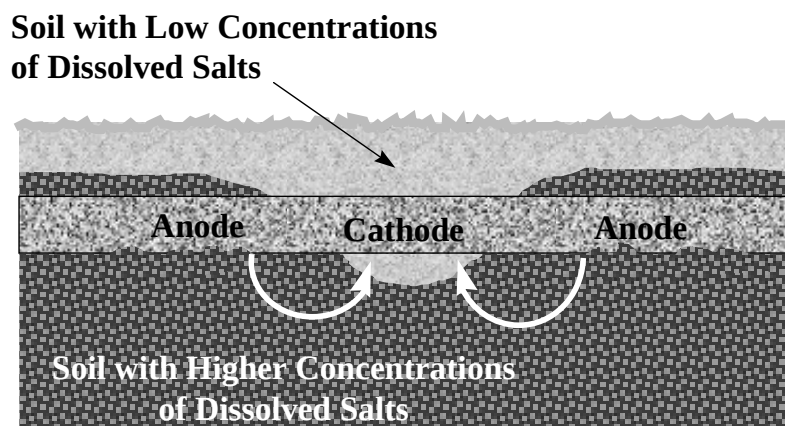


Figure 1.7 Ion Concentration Cell

The two most common types of concentration cells involved in promoting corrosion are oxygen and metal ion.

Oxygen Concentration Cell

Oxygen is the most common of the cathodic depolarizers. The oxygen content of any electrolyte ranks high on the list of factors influencing the corrosion of iron and numerous other metals. Oxygen can maintain and promote a cathodic reaction.

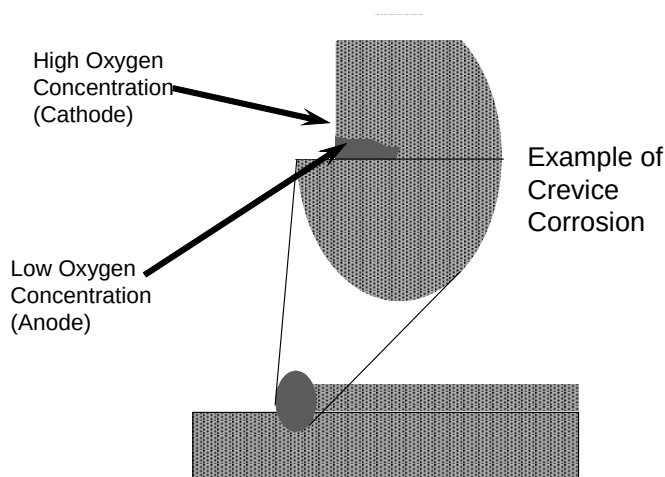


Figure 1.8 Oxygen Concentration Cell

Surfaces in contact with the solution containing a higher concentration of oxygen will become cathodic, as shown in Figure 1.8.

Oxygen concentration cells may occur on buried pipes. For example, the pipe usually rests on undisturbed soil at the bottom of the ditch. Around the sides and on the top of the pipe is relatively loose backfill that has been replaced in the ditch. Because the backfill is more permeable (than undisturbed earth) to oxygen (and the path is shorter) diffusing down from the surface, a cell is formed. The anode is the bottom surface of the pipe, and the cathode is the rest of the surface. The electrolyte is the soil, and the connecting circuit is the pipe metal itself. This explains why most corrosion on pipelines is on the bottom portion of the pipe.

When buried metal passes under pavement, such as an airport runway, parking lot, or street, as shown in Figure 1.9, the portion of the piping under the pavement has less access to oxygen than the piping in the unpaved soil. Thus a cell is formed: the anode is the metal under the pavement; the cathode is the metal outside the pavement; the electrolyte is the soil; and the connecting circuit is the metal itself. Although the entire length of pipe under the pavement could be anodic, most of the attack will take place not far from the edge of the pavement where the oxygen concentration difference is greatest.

Oxygen Concentration Corrosion Cell

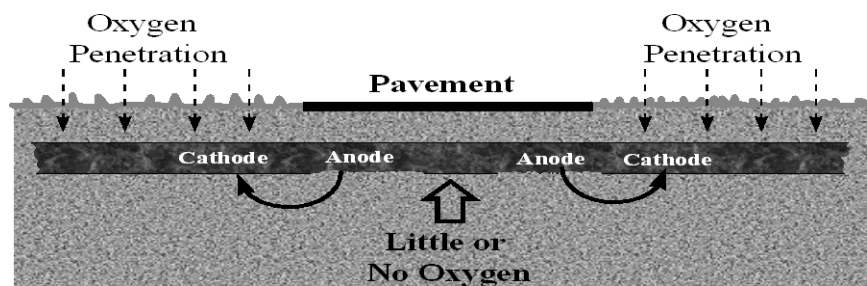


Figure 1.9 Oxygen Concentration Cell Example

The casing of an oil or gas well usually is connected to a network of surface piping, which lies just below the surface. This can form an oxygen concentration cell: the casing, at depth, forms the anode; the surface piping, with greater access to oxygen, becomes the cathode; again, the soil is the electrolyte; and the piping and casing together make the connecting circuit. Isolating the surface piping from the casing by means of a special isolating union or fitting can control the action of this cell.

Oxygen concentration cells are responsible for much of the corrosion near the water line on piling driven into the bed of the sea or in fresh water bodies. Wave action maintains a constant supply of oxygen to the metal just below the surface, while at greater depths there is little oxygen penetration.

Metal Ion Concentration Cell

Metal ion concentration cells exist where there is a lower concentration of ions at one point on a metal surface and a higher concentration at another point.

The surface in contact with lower concentration of metal ions acts as the anode.

Effects of pH

Theoretically, the potential of a structure changes by about 60 mV for each pH unit. For example, the corrosion potential (E_{CORR}) of a metal might be -500 mV in an environment with a pH of 7, but the value of E_{CORR} will be -560 mV at a pH of 8. This can lead to galvanic corrosion cells caused by differences in environment pH.

Environments with an acidic pH can also be harmful to concrete, such as reinforced concrete structures and concrete coated structures (e.g., pipes). The acid dissolves the alkaline components in the cement paste causing the concrete to fall apart. A pH less than 5 is considered harmful to concrete.

Corrosion Rate

The rate of corrosion is directly proportional to current flow. This section will examine factors that affect current flow as well as current density. Current density is more important in gauging the potential destructiveness caused by current flow.

Faraday's Law

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:

$$W = \frac{M t I}{n F} \quad \text{Eq. 1-3}$$

where:

W	= weight loss of corroding metal (grams)
M	= atomic weight of the metal
t	= time during which current flows (seconds)
I	= current flow (A)
n	= number of electrons transferred per atom of metal
F	= Faraday's constant (96,500 coulombs per equivalent)

Another form of Faraday's Law is given by the following equation:

$$W = K I t \quad \text{Eq. 1-4}$$

where:

W	= weight loss, kg or lbs
K	= electrochemical equivalent, kg/A-yr or lb/A-yr
I	= current, A
t	= time (years)

Table 1.4 Electrochemical Equivalents

Reduced Species	Oxidized Species	Molecular Weight, M (g)	Electrons Transferred (n)	Equivalent Weight, M/n (g)	Theoretical Consumption Rate (Kg/A-y)	Theoretical Consumption Rate (lb/A-y)
Al	Al ⁺⁺⁺	26.98	3	8.99	2.94	6.48
Cd	Cd ⁺⁺	112.4	2	56.2	18.4	40.56
Be	Be ⁺⁺	9.01	2	4.51	1.47	3.24
Ca	Ca ⁺⁺	40.08	2	20.04	6.55	14.44
Cr	Cr ⁺⁺⁺	52.00	3	17.3	5.65	12.46
Cu	Cu ⁺⁺	63.54	2	31.77	10.38	22.88
H ₂	H ⁺	2.00	2	1.00	0.33	0.73
Fe	Fe ⁺⁺	55.85	2	27.93	9.13	20.13
Pb	Pb ⁺⁺	207.19	2	103.6	33.85	74.63
Mg	Mg ⁺⁺	24.31	2	12.16	3.97	8.75
Ni	Ni ⁺⁺	58.71	2	29.36	9.59	21.14
OH ⁻	O ₂	32.00	4	8.00	2.61	5.75
Zn	Zn ⁺⁺	65.37	2	32.69	10.7	23.59

Note that the electrochemical equivalent (K) is the theoretical consumption rate in Table 1.4 and from Equations 1-2 and 1-4:

$$K = \frac{M}{nF}$$

Example 1:

The theoretical consumption rates can be calculated noting that if K is per year then a conversion from one (1) year to the equivalent time in seconds has to be made as “t” in Equation 1-3 is in seconds.

Using lead (Pb) as an example:

$$M = 207.19 \text{ grams}$$

$$1 \text{ year} = 60\text{sec/min} \times 60\text{min/hour} \times 24\text{hour/day} \times 365\text{day/year} \text{ or } 31,536,000 \text{ sec/year}$$

$$I = 1.0 \text{ amperes}$$

$$n = 2$$

$$F = 96,500 \text{ coulombs per equivalent}$$

$$K = \frac{207.19\text{grams} \times 31,536,000 \text{ sec/ year}}{2 \times 96,500 \text{ coulombs} - \text{sec}} = 33.85 \text{ kg/ampere} - \text{year}$$

Or

$$74.64 \text{ pounds/amp-year (1 pound = 0.453597 kilograms).}$$



Example 2:

If a 1 ampere (A) CP system must last 40 years (yr) and the electrochemical equivalent for silicon chromium cast iron anodes is 0.34 kg/A-yr or 0.75 lb/A-yr, how many kilograms (kg) or pounds (lb) of anodes are needed?

$$W = K I t$$

In Metric

$$\begin{aligned} &= 0.34 \text{ kg/A-yr} \times 1 \text{ A} \times 40 \text{ years} \\ &= 13.6 \text{ kg} \end{aligned}$$

In Imperial

$$\begin{aligned} &= 0.75 \text{ lb/A-yr} \times 1 \text{ A} \times 40 \text{ years} \\ &= 30 \text{ lbs} \end{aligned}$$

Voltage Difference

Regardless of the source of the voltage difference, the greater the magnitude of the difference, the higher the current flow and rate of corrosion, all other things being equal.

For example, magnesium will corrode at a faster rate when connected to steel rather than zinc, simply because the voltage difference between magnesium and steel is greater than that between magnesium and zinc.

A voltage can be measured between different metals in an electrolyte or from a metal to a reference electrode both contacting the same electrolyte.

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. The standard hydrogen electrode (SHE) is considered a primary reference electrode because it is used to determine the potential of other (secondary) reference electrodes that are better suited for field use. A structure-to-electrolyte potential is actually the potential difference 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.



Standard Hydrogen Electrode

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 SHE 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. It is not suitable for use in a chloride electrolyte as the chloride ions will migrate through the porous plug and contaminate the CSE. 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 1.10 and 1.11. The copper ions in the saturated solution prevent corrosion of the copper rod and stabilize the reference electrode.

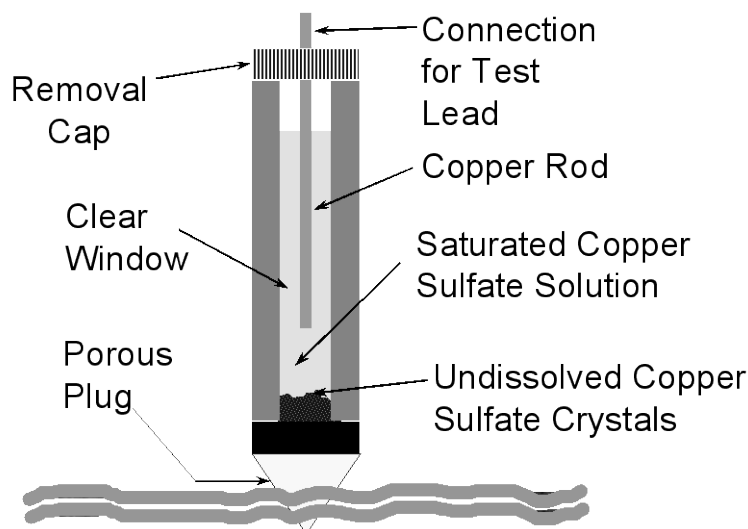


Figure 1.10 Copper-Copper Sulfate Reference Electrode in Contact with Earth



Figure 1.11 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.
- Keep one fresh electrode in the office or shop to be used to calibrate your field electrodes, preferably daily. Clean or replace field electrodes if they are more than 5 mV different from your calibrating electrode.
- Correct for potential variations due to temperature. Record the temperature when taking readings in the event temperature correction is needed. A

temperature correction of 0.5 mV/°F or 0.9 mV/°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.

Other Reference Electrodes

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. There are two types; in one the silver electrode is exposed to seawater and in the other the electrode is immersed in a potassium chloride (KCl) solution contained in a cylinder with a porous plug. A correction is needed for readings taken with the first reference if not in pure seawater (see NACE Standard SP0176, Figure 1).

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.

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. Zinc is not stable in carbonates or at high temperatures.

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 used in reinforced concrete structures.

Graphite Electrode

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

Polarity

It is imperative that the polarity of a measurement be noted and recorded. Since most instruments used today are digital with automatic polarity display, a CP Tester or Technician 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. 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 direction of current as illustrated in Figure 1.12.

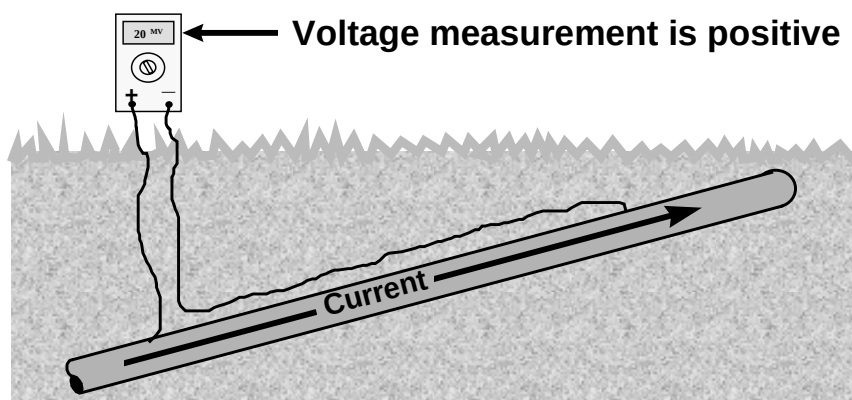


Figure 1.12 Current Direction

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 (see Figure 1.13). Current will go 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 going into the positive terminal of the voltmeter.

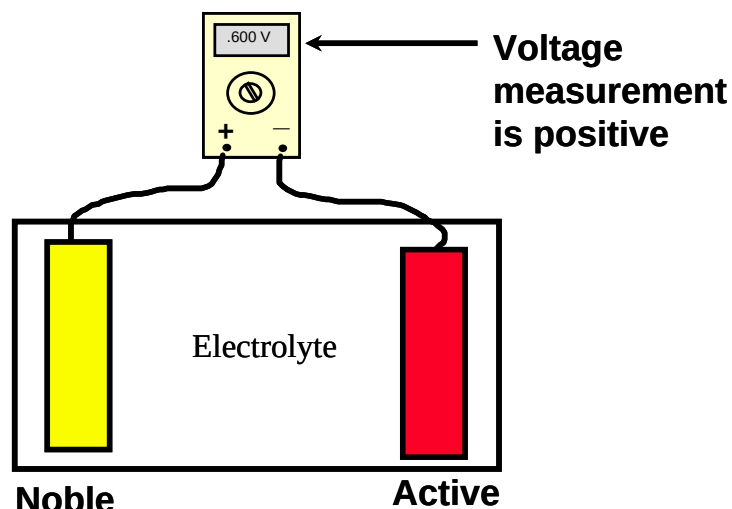


Figure 1.13 *Measurement of a Noble Metal and an Active Metal Immersed in an Electrolyte*

The term structure-to-electrolyte potentials suggests that the structure is being measured with respect to a reference in the electrolyte thus the structure is connected to the positive terminal and the reference is connected to the negative terminal. If the meter indicates the reading is negative then it is recorded as such. A digital voltmeter indicates a negative reading with a negative sign. On an analog meter, the needle will swing to the right when the reading is positive. When using an analog meter with a center zero, with the reference electrode to the negative terminal, the needle will swing to the left, indicating the negative reading. With a left hand zero instrument, the needle will pin unless the leads are reversed or a polarity switch is available. The meter will now read to the right, but the leads or position of the switch will indicate that it is a negative reading and must be recorded as such.

Converting Between Reference Electrode Values

A potential measured using any of these reference electrodes can be converted easily to a value that corresponds to a different reference electrode.

Relative electrode values vary but the values used for this course are shown in Table 1.5.

Table 1.5 Relative Values of Typical Reference Electrodes to a Hydrogen Electrode

Electrode (Half-Cell)*	Potential (volt)
Standard Hydrogen	0.000
Copper-Copper Sulfate (CSE)	+0.316
Silver-Silver Chloride (SSC)	+0.256
Saturated Calomel (SCE)	+0.244
Zinc (ZRE)	−0.800

The graphical method is illustrated using the scale in Figure 1.14 for an original potential of -0.810 mV measured on a metal "X" with respect to a copper-copper sulfate reference electrode (CSE).

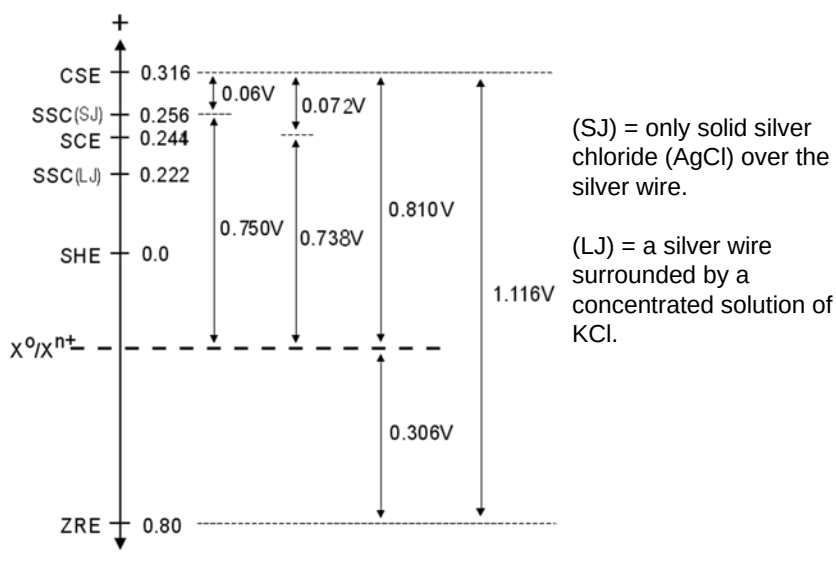


Figure 1.14 Reference Electrode Conversion Scale

For a potential of -0.810 V_{CSE}, the measurement of an unknown metal electrode X^0/X^{n+} with respect to a CSE electrode converts to the following potentials with respect to other secondary reference electrodes:

$$X^0 / X^{n+} /_{SCE} \quad \text{is} \quad -0.810 \text{ V}_{CSE} - (-0.072 \text{ V}_{SCE}) = -0.738 \text{ V}_{SCE} \quad \text{Eq. 1-5}$$

$$X^0 / X^{n+} /_{SSC} \quad \text{is} \quad -0.810 \text{ V}_{CSE} - (-0.060 \text{ V}_{SSC}) = -0.750 \text{ V}_{SSC} \quad \text{Eq. 1-6}$$

$$X^0 / X^{n+} /_{ZRE} \quad \text{is} \quad -0.810 \text{ V}_{CSE} - (-1.116 \text{ V}_{ZRE}) = +0.306 \text{ V}_{ZRE} \quad \text{Eq. 1-7}$$

This conversion process can be completed arithmetically by the following steps:

1. Determine the potential difference between the first reference electrode and the second reference electrode (e.g., CSE is +72 mV to SCE).
2. Add the original potential difference to obtain the converted potential.

$$\begin{aligned}
 \text{e.g., } X^0 / X^{n+} / \text{SCE} &= +72 \text{ mV} + (-810 \text{ mV}_{\text{CSE}}) \\
 &= -738 \text{ mV}_{\text{SCE}}
 \end{aligned}$$

STUDENT PRACTICE CALCULATIONS

Given Structure-to-electrolyte in reference to CSE = -0.87 V

Calculate Structure-to-electrolyte in reference to the following electrodes using the values in Table 1.5.

Silver-Silver Chloride = _____

Saturated Calomel = _____

Zinc = _____

Portable vs. Stationary Electrodes

Portable reference electrodes can, as the name applies, be transported from one location to another. These are used for field and laboratory testing purposes and can be maintained regularly (cleaned and refilled).

Stationary (formerly called permanent) reference electrodes are intended for installation in or near a structure (i.e., buried next to a tank or pipe, embedded in concrete, or installed inside a waterbox) to monitor the structure-to-electrolyte potential. These electrodes cannot be moved from location to location and cannot be maintained after installation. Stationary electrodes remain calibrated only for a particular length of time and will eventually become unusable. The potential of a stationary reference electrode should be checked from time to time with a portable reference electrode that is known to be accurate under “no current” conditions.

Polarization

As current is impressed on a metal over time, polarization occurs at both the anode and cathode. Polarization lowers the potential difference between the anode and cathode areas and, by Ohm’s Law, the current, I , drops and the



corrosion rate decreases until an equilibrium is reached between polarization and depolarizing effects. Depolarizers include:

- dissolved oxygen
- microbiological activity
- water flow

Polarization always occurs in the direction to oppose the current flow causing it. When the anode and cathode of a corrosion cell are connected, the resulting current will cause the potential of the anode to approach the potential of the cathode and the potential of the cathode will approach the potential of the anode. As the resistance of the electronic and/or electrolytic paths reduces, the voltage difference between the polarized electrodes also reduces, and both electrodes come to a steady state polarized potential. However, in the real world there will always be resistance in the current paths, so the mixed potential is somewhere between the polarized potentials of the two electrodes. The difference between the polarized potentials of the anode and cathode is the driving voltage of the corrosion cell. The current at this steady state condition is defined as the *corrosion current* (I_{CORR}) of the system. The potential normally measured is a mixed potential (E_M) between the polarized cathode potential (E_{pc}) and the polarized anode potential (E_{pa}).

Figure 1.15 graphically illustrates the concept of polarization. Such diagrams are called *Evans diagrams*. *Open circuit potentials*, are the potentials of the cathode and anode, E_{OC} and E_{OA} , when the corrosion current is zero. E_{PA} is the polarized potential of the anode and E_{PC} is the polarized potential of the cathode. I_{CORR} is the corrosion current of the corrosion cell. As the current is increased, the value of E changes either anodically or cathodically depending on current direction.

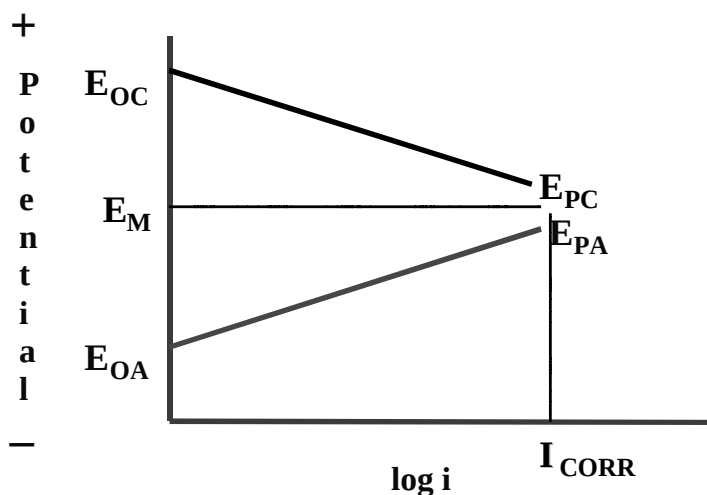


Figure 1.15 Polarization Diagram (Evans Diagram)

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

There are two types of polarization—activation and concentration.

Activation polarization is the result of the reaction steps at the structure/electrolyte interface including the actual transfer of charge. These are the reaction steps occurring after all of the necessary reactants are in place at the interface and are ready to take place. The charge transfer reaction involves moving an electron from the metal surface to the reactant on the electrolyte side of the interface. If the charge transfer reaction or any reaction step on the metal surface is the slowest step in the overall reaction process, the process is under activation polarization.

Activation polarization usually predominates initially or in electrolytes where abundant reactants and/or products involved in the electrochemical reaction are easily removed. In concentrated acids, activation polarization predominates.

Concentration polarization is the result of reaction steps involving the diffusion of reactants up to or the reaction products away from the reaction surface (structure interface). Anything that causes a depletion of available reactants or a buildup of reaction products results in a decrease in the reaction rate and an increase in concentration polarization. If the slowest step in the overall process involves waiting for arrival of reactants or the removal of reaction products, the reaction is under concentration polarization control.

Concentration polarization usually predominates in electrolytes where the concentration of the reactants is low, as with dilute solutions, or there is a buildup of reaction products from activation polarization or in stagnant environments.

The ability of the reactants to reach the reacting surface and the reaction products to move away from the reacting surface determines the limiting current density.

The total polarization of a structure is the sum of the activation and concentration polarization.



With the application of the first increments of CP current, the reaction rate is relatively slow, the reactants are plentiful and the reaction products can move away with sufficient speed to avoid blocking the reacting surface. In this case the structure is most likely under activation control. However as the CP current is increased, the availability of reactants at the interface decreases and the reaction products start to accumulate and concentration polarization begins to control. As the current nears the limiting current density the potential at the interface becomes more negative very fast. Unless another cathodic reaction is possible at the more negative potentials, the reaction rate reaches the limit and the current density cannot increase further.

If another cathodic reaction becomes possible, the current density can continue to increase with the availability of new reactants. This can occur for steel under CP in neutral aerated soils where oxygen reduction occurs at first up to the limiting current density and then water electrolysis occurs as the potentials become more negative (Figure 1.16).

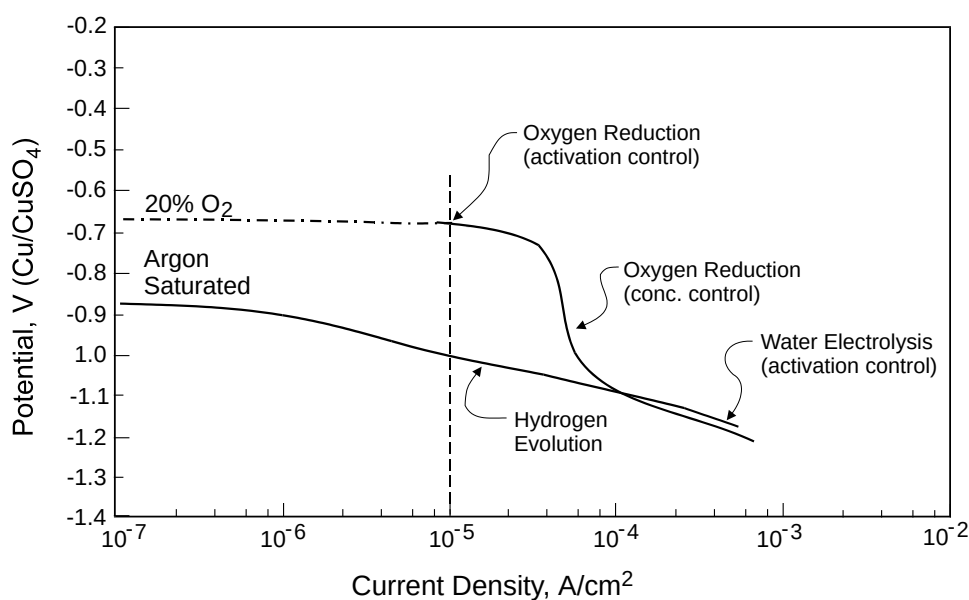


Figure 1.16 Polarization Curves in Aerated and Deaerated Solutions of pH 7

Source: N. G. Thompson and T. J. Barlo, "Fundamental Processes of Cathodically Protecting Steel Pipelines," Gas Research Conference Proceedings, presented 1983 (Rockville, MD: Government Institutes, Inc.).

Note that there is little potential change under activation control while there is a rapid change under concentration control.

IR Drop

Polarization measurements include a voltage ("IR Drop") component that is produced by current, I , through electrolyte to the electrode. Similar to the

voltage produced across a resistor with current. The IR component occurs across the soil or the structure interface, or both. Whereas polarization decays at measurable rates once the current is interrupted the IR component disappears instantly. This IR component is not polarization and must be taken into consideration or eliminated from measurements when the potential is used to meet a criterion.

Factors Affecting Polarization

Several factors affect polarization:

- Current (charge transfer)
- Electrolyte resistivity (total ion concentration)
- Anode/Cathode Ratio
- Temperature effect
- Relative electrolyte/electrode movement effect
- Electrolyte concentration effect

Current (Charge Transfer)

Since polarization is caused by current, then as current increases, polarization increases. A greater current results in a high reaction rate, causing a depletion of reactants and a buildup of reaction products. It may be a little confusing, but remember where the controlling factor is current, an increase in current causes an increase in polarization, but where the controlling factor is polarization, an increase in polarization will cause a decrease in current.

Electrolyte Resistivity (Total Ion Concentration)

Since the transfer of current (charge) through the electrolyte depends on ions, the total number of ions present will have a significant impact on the electrolyte resistivity and therefore on the current flow in the circuit. An increase in ions will result in a decrease in resistivity.

Anode/Cathode Ratio

Polarization is a function of the current density or current per unit area. The effect of current concentrated on a small area will be greater than the effect of the same amount of current on a larger area. For example, a coated structure will polarize more rapidly than a bare structure with a given amount of current.

Area effect is also a concern when considering the destructiveness of corrosion. If the current is small, the metal loss due to corrosion is also small but if concentrated in a small area a pit results that is more destructive to structures than a larger loss of metal due to uniform corrosion. For a corrosion cell, the

area ratio of the anode and cathode is important. A small anode and large cathode is undesirable because the pitting is greater compared to a large anode and small cathode.

Temperature

Temperature affects the kinetics of both the anodic and cathodic reactions. In other words, an increase in temperature has a tendency to speed up chemical reactions, which depolarizes the electrodes and increases current. Likewise, a decrease in temperature results in an increase in polarization. The following polarization diagram (Figure 1.17) illustrates the effect of temperature on current flow.

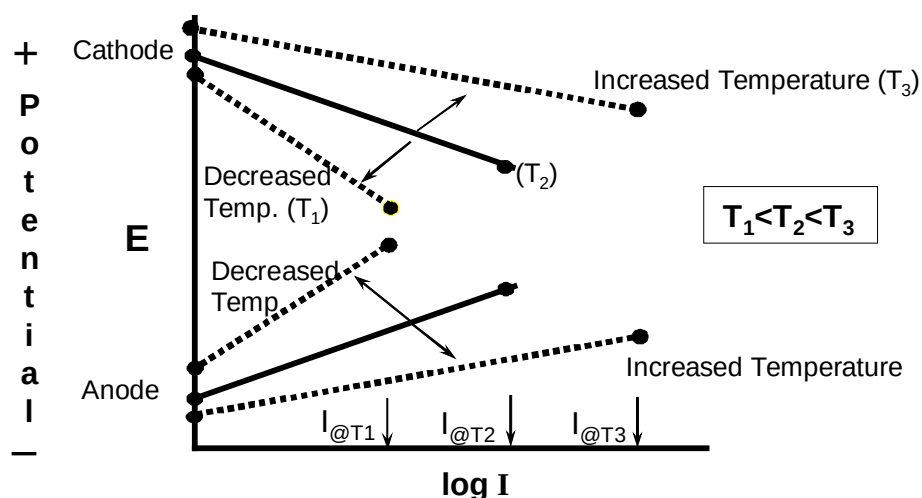


Figure 1.17 Effect of Temperature (T) on Polarization

Electrolyte/Electrode Movement Effect

Increased movement between the electrodes and the electrolyte, whether caused by electrolyte agitation or electrode vibration, serves to remove reaction products at the anode and cathode, replenishing reactants at the cathode surface. Increased movement results in a decrease in polarization and an increase in current. In stagnant electrolytes the movement decreases, causing an increase in polarization and a decrease in current, as shown in Figure 1.18.

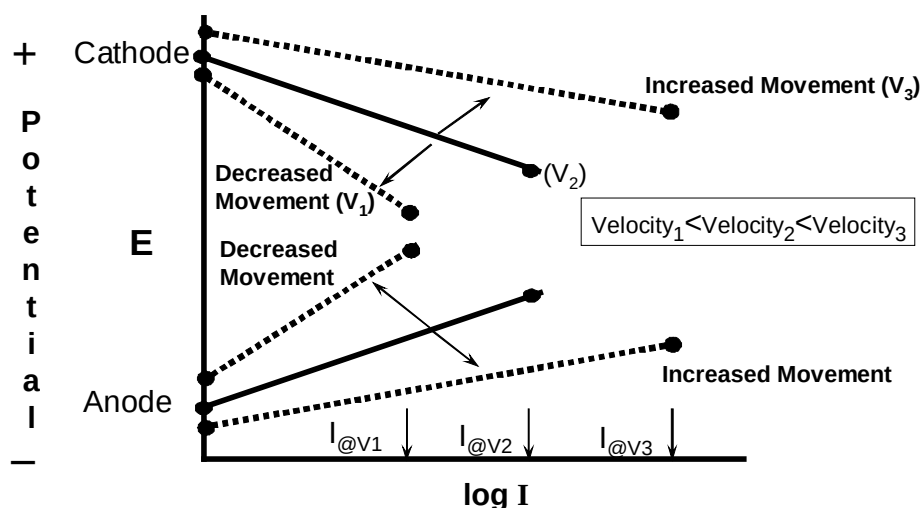


Figure 1.18 Effect of Electrolyte/Electrode Movement (V) on Polarization

Electrolyte Concentration Effect (Interface Area)

Anodic Polarization

Polarization of the anode can be affected by the concentration of the corroding metal ion, M^{+ne} , the product of the metal oxidation (Figure 1.19). An increase in the metal ion concentration of the anode metal results in an increase in polarization of the anode and a decrease in current. Likewise, a decrease in anode metal ions causes a decrease in polarization of the anode and an increase in current.

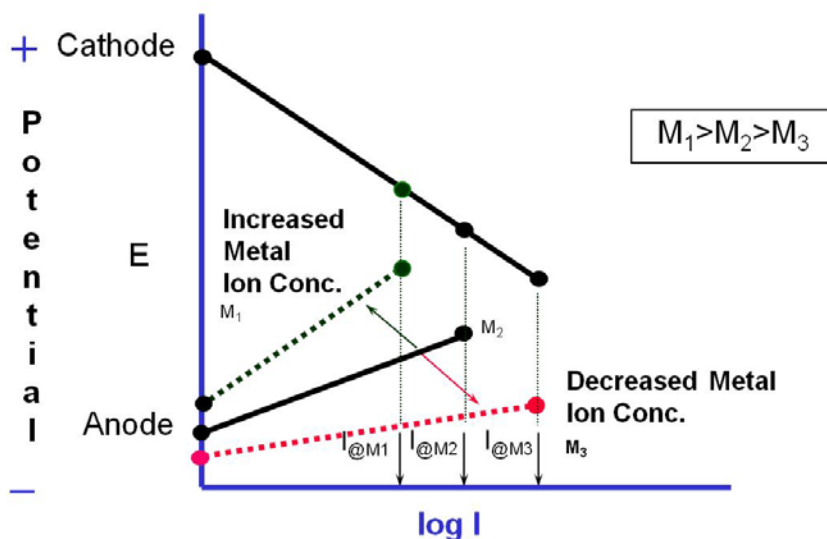


Figure 1.19 Effect of Corroding Metal Ion Concentration (M_x)

Cathodic Polarization

Polarization of the cathode can be affected by the concentration of cathodic reactants, such as oxygen or hydrogen ions. An increase in the concentration of either of these reactants will decrease polarization of the cathode and increase current and vice versa. The next two diagrams illustrate the effect of changing the concentration of cathodic reaction reactants (Figures 1.20 and 1.21).

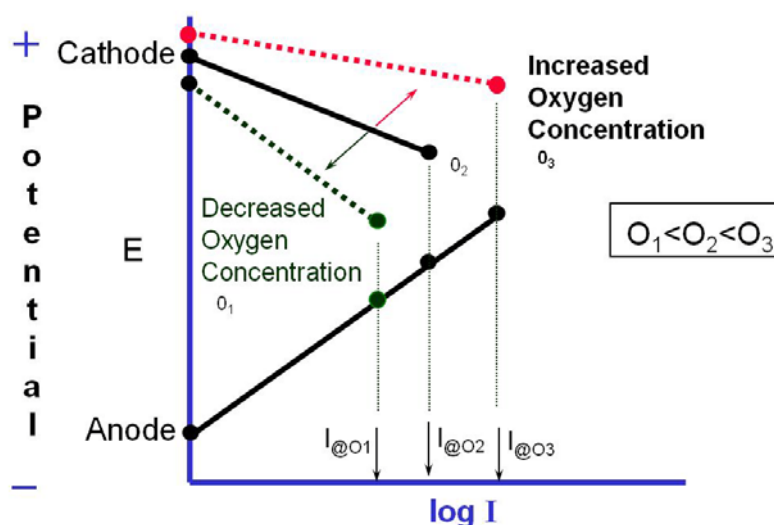


Figure 1.20 Effect of Oxygen Concentration (O_x) on Cathodic Polarization

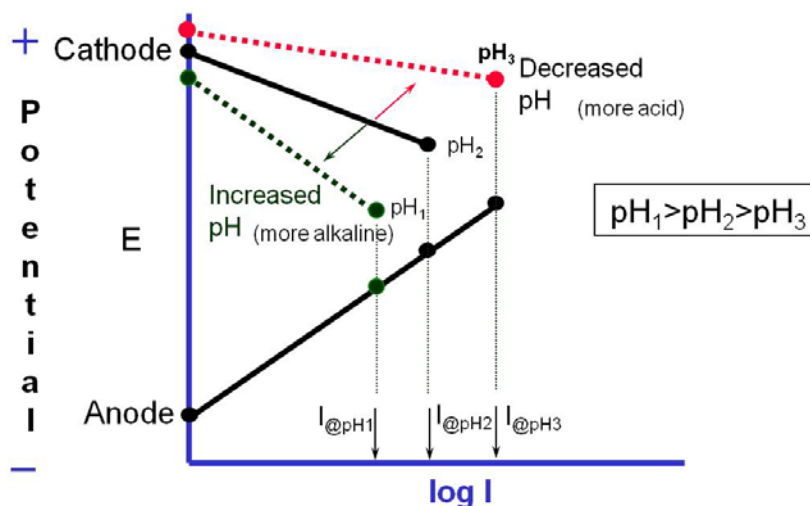


Figure 1.21 Effect of pH on Cathodic Polarization

Passivity

Passivity can be defined as the loss of chemical reactivity:

- exhibited by specific metals and alloys
- under specific environmental conditions
- caused by the formation of a surface film
- acts as a barrier to further corrosion.

Certain metals and alloys such as stainless steels, chromium, titanium and nickel alloys can become essentially inert and act as if they were noble metals under certain environmental conditions.

Passivating vs. Nonpassivating

One way of showing the unusual characteristics of a metal or alloy that demonstrates passivity is to compare it with a metal that does not show this effect.

Figure 1.22 illustrates passivating vs. nonpassivating metals by their anodic polarization behavior.

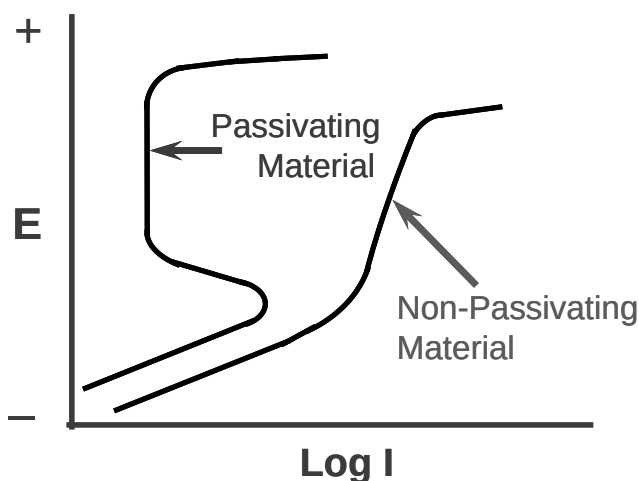


Figure 1.22 *Passivating vs. Nonpassivating Behavior*

Note that for the passivating metal:

- initially, a slight increase in corrosion potential causes the corrosion current to increase. This is the *active* region.

- when the corrosion potential increases to a certain point, however, the corrosion current suddenly decreases and remains essentially constant. This is the *passive* region.
- eventually, if the potential is increased sufficiently, current again increases. This is the *transpassive* region.

For the active (or nonpassivating) metal, as corrosion potential increases, corrosion current increases, more or less logarithmically (or linearly on a semi-log graph).

Oxide films, which form naturally on most metals when they are exposed to the air, can provide substantial protection against further attack by many environments. If it were not for such films, many common metals, such as aluminum or stainless steels, would corrode rapidly in ordinary air and water.

Forms of Corrosion

Corrosion may be grouped into the following general forms:

Uniform Attack — This is a uniform type of corrosion with an even loss of metal over the entire area or a large area of the structure.

Crevice Corrosion — This type of corrosion occurs where two tightly spaced surfaces – either two metals or a metal and nonmetal – are exposed to a corroding environment. Holes, gasket surfaces, lap joints, surface deposits, and crevices are likely places for this type of corrosion.

Galvanic Attack — This corrosion occurs when two dissimilar metals are connected. The potential of the two metals creates a voltage difference, the driving force for corrosion.

Pitting – Localized corrosion that occurs over a small area of the metal surface and leaves holes in the surface. Pits can be isolated or closely spaced. Pits can be small or large in diameter.

Intergranular Attack — This is a local corrosion attack at the grain boundaries of an alloy. It is caused by a difference in element composition near the boundaries, compared to the rest of the alloy.

Selective Leaching — This type of corrosion involves the selective removal of one of the elements from an alloy. Examples of this type of corrosion are dezincification of brass and graphitic corrosion of cast iron.

Velocity Phenomena — This corrosion is associated with rapid movement of a corrosive fluid over a metal, removing corrosion products. It is recognized by the appearance of grooves, trenches, etc., in the direction of fluid flow.

Environmental Cracking — Environmental cracking results from the reaction of the metal with a corrosive environment and the presence of a stress. There are three types of environmental cracking:

- *Corrosion Fatigue* — results in fatigue of the metal under an alternating stress in a corroding media.
- *Hydrogen Embrittlement* — the reduction in ductility of the metal from hydrogen that has diffused into the metal.

➤ **Hydrogen Damage**

Atomic hydrogen generated at the surface by cathodic protection can diffuse into the metal. This atomic hydrogen can cause blistering of the metal, the formation of hydrides (in the case of titanium) that embrittle the titanium, and the embrittlement of steel (particularly high-strength steel), martensitic stainless steel, high-strength aluminum alloys (particularly 7,000 series), and prestressed concrete. The embrittlement of the metal can cause cracks to form, which can grow and cause the structure to fail.

The prevention of hydrogen embrittlement depends on keeping the potential below the hydrogen evolution potential, which depends on the pH. In general, hydrogen is generated in neutral environments at $-1,044 \text{ mV}_{\text{CSE}}$. The lower the pH, the lower the hydrogen evolution potential. For aluminum, the polarized potential must be kept below $-1,200 \text{ mV}_{\text{CSE}}$ to avoid alkali corrosion. For titanium, the maximum potential is $-700 \text{ mV}_{\text{SSC}}$ to prevent hydriding. Overprotection levels are discussed in some cathodic protection criteria documents and might differ from these somewhat. For prestressed concrete, polarized potentials more negative than $-1,000 \text{ mV}$ should be avoided.

Care must be taken in designing and operating cathodic protection systems where materials susceptible to hydrogen embrittlement are

used to limit the structure-to-soil potential below the hydrogen evolution potential.

- *Stress Corrosion Cracking (SCC)* — the cracking of a metal under an applied tensile stress in the presence of a corrosive environment. Many metals, including high-strength steel, aluminum (2,000 and 7,000 series alloys), stainless steels, and brass alloys are susceptible to SCC. Cathodic protection generally reduces or eliminates SCC because it stops the corrosion process. However, SCC of high-strength pipeline steels caused by cathodic protection has occurred. This type of cracking occurs in a narrow potential range (-525 to -725 mV_{CSE}) at a pH between 8 and 10.5, and is more likely at higher temperatures. The cracking occurs because of the formation of carbonates and bicarbonates at the steel surface. Research in this area is ongoing.
- *Microbiologically Influenced Corrosion (MIC)* — Certain bacteria that exist under anaerobic conditions (absence of oxygen) can reduce sulfates and consume hydrogen in the process. Consumption of hydrogen at the structure surface depolarizes the steel at cathodic areas and permits more rapid consumption of the metal by galvanic corrosion cells. The bacteria then do not directly attack the structure, but create conditions conducive to more rapid attack by existing corrosion cells, which in turn are normally stifled by the development of a polarization film of hydrogen.

Experiment 1.1

Investigation of Changes in Corrosion Cell

Operation to Changes in the Electrolyte

The experimental arrangement shown in Figure 1.23 below can be used to demonstrate typical changes that can occur in an operating corrosion cell.

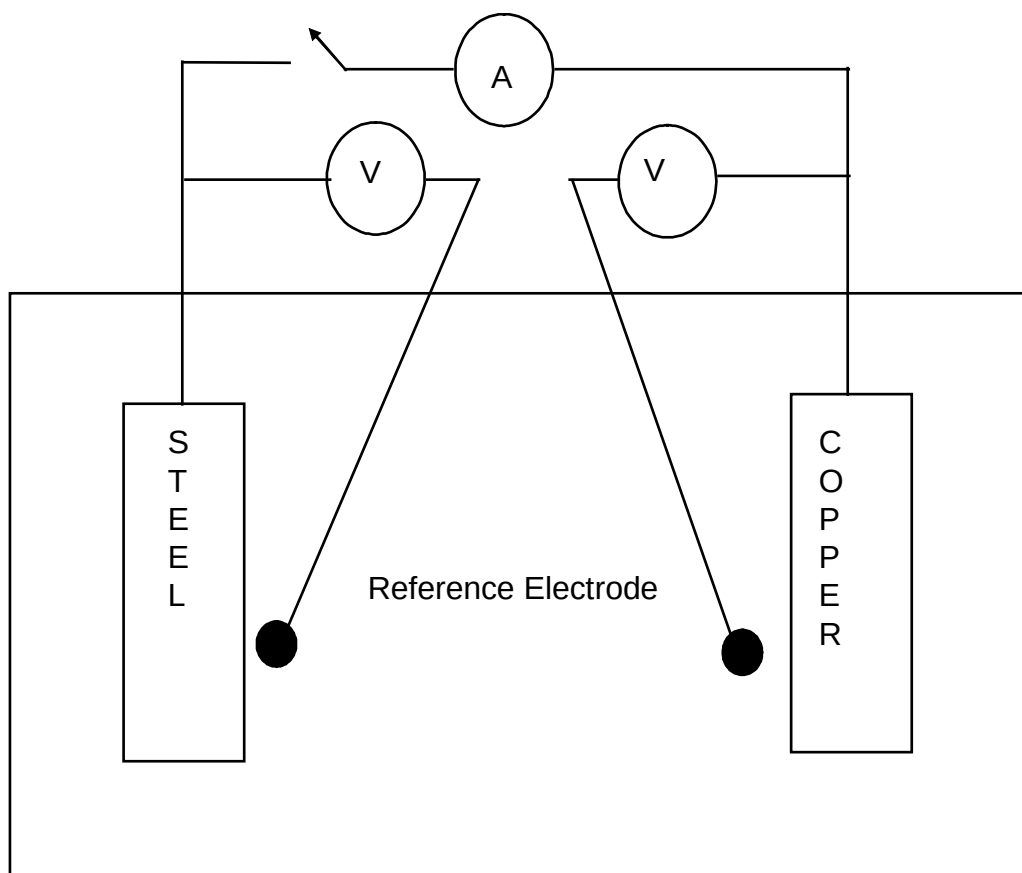


Figure 1.23 Experiment to Show Effect of Environmental Changes on Corrosion Behavior

In the following experiment both a cathodic depolarizer (hydrogen peroxide) and an anodic inhibitor (sodium nitrite) are used to cause polarization and open circuit potential changes at the anode and cathode, respectively. Changes in the corrosion cell current also occur.

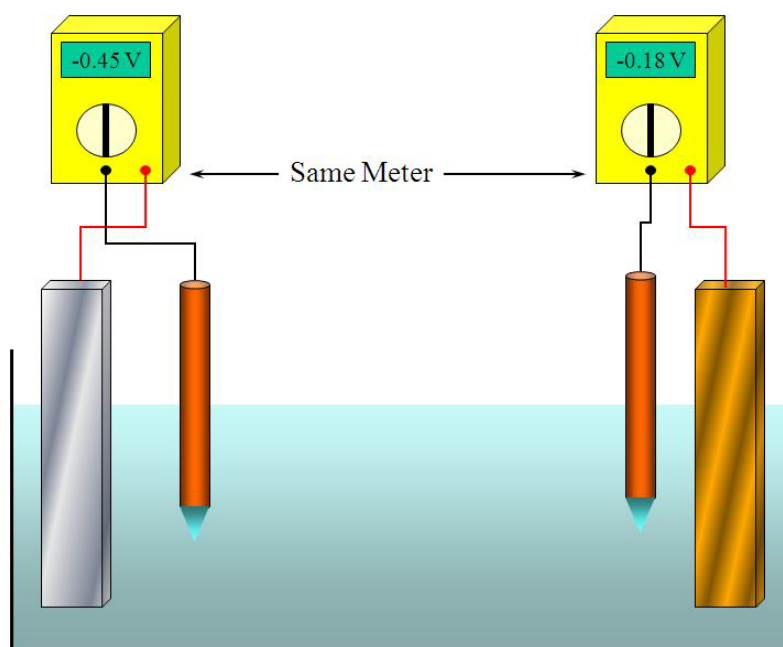
PROCEDURE

Part A Set-up

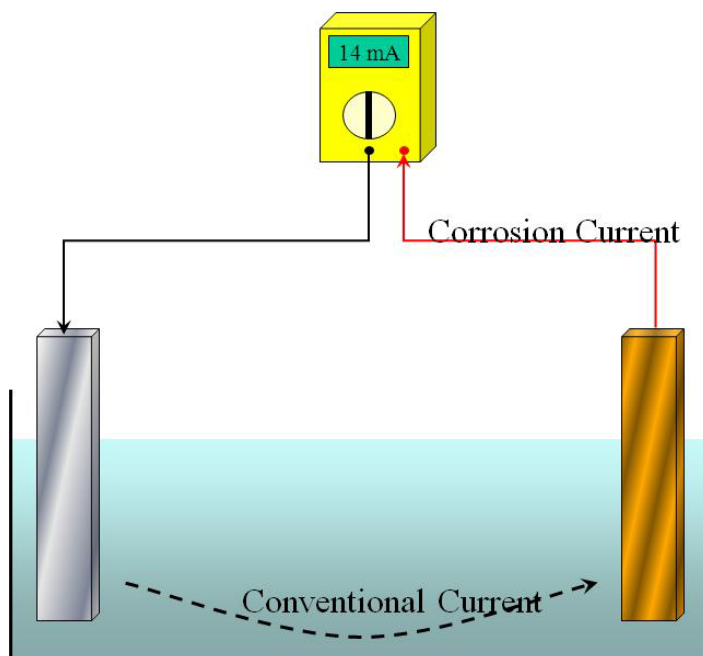
1. Place tap water in tray.
2. Place steel sheet in left side of tray.
3. Place copper sheet in right side of tray.
4. Connect experimental circuit as shown in Figure 1.23.

Part B Cathodic Depolarization Effect of Hydrogen Peroxide

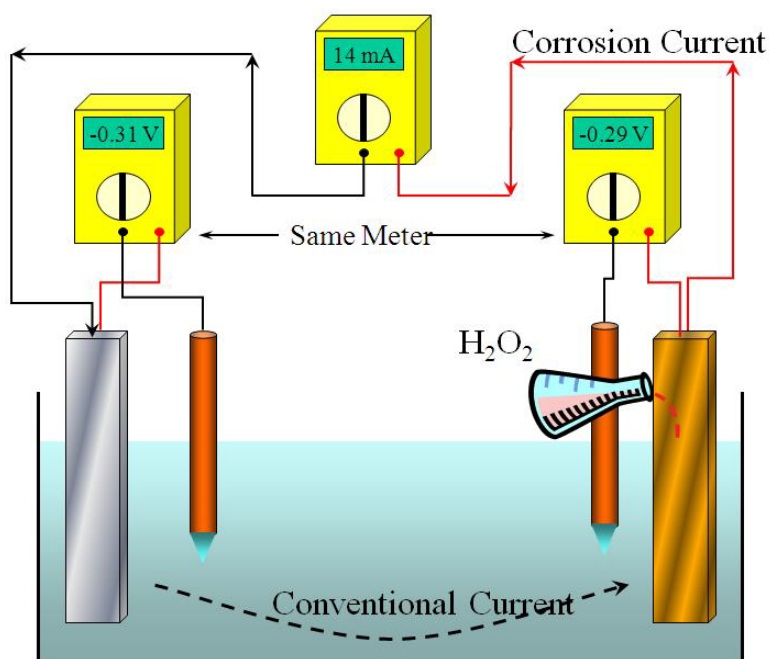
1. Measure open circuit potential of steel and copper using a copper sulfate electrode and a voltmeter.



2. Connect the two metals together using an ammeter and a pair of leads and record closed circuit polarized potential of steel and copper.



3. Measure corrosion current.
4. Add hydrogen peroxide solution to electrolyte at copper sheet (approximately 1 cap full) directly to the copper.



5. Repeat Steps 2 and 3.
6. Disconnect the ammeter and repeat Step B-1.
7. Empty electrolyte from tray.
8. Construct polarization (Evans) diagrams.

RESULTS

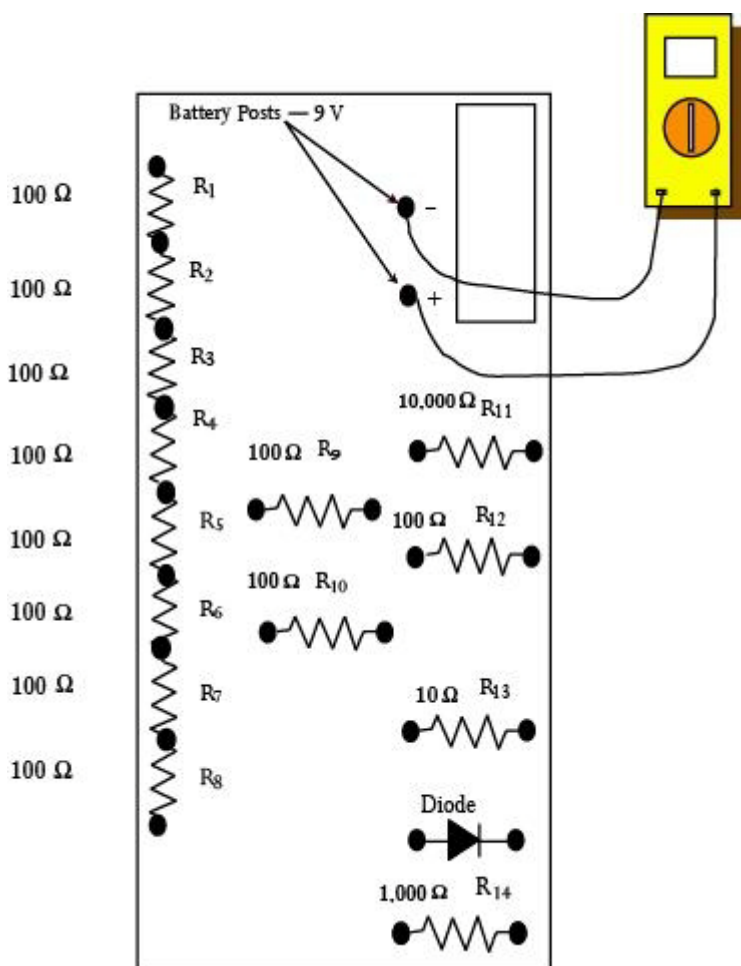
	E_{steel}	E_{copper}	I_{corr}
Part B			
Open Circuit			
Corrosion Cell			
Corrosion Cell (H_2O_2)			
Open Circuit (H_2O_2)			

CONCLUSIONS

1. The addition of the hydrogen peroxide solution to the electrolyte at the copper cathode results in positive shifts of the anodic and cathodic polarization potentials and the cathodic open circuit potential. It also increases the corrosion cell current.

Exercise 1.1 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 below.



Record the data collected on the Exercise 1.1 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).
- Step 4.** Wire the $1,000\Omega$ (R_{14}), 100Ω (R_{12}), and 10Ω (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? 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?
- Step 8.** Calculate the resistance of the $10,000\Omega$ (R_{11}), $1,000\Omega$ (R_{14}), and 100Ω (R_{12}) resistors below the battery in parallel.
- Step 9.** Wire the $10,000\Omega$ (R_{11}), $1,000\Omega$ (R_{14}), and 100Ω (R_{12}) resistors located below the battery in parallel and measure the total resistance, R_T . Is this value equal to the value calculated in Step 8? If not, why?
- Step 10.** Calculate the total current (I_T) through the parallel circuit described in Step 9.
- Step 11.** Measure the total current (I_T) with the ammeter. How does it compare with your calculation in Step 10?

- Step 12.** Calculate the current flow through the $10,000\Omega$ (R_{11}), $1,000\Omega$ (R_{14}), and 100Ω (R_{12}) resistors and the total current (I_T).
- Step 13.** Measure the current through each of the resistors $10,000\Omega$ (R_{11}), $1,000\Omega$ (R_{14}), and 100Ω (R_{12}) with the ammeter. How close do you come to your calculated value?
- Step 14.** Add the currents through each resistor. Do they equal the total measured or calculated current (I_T)? If not, why?
- Step 15.** Show current direction in each resistor. Was Kirchhoff's Current Law fulfilled?

DIODE CHECK

Check the diode with the diode checking circuit. Is it functioning properly?

EXERCISE 1.1 DATA SHEET

STEP 1. RATED BATTERY VOLTAGE (E_T) : _____ Volts

BATTERY VOLTAGE (E_T) : _____ Volts

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

$V_{14} =$: _____ V Across 1000 Ω resistor

$V_{12} =$: _____ V Across 100 Ω resistor

$V_{13} =$: _____ V Across 10 Ω resistor

Calculated Total $V_T =$: _____ Volts

Measured Source Voltage (E_T) : _____ Volts

PARALLEL CIRCUIT

STEP 8.

Calculated Total Resistance $R_T = 1/(1/R_{11} + 1/R_{14} + 1/R_{12}) =$ _____ Ω

STEP 9.

Measured Total Resistance $R_T =$ _____ Ω

STEP 10.

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

STEP 11.

Measured Current (I_T)= : _____ A

STEP 12. CALCULATE RESISTOR CURRENTS

$I_1 = E_T / R_{11} :$ _____ A 10,000 Ω resistor

$I_2 = E_T / R_{14} :$ _____ A 1000 Ω resistor

$I_3 = E_T / R_{12} :$ _____ A 100 Ω resistor

Calculated Total (I_T) = : _____ A



STEP 13. MEASURED RESISTOR CURRENTS $I_{11} = : \underline{\hspace{2cm}}$ A 10,000 Ω resistor $I_{14} = : \underline{\hspace{2cm}}$ A 1,000 Ω resistor $I_{12} = : \underline{\hspace{2cm}}$ A 100 Ω resistor**STEP 14.**Calculated Total $I_T = : \underline{\hspace{2cm}}$ A**STEP 15.**

DRAW SCHEMATIC AND INDICATE CURRENT DIRECTION
(CLOCKWISE OR COUNTERCLOCKWISE) ON THE SCHEMATIC.

DIODE CHECK

Decide the diode status and insert readings in the appropriate line.

		FORWARD READING	REVERSE READING
Good	☐	<u> </u>	<u> </u>
Open	☐	<u> </u>	<u> </u>
Shorted	☐	<u> </u>	<u> </u>

Concept of Cathodic Protection

Corrosion is the result of an electrochemical reaction driven by a potential difference between two electrodes, an anode and a cathode, connected by an electronic path and immersed in the same electrolyte (see Figure 2.1). In the case of uniform corrosion, a multitude of microscopic anodic and cathodic sites exist on the surface of the metal structure.

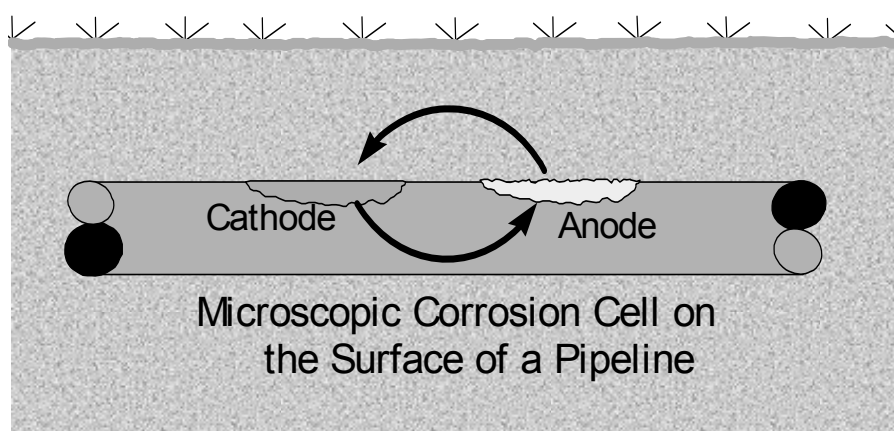


Figure 2.1 Microscopic Corrosion Cell

The concept of cathodic protection (CP) involves reducing the potential difference between the local anodic and cathodic sites to zero, resulting in zero corrosion current flow. This can be accomplished by impressing current onto the structure from an external electrode and polarizing 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, corrosion is eliminated on the structure. The structure is now the cathode of an intentional macroscopic corrosion cell.

Corrosion of the metal will cease once the applied cathodic protection current equals or exceeds the corrosion current.

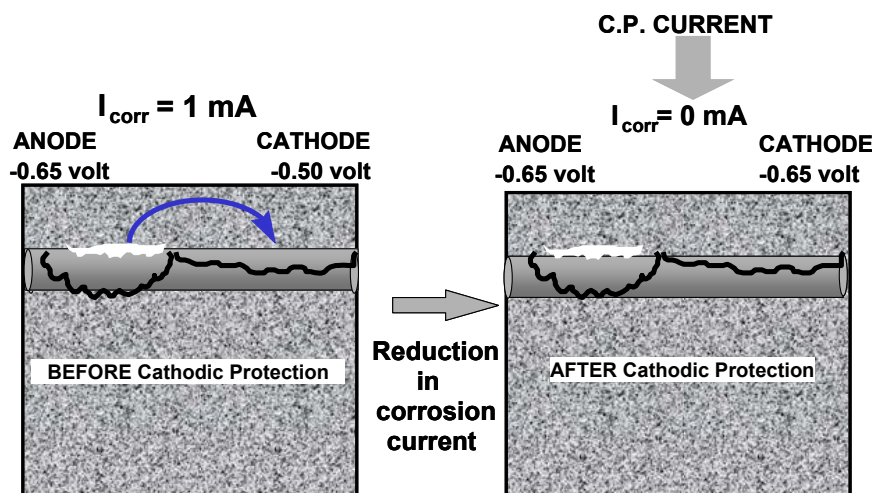


Figure 2.2 Cathodic Protection Applied to a Structure

Cathodic protection current is impressed from an external cathodic protection anode through the electrolyte to the metal and reduces the potential difference between anodic and cathodic sites (see Figure 2.2).

Polarization of a Structure

Cathodic protection is a polarization phenomenon and polarization is a change in potential caused by current. When current goes from the electrolyte to the metal, a reduction reaction occurs. Products from these reactions change the chemical composition of the electrolyte at the structure/electrolyte interface. The chemistry difference at the interface, as measured by the structure potential, is referred to as *polarization*. When cathodic protection current is interrupted, the polarization will dissipate similarly to the voltage dissipation of a capacitor but may never reach the original native potential depending on the reaction products.

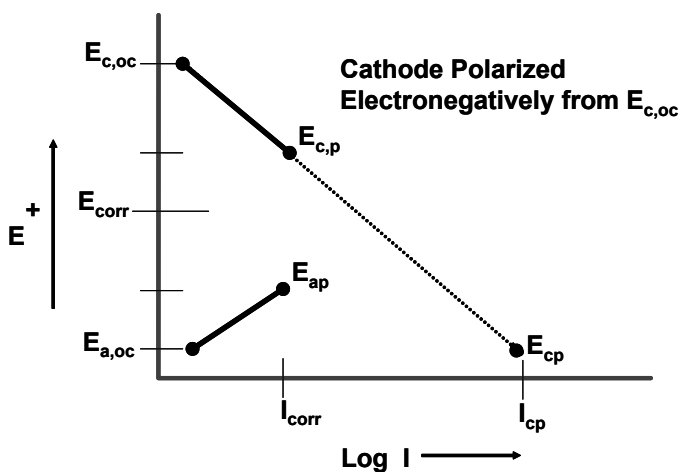


Figure 2.3 Polarization of a Structure

As a structure polarizes, its potential changes in an electronegative direction (see Figure 2.3). Polarization occurs in a step-like manner with the more positive or cathodic sites polarizing first. As the potential of the first cathodic sites equals the potential of other sites, polarization begins at other sites. A simplified description is given in Figure 2.4.

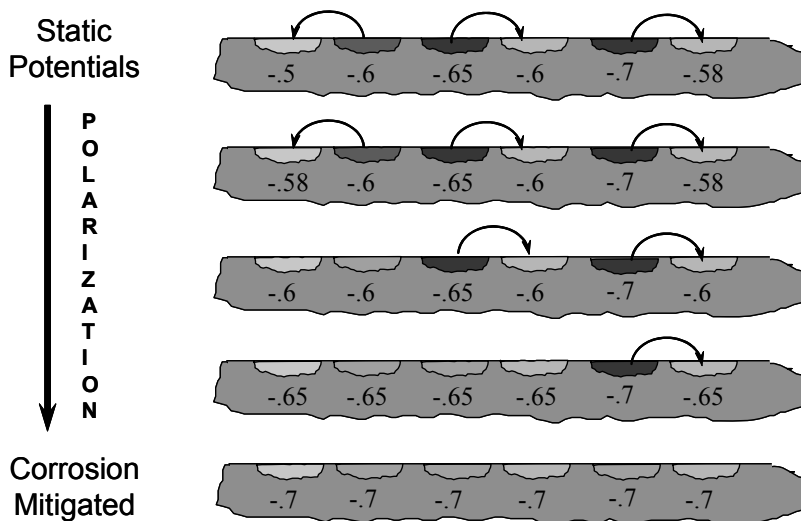
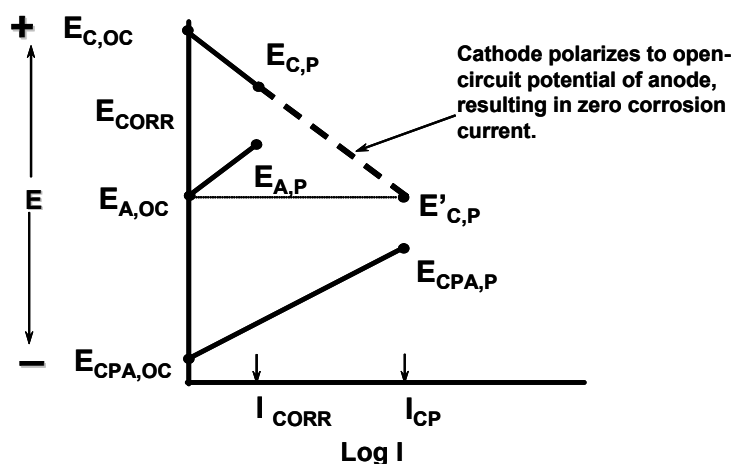


Figure 2.4 Polarization of a Structure

To mitigate corrosion, all existing cathode sites must be electronegatively polarized to a potential equal to the open circuit potential of the most active anode potential existing on the structure. Polarization of a structure is accomplished by applying external current, the magnitude of which depends on the cathodic polarization behavior. Discussed later in this chapter are factors that affect current requirements for adequate cathodic protection of a structure. Figure 2.5 represents the polarization of the cathode to the open circuit potential of the anode of a corrosion cell on a structure using cathodic protection.



where:

$E_{c,oc}$ = Structure cathode potential, open circuit, corrosion cell not active

$E_{A,OC}$ = Structure anode potential, open circuit, corrosion cell not active

$E_{C,P}$ = Structure cathode potential, corrosion cell active, before CP applied

E_{AP} = Structure anode potential, corrosion cell active, before CP applied

E_{CORR} = Corrosion potential with structure anode and structure cathode connected

 I_{CORR} = Corrosion current before CP applied
$$E_{CPA, OC} = \text{CP anode potential, no CP current}$$

E'_{CP} = Structure cathode potential with CP current applied

$$E_{CPAP} = \text{CP anode potential, CP current flowing}$$

I_{CP} = Cathodic protection current between CP anode and structure

Figure 2.5 Cathode Polarized to the Open Circuit Potential of the Anode

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

Current Requirement

The amount of current required to provide adequate protection depends on the surface area to be protected and the polarization behavior of the structure in its environment.

Surface Area

Current requirement is directly proportional to the exposed metal surface area to the electrolyte. For example, a coated structure requires less current than a bare structure. A coated structure needs protective current only at coating

defects (holidays). To consider an actual example, let us look at the following calculations.

Example

What is the current required to protect an uncoated 30.48 cm (12 in.) diameter steel pipeline 1,524 m (5,000 ft) in length that is buried in soil with a resistivity of 10,000 Ω -cm? Assume experience has shown that adequate levels of cathodic protection can be achieved from 10.76 mA/m² (1 mA/ft²) of bare surface area. Compare this with the current required to protect the same pipeline if it is coated.

Bare Example:

$$I_p(\text{given}) = (10.76 \text{ mA/m}^2) \text{ } 1.0 \text{ mA/ft}^2$$

Metric:

$$\begin{aligned} \text{Total Surface Area} &= \\ \pi dL &= \pi \times \frac{30.48 \text{ cm}}{100 \text{ cm/m}} \times 1524 \text{ m} \\ &= \pi \times 0.3048 \times 1524 \\ &= 1459.3 \text{ m}^2 \end{aligned}$$

$$\therefore I_{\text{req'd}} = 10.76 \text{ mA/m}^2 \times 1459 \text{ m}^2 = 15.7 \text{ A}$$

Imperial:

$$\begin{aligned} \text{Total Surface Area} &= \pi dL = \pi \times (12 \text{ in} \times 1 \text{ ft/12 in}) \times 5000 \text{ ft} \\ &= \pi \times 1 \text{ ft} \times 5000 \text{ ft}^2 \end{aligned}$$

$$\text{Total Surface Area} = 15,708 \text{ ft}^2$$

$$\therefore I_{\text{req'd}} = 1.0 \text{ mA/ft}^2 \times 15,708 \text{ ft}^2 = 15,708 \text{ mA} = 15.7 \text{ A}$$

Coated Example:

Assume that 5 percent of the pipe contains holidays or defects in the coating. Then:

Metric:

$$\begin{aligned} \text{Surface Area of portion of Coated Pipe that is bare} \\ = 0.05 \times 1459 \text{ m}^2 = 73 \text{ m}^2 \end{aligned}$$

$$\therefore I_{\text{req'd}} = 10.76 \text{ mA/m}^2 \times 73 \text{ m}^2 = 785 \text{ mA} = 0.785 \text{ A}$$

Imperial:

$$\begin{aligned} \text{Surface Area of portion of Coated Pipe that is bare} \\ = 0.05 \times 15,708 \text{ ft}^2 = 785 \text{ ft}^2 \end{aligned}$$

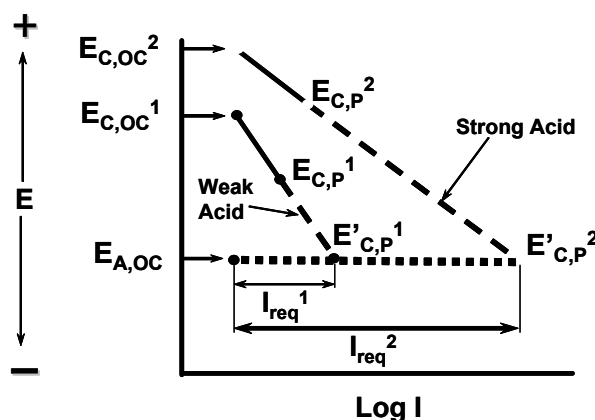
$$\therefore I_{\text{req'd}} = 1.0 \text{ mA/ft}^2 \times 785 \text{ ft}^2 = 785 \text{ mA} = 0.785 \text{ A}$$

Polarization

Factors that affect polarization, which in turn affect corrosion current have been discussed. In the case of a corrosion cell, an increase in polarization is desired whether it is anodic, cathodic, or both, because it decreases corrosion current. For a cathodic protection system, an increase in the cathodic polarization is desired to decrease the current requirement for the structure. However, cathodic protection anodes are designed to have minimal anodic polarization to increase current output.

Effect of Environment pH on CP Current Requirement

The current required for cathodic protection generally is greater in low pH (acids) than in high pH (basic) and neutral environments. Two phenomena account for this increase: (1) a shift in the positive direction of the structure's open circuit cathode potential, and (2) a flattening of the cathodic polarization curve for the structure, as indicated in Figure 2.6.

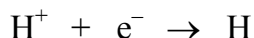


where:

$E_{C,OC}^2$	= Cathode potential, strong acid solution, no corrosion
$E_{C,OC}^1$	= Cathode potential, weak acid, no corrosion
$E_{A,OC}$	= Anode potential
$E_{C,P}^2$	= Cathode potential, strong acid, corroding
$E_{C,P}^1$	= Cathode potential, weak acid, corroding
$E'_{C,P}^1$	= CP potential required, weak acid
$E'_{C,P}^2$	= CP potential required, strong acid
I_{req}^1	= CP current needed for weak acid
I_{req}^2	= CP current required for strong acid

Figure 2.6 Effect of Environment pH on Current Required for Protection

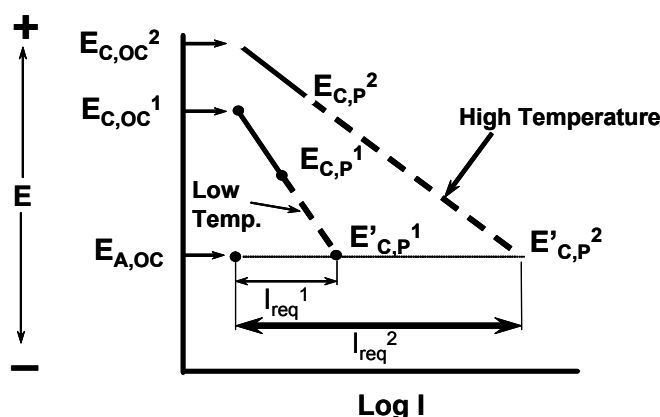
The structure's cathodic polarization slope is flattened with increasing acidity because of the increased concentration of reducible hydrogen ion (H^+) according to the reaction:



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

Temperature Effect on CP Current Requirement

Increased temperature has a depolarizing effect because of the increased rate of diffusion of reducible species to the cathodic sites, a decrease in concentration polarization. Accordingly, the rate of the reduction reaction is increased, thus decreasing the level of polarization and increasing the cathodic protection current requirement, as illustrated in Figure 2.7.



where:

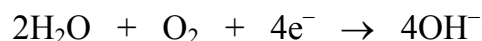
$E_{C,OC}^2$	=	Cathode potential, high temperature, no corrosion
$E_{C,OC}^1$	=	Cathode potential, low temperature, no corrosion
$E_{A,OC}$	=	Anode potential
$E_{C,P}^2$	=	Cathode potential, high temperature, corroding
$E_{C,P}^1$	=	Cathode potential, low temperature, corroding
$E'_{C,P}^1$	=	CP potential required, low temperature
$E'_{C,P}^2$	=	CP potential required, high temperature
I_{req}^1	=	CP current needed for low temperature
I_{req}^2	=	CP current required for high temperature

Figure 2.7 Effect of Temperature on Current Required for Cathodic Protection

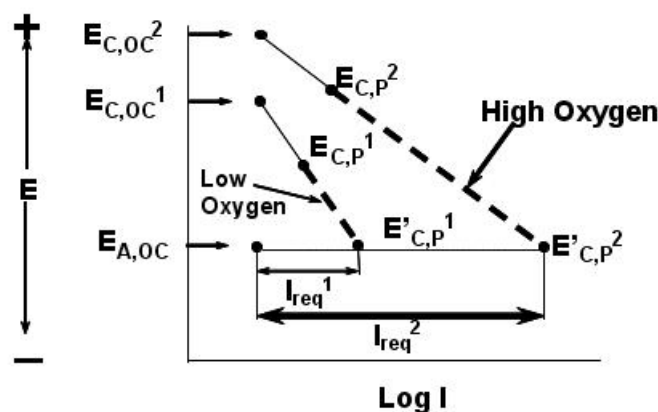
Also, increased temperature will increase ionization. As ionization increases, the electrolyte's conductivity increases, which increases corrosion current and the amount of cathodic protection current required for adequate protection. Activation polarization decreases because electrochemical reactions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

Effect of Oxidizers on CP Current Requirement

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



thereby reducing polarization. Figure 2.8 illustrates this effect.



where:

$E_{C,OC}^2$ = Cathode potential, high oxygen, no corrosion

$E_{C,OC}^1$ = Cathode potential, low oxygen, no corrosion

$E_{A,OC}$ = Anode potential

$E_{C,P}^2$ = Cathode potential, high oxygen, corroding

$E_{C,P}^1$ = Cathode potential, low oxygen, corroding

$E'_{C,P}^1$ = CP potential required, low oxygen

$E'_{C,P}^2$ = CP potential required, high oxygen

I_{req}^1 = CP current needed for low oxygen

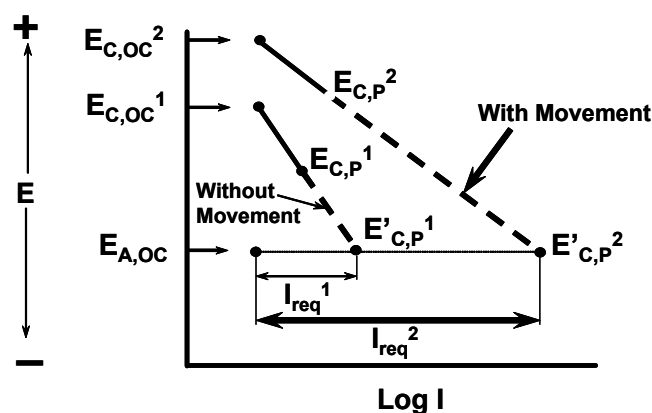
I_{req}^2 = CP current required for high oxygen

Figure 2.8 Effect of Oxygen on Current Required for Cathodic Protection

Accordingly, structures in well aerated soils, such as sand and gravel, require more cathodic protection current than structures surrounded by relatively deaerated soils, such as clay.

Effect of Relative Movement Between the Structure and Electrolyte on CP Current Requirements

An increase in the relative movement between the electrolyte and the structure causes an increase in current requirement. This is due primarily to the increased availability of reducible species at the structure surface and the resulting increase in the rate of the reduction reaction. This effect, illustrated in Figure 2.9, is exhibited on such structures as ships and their propellers, docks exposed to water flow or tides, offshore structures, and internal surfaces of condenser water boxes.



where:

$E_{C,OC}^2$ = Cathode potential, with movement, no corrosion

$E_{C,OC}^1$ = Cathode potential, no movement, no corrosion

$E_{A,OC}$ = Anode potential

$E_{C,P}^2$ = Cathode potential, with movement, corroding

$E_{C,P}^1$ = Cathode potential, no movement, corroding

$E'_{C,P}^1$ = CP potential required, no movement

$E'_{C,P}^2$ = CP potential required, with movement

I_{req}^1 = CP current needed for no movement

I_{req}^2 = CP current required for with movement

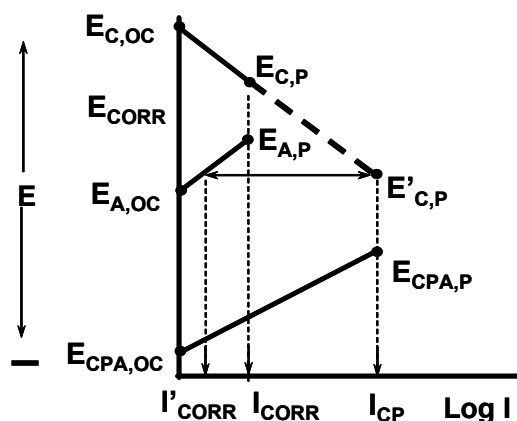
Figure 2.9 Effect of Relative Movement on Current Required for Cathodic Protection

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

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

Applied Current vs. Corrosion Rate

If all cathodes are not sufficiently polarized in the electronegative direction, then a residual corrosion current (I_{CORR}) will remain and some corrosion will continue to take place. See Figure 2.10.



where:

- $E_{C,OC}$ = Structure cathode potential, open circuit, corrosion cell not active
- $E_{A,OC}$ = Structure anode potential, open circuit, corrosion cell not active
- $E_{C,P}$ = Structure cathode potential, corrosion cell active, before CP applied
- $E_{A,P}$ = Structure anode potential, corrosion cell active, before CP applied
- E_{CORR} = Corrosion potential with structure anode and structure cathode connected
- I_{CORR} = Corrosion current before CP applied
- $E_{CPA,OC}$ = CP anode potential, no CP current
- $E'_{C,P}$ = Structure cathode potential with CP current applied [not quite at open circuit potential of anode ($E_{A,OC}$)]
- $E_{CPA,P}$ = CP anode potential, CP current flowing
- I_{CP} = Cathodic protection current between CP anode and structure
- I'_{CORR} = Corrosion current with partial CP applied

Figure 2.10 Corrosion Current Reduced by Application of Cathodic Protection Current

If the criterion for protection is not achieved, the corrosion rate is reduced nevertheless (see Figure 2.10).

To reduce the residual corrosion current to zero, cathodic protection current must be disproportionately increased. The relationship between applied cathodic protection current and corrosion rate is logarithmic. The first increment of applied cathodic protection results in the largest decrease in corrosion.

On the other hand, cathodic polarization at potentials more electronegative than the static anode potential has no benefit and, in extreme cases can be detrimental to the structure and/or its coating. This so called *overprotection* can be

detrimental to amphoteric metals and alloys, such as aluminum, zinc, and lead, which may corrode at high rates in both basic and acidic environments. The formation of hydroxyl ions at the cathode causes the pH of the electrolyte next to the cathode to become alkaline. This can deteriorate amphoteric metals and cause the coating to disbond from the substrate. Overprotection causing coating disbondment depends on the particular coating. For pipeline coatings, polarized potential values more negative than $-1,200 \text{ mV}_{\text{CSE}}$ should be avoided. For non-pipeline coatings, the coating manufacturer should be consulted to determine if the coating is compatible with CP. Excessive protection can result in hydrogen damage to some metals. Hydrogen embrittlement is discussed in more detail under “Environmental Cracking.”

Figure 2.11 illustrates the logarithmic relationship between cathodic protection current and corrosion rate.

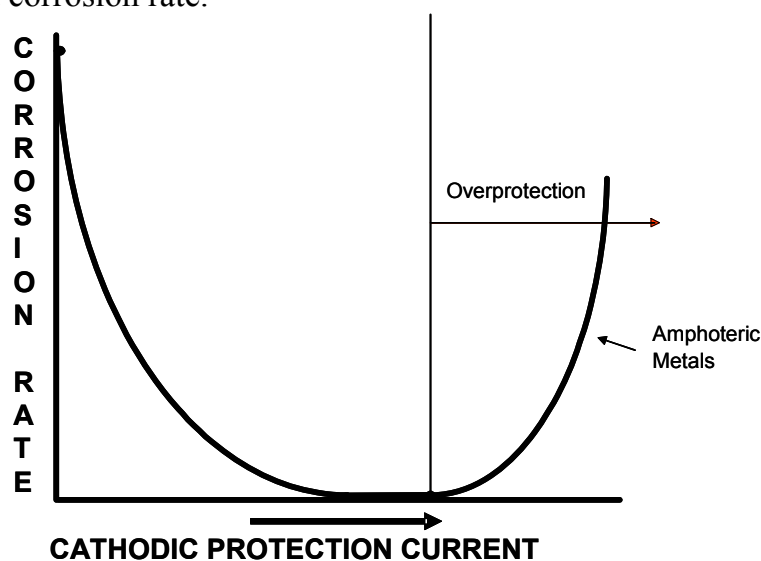


Figure 2.11 Cathodic Protection Current vs. Corrosion Rate

In some circumstances, the cost to reduce the corrosion rate to zero may not be justified. A low, rather than zero, corrosion rate may be both tolerable and acceptable in terms of minimizing total annual expenses if safety and compliance with government regulations are not jeopardized.

From a practical standpoint, how can we determine the amount of current required to mitigate corrosion on a structure in its particular environment? When all of the cathodic sites have polarized to the open circuit potential of the most active anodic site, corrosion is mitigated but we can not measure the potential of the individual anodes and cathodes. A surrogate criterion is therefore required.

Criteria for Cathodic Protection

In the Appendices section of this manual you will find NACE Standard SP0169, “Control of External Corrosion on Underground or Submerged Metallic Piping Systems.” Several criteria for determining the achievement of adequate cathodic protection are found in Section 6 of this standard, “Criteria and Other Considerations for Cathodic Protection.” Students are advised to read at least this section. These criteria were developed through laboratory experiments or were determined empirically by evaluating data from successfully operated cathodic protection systems. They may be used independently or in combination with one another.

For this course we will discuss primarily the criteria for mitigating corrosion on steel and cast iron piping. It is important to note that there are also different criteria for copper, aluminum, lead, and also steel embedded in concrete. Government regulations regarding criteria differ in different countries, and the selection of an appropriate criterion will depend on local governmental regulations.

There are three NACE criteria that apply to steel: two involve a structure-to-electrolyte potential of equal to or more negative than -850 mV in reference to a copper-copper sulfate reference electrode (CSE), and one is a polarization change of 100 mV.

Earlier in this chapter, we learned the true criterion for corrosion mitigation is polarizing the entire structure to the open circuit potential of the most active anodic site on the structure. Since the above criteria are only surrogates for the true criterion, the basis of each is important to understand for appropriate application and limitation.

SP0169 Criteria

The three criteria defined in the NACE Standard SP0169 for steel and cast iron (including ductile iron) are:

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

$$E_{-850} = E_{\text{on}} - IR.$$



A negative polarized potential of at least 850 mV relative to a saturated copper-copper sulfate reference electrode (Instant Off Potential).

A minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte. The formation or decay of polarization can be measured to satisfy this criterion.

$$\Delta E_{100} = E_{\text{OFF}} - E_{\text{DEPOLARIZED}}$$

OR

$$\Delta E_{100} = E_{\text{OFF}} - E_{\text{CORR}}$$

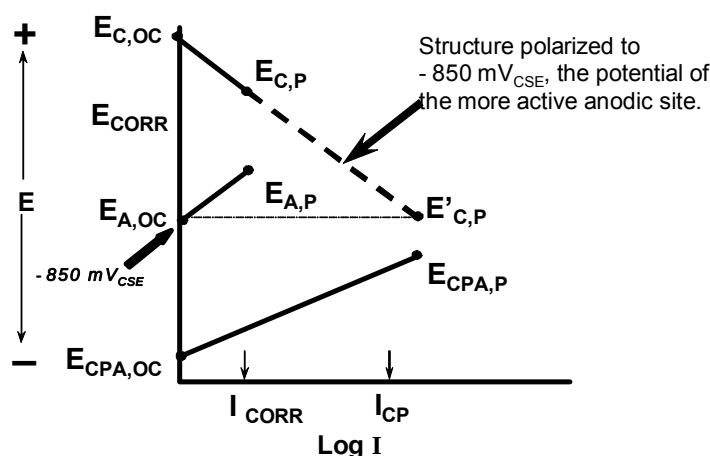
NOTE: The most recent version of NACE or any standard must be referenced in order to obtain the most recent criteria and information regarding the application of that criteria.

Basis of SP0169 Criteria

–850 mV_{CSE} Potential for Steel

For any metal, its energy level is highest when it is new or “bright and shiny.” Laboratory measurements of new steel samples in many different soil environments have indicated the most active corrosion potential is between –800 mV and –850 mV both referenced to a saturated copper-copper sulfate reference electrode (CSE). Therefore, polarizing a steel structure to –850 mV_{CSE} would satisfy the true criterion based on the most active anodic site being –850 mV_{CSE}. If the most active corrosion potential is less negative than –850 mV_{CSE} for a given steel structure, then this criterion is conservative in mitigating corrosion, as shown in Figure 2.12.

The –850 mV_{CSE} polarization potential is further supported by long term laboratory application of this value to test coupons. It is generally agreed that this criterion reduces corrosion to approximately one (1) mil/year [0.0254 mm/yr]. The –850 mV_{CSE} potential is the basis for the first two criteria. The difference between the two criteria will be discussed later in the IR Drop section.



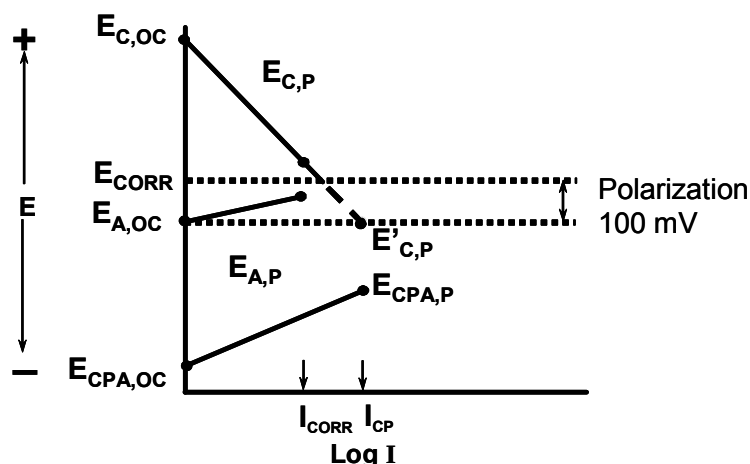
where:

- $E_{C,OC}$ = Structure cathode potential, open circuit, corrosion cell not active
- $E_{A,OC}$ = Structure anode potential, open circuit, corrosion cell not active
- $E_{C,P}$ = Structure cathode potential, corrosion cell active, before CP applied
- $E_{A,P}$ = Structure anode potential, corrosion cell active, before CP applied
- E_{CORR} = Corrosion potential with structure anode and structure cathode connected
- I_{CORR} = Corrosion current before CP applied
- $E_{CPA,OC}$ = CP anode potential, no CP current
- $E'_{C,P}$ = Structure cathode potential with CP current applied
- $E_{CPA,P}$ = CP anode potential, CP current flowing
- I_{CP} = Cathodic protection current between CP anode and structure

Figure 2.12 Structure polarized to -850 mV_{CSE}

100 mV Polarization

Although polarization of a steel structure to -850 mV_{CSE} provides adequate cathodic protection, it may be too conservative or too costly for older structures. For older structures, the most active anodic site can be significantly more noble than -850 mV_{CSE} . Consequently, the mixed or corrosion potential (E_{CORR}) is more noble on older structures. From laboratory experiments and data obtained from successfully operating cathodic protection systems, it has been determined that a minimum of 100 mV of polarization on a structure should provide adequate cathodic protection. Figure 2.13 illustrates this situation where the structure is polarized to a point ($E'_{C,P}$) that is 100 mV more active than E_{CORR} . While there can still be some corrosion occurring and shown by the point I'_{CORR} , the reduction in corrosion can be significant. (Keep in mind that the scale is logarithmic.) The 100 mV criterion is also applicable for metals other than steel and with reference cells other than copper-copper sulfate.



where:

- $E_{C,OC}$ = Structure cathode potential, open circuit, corrosion cell not active
- $E_{A,OC}$ = Structure anode potential, open circuit, corrosion cell not active
- $E_{C,P}$ = Structure cathode potential, corrosion cell active, before CP applied
- $E_{A,P}$ = Structure anode potential, corrosion cell active, before CP applied
- E_{CORR} = Corrosion potential with structure anode and structure cathode connected
- I_{CORR} = Corrosion current before CP applied
- $E_{CPA,OC}$ = CP anode potential, no CP current
- $E'_{C,P}$ = Structure cathode potential with CP current applied (100 mV polarization)
- $E_{CPA,P}$ = CP anode potential, CP current flowing
- I_{CP} = Cathodic protection current between CP anode and structure
- I'_{CORR} = Corrosion current with 100 mV CP applied

Figure 2.13 Polarization of 100 mV

Polarized Potential

Since cathodic protection is a polarization phenomenon, the polarized potential of a structure must be measured to determine the level of protection it is receiving. The following is the definition of a polarized potential:

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

The potential of interest when determining adequate cathodic protection is the polarized potential across the structure/electrolyte interface (see Figure 2.14).

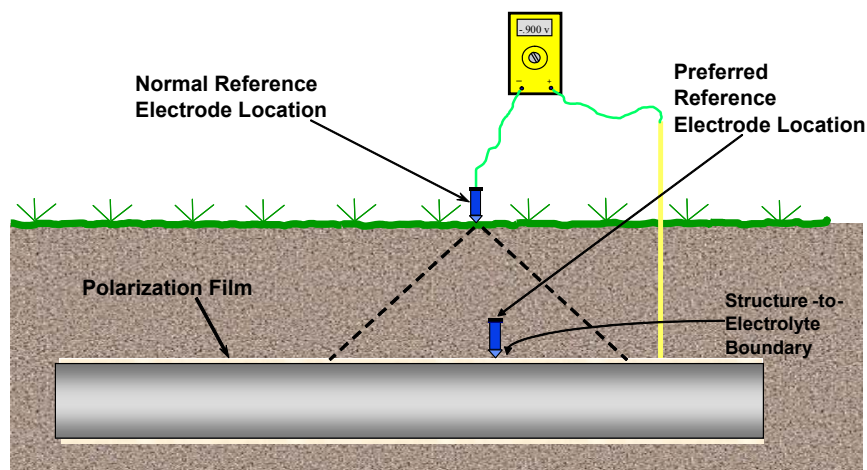
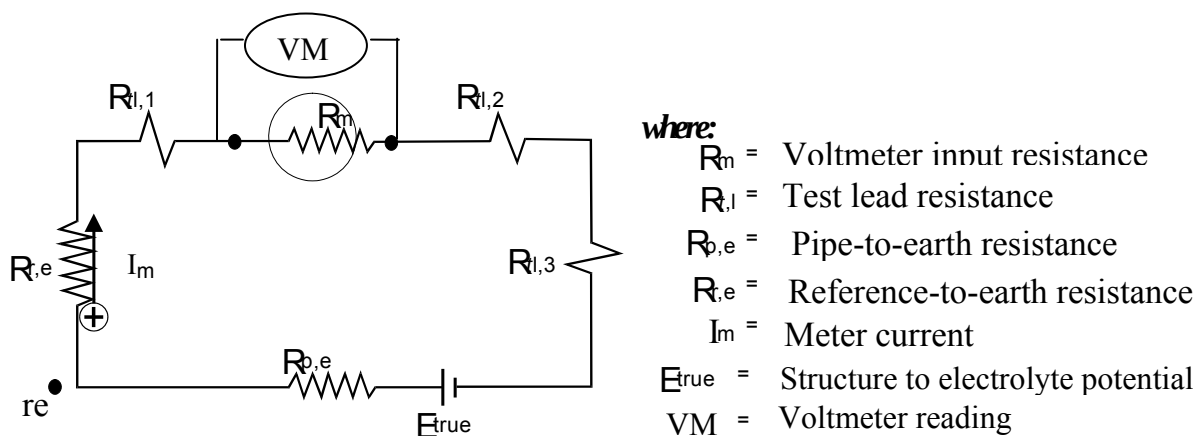


Figure 2.14 Measuring Surface Structure-to-Electrolyte Potential

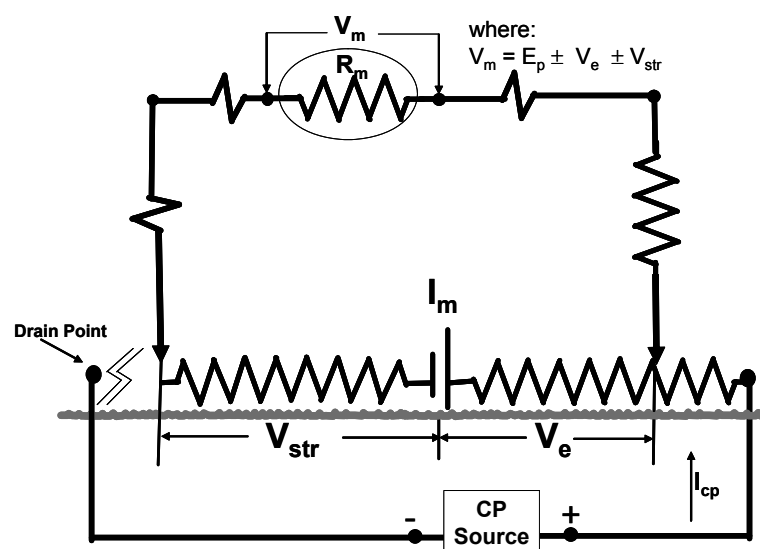
The metering circuit can be shown by the two electrical schematics in Figures 2.15(a) and 2.15(b).



where:

$$V_m = \frac{R_m}{R_t} \times E_{true}$$

Figure 2.15(a) Electrical Schematic of the Structure-to-Electrolyte Measurement Circuit



V_e = voltage drop in earth between reference and structure

V_{str} = voltage drop in structure between point of contact and location of reference

$$\text{where : } V_m = E_p \pm V_e \pm V_{str}$$

Figure 2.15(b) Electrical Schematic Illustrating Voltage Drops External to the Meter Circuit

However, when a potential is measured, the result is the algebraic sum of all the voltage drops in the measuring circuit, as shown in Figure 2.15.

For a measured potential to represent the polarized potential across the structure/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; however, the measurement current or stray currents can be significant. The measurement circuit current is small if the input resistance of the meter is large. 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 impedance meter 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 across the electrolyte. The IR drop across the electrolyte can be reduced to near zero by placing the reference electrode near the structure coating holiday or 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 subtracting the IR drop.

Application of Criteria

The first criterion for steel, a potential of $-850 \text{ mV}_{\text{CSE}}$ obtained with current applied, is based on negligible IR drop or eliminating the IR drop from the measurement. Consideration should be given to the specific structure and its environment in determining if IR drop is negligible prior to employing this criterion. The IR drop is usually negligible when the current density and/or the resistivity are low.

The second criterion, a polarized potential of $-850 \text{ mV}_{\text{CSE}}$, is based on eliminating IR drop during the measurement. Either removing the resistance (electrolyte) or the current can eliminate IR drop. If the potential is measured at the structure/electrolyte interface, then the electrolyte is no longer in the measuring circuit and resistance is 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 or the polarized structure potential, or determining the other. In fact, the criterion is based on the difference between these two potentials. Of course, the IR drop must be eliminated from the measured “on” potential to determine the polarized potential. In practice, for a structure not cathodically protected, the measurement technique may involve measuring the corrosion potential first. Then, current is applied until the structure is polarized. Current is then interrupted momentarily in order to measure the polarized potential.

A technique used to evaluate a structure that is receiving cathodic protection begins with momentary interruption of the current to determine the polarized potential. Then, with the CP current remaining off, dissipation of the polarized potential is monitored. When no further potential change is evident over time or the desired depolarization has occurred, then the potential is referred to as the depolarized corrosion potential of the structure. Figure 2.16 illustrates a depolarization measurement.

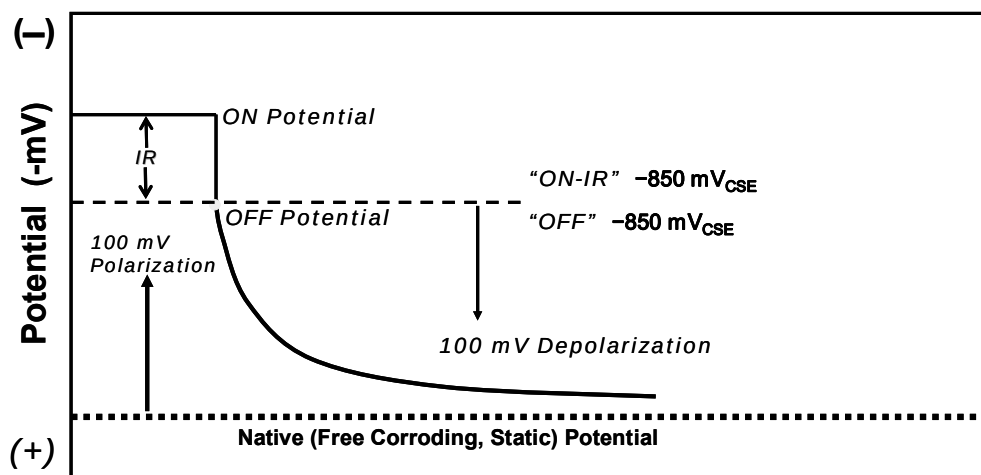


Figure 2.16 Example of a Depolarization Curve

Ineffective or partial protection may be the result of abnormal conditions. Such conditions may include elevated temperatures, disbonded coatings, electrical shielding, bacterial attack, and unusual contaminants in the electrolyte.

Other Criteria

Aluminum

The criterion for cathodically protecting aluminum based on NACE Standard SP0169 is a minimum of 100 mV of polarization as measured between the structure surface and a stable reference electrode contacting the electrolyte.

Aluminum is amphoteric. That is, the metal corrodes under both acid and alkaline conditions. The polarized potential should not be more negative than $-1,200 \text{ mV}_{\text{CSE}}$ measured between the pipe surface and a saturated copper-copper sulfate reference electrode to prevent a buildup of alkali on the surface that could *increase* the corrosion rate. Likewise, if the pH of the environment is above 8.0, the conditions should be re-evaluated before cathodic protection is applied. Amphoteric metals should be isolated from all other metal in the system and protected separately.

Copper

The criteria for the cathodic protection of copper based on NACE Standard SP0169 is a minimum of 100 mV of polarization as measured between the structure surface and a stable reference electrode contacting the electrolyte.

In the case of dissimilar metal piping, a negative voltage between all pipe surfaces and a stable reference electrode equal to that required for the protection of the most anodic metal is required.

Reinforced Concrete Structures

NACE Standard SP0290, “Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures,” specifies two criteria for steel reinforcement embedded in concrete. One criterion is that the structure exhibits a 100 mV polarization development or 100 mV polarization decay after disconnecting or turning off the CP current.

A second criterion is that the polarized potential be at least as negative as the potential at the base of the Tafel Slope on an E-Log I curve. The E-Log I test is performed by incrementally increasing the cathodic protection current from the installed system. At each interval, the IR drop free potential of the steel reinforcement is measured relative to a stable reference electrode. The plot of potential vs. applied current is called an E-Log I plot. The straight line portion of the plot is called the Tafel Slope and corresponds to line $E_{C,P}-E'_{C,P}$ in Figure 2.17. The structure-to-reference electrode potential at the base of the Tafel Slope will be above point E_{CORR} , and at this point, the amount of corrosion should be significantly reduced (although not completely stopped).

A third criterion in this standard is that the polarized potential is statistically more negative than the statistical standard deviation of the native potentials.

Other NACE International Recommended Practices

NACE Standard RP0285, “Corrosion Control of Underground Storage Tank Systems by Cathodic Protection.” Criteria are the same as NACE Standard SP0169.

NACE Standard SP0388, “Impressed Current Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks.” The criteria defined in this standard are as follows: (1) –850 mV vs. a copper-copper sulfate electrode or (2) a minimum 100 mV of polarization between the tank surface and a stable reference electrode contacting the electrolyte (the formation or decay of



polarization can be measured to satisfy this criterion). The 100 mV criterion is only applicable to steel water tanks not having corrosion cells caused by connection to more noble metals such as copper, brass or passive stainless steel. There is also a caution about possible coating damage at potentials above $-1,100$ mV.

NACE Standard SP0169 “Control of External Corrosion on Underground or Submerged Metallic Piping Systems.” The three criteria defined in this standard are as follows:

- 1) -850 mV applied vs. a copper-copper sulfate reference electrode, after IR drop is considered
- 2) -850 mV polarized vs. a copper-copper sulfate reference electrode,
- 3) minimum of 100 mV polarization between the structure surface and a stable reference electrode. The formation or decay of polarization can be measured to satisfy this criterion.

NACE Standard RP0196 “Galvanic Anode Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks.” This standard uses the -850 mV_{CSE} applied and the -850 mV_{CSE} polarized potential criteria found in NACE Standard SP0169.

NACE Standard SP0575 “Internal Cathodic Protection Systems in Oil-Treating Vessels.” This standard also uses a criterion of -850 mV to a copper sulfate reference electrode for steel vessels. The criterion changes to -950 mV_{CSE} if sulfides are present in the fluid. It also specifies a current density of 10 mA/ft² (110 mA/m²) as an alternative criterion. The leak history is also a criterion.

NACE Standard RP0180 “Cathodic Protection of Pulp and Paper Mill Effluent Clarifiers.” This practice uses the NACE Standard SP0169 criteria. In addition, the practice defines protection as polarizing the entire surface to the potential of the most active anode.

NACE Standard RP0193 “External Cathodic Protection of On-Grade Metallic Storage Tank Bottoms.” This standard uses the same criterion as those found in NACE Standard SP0169 measured at the tank periphery, center, and in between. The potential at the periphery will not necessarily reflect potentials in the center of the tank when anodes are around the outside ring.

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 $100 \Omega\text{-m} < \rho < 1,000 \Omega\text{-m}$
 - $-650 \text{ mV}_{\text{CSE}}$ 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 $-850 \text{ mV}_{\text{CSE}}$.

American Water Works Association (AWWA)

D104 “Automatically Controlled, Impressed Current Cathodic Protection for the Interior of Steel Water Tanks.” This standard specifies a criterion of $-850 \text{ mV}_{\text{CSE}}$ to $-1,050 \text{ mV}_{\text{CSE}}$ polarized potential.

Non-NACE International Criteria

American Petroleum Institute (API)

API Recommended Practice 651 “Cathodic Protection of Aboveground Petroleum Storage Tanks.” Refers to NACE Standard SP0169 for external cathodic protection and NACE Standards SP0575 and SP0388 for internal cathodic protection. The standard does provide additional information.

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

Saudi Aramco Engineering Standards (SAES-X-400)

- Pipelines: $-1,200$ mV minimum and $-3,000$ mV maximum to CSE with the current ON
- Valves and Compressor piping: $-1,000$ mV min. and $-3,000$ mV max. to CSE with the current ON
- Pipeline junctions, pump stations, compressor stations: $-1,050$ mV min. and $-3,000$ mV max. to CSE with the current ON

Petroleum Development of Oman (PDO-65-12)

- -850 mV min. to CSE instant-off. Avoid potentials more negative than $-1,200$ mV CSE (off)

Abu Dhabi National Oil Company (ADNOC)

Steel in soil:	-950 to $-1,150$ mV instant off CSE -900 to $-1,100$ mV instant off SSC
Steel in concrete:	-700 to $-1,100$ mV instant off CSE -650 to $-1,050$ mV instant off SSC
Steel in water:	-850 to $-1,050$ mV instant off CSE -800 to $-1,000$ mV instant off SSC

Canada

CSA Standard Z662, “Oil and Gas Pipeline Systems,” references CGA Recommended Practice OCC-1, “For the Control of External Corrosion on



Buried or Submerged Metallic Piping Systems,” for criteria and methods. The criteria are the same as in the NACE Recommended Practice except for a condition when using the 100 mV criterion. The polarized potential must be more negative than -770 mV if SCC is suspected.

CSA Standard Z169 covers cathodic protection of aluminum.

Australia

Australia Standards Institute Standard No. 2832. This standard has three parts – Part 1 is concerned with pipes, cables and ducts, the subject of Part 2 is compact buried structures, and the topic of Part 3 is fixed immersed structures. The criteria listed are the same as NACE Standard SP0169.

Japan

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

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

The document further lists the protective current density as:

	Clean areas, mA/m²	Polluted areas, mA/m²
Seawater	100	130 to 150
Sea rubble	50	65 to 75
Sea mud	20	30
Soil	10	10

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

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

E log I

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

In conducting the test, several factors are important. The time interval between measurements and the current increments should be kept as consistent as possible to eliminate distortions due to the change of polarization with time. The range of test current must be greater than the estimated current required for protection. In addition, the measured potential must be corrected for IR-drop error to obtain a polarized potential (Instant Off).

The test data are then plotted on linear and semi-logarithmic paper (Figure 2.17). The data should first be plotted on a linear scale to ensure that the plot deviates from a straight line relationship. In relatively deaerated environments, such as well casings, the polarization curve often exhibits linear (Tafel) behavior with increased test current. A straight line is then drawn tangent to the Tafel portion of the E log I curve that is beyond the break in the linear plot. From this Tafel extension a wide number of interpretations are commonly in use. The most common interpretation of the E log I curve is to select the point where the tangent to the Tafel slope breaks away from the data. The current at the break-away point is considered to be the current required to achieve complete protection. In Figure 2.17, this break occurs at a current of approximately 4 A.

Note that the first points in Figure 2.17 define a curved line. The last of the points define a straight line on the semi-log graph. The point where the curvature stops and the straight line begins represents the start of Tafel behavior indicating where most all corrosion has ceased. E_{cp} is considered as an adequate potential for cathodic protection under the E log I method.

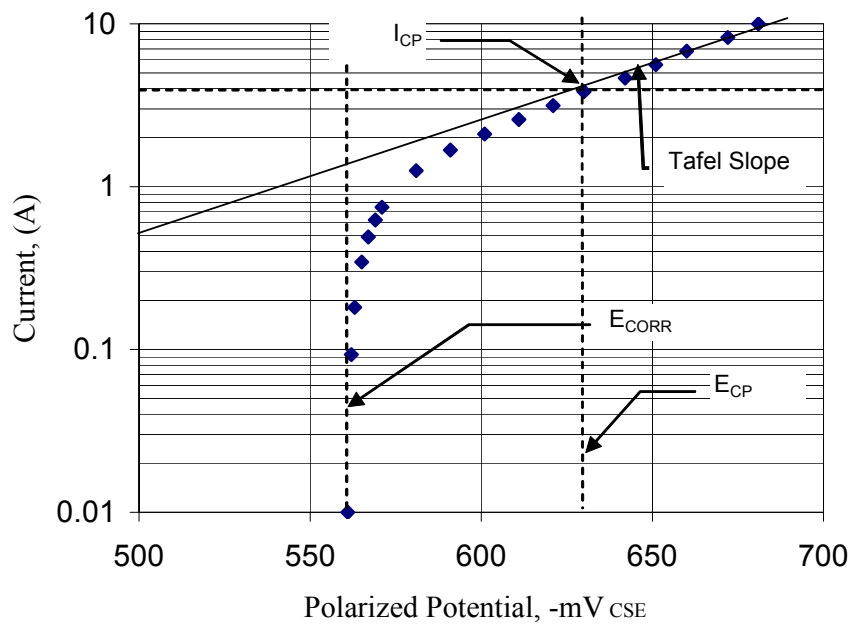


Figure 2.17 Cathodic Polarization Log I Plot

CHAPTER 3

Cathodic Protection Systems

There are 2 general types of cathodic protection systems:

- Galvanic
- Impressed Current

Components of Galvanic Cathodic Protection

There are four basic components of a galvanic anode cathodic protection system: (1) the anode, (2) the anode backfill, (3) a means of connecting the anode to the structure, (4) and the structure (see Figure 3.1).

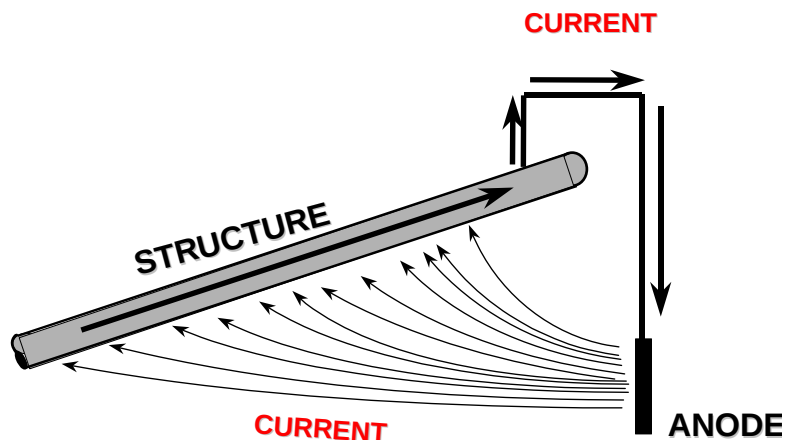


Figure 3.1 Typical Galvanic Anode Cathodic Protection

Anodes

Galvanic cathodic protection operates on the principle that a more active metal connected to a less active material will form a galvanic corrosion cell. This is used to our benefit to protect the less active metal. The more active alloy will corrode (“sacrifice” itself) to protect the protected metal; therefore, these anodes are often called *sacrificial anodes* (see Figure 3.2).

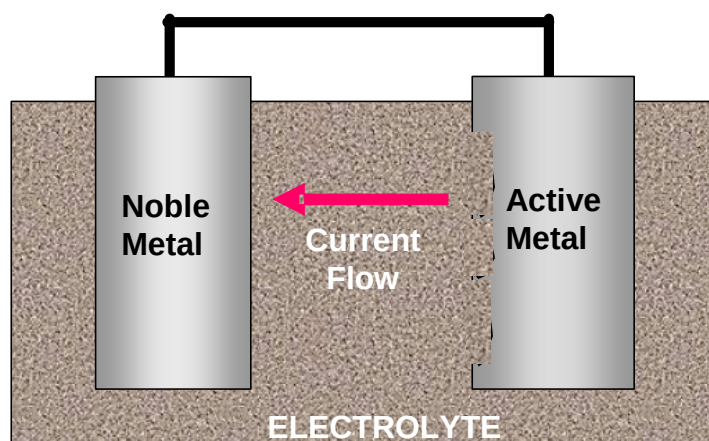


Figure 3.2 Galvanic Corrosion Cell

The practical galvanic series of metals (shown in Table 3.1) shows three metals more active than iron—magnesium, zinc, and aluminum. (Note: a complete emf series table or galvanic series table will show other metals more active than iron, but these three are the most useful.) The most common active metals used as anodes to protect iron alloys, copper, and lead are alloys of magnesium, zinc, and aluminum.

Table 3.1 Practical Galvanic Series in Seawater

Metal	Volts vs. Cu-CuSO₄	Volts vs. Ag-AgCl
	Active or Anodic End	Active or Anodic End
Magnesium	−1.60 to −1.75	−1.55 to −1.70
Zinc	−1.10	−1.05
Aluminum	−1.05	−1.00
Clean Carbon Steel	−0.50 to −0.80	−0.45 to −0.75
Rusted Carbon Steel	−0.30 to −0.50	−0.25 to −0.45
Cast/Ductile Iron	−0.50	−0.45
Lead	−0.50	−0.45
Steel in Concrete	−0.20	−0.15
Copper	−0.20	−0.15
High Silicon Iron	−0.20	−0.15
Carbon, Graphite	+0.30	+0.35
	Noble or Cathodic End	Noble or Cathodic End

Alloys of magnesium, zinc, and aluminum have been developed to enable the anode to remain active and extend the life of the anode. The pure forms of the metals are often not suitable as anodes because they undergo too much “self

corrosion” in the environment and do not stay active. Galvanic anode alloys include:

- Magnesium

Magnesium anodes are available in two alloys: a high-potential alloy having a nominal corrosion potential of -1.75 V 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.

Standard Alloy – for use in low-resistivity soils and water

High-Potential Alloy – provides a higher driving voltage than the standard alloy.

- 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.

MIL-A-18001 or ASTM B418 Type I – for salt water and brackish water use

ASTM B418 Type II – high purity for underground and fresh water use

- 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.

Galvalum I™* - contains zinc and mercury for use in seawater

Galvalum II™* - contains zinc and mercury for use in saline mud

Galvalum III™ - contains zinc and indium for use in seawater, brackish water, and saline mud

** Seldom used due to mercury content.*

Galvanic anodes are available in a wide range of shapes and sizes for specific applications. Custom shapes and sizes can be made.

For marine environments (platforms), dual galvanic anodes can be made with a highly active anode metal casing (e.g., magnesium) on a less active anode core (e.g., zinc). These are used to provide a high initial current density to achieve initial cathodic protection polarization on offshore structures. Once the protection potential is achieved, the less active anode can maintain an adequate cathodic protection polarization.

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. For magnesium, the anode efficiency is generally less than 50%, while zinc has an efficiency of 90%.

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 lower resistivity electrolytes.
- For local cathodic protection to provide current to a specific area on a structure. Some pipeline 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.
- Poorly coated buried valves
- Interiors of water storage tanks
- Shorted casings that cannot be cleared (to improve potentials in the surrounding area)
- Underground storage tanks
- 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 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 also used 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.

Anode Backfill

Zinc and magnesium anodes used in cathodic protection applications in soil are sometimes supplied prepackaged with a prepared backfill material in a cloth or cardboard container. The special backfill prevents direct soil contact to reduce localized corrosion of the anode, prevents passivation of the anode caused by reactions with soil salts, provides a low-resistivity environment around the anode, and expands when wet to fill the hole and eliminate air voids. The most common backfill material contains 75% hydrated gypsum, 20% bentonite clay, and 5% sodium sulfate. Zinc anodes can also be packaged in a backfill consisting of 50% hydrated gypsum and 50% bentonite clay. Since zinc anodes are normally installed in low-resistivity soil, it is not necessary to add sodium sulfate to lower resistivity.



Wiring and Connections

Galvanic anodes can be attached to the structure either directly by welding or bolting integral straps to the structure, e.g., hull mounted anodes and bracelet anodes, or by connecting a wire between the anode and structure.

If a wire is used, the manufacturer attaches it to the anode. The wire is attached to the structure using a mechanical connection, thermite weld, or other suitable method. The thermite weld is the preferred method since it provides the most reliable connection. The wire should be coated with a dielectric insulation and the connections should be coated.

Components of Impressed Current Cathodic Protection

The components of an impressed current cathodic protection system are anodes, anode backfill, a power supply (rectifier), structure, wiring, and connections. The anodes used in impressed current CP systems are different from those used in galvanic systems. Impressed current anodes are manufactured from materials that are consumed at low rates. Impressed current CP systems generally operate at higher current and driving voltage levels than galvanic anode CP systems.

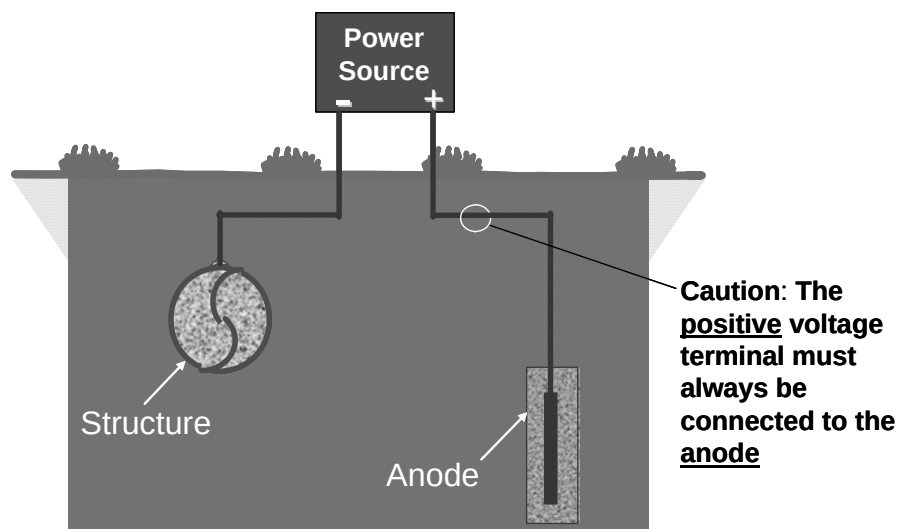


Figure 3.3 Typical Impressed Current Cathodic Protection

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 aboveground storage tanks
- for underground storage tanks
- for underwater components of offshore structures
- for foundation piles and sheet piling, both underground and in the water.

Anodes

- Graphite

Graphite anodes are used in soils, flowing seawater, and mud. They are practically immune to chlorine attack. Graphite anodes are usually impregnated with a sealer to prevent mechanical failure from gas evolution in pores. Graphite is also brittle. Consumption rates are 0.45 kg/A-y (1 lb/A-y) in seawater, 0.9 kg/A-y (2 lb/A-y) in carbon backfill, and 1.36 kg/A-y (3 lb/A-y) in mud. Graphite anodes are usually available as cylindrical anodes.

- Conductive Polymer

Carbon is used as filler in polymer materials having a copper core for use as an impressed current anode. This type of anode looks like an insulated wire but the covering is conductive. (Note: this type of anode wire must not be used where dielectrically insulated wire is needed.) This material has a maximum rating of 51 mA/m (16 mA/ft) of material.

Carbon has also been used as conductive filler in water- or solvent- based coatings for application as an anode to protect reinforced concrete structures.

- High-Silicon Chromium-Bearing Cast Iron

High-silicon cast iron (HSCI) is a chemically resistant alloy containing silicon, chromium, and iron. HSCI anodes are commonly used in fresh water, seawater, or underground applications. HSCI is very brittle and forms a SiO_2 film on the surface in underground applications that can increase the resistance of the anode in dry environments. The consumption rate of HSCI ranges from 0.25 to 1 kg/A-y (0.55 to 2.20 lb/A-y).

- Lead

Lead-silver alloys have been used in seawater applications. The lead under anodic current develops a PbO_2 film that is conductive and prevents deterioration of the lead. The consumption rate of lead-silver alloys is on the order of 0.09 kg/A-y (0.2 lb/A-y).

Extruded lead with platinum pins has also been used in seawater applications. The purpose of the platinum pins is to promote the formation of the PbO_2 film.

- Mixed-Metal Oxide

Mixed-metal oxide (MMO) anodes, also called dimensionally stable anodes, consist of rare earth oxides baked onto a titanium substrate. These anodes were developed for the electrolytic production of chlorine and hypochlorites, but are now used for cathodic protection applications. The consumption rate is on the order of 1 mg/A-y. This anode material is typically available in rod, wire, tubular, or mesh form.

- Platinum

Platinum is used as an anode material when either metallurgically clad or plated onto either a titanium or niobium substrate. Titanium and niobium form stable oxide layers when made anodic. These layers are stable up to 12 V in the case of titanium and 90 V in the case of niobium. The consumption rate of platinized anodes is on the order of 6 to 10 mg/A-y. Platinized anodes are available in wire or mesh form. Platinized anodes are subject to rapid deterioration if the breakdown voltage is exceeded or if the environmental conditions surrounding the anode become acidic. Other deleterious factors include the presence of low-frequency AC ripple, current reversal, biofouling, scales, and the presence of certain organic materials.

Platinized anodes are most suitable in fresh-or salt-water applications rather than in underground applications.

- Scrap Metal

Scrap iron or steel can be used as an anode material. In situations where the current requirements are low, scrap iron is readily available, and the anode can be readily replaced, scrap iron might be an economical choice. The consumption rate of iron is 6.8 to 9.1 kg/A-y (15 to 20 lb/A-y). The relatively rapid dissolution rate and difficulty in maintaining the integrity of the connection between the power supply and anode are disadvantages of this material.

- Metallized Titanium

Metallized titanium is being tested for use on reinforced concrete structures. The titanium is first sprayed to the concrete surface using an arc spray technique and then a liquid catalyst is applied to activate the anode.

- Thermal Sprayed Zinc and Aluminum Alloys

Thermal sprayed zinc and aluminum alloys have been used as impressed current anodes on reinforced concrete structures. The relatively low current requirement for this type of structure has made the use of zinc and aluminum alloys practical in these applications.

- Magnetite

Magnetite is a sintered material made up of Fe_3O_4 . It is used in seawater, brackish water, fresh water, and high-resistivity soil. The consumption rate of magnetite is 0.005 to 0.08 kg/A-yr. Magnetite is available in cylindrical form.

- Aluminum

Aluminum has also been used as an impressed current anode, primarily in fresh water applications such as water storage tanks. The dissolution rate of aluminum as an impressed current anode is about 4.5 kg/A-y (10 lb/A-y).

Anode Backfill

Carbon is used as a backfill material around impressed current anodes for underground CP applications. The purpose of the backfill material is to:

- reduce the resistivity of the environment surrounding the anode to increase the amount of current the anode can discharge
- extend the anode surface area, thus increasing the amount of current the anode can discharge; and
- reduce consumption of the anode since the carbon becomes the part of the anode consumed before the anode itself.

Carbon backfill for cathodic protection purposes is available as calcined petroleum or metallurgical coke, each being the product of its respective industry. Non-calcined carbon is also available, but is not suitable for CP use since it can have too high an electrical resistance.

The typical composition of carbon backfill is:

	Metallurgical	Calcined
Carbon	85%	99%
Ash	8 to 10%	0.1%
Moisture	6 to 9	0%
Sulfur	1%	
Volatile matter	3%	<0.5%
Density kg/m ³ (lb/ft ³)	730 (45)	875 to 1,200 (54 to 74)

The resistance of carbon backfill is dependent on how well it is compacted. The higher the degree of compaction, the lower the resistance. The size of the carbon particles is important in compaction. A mixture of large and small sizes is advisable to attain good density and low resistance. The size range may be on the order of 0.5 to 12.7 mm (0.02 to 0.5 in.). Finer grade coke is often used for deep anode systems and the particles may range from 0.10 to 1 mm (0.004 to 0.04 in.) in size.

Impressed current anodes for underground applications can be supplied prepackaged in carbon backfill. The carbon backfill and anode are packaged in an individual galvanized steel canister. Carbon backfill for deep anode systems is added during installation of the anode bed by pumping a fluidized mixture of

water and carbon backfill to the bottom of the hole and allowing the carbon particles to settle out.

Power Supply

Unlike galvanic anode systems where the natural potential difference between the anode and cathode provides the driving force for current, an impressed current CP system must be supplied with power from an external source. Cathodic protection power supplies are covered in Chapter 4.

Wiring and Connections

In impressed current CP systems, all wiring and connections must be made to totally isolate the metal from the electrolyte. Unlike a galvanic anode system where exposed wire and connections are protected by the anode, any exposed metal in an impressed current CP system is part of the **anode**. Thus, exposed metal will corrode rapidly. Only cable having approved cathodic protection dielectric insulation can be used. Types of insulation found on CP cables include:

- High-Molecular-Weight Polyethylene (HMWPE)

This insulation is commonly used for direct burial cathodic protection installations for both anode and structure wiring. The insulation for cathodic protection cable (type CP) is thicker than standard polyethylene insulation (e.g., THW). HMWPE insulation is not recommended for use in environments containing chlorine, hydrochloric acid, or petroleum hydrocarbons.

- Halar/Polyethylene Layered Insulation

Halar/polyethylene is a dual jacketed insulation. The outer jacket (HMWPE) provides mechanical protection to the wire as well as chemical resistance and dielectric insulation. The inner jacket is Halar, which is a thermoplastic fluoro-copolymer which is resistant to chemicals, including chlorine, hydrochloric acid, sulfuric acid, petroleum hydrocarbons, alkalis, and strong oxidizing acids. The temperature range of this insulation is -62°C (-80°F) to 121°C (250°F).

- Kynar/Modified Polyolefin

Kynar (polyvinylidene fluoride)/modified polyolefin is a dual jacketed insulation similar to Halar/polyethylene. The outer jacket (HMWPE) provides mechanical protection to the wire as well as chemical resistance and dielectric insulation. It is resistant to chlorine, hydrochloric acid,



sulfates, hydrogen sulfides, alkalis, other acids, petroleum-based chemicals, and chlorine gas.

Total encapsulation of splices and connections is required to prevent water from getting into the splice, which will eventually destroy the connection. Encapsulation is achieved using an epoxy resin cast into a mold around the splice, heat-shrink sleeves containing adhesive mastic manufactured for CP purposes, or multi-component wrapped connections. Prior to applying the splicing material, the wire should be thoroughly cleaned to remove greases, oil, and dirt. The wire insulation should be lightly abraded prior to applying the splice. This is one area where a little care will prevent problems later on.

Splices should be avoided if possible, especially in the anode circuit.

Environmental Issues

Deep anode CP systems present environmental concerns as the borehole can penetrate different geological layers and water aquifers. The layers must be sealed to prevent the transfer of undesirable components, such as pollution, between layers. This can be done through the use of clay sealing materials or specialized conductive cementitious backfills.

The primary reactions at the anode surface are:

- metal oxidation
- oxygen and chlorine evolution, and
- chlorine generation.

Galvanic anodes and impressed current anodes release small quantities of corrosion products as they deteriorate. The corrosion products of carbon anodes and carbonaceous backfill are gases – carbon monoxide and carbon dioxide. The corrosion products of high-silicon cast iron anodes are the same as those produced from iron-based alloys. These tend to stay in close proximity to the anode in soil. Dimensionally stable anodes produce few if any of these products. Gases, including chlorine, oxygen, carbon dioxide, and carbon monoxide (depending on the anode and the environment) are produced by anodes. These gases can be flammable, poisonous, or corrosive and can block the groundbed reducing anode performance. The gases need to be vented, particularly in deep anode systems.

Reactions at the anode produce an excess of hydrogen ions.





These will acidify the environment immediately adjacent to the anode, but this is usually not significant since the environment away from the anode neutralizes the acid.

Sacrificial anodes installed on ship hulls or in applications where they are immersed in a natural water environment (e.g., pond, bay, river, and ocean) will corrode releasing corrosion products into the water. Whether or not this is an environmental concern depends on the relative water volume compared to the volume and nature of the corrosion products released. Aluminum anodes containing mercury can be used in open seawater and saline mud, but not in fresh water (aluminum containing indium is used in these applications).

Anodes and other cathodic protection materials to be installed into potable water tanks or other potable water systems must have approval of NSF International. ANSI/NSF 60, “Drinking Water Treatment Chemicals,” and ANSI/NSF 61, “Drinking Water System Components – Health Effects,” list materials approved for use in contact with potable water.

Anode Configurations

The objective of cathodic protection is to supply the structure being protected with adequate current for cathodic polarization to occur. This means that anodes must be located to distribute current as evenly as possible to the structure. Previous discussion introduced the various types of anodes used – galvanic and impressed current. Anode configurations can be described as *distributed* or *remote*.

Current from the anode through the electrolyte produces voltage drops from point to point in the electrolyte (gradients). The magnitude of the gradient is dependent on the amount of current, the electrolyte resistivity, and the distance between points. The anode gradients are largest within a few feet of the anode. The term *remote earth* refers to the point where further distance from the anode produces no further change in voltage gradient.

A *distributed* configuration uses anodes located at relatively close intervals along the structure. The anodes are spaced close together and close to the structure so as to distribute the current evenly over the surface of the structure and to raise the potential of the earth adjacent to the structure (Figure 3.4). “Close” means that the structure being protected will fall within the anode voltage gradient. This means that the anodes will cause the electrolyte around the structure to become positive with respect to remote earth (Figure 3.5). The definition of “close” is not firm, but is usually within ten to fifteen feet of the structure. Situations where distributed anode systems are used include uncoated structures, structures that are not electrically isolated from other structures, and in congested areas, where shielding or interference is possible.

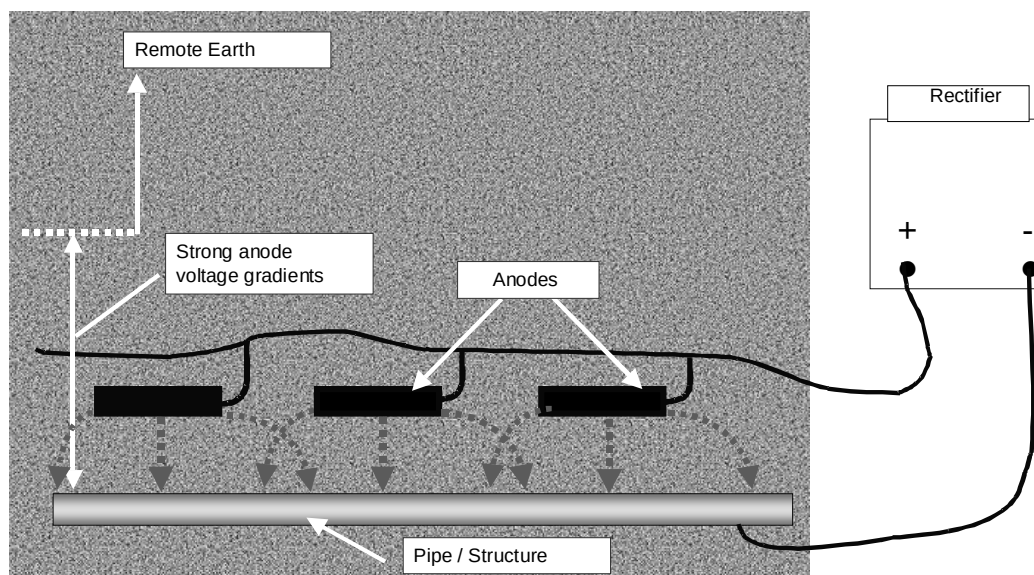


Figure 3.4 *Illustration of a Distributed Anode System (the anodes are placed so that the structure is within the anode voltage gradient)*

Cathodic protection systems for reinforced concrete use a distributed anode configuration consisting of a continuous anode on the concrete surface or closely spaced strips embedded in the concrete surface.

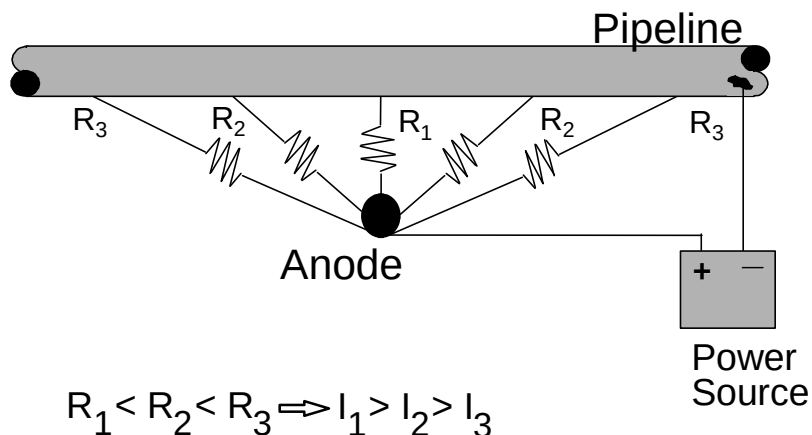


Figure 3.5 Current Distribution from a Close Anode

A *remote* configuration (Figure 3.6) uses anodes placed at a location considered electrically remote from the structure. The term *electrically remote* is not necessarily the same as *geometrically remote* (Figure 3.7). Remote anodes are used for coated structures where only holidays in the coating are protected by the CP system and for structures that are electrically isolated from other structures. In these cases, the only metal requiring cathodic protection is at holidays in the coating. These holidays can be defined as electrically remote from the anode.

All anodes can be installed either horizontally or vertically. The choice of whether to use a horizontal or vertical groundbed depends on the conditions present at the groundbed location.

- Vertical groundbeds may be easier to install, requiring augering a hole rather than digging a ditch.
- Vertical groundbeds, in general, require less room and less excavation.
- Vertical anodes might have a lower resistance than horizontal anodes installed under the same conditions.
- Soil conditions, i.e., resistivity layering or rock formations, might prevent the use of vertical anodes.
- Site geometry might require one or the other type of groundbed.

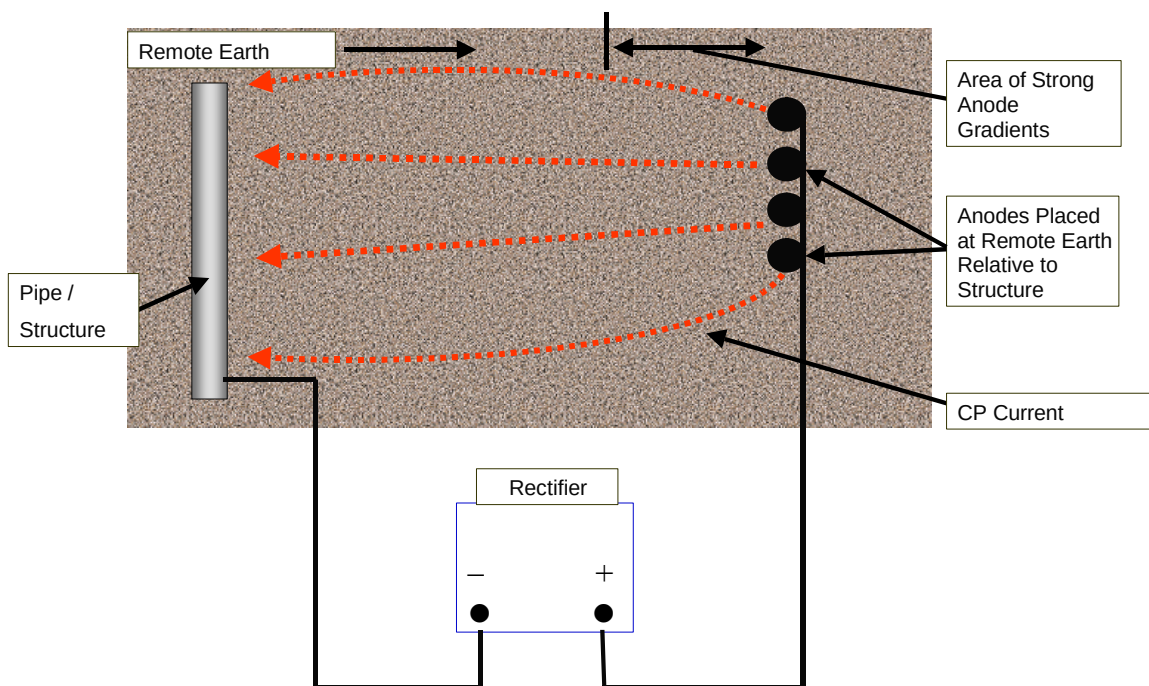


Figure 3.6 Illustration of a Remote Anode

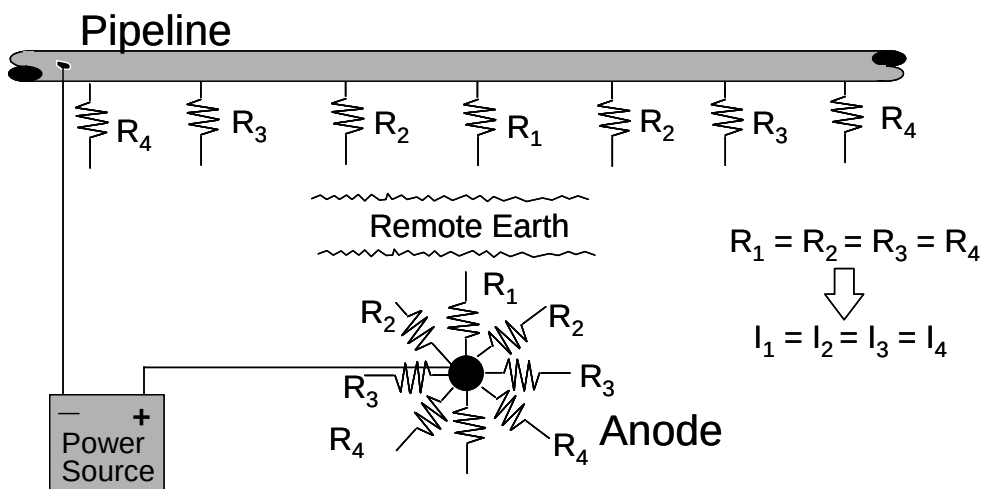


Figure 3.7 Current Distribution for a Remote System

Galvanic Anodes

Galvanic anodes can be placed in either a distributed or remote fashion. Galvanic anodes are usually buried at relatively shallow depths at or below the ground water level, e.g., at or below pipe depth. Magnesium and zinc are available as continuous ribbon to allow use as one continuous distributed anode.

Galvanic anodes for atmospherically exposed reinforced concrete structures are placed over the entire surface to distribute the current evenly.

Galvanic anodes are usually installed in a distributed manner on offshore platforms. The anodes are directly connected to the platform.

Impressed Current Anodes

Impressed current anodes are installed either as distributed or remote anodes. Anodes can be installed in surface groundbeds (up to 7.62 m [25 ft] deep). In addition, impressed current anodes are used in the remote configuration by installing them in a deep hole drilled from the surface. These are called *deep anodes*. Deep anodes are at least 15.24 m (50 ft) deep. Semi-deep anodes are 7.62 to 15.24 m (25 to 50 ft) in depth. Deep anodes can be several hundred feet deep to achieve the remote anode configuration. Figure 3.8 illustrates a deep anode configuration.

In the case of a buried pipeline or elongated structure (e.g., sheet pile wall), anodes can be placed parallel to a structure or perpendicular to the structure. Parallel or distributed placement of the anodes results in the current being evenly distributed along the length of the structure. This configuration “closely couples” the anode to the structure and is useful in situations where the structure is not well coated or where other nearby structures might be subjected to interference. A parallel or distributed configuration might be needed if there is insufficient right-of-way for a remote anode bed. Perpendicular anode placement can be used where the structure is well coated, where current requirements are relatively low, and where property access permits.

Anode placement on atmospherically exposed reinforced concrete structures (e.g., bridges and buildings) requires that a distributed anode be used. Normally this means placing the anode over the entire surface of the concrete (e.g., metallized coating, anode mesh, or conductive paint) or using closely spaced anode strips (e.g., ribbon).

Impressed current anodes used in condenser water boxes are distributed to provide uniform current and are also placed to achieve current to hard-to-reach areas such as corners.

Impressed current anodes are installed in a distributed manner on offshore structures to evenly distribute current to the structure.

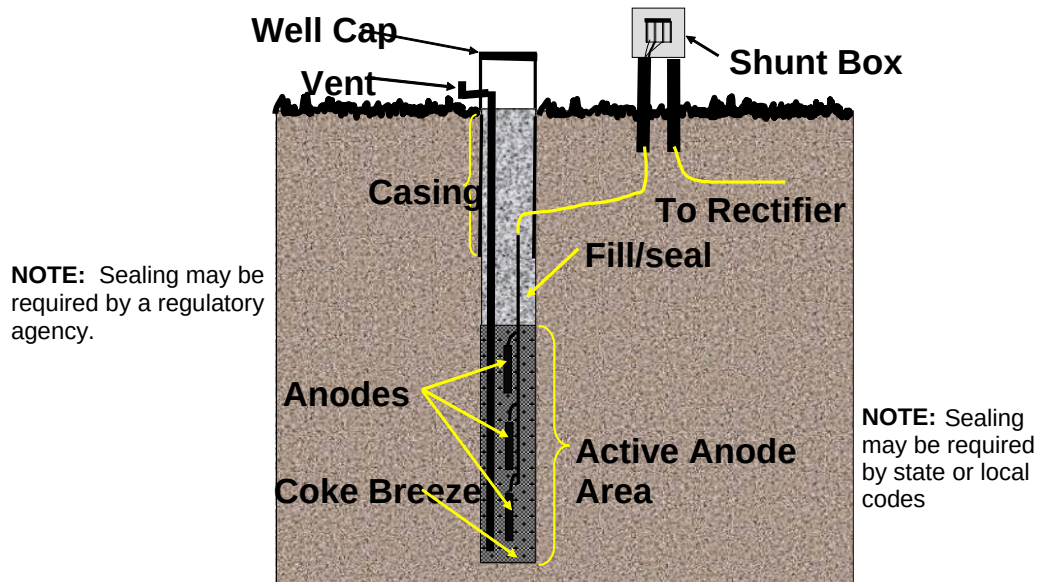
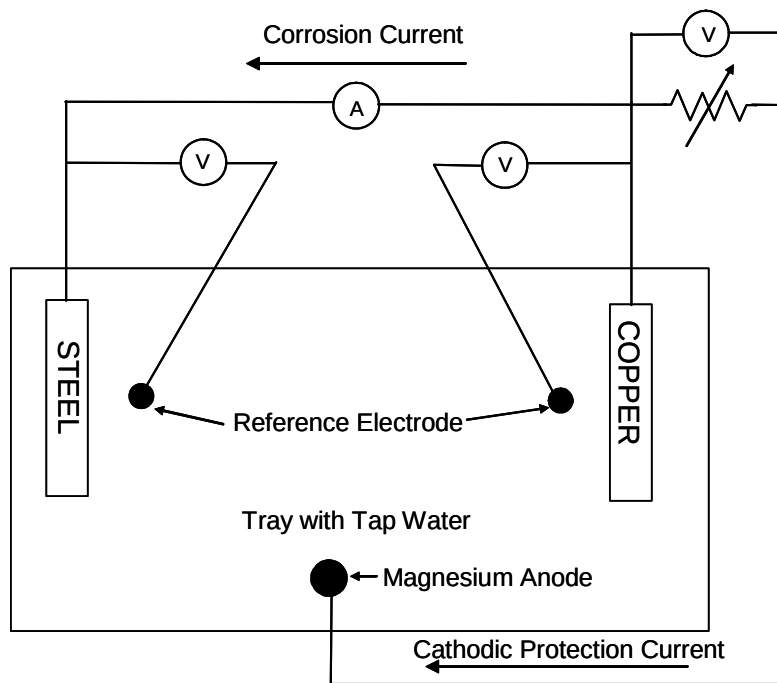


Figure 3.8 Deep Anode Remote System

Experiment 3.1 Demonstrate the Use of a Sacrificial Anode to Mitigate Corrosion in a Local Action Cell

The operation of a sacrificial anode cathodic protection system can be demonstrated as illustrated below. In this experiment the steel and copper represent a local action corrosion cell. Corrosion in this cell is mitigated by cathodic protection.

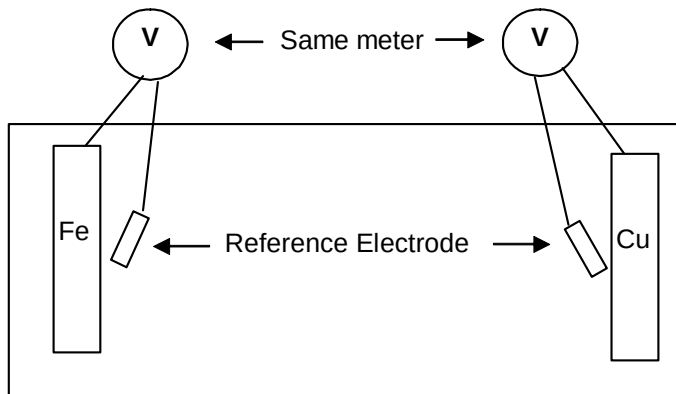


Experiment to Demonstrate Corrosion Mitigation of Local Action Cells by Sacrificial Anode Cathodic Protection

PROCEDURE

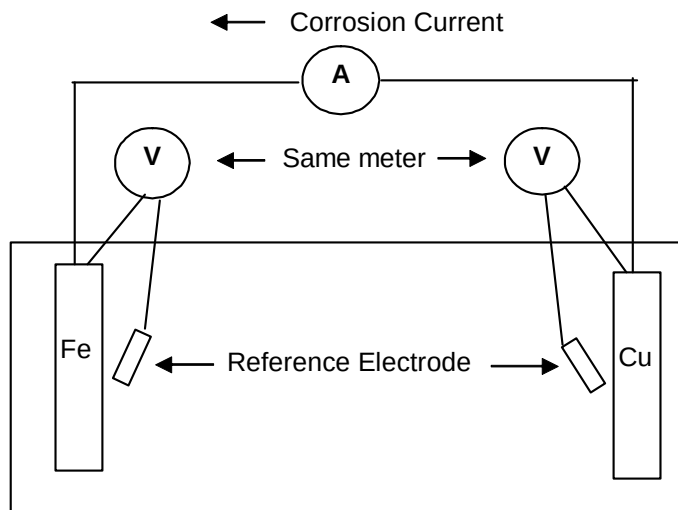
Part A

1. Insert steel and copper sheet in side of tray and add water.
2. Measure static potential of steel and copper.



3. Connect ammeter between copper and steel sheet and measure corrosion current (I_{corr}).

Leave ammeter in place once installed

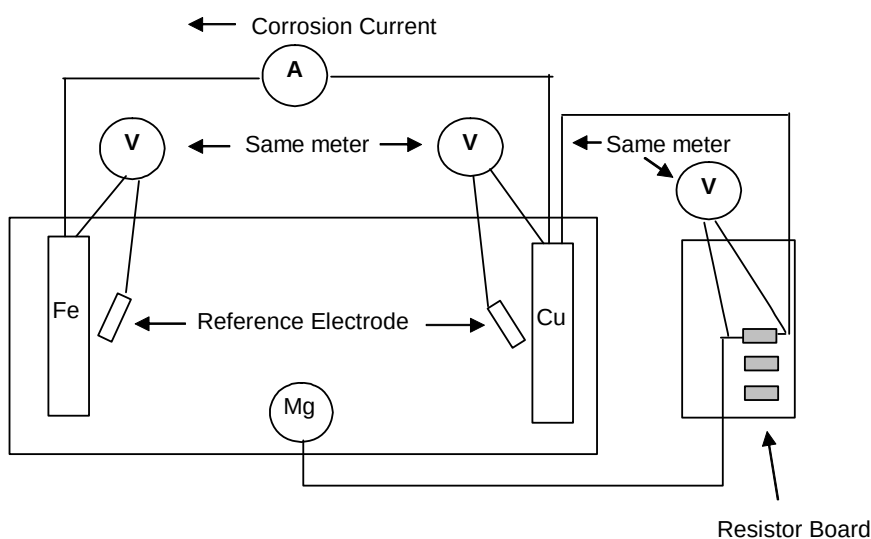


4. Measure polarized potentials of steel and copper.

Part B

1. Place magnesium anode in tray and connect to the copper sheet through a 10,000- Ω 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 resistor.
4. Measure polarized potentials of steel and copper.

Leave ammeter in place once installed

**Part C**

1. Repeat Part B using 1,000- Ω , 100- Ω , and 10- Ω resistors.

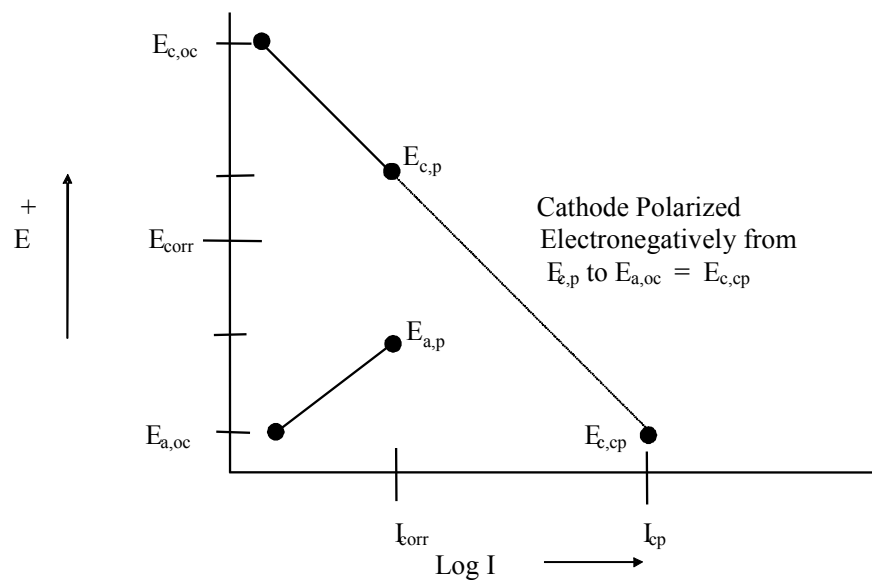
Part D

1. Construct polarization diagram.
(See example next page)

RESULTS

Circuit Conditions	E_{steel} (mV _{CSE})	E_{copper} (mV _{CSE})	Corrosion Current I_{corr} (mA)	CP Voltage Drop (V_r) Across Resistor (mV)	Calculate CP Current $I_{c,p}$ (mA)
Static (OC)	$E_{a,oc}$ _____	$E_{c,oc}$ _____			
Polarized	$E_{a,p}$ _____	$E_{c,p}$ _____	_____		
10,000 Ω	_____	$E_{c,cp}$ _____	_____	_____	_____
1,000 Ω	_____	_____	_____	_____	_____
100 Ω	_____	_____	_____	_____	_____
10 Ω	_____	_____	_____	_____	_____

Polarization Diagram Example



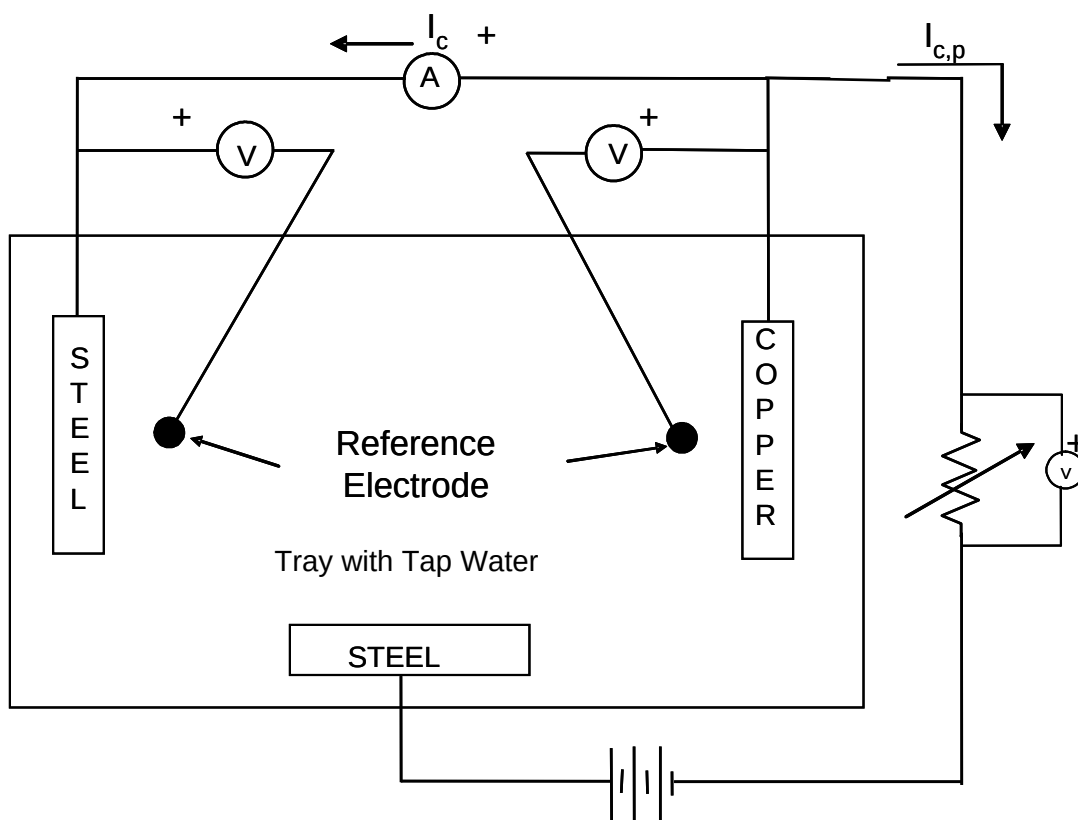
CONCLUSIONS

Corrosion current decreases as cathodic protection current increases.

Corrosion current decreases as polarized potential of cathode is made more electronegative.

(Option To Experiment 3.1)**Experiment 3.2 Demonstrate the Use of an Impressed Current System to Mitigate Local Action Cell Corrosion**

The operation of an impressed current cathodic protection system can be demonstrated as illustrated in the figure below.



Experiment to Demonstrate Corrosion Mitigation of Local Action Cells by Impressed Current Cathodic Protection

PROCEDURE

Part A

1. Insert steel and copper sheet in side of tray and add water.
2. Measure open circuit static potential of steel and copper.
3. Connect ammeter between copper and steel sheet and measure the corrosion current.
4. Measure the polarized potential of steel and copper.

Part B

1. Place second steel sheet (anode) in opposite side of tray and connect to the positive side of the battery (power source) via a 10,000- Ω resistor. Connect the negative side of the battery to the copper sheet.
2. Measure the corrosion current (I_{corr}).
3. Determine the cathodic protection current ($I_{\text{c,p}}$) by measuring the voltage drop across the resistor and calculating the current using Ohm's Law.
4. Measure the polarized potentials of steel and copper.

Part C

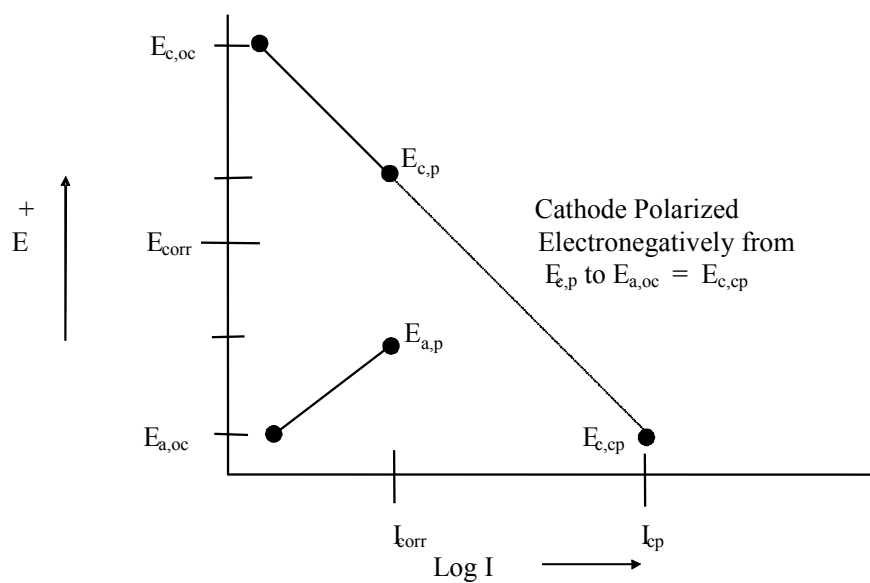
1. Repeat Part B using 1,000- Ω , 100- Ω , and 10- Ω resistors.

Part D

1. Construct a polarization diagram (see example on next page).

RESULTS

Circuit Conditions	E_{steel} (mV _{CSE})	E_{copper} (mV _{CSE})	Corrosion Current I_{corr} (mA)	CP Voltage Drop (V_r) Across Resistor (mV)	Calculate CP Current $I_{\text{c,p}}$ (mA)
Static (OC)	$E_{a,oc}$ _____	$E_{c,oc}$ _____			
Polarized	$E_{a,p}$ _____	$E_{c,p}$ _____	_____		
10,000 Ω	_____	$E_{c,cp}$ _____	_____	_____	_____
1,000 Ω	_____	_____	_____	_____	_____
100 Ω	_____	_____	_____	_____	_____
10 Ω	_____	_____	_____	_____	_____



*Example of Polarization***CONCLUSIONS**

1. Corrosion current decreases as cathodic protection current increases.
2. Corrosion current decreases as the polarized potential of the cathode becomes more electronegative.
3. More cathodic protection current and, therefore, more polarization can be achieved with impressed currents than with a sacrificial system.

CHAPTER 4

DC Power Sources for Cathodic Protection

Depending on economics any source of DC power can serve as an impressed current power source and may consist of:

- Transformer-rectifier (rectifier)
- Thermoelectric Generators (TEG)
- Solar Power
- Wind-Driven Generators
- Engine Driven Generators
- Batteries
- Fuel Cells
- Closed Cycle Vapor Turbo Generator

Transformer-Rectifier

The most common type of power supply used for impressed current cathodic protection is a transformer/rectifier, commonly referred to simply as a *rectifier*. A rectifier converts the AC power supply voltage to the required output voltage and then converts it to DC.

Rectifiers are either supplied in ventilated cases to allow convective air cooling or are immersed in transformer oil. Rectifiers are normally powered by an AC power system.

The rectifier input is an AC voltage from the commercial electrical power grid or an engine-generator. A transformer with tap adjustments in the secondary side provides a method to reduce and adjust the output voltage level and to isolate the DC circuit from the input power system. A rectifying circuit next converts the adjusted AC voltage to produce a DC voltage output.

The basic units of a rectifier consist of:

- AC Supply
- Circuit breaker
- Transformer
- Rectifying elements
- Meters
- DC Output Terminals
- Fuses*
- Surge protection*

** depending on unit*

Circuit Breakers

The primary function of a circuit breaker is to provide protection to the rectifier components from current surges or overload. A secondary function is to act as an AC disconnect when working on the face of the panel.

CAUTION: Circuit breaker contacts can “weld” together and not open when the lever is in the tripped position. Confirm that power is off by measurement before proceeding.

Circuit breakers are normally installed in the AC supply with the trip lever exposed on the rectifier panel. In a 115 V_{AC} supply a single breaker in the “hot” line is installed but with 230 V_{AC} or higher, a dual breaker with linked trip levers are used with a breaker in each line. Three phase units will have a breaker in each of the three lines with linked trip levers.

There are three types of circuit breakers which are described below.

Thermal Breakers

These breakers have a bimetallic element that carries current. An excessive amount of current will heat the element causing the two metals to expand but at different expansion rates since they are selected for their different temperature coefficients (Figure 4.1). The element is then pulled to one side thus breaking the connection. The element must cool before it can be reset.

The thermal breaker is dependent on the ambient temperature allowing more current in a cold environment or less current in a hot environment to pass before opening.

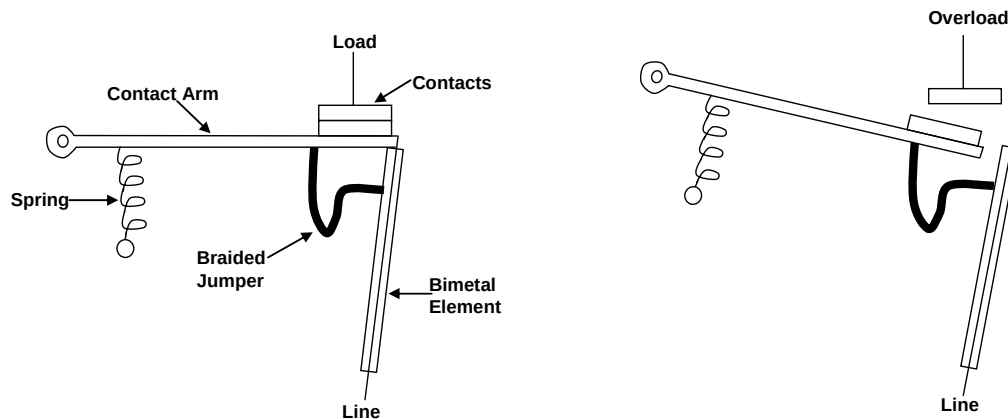


Figure 4.1 Thermal Breaker Mechanisms

Magnetic Breaker

The magnetic breaker consists of an iron core surrounded by a coil of wire acting as an electromagnet. When the current increases beyond the rating the magnetic field created will cause the core to pull a trip lever towards it thus causing an open circuit (Figure 4.2). Under high current surges the breaker will trip immediately and is considered the most suitable for CP rectifiers.

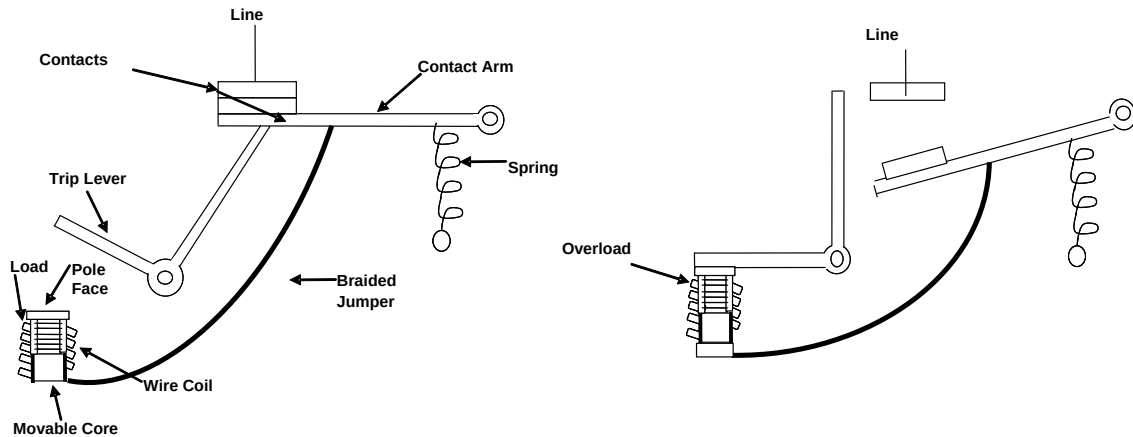


Figure 4.2 Magnetic Breaker Mechanisms

Thermal Magnetic Breakers

The thermal-magnetic breaker is similar to a thermal breaker except that it has a magnetic plate attached to the element to increase the speed in tripping the circuit (Figure 4.3). A large surge of current creates a magnetic field around the plate that in turn is attracted to another plate thus tripping the circuit before the element itself reacts due to overheating.

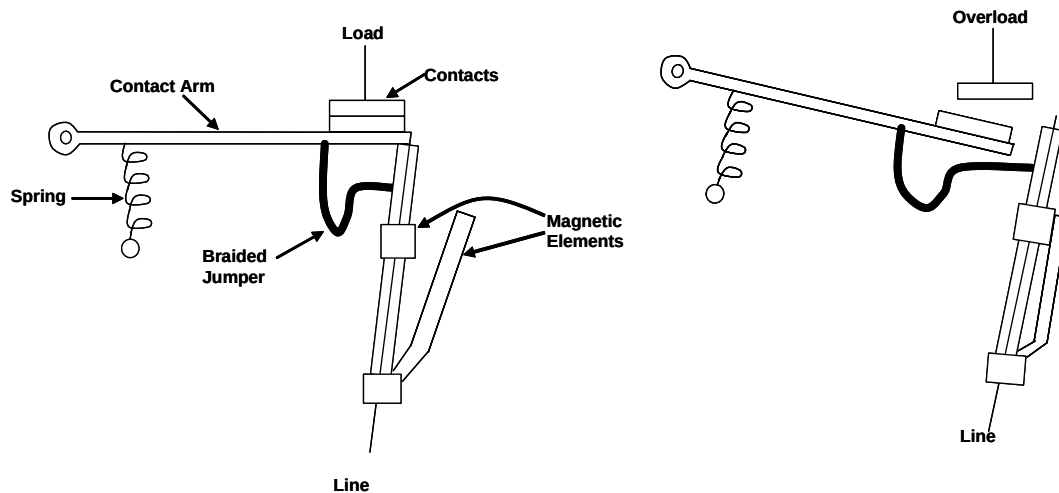


Figure 4.3 Thermal Magnetic Mechanisms

Although faster than the thermal breaker it has a slower reaction time to the magnetic breaker and can be used where an interrupter continues to trip the breaker.

Transformer

The purpose of a transformer is to either “step up” or “step down” an AC supply voltage. It could also be used as an isolation transformer at the same voltage. Depending on the design of the transformer it can provide an adjustable range of secondary AC voltages.

The transformer consists of an iron core with two sets of wires coiled around it. One coil, the primary windings, is connected to the primary AC voltage supply and the alternating magnetic field induces an AC voltage in the second coil or the secondary windings through this magnetic couple (Figure 4.4).

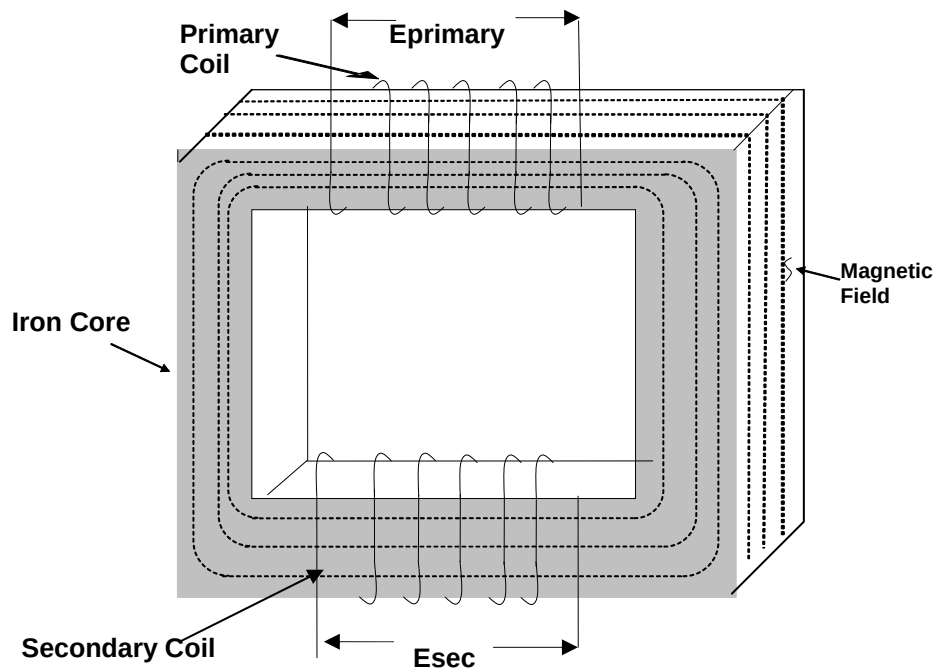


Figure 4.4 Transformer Schematic

The ratio of the primary AC voltage to the induced secondary AC voltage is in proportion to the windings in each coil (Equation 4.1).

$$\frac{E_{\text{primary}}}{E_{\text{secondary}}} = \frac{\text{Primary Turns}}{\text{Secondary Turns}} \quad \text{Eq. 4-1}$$

Example:

If a transformer has no losses, what is the secondary voltage of a transformer being supplied with 115 V_{AC} that has 400 turns on the primary and 100 turns on the secondary windings?

Rearranging equation 4-1:

$$E_{\text{secondary}} = \frac{E_{\text{primary}} \times \text{Secondary Turns}}{\text{Primary Turns}}$$

$$E_{\text{secondary}} = 115 \text{ V}_{\text{AC}} \times 100 / 400 = 28.75 \text{ V}_{\text{AC}}$$

The secondary windings can be tapped at intervals which change the number of windings and proportionally change the secondary AC voltage. By moving “taps”, the number of windings changes with a corresponding change in voltage. This is the approach taken in most constant voltage rectifiers.

Rectifying Circuits

Bridge Circuits

Rectifiers are available for either single-phase or three-phase input power. Although single-phase rectifiers are available in half-wave (1 diode), center-tapped (2 diodes), and full-wave (4 diodes) bridges, the full-wave bridge is the standard most often used, as shown in Figure 4.5 (A,B,C,D).

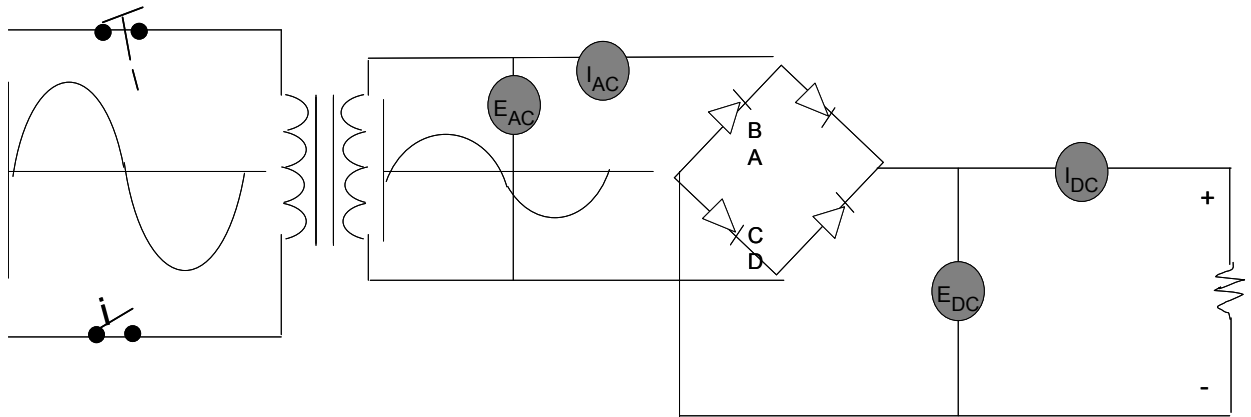


Figure 4.5 Single-Phase Bridge Rectifier Circuit

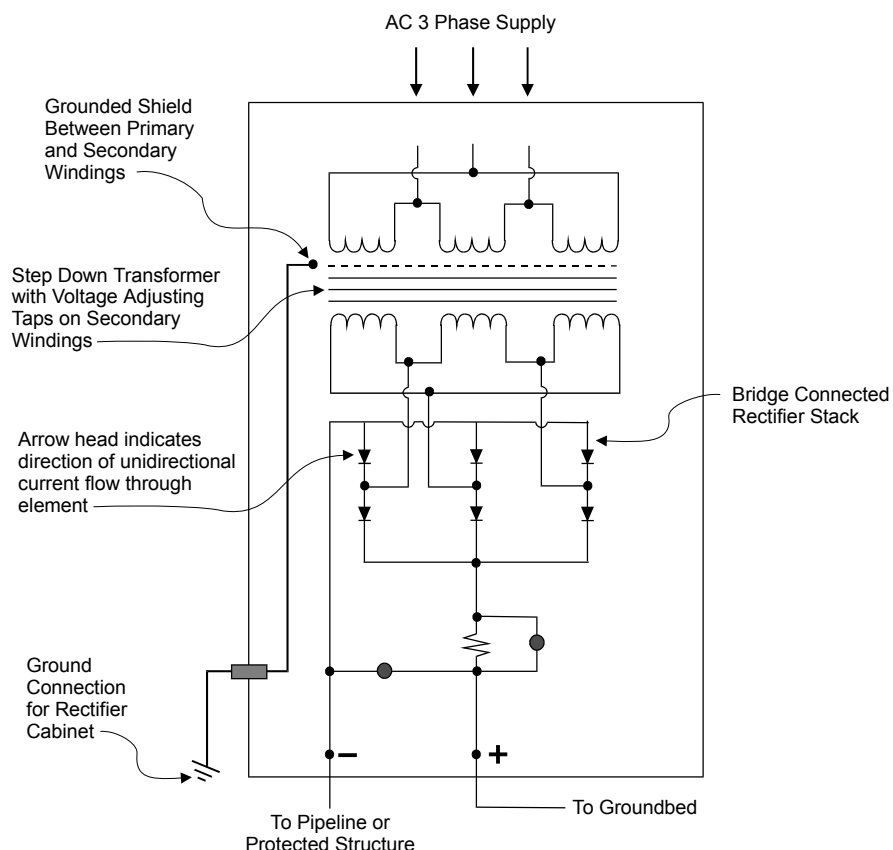


Figure 4.6 Three-Phase Bridge Rectifier Circuit

Three-phase rectifiers are available in wye (3 diodes) or full-wave (6 diodes) with full-wave bridges (shown in Figure 4.6) being the most commonly used. Three-phase units are more efficient than single-phase units, but the initial investment costs are higher. The theoretical maximum efficiency for a three-phase, full-wave bridge rectifier is 96.5% compared to 81% for a single-phase, full-wave bridge rectifier. The actual operating efficiency depends on the specific output of the unit. The type of power available and the economic comparison of overall costs are the primary considerations in selecting a single-phase or three-phase rectifier.¹

Modern rectifiers employ either selenium or silicon diodes to provide the rectifying action. Diodes are electrical devices that allow current to pass in one direction but block current in the opposite direction. A PN junction accomplishes this with a semiconductor boundary with one side of the junction doped with positive charge carriers and the other side doped with negative charge carriers. If we apply a positive potential to the P or positive-doped

¹ R. L. Bianchetti, ed., *Control of Pipeline Corrosion*, Second ed. (Houston, TX: NACE, 2001), p. 90, 166-173, 308-310, and 315-317.

semiconductor, the diode is forward biased and conduction can occur. However, if we apply a positive potential to the N junction or negative-doped semiconductor, the diode is reverse biased and current is blocked. In this manner, an AC voltage applied across a diode results in the diode alternating between being forward biased and conducting for one-half cycle and being reverse biased and blocking for the other half cycle. By proper interconnection of four diodes in the case of a single-phase rectifier, a complete AC current cycle can pass through the bridge, but with the positive portion of the cycle directed to the positive DC output terminal and the negative portion of the cycle directed to the negative DC output terminal. The result is full rectification of the complete AC cycle. However, this is not true DC in the sense that the signal output is completely constant, but rather a varying, single-directional output is produced.²

The rectification process is illustrated by the bridge circuit shown in Figure 4.7. The two AC input terminals to the rectifying bridge are I1 and I2. The two DC output terminals are O1 and O2. During the portion of the AC cycle when I1 becomes positive relative to I2, diodes 1 and 4 are forward biased (conducting). During this interval, the positive potential at I1 passes to output terminal O1, and the negative potential at I2 passes to output terminal O2. During the portion of the AC cycle when I1 becomes negative relative to I2, diodes 2 and 3 are forward biased (conducting). During this interval, the negative potential at I1 passes to output terminal O2, and the positive potential at I2 passes to output terminal O1. As indicated, the positive potentials always transfer to output terminal O1, and the negative potentials transfer to output terminal O2. Therefore, output terminal O1 is always positive relative to terminal O2. The top portion of Figure 4.8 shows the input signal between terminals I1 and I2, and the bottom portion of Figure 4.8 shows the resulting output signal between terminals O1 and O2.

² R. L. Bianchetti, ed., *Control of Pipeline Corrosion, Second ed.* (Houston, TX: NACE, 2001), p. 90, 166-173, 308-310, and 315-317.

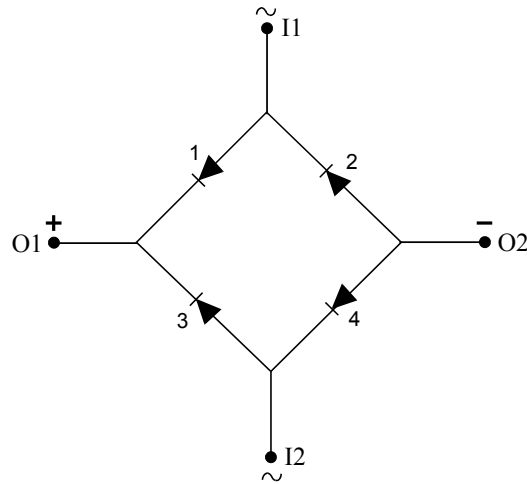


Figure 4.7 Single-Phase Diode Bridge

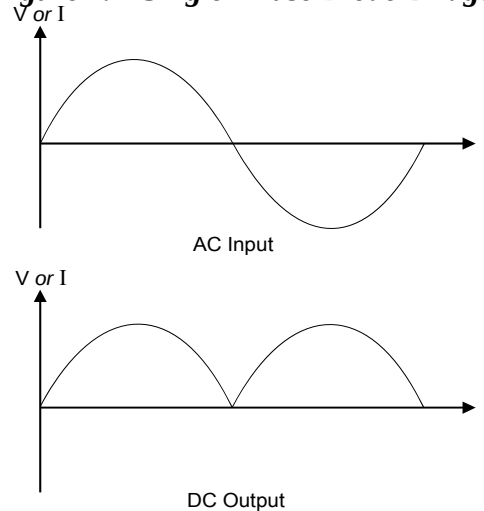


Figure 4.8 Input and Output Signals from Single-Phase Diode Bridge

Rectifying elements are made of either selenium coated plates or silicon diodes. In a selenium stack, steel, nickel, or aluminum plates are coated with selenium rectifier crystals. Plates are arranged in "stacks," with the number and size of plates being determined by the voltage and current output capacity of the rectifier. Significant facts about selenium stacks are:

- Selenium diodes are often called "self-healing"; that is, damaged areas become nonconductive and the stack continues to operate, however, the efficiency of the stack decreases.
- Selenium stacks can tolerate current overloads up to ten times rated capacity for a few minutes.
- Aging occurs due to heating resulting in reduced output voltage.

- Overheating occurs if the AC voltage exceeds the stack rating.
- Breakdown of the selenium coating and overheating due to transient voltages (e.g., lightning) can occur.
- Insulation breakdown of the insulating tube around the mounting stud due to transient voltages can occur.
- Corrosion due to salt, acids, hydrogen sulfide, or other chemicals can damage selenium stacks.
- Physical damage to the coating can occur due to overtightening or overheating due to undertightening of the contact washers during assembly.

Silicon diodes consist of a wafer sliced from a pure single crystal of silicon. The wafer is hermetically sealed inside a metal case with a threaded stud on one end and a wire connector on the other.

Silicon diodes are more efficient than selenium stacks and do not age.

The silicon diode must be attached to a heat sink since they heat up quickly.

Silicon diodes are more sensitive to current surges and can be quickly destroyed by any current overload. Diodes should have a high peak inverse voltage rating (1,000 V).

Silicon diodes fail completely rather than slowly like selenium stacks.

Although the standard transformer-rectifier is by far the most common power supply used for impressed current cathodic protection systems due to economics, variations of the standard transformer-rectifier are available such as silicon-controlled rectifiers, switching-mode rectifiers, and pulse-type rectifiers.

Center Tap Circuits

Full-wave rectification can be achieved with two diodes in a center tap configuration as shown in Figure 4.9 for single phase and a variation in Figure 4.10 for a three-phase wye connection.

In the single phase circuit, only one diode conducts during each AC cycle and produces a large ripple. This rectifier requires a larger transformer and adjustments by tapping the rectifier are more difficult as each leg needs to be

balanced. This method is often used where the output is electronically controlled.

The three phase wye requires the largest iron core for the transformer to prevent DC saturation of the core from the DC ripple.

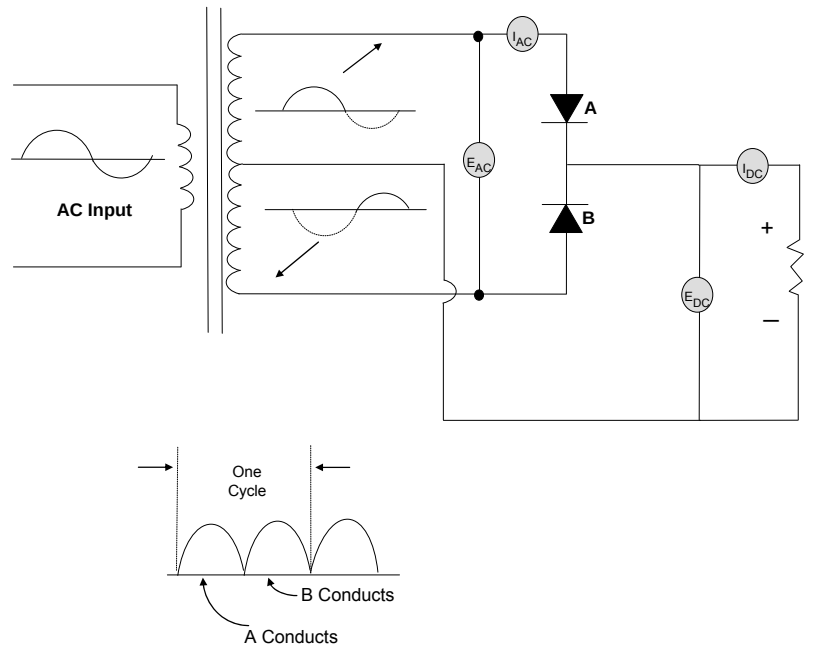


Figure 4.9 Single Phase Center Tap Rectifier Schematic

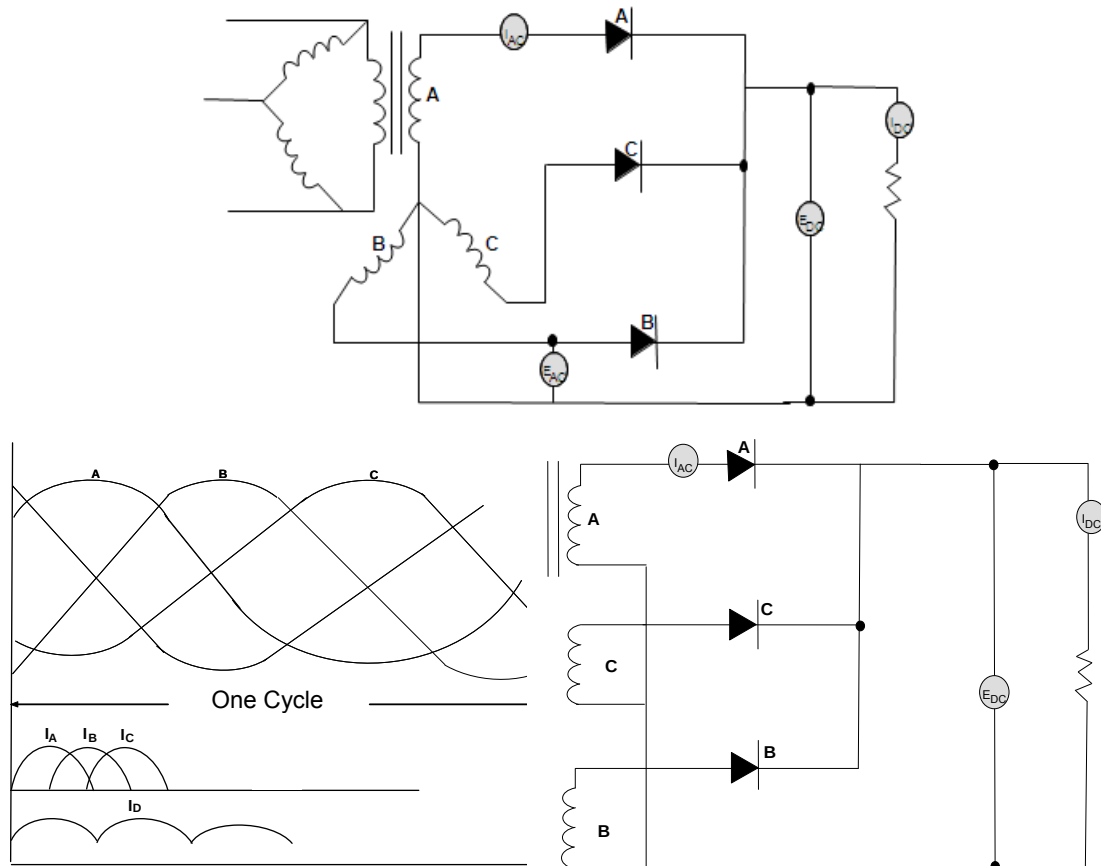


Figure 4.10 Three Phase Wye Rectifier Schematic

Silicon-Controlled Rectifiers (SCR)

Silicon-controlled rectifiers (SCR) are sometimes added to provide additional control of the rectification process for some types of cathodic protection rectifiers. SCRs are three-junction PN devices, as shown in the top of Figure 4.11. An SCR, much like a diode, is a rectifying device, which will permit current conduction in only one direction. However, unlike a diode, applying proper voltage polarity between the anode and cathode will not cause the SCR to conduct (fire). In order for the SCR to be forward biased and begin conducting, a positive potential (V_{AC}) must be applied between anode (P side) and cathode (N side), and a positive voltage pulse must also be applied between the gate and the cathode (V_{GC}) as seen in the center of Figure 4.11. At the instant the gate pulse is applied, the SCR fires and begins to conduct current from the anode to the cathode. Regardless of the gate current, the SCR continues to conduct until the applied voltage (V_{AC}) goes to zero and the current returns to zero.

If we apply an AC voltage across the SCR, we can control the output voltage waveform by controlling the timing for the gate pulse, which fires the SCR. For example, if the gate pulse arrives at the same time the applied voltage crossed the zero axis and begins to move in the positive direction, the SCR will conduct through a complete half cycle (180°) of the input waveform. If the gate pulse is delayed for one quarter of a cycle from the time the applied voltage crosses the zero axis and moves in the positive direction, one-half of the half cycle (90°) waveform will be allowed to pass. If the gate pulse is never applied, none of the half cycle waveform will pass (0°).

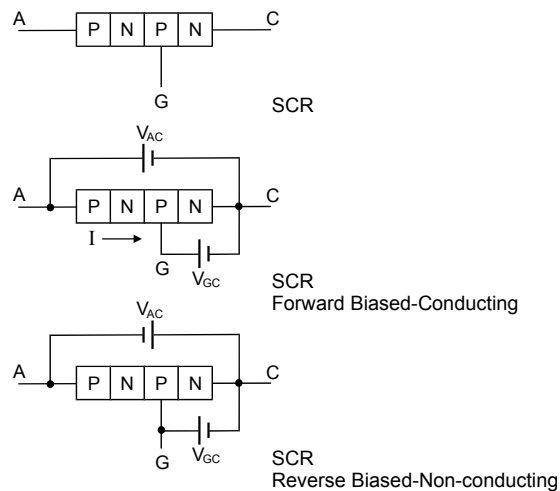


Figure 4.11 Silicon Controlled Rectifier (SCR)

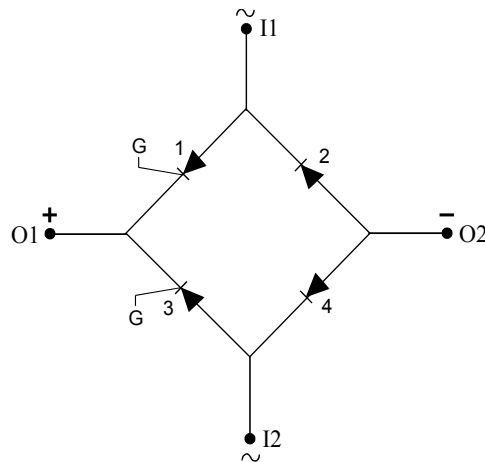


Figure 4.12 Single-Phase SCR Controlled Bridge

By replacing diodes 1 and 3 with SCRs in a full wave bridge circuit as shown in Figure 4.12, we can control the full-wave rectified output by controlling the timing of the gate pulses for the two SCRs. If the gate pulses are applied at the zero crossing of the input waveform (180° conduction angle), the output waveform is a fully rectified version of the input waveform, as shown in Figure 4.13. If we delay application of the gate pulse for one-third of the half-cycle (120° conduction angle), we block one-third of each half cycle at the output. The result is a reduction in the average DC voltage output. Therefore, by controlling the timing of the gate pulses we can continuously vary the level of the DC voltage output. However, the output waveform is not a continuous DC voltage, but rather a pulsing DC with ripple. The longer the control circuit delays the gate pulse, the greater the ripple in the output waveform will be. To improve efficiency and reduce ripple, manufacturers normally add filters to the output terminals.

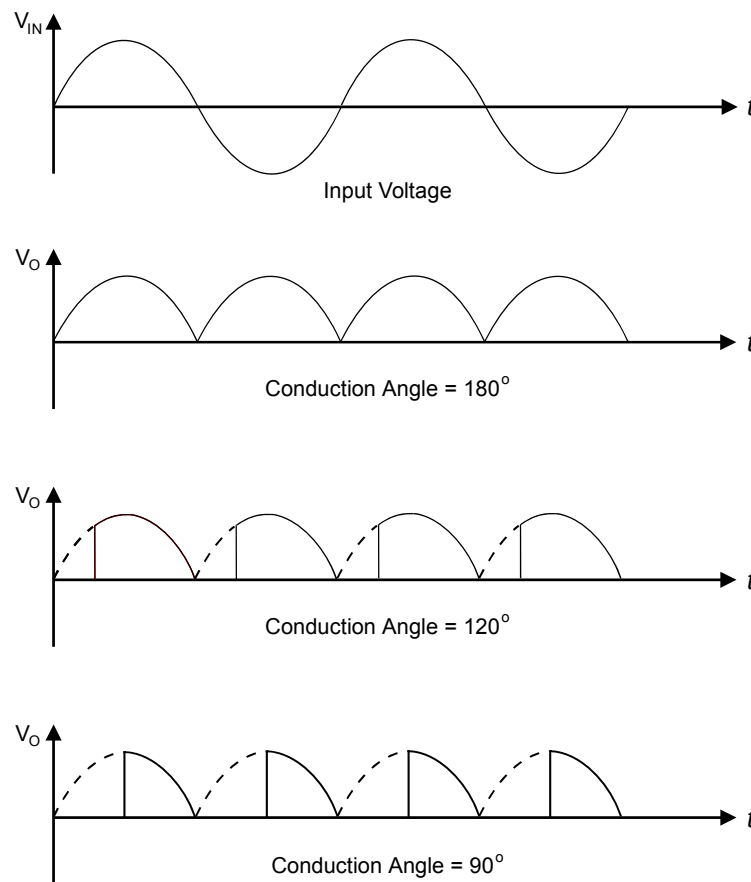


Figure 4.13 Full-Wave SCR Bridge Output Waveforms

The above explanation of the full-wave SCR-controlled rectifier operation assumes a pure resistance load at the output terminals. However, if the rectifier contains an output filter (energy storage), the SCRs may not be able to turn off when the input waveform crosses the zero axis due to the energy released from the filter. This condition is known as “latching” of the SCR. If we add a “free-wheeling” diode (see Figure 4.18) across the output, the SCRs can again turn off normally at the end of each half-cycle.

Switching-Mode Rectifiers

A different type of rectifier began to emerge in the late 1970s when switching-mode technology became commercially available. Rather than adjusting the output voltage level using a large, laminated steel core transformer, switching-mode rectifiers control the DC output voltage level by producing a series of high frequency (typically 50 to 500 kHz) DC pulses and adjusting the timing of DC pulses to produce the required output DC voltage level. Although switching-mode rectifiers use transformers for energy storage and for isolation of the output circuit, the transformer is a much smaller, high frequency, ferrite-core transformer. The block diagram for a typical switching-mode rectifier is shown in the bottom half of Figure 4-14. This diagram can be compared to the block diagram for a standard transformer/rectifier shown in the top of Figure 4.14.

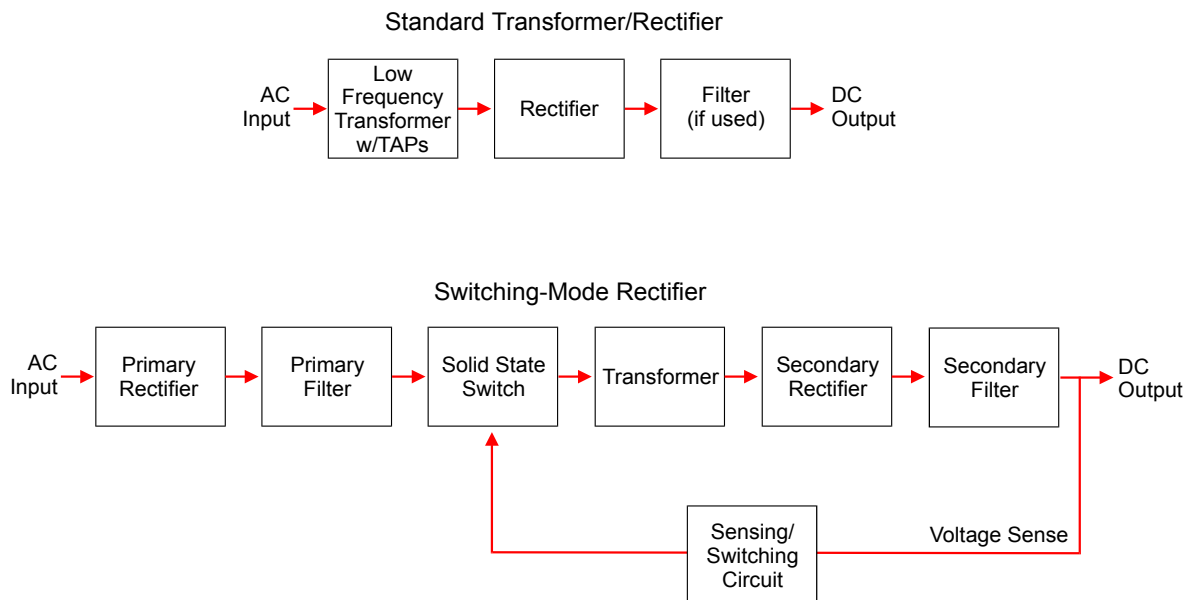


Figure 4.14 Block Diagrams for Switching-Mode and Standard Rectifiers

Source: Redrawn from Emerson Network Power, Switching Power Supplies, <http://www.emersonnetworkpower-medical.com> (January 7, 2004).

As indicated in Figure 4.14, the switching-mode rectifier first converts and filters the input AC voltage to a DC voltage. The solid state switch next converts the DC to high frequency DC pulses. The DC pulses are fed through a high frequency transformer to isolate the output. Because the high frequency signal contains significant noise (positive and negative spikes), it is necessary to provide secondary rectification of the signal along with filtering. Finally, the sensing/ switching control circuit provides feedback control to the solid state switch to control the “on” and “off” timing (pulse width) of the switch. Therefore, using pulse width control, the magnitude of the output voltage is adjusted and controlled.³

The primary advantages of a switching-mode rectifier over a standard transformer/ rectifier are:

- Small size and weight
- Output voltage regulation
- High efficiency at low rated output
- Current-limiting features available
- Modular design for ease of repair
- Multiple modes of operation possible (constant voltage, constant potential, constant current, IR-free constant potential)

The disadvantages are:

- Can be a significant source of high frequency noise (EMI/RFI)
- Lower reliability due to number of components
- Prone to higher ripple (more filtering required)
- Repair of individual modules not practical

Pulse Rectifier

Pulse rectifiers supply current in a cyclic fashion. The current is delivered as a high frequency (1,000 to 5,000 pulses per second) at a relatively high voltage but usually at a low duty cycle (15%). Adjustment of the output is a combination of varying the frequency and adjusting capacitors that in turn set the duty cycle. As a result they have a high noise level for a short distance from the installation. The primary use of these rectifiers is on well casings. These rectifiers are intended to optimize current distribution and minimize interference.

³ Lambda Power, Switch-mode Power Supplies,
http://www.lambdapower.com/ftp/linera_versus_switching.pdf (January 7, 2004)

Operational Modes

The common rectifier operation modes include:

- Constant Voltage
- Constant Current
- Constant Potential

Constant Voltage

In this type of rectifier, the output voltage is adjusted by changing the secondary transformer taps. The output of the rectifier is dependent on the external resistance of the anode-soil-structure circuit. This type of control is useful where the external circuit resistance does not change appreciably. Figure 4.15 shows a schematic diagram of a typical voltage control rectifier.

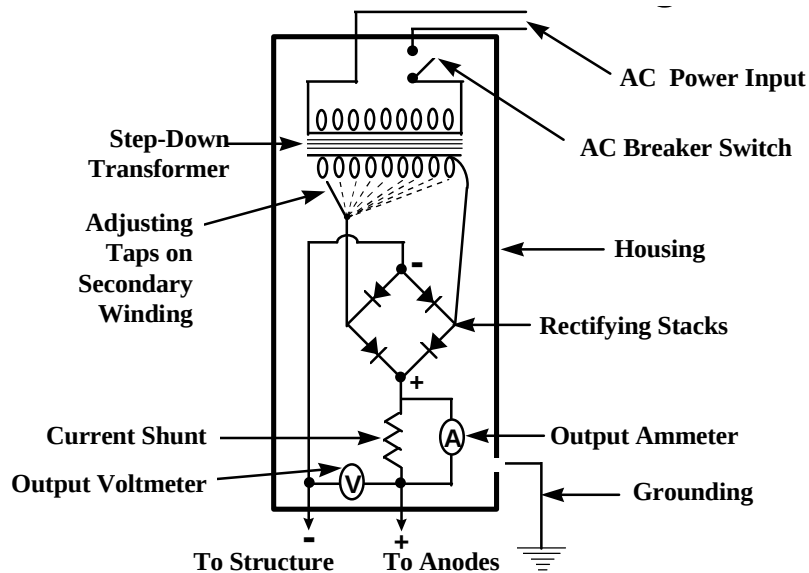


Figure 4.15 Constant Voltage Rectifier Schematic – Single Phase

Constant Current

In this type of rectifier, the output current is maintained at a constant preset value. If the external resistance changes, the rectifier output voltage is increased or decreased to maintain the preset value. An external reference electrode is not used in this type of rectifier. Figure 4.16 shows a schematic of a typical constant current control rectifier using a saturable reactor. A constant current rectifier can also be achieved using silicon-controlled diodes.

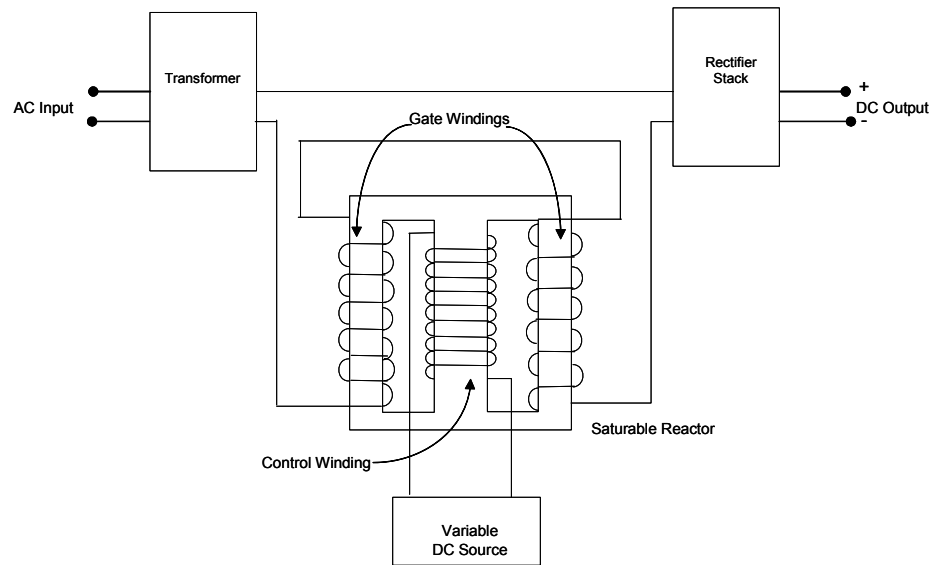
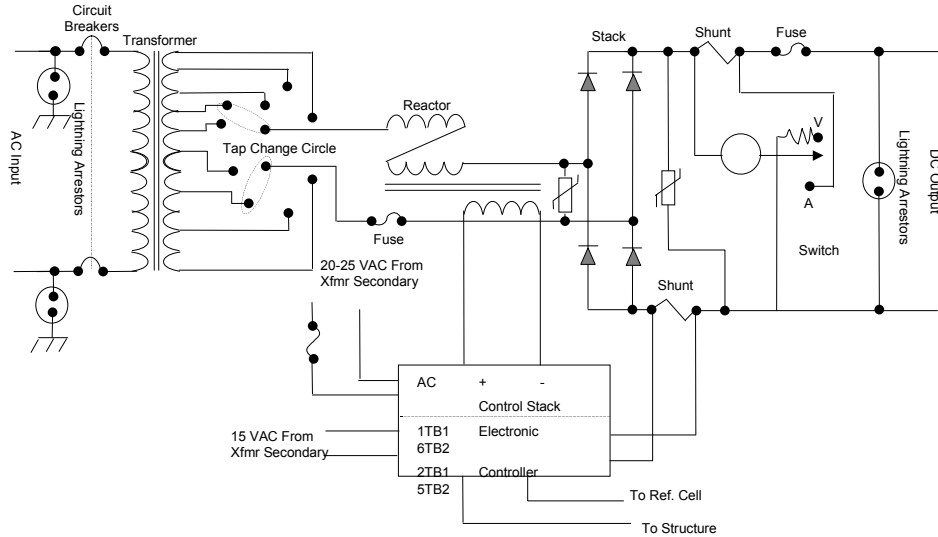


Figure 4.16 Constant Current Rectifier Schematic

Constant Potential

The output current of constant potential rectifiers is controlled by a preset structure-to-electrolyte (or structure-to-water) potential. The rectifier constantly monitors an external structure-to-electrolyte potential and compares it to the preset value. If the structure-to-electrolyte potential changes from the preset value, the rectifier current either increases or decreases current output to bring the potential back to its preset value. This type of rectifier is useful where external conditions vary, in particular, the resistivity of the electrolyte that can cause large changes in corrosion protection requirements. For this system to work, a stable reference electrode must be buried or immersed in the environment to monitor the structure-to-electrolyte potential. Potential control rectifiers can be controlled by either saturable core reactors or silicon controlled rectifiers (SCR). Figure 4.17 shows a schematic of a typical voltage control rectifier using a saturable reactor and Figure 4.18 shows a potential control rectifier with SCR control. These rectifiers should be manufactured with a current limiting circuit in the event of a loss of reference cell input signal.



Single Phase Reactor Controlled Auto-Volt

Figure 4.17 Constant Potential Rectifier Schematic

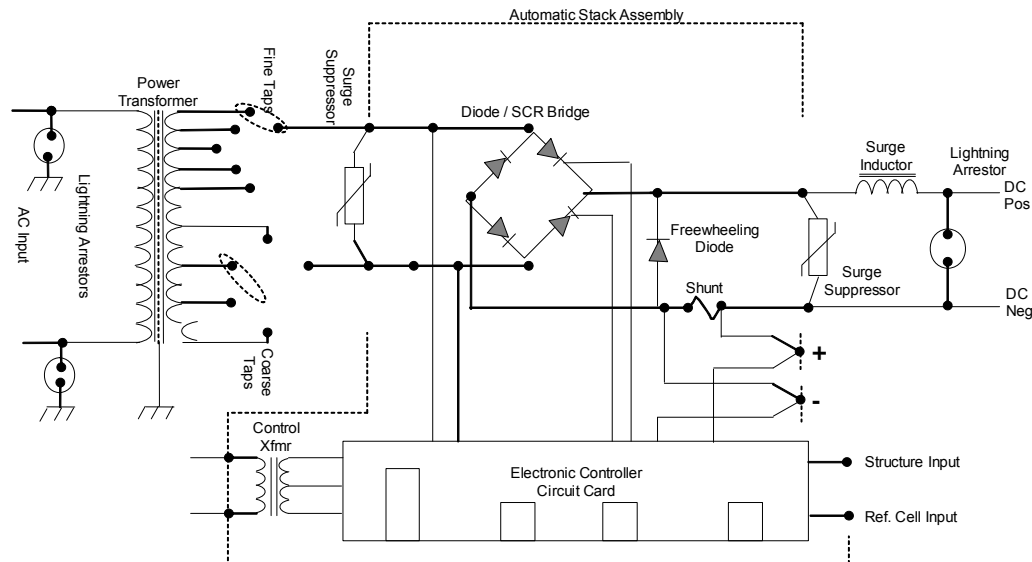


Figure 4.18 Constant Potential Rectifier Schematic - SCR

Other Rectifier Components

Filters

Efficiency filters are used to decrease the AC ripple of the DC output, which decreases the operating cost of the rectifier. Filters are most often used on

single-phase bridge and center tap rectifiers. Filters consist of chokes, capacitors, or a combination of capacitors and chokes.

Surge Protection

Surge protection is used to protect the rectifier from lightning.

Interrupters

Built-in interrupters can be supplied with the rectifier to allow cycling the unit on and off for testing purposes.

Warning Devices and Signal Lights

These are used to alert personnel to operating malfunctions of the unit. They will not provide information on irregularities with the cathodic protection system other than what is occurring within the rectifier itself.

Remote Monitoring

Devices can be installed to monitor current, voltage, and structure potential from a remote location. Some of these devices can be used to control the output.

Adjustments of AC and DC

As described above constant voltage rectifiers are usually adjusted by changing the transformer tap settings. These adjustments change the AC voltage supplied to the rectifier stacks. The adjustment taps are found on the front panel of the unit and consist of shorting bars for coarse and fine adjustment. The rectifier **MUST** be turned off at the breaker before any taps are changed. A lock out/tag out procedure is also recommended. Changes should be made one step at a time.

The general procedure to change taps is to increase the Fine tap one setting making certain that the connections are tight. Turn on the unit and measure the DC output voltage and current. If not satisfactory, increase the Fine taps again and repeat the process. When the Fine taps have reached the maximum, lower it to the first setting and increase the Coarse taps one setting. Continue in this manner until the desired output is reached. To lower the output, the reverse procedure is used except that a major reduction may be in order if the reason to reduce the taps is because the circuit breaker tripped.

Potential control and constant current rectifiers are controlled using a potentiometer adjustment found on the controlling circuit board. On potential



control rectifiers, this adjustment controls the structure-to-reference potential, which controls the output voltage and current. Transformer tap setting bars are often also found on potential control and constant current rectifiers as another control on the DC voltage.

Other Power Sources

Other sources of power are available where AC power is not readily accessible.

Engine Generator Sets

Engine generator sets consist of a fuel-powered engine that drives a generator to provide the AC for the rectifier (see Figure 4.19). The pipeline or a nearby source could supply the fuel. DC generators can be considered but usually require high maintenance.

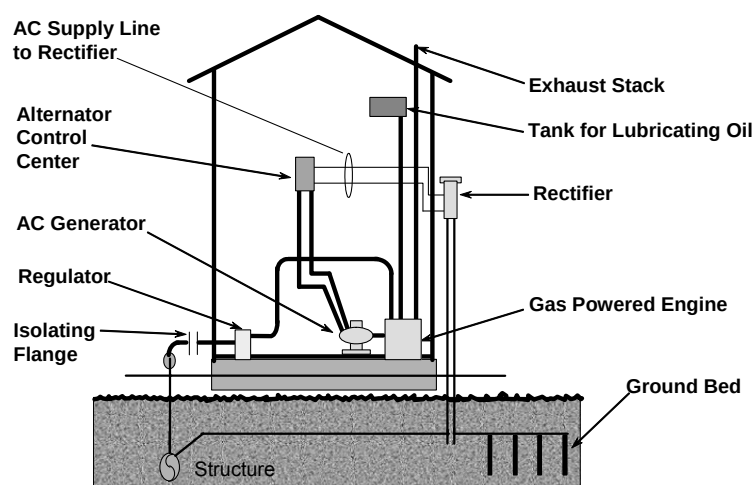


Figure 4.19 Engine-Generator CP Installation

Thermoelectric Generators

Another alternative energy power supply available for cathodic protection applications is the thermoelectric generator (TEG) (Figure 4.20). Thermoelectric generators convert heat energy directly into electrical energy. A clean fuel such as natural gas or propane is required. They are a relatively low power (wattage) unit and must operate near their optimum load resistance to realize the rated output.

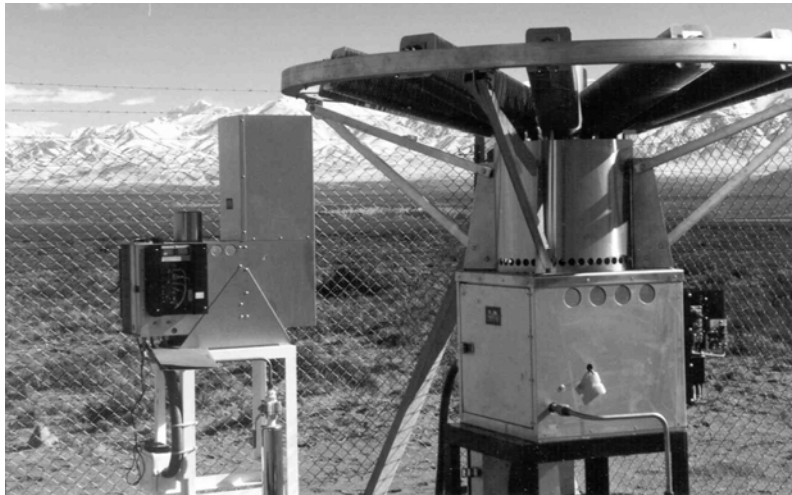


Figure 4.20 Thermoelectric Generator for CP

This power supply uses the Seebeck effect to generate small potentials across a dissimilar metal junction. Thomas Seebeck discovered that if a junction made up of two different metals is heated on one side and cooled on the other, a potential difference develops across the junction and charge flow will occur. Thermoelectric generators require only three primary components: a heat source, a thermopile, and cooling fins.⁴

Modern thermoelectric generators employ semiconducting PN junctions rather than dissimilar metal junctions. A burner applies heat to one side of the PN junction while a heat transfer system cools the other side of the junction. The thermoelectric couple is a low voltage, high current power source. Although the potential generated across an individual PN junction is very small, approximately 90 mV, the manufacturer increases the output voltage level by connecting many junctions in series modules (thermopiles). They can also connect several thermopiles in parallel to increase the current output. Burning of a fuel such as propane, butane, or natural gas produces the heat for one side of the junction. Temperatures on the hot side of the junction are approximately 535°C (1,000°F), while a heat transfer and elimination system maintains the temperatures of the cool side at about 165°C (325°F). The power produced by the unit is a direct function of the temperature difference across the junction. Some semi-conducting designs cannot be operated in the no-load condition since current output is necessary to cool the PN junction.^{5,6}

⁴Donald G. Fink and H. Wayne Beaty, ed., *Standard Handbook for Electrical Engineers*, Eleventh ed. (New York, NY: McGraw-Hill, 1978), p. 2-3, and 11-71 to 11-81.

⁵CP 4—Cathodic Protection Specialist Course Manual (Houston, TX: NACE, 2002), p. 1:25-1:27, 3:4-3:11, 3:18-3:33, and 8:34-8:35.

⁶R. L. Bianchetti, ed., *Control of Pipeline Corrosion*, Second ed. (Houston, TX: NACE, 2001), p. 90, 166-173, 308-310, and 315-317.

Since thermoelectric generators use no moving parts, no significant maintenance is required. Normally, only annual cleaning or replacing the fuel filter and fuel orifice is required. Units are available with output voltages of up to 48 V and power ratings of over 500 W. Manufacturers design and rate thermoelectric generators on a power output basis. For efficient application, TEGs should be matched to a specific load resistance (usually 1 Ω). The operator can make limited adjustment to the current output by adjusting the input fuel supply; however, a variable power resistor in series with the output or other type of voltage control is required to adjust output.⁷

Solar Power Supplies

Figure 4.21 shows a solar power supply consisting of a solar panel, a charge controller, and a battery system. Specially designed doped silicon semiconductors, which are photosensitive, convert solar energy to electrical energy. These semiconducting devices (photovoltaic cells) produce a voltage by absorbing energy from light photons striking the semiconductor and freeing electrons within the semiconductor. The conversion efficiencies for silicon-based photovoltaic cells are in the range of 8 to 14%. Research and development teams continue to improve the conversion efficiency and lower the production costs for photovoltaic technology. Recent innovations in thin film modules using a fine layer of copper indium diselenide (CuInSe_2 or CIS) on a glass backing can potentially lower production costs significantly in the future. Research is currently under way combining the amorphous silicon with CIS producing a double layer, thin film photovoltaic cell with a conversion efficiency of 15.6%.^{8,9,10}

⁷Global Thermoelectric, 8550 Thermoelectric Generator Operating Manual (Calgary, Alberta, Canada: Global Thermoelectric, 2002).

⁸Shell Solar, Solar Panels, <http://www.shell.com> (November 11, 2003).

⁹Siemens, Solar Panels, <http://siemenssolar.co.uk> (November 11, 2003).

¹⁰Go Solar Company, Solar Panels, <http://www.solarexpert.com> (November 11, 2003).

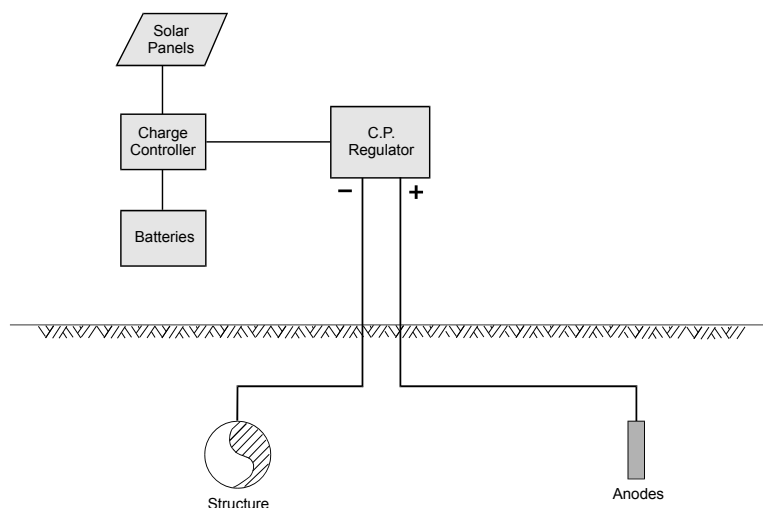


Figure 4.21 Solar Power Supply System for CP

A single photovoltaic cell produces a very small voltage and current. By connecting a number of cells in series, the output voltage available increases or by connecting cells in parallel, the current output available increases. Therefore, manufacturers produce standard solar panels consisting of a number of photovoltaic cells connected in a series/parallel arrangement to produce a specific output voltage and current. Solar panels are available in output voltages of 6, 12, and 24 V with power outputs ranging from 5 to 160 W. Designers can also connect solar panels in series or parallel, as necessary, to produce an even larger output current or voltage.¹¹

A backup battery system is necessary with a solar power supply to produce the required current output when solar energy is unavailable (night and overcast days). The designer must size the solar panel to produce the required current output plus additional current to charge the battery system when solar energy is available. Whenever the solar energy available is insufficient, the battery system supplies the current required for cathodic protection. A charge controller is an electronic monitor to determine the state-of-charge of the battery allowing charging current to the batteries when needed and preventing overcharging of the batteries.

Wind-Driven Generators

If a sufficient, steady source of wind is available, wind-driven generators are another possible alternate energy source for cathodic protection. These DC generators generally begin producing useable current outputs at wind speeds of

¹¹Go Solar Company, *Solar Panels*, <http://www.solarexpert.com> (November 11, 2003).

about 16 km/h (10 mph) with maximum output achieved at speeds of 40 to 55 km/h (25 to 35 mph). Since the output varies with wind speed, a battery system is required not only as a backup when the wind is flat, but also to provide a constant DC output for the cathodic protection system. The generator output charges a battery system, and the battery system supplies the output cathodic protection current (Figure 4.22).

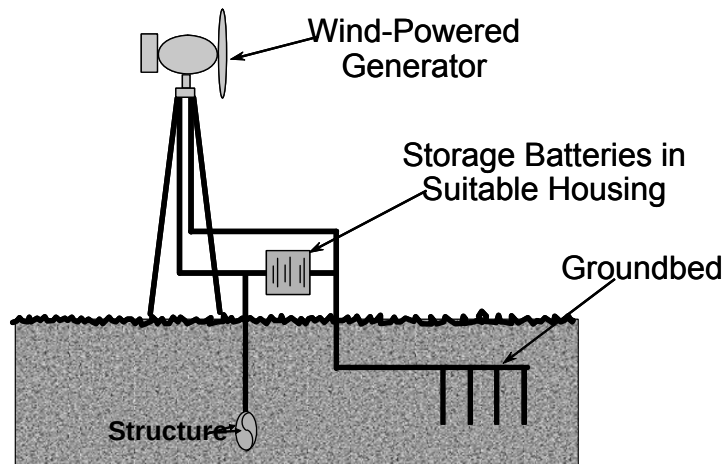


Figure 4.22 Wind-Driven Generators for CP

Due to the high maintenance requirements of wind-driven generators, these power sources are not as popular especially with the continuing development of other more cost competitive alternate power sources. Wind-driven generators are available in 400 to 3,000 W sizes with voltage outputs ranging from 12 to 240 V.¹²

Batteries

If the current requirement for a specific cathodic protection system is relatively small, it is possible to use batteries to supply the output current. A small, isolated, well coated structure in a high resistivity environment might use a battery power supply, perhaps in conjunction with galvanic anodes, to supply the required current output. Batteries used in cathodic protection applications should be deep-cycle batteries designed for many charge/discharge cycles.

Battery manufacturers rate batteries in terms of ampere-hour capacity. Simply stated, this is the amount of current in amperes a battery can supply for a specific time interval, hours. Temperature can have a significant effect on

¹²JATS Alternative Power Company, *Wind-driven Generators*, <http://www.jatsgreenpower.com/wind-power.html> (November 11, 2003).

output capacity of batteries, especially lead-acid batteries. At a temperature of -19°C (0°F), the capacity of a lead-acid battery drops to about 50% of rated output. A successfully designed battery system must be able to supply the output current required for a relatively long time before battery replacement is necessary.¹³

Whether batteries are the primary power supply or a backup for another primary power source, regular maintenance is required to ensure the batteries operate successfully over the long term. If batteries are the primary power supply, they must be replaced with new fully charged batteries on a regular schedule. Due to the maintenance and regular replacement schedule requirement, the cost associated with battery systems can be relatively high.

Closed Cycle Vapor Turbogenerator

The ORMAT[®] Energy Converter (OEC), a Closed Cycle Vapor Turbogenerator (CCVT), is certified for operation in Class I, Division 2 (Zone 2, Group II) conditions in onshore and offshore applications. Basically it is a self-contained power package consisting of a combustion system, a vapor generator, a turboalternator, an air-cooled condenser, a rectifier, alarms, and controls housed in a shelter. It will supply 200 to 3,000 W of filtered DC power on a continuous 24 hour-per-day basis for periods of up to 20 years with limited maintenance or repairs. Failures, however, can occur and close monitoring is thus required.

The concept utilizes a hermetically sealed Rankin cycle generating set that contains only one rotating part: the shaft on which the turbine wheel and the brushless alternator rotor are mounted. The turboalternator shaft is supported by working fluid film bearings, which eliminate any metal-to-metal contact, resulting in increased trouble-free operation.

It can be run with different heat sources because the fluid cycle is closed and requires only the application of external heat. Fuels that can be used include natural gas, liquefied petroleum gas, kerosene, jet fuel, and diesel fuel.

The burner heats the organic working fluid in the vapor generator. The vapor expands through a turbine wheel, thereby producing shaft power to drive the alternator. The vapor then passes into a condenser where it is cooled, condensed back into the liquid state, and driven back into the vapor generator; it cools the alternator on its way and lubricates the bearings. The cycle

¹³Go Solar Company, *Solar Panels*, <http://www.solarexpert.com> (November 11, 2003).

continues as long as heat is applied to the vapor generator. Because the liquid/vapor stainless steel envelope is sealed, none of the organic fluid is lost in the process.

The turboalternator produces three-phase AC power, which is then rectified to DC and filtered. The DC power is regulated for varying load by automatically controlling the amount of fuel supplied to the burner. The system is equipped with a digital turbine control unit with safety controls to protect it against any abnormalities, including overheating.

Fuel Cells

An emerging alternative energy power supply is the fuel cell and although not presently in use for cathodic protection it can possibly be a DC power source for the future. NASA originally developed this technology for the space program but only recently have commercial applications exploited the technology. A fuel cell requires three parts: an anode, a cathode, and an electrolyte. The fuel, hydrogen, passes through a porous anode catalyst, which causes the hydrogen to release its electron into the metal electrode. The hydrogen ion moves through the electrolyte where it combines with oxygen gas passing through the porous cathode and the electrons from the anode to produce heat and water.¹⁴

Depending on the specific design of the fuel cell, fuel may be in many forms including gaseous hydrogen, methane, propane, and even gasoline. Air from the atmosphere usually provides the oxygen required at the cathode. The fuel cell produces current electrochemically; therefore, no moving parts are required, and maintenance is minimal. Fuel cells are more efficient than any other form of energy conversion and free of polluting emissions.

¹⁴Online Fuel Cell Information Center, *Fuel Cells*, <http://www.fuelcells.org> (November 11, 2003).

Rectifier Testing

- **CAUTION:** Only qualified personnel are to test and work on a rectifier. Safety is of the utmost importance when working on an electrical device.
- Note the precautions in Chapter 5–Safety.
- Determine if the rectifier or any associated electrical equipment is in an electrically hazardous area. Do not open any explosion-proof junction boxes unless otherwise qualified and then only if the circuits are turned off and locked out/tagged out.
- Do not work on or remove any rectifier component without first turning the upstream power off and locking/tagging out (Figure 4.23).
- When first approaching the rectifier confirm that the case is not electrically “hot” either by taking an AC voltage-to-ground measurement or with a voltage alert device.
- On first opening the rectifier identify any exposed terminals that will have a voltage and take measures to protect yourself from them.



Figure 4.23 Typical Lock Out / Tag Out Kit

It is important to ensure that the power source in an impressed current system, such as a rectifier, remains operational and that the cathodic protection system is connected with proper polarity.

The negative (–) terminal of the power source must be connected to the structure and the positive (+) terminal must be connected to the anode bed (see Figure 4.24).

The proper connection of a rectifier is CRITICAL and if done improperly can result in catastrophic damage to the structure that is supposed to be protected, resulting in loss of product, structural damage, property damage, environmental damage, or loss of life.

Often the cathodic protection cables are either not identified or are incorrectly identified. It is therefore mandatory to verify the proper connection polarity. This can be accomplished by measuring the structure-to-electrolyte potential near the power source both before and after the source is activated. A shift in potential in the electronegative direction with the power source energized, confirms the correct polarity. For this test the cable connected to the negative terminal of the rectifier should not be used as the test lead for the structure-to-electrolyte potential measurement.

When connecting a rectifier to an AC power supply, the AC supply circuit should be dedicated and separately fused. The rectifier should never share an AC circuit with normally interruptible facilities such as lighting and pumps.

The voltage and current output of the power source should be monitored regularly to ensure that the unit remains operational. Basic rectifier operational data includes:

- AC input voltage
- DC output voltage and DC output current
- Tap settings and/or potential set point (if constant potential) or current set point (if constant current)
- Anode-to-structure resistance.

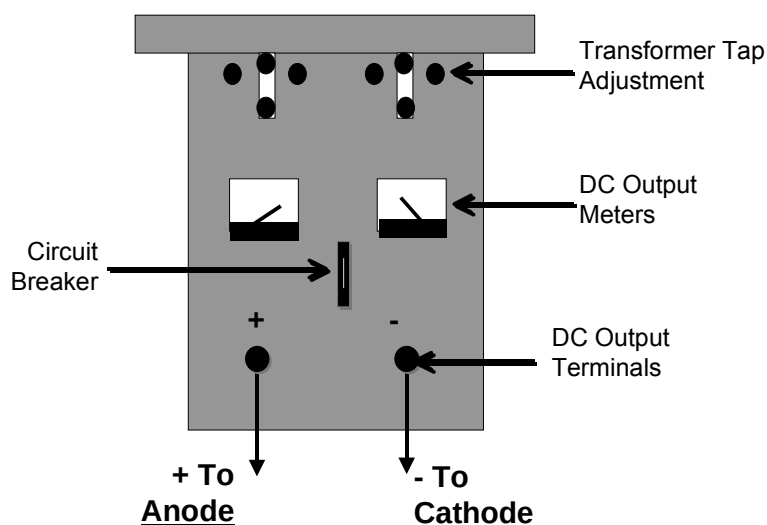


Figure 4.24 Typical Rectifier Connections

Output Problems

A good maintenance program can often detect potential rectifier failures beforehand 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: (1) zero current and voltage outputs, (2) zero current output with unchanged output voltage, (3) significant current change with unchanged voltage, or (4) 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.

The sequence of short circuit location based on a circuit breaker tripping is shown in Figure 4.25.

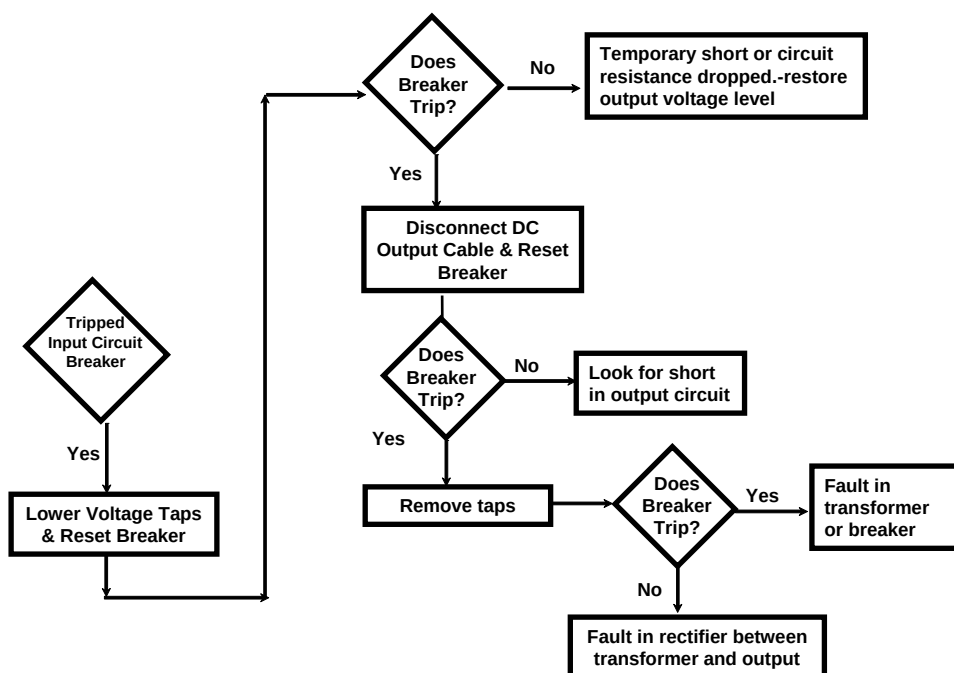


Figure 4.25 Locating a Short Circuit in a Rectifier Circuit Based on a Circuit Breaker Tripping

To determine if the short circuit is external to the rectifier, turn off the AC power supply, 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. Next, the best approach involves isolating the problem to a particular section of the rectifier by beginning at the input terminals and adding one component at a time to the circuit until the circuit breaker trips. The short circuit must be the last component connected when the circuit breaker trips. For example, the transformer can be connected to the input circuit breaker with the tap adjustment bars removed.

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. If an open fuse in the output circuit is found, either a high temporary current surge or a short exists (or has existed) in the output circuit.
- Faulty connections.
- An open positive or negative lead cables.
- Failed anodes.

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, anode 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.

The existing rectifier operational data should be compared to prior data from when the rectifier was known to be operating properly. If abnormal data is obtained, then troubleshooting procedures need to be used.

If the anode-to-structure resistance is normal, then the problem is with the rectifier.

If the anode-to-structure resistance is not normal, the problem could be outside the rectifier.

Open circuit and short circuit failure modes can occur on all impressed current systems. Usually a short circuit condition will cause either the rectifier breaker

or AC supply breaker to trip. In many instances, the power source fuses are also blown. The short circuit can appear either within the rectifier or external to the power supply.

The following conditions can cause internal short circuits:

- Failed diode(s)
- Contact in transformer windings
- Contact between positive circuit and the rectifier cabinet or negative circuit
- Spark-gap type lightning arrestors failed in the shorted condition

External short circuits can occur due to any metallic contact between the positive and negative circuits. Inadvertent contact between the anode or its low resistivity backfill and the structure is the most common type of external short circuit.

When confronted with a possible short circuit, disconnect all external positive and negative cables at the rectifier before re-energizing the rectifier. If the rectifier operates normally upon re-energizing, then the short is external to the unit, providing the short reappears when the cables are reconnected. Some rectifier units can be operated in the shorted condition when on the lowest AC tap setting. This facilitates troubleshooting to find the defective component. A pipe or cable locator connected between the positive and negative cables at the rectifier can also be used to pinpoint an external short circuit. Disconnecting the components in sequence starting at the output of the unit and working back toward the transformer is a relatively convenient method of locating the shorted component.

Open circuits can appear within the power source or external to it. The open circuit condition is characterized by a zero current output. If the open circuit is external to the rectifier then the voltage output will appear at the terminals of the rectifier. If the open circuit is internal, then the voltage will appear across the internal component with open circuit. Common causes of internal open circuits include the following:

- Failed diode(s)
- Broken cables
- Open connections
- Failed or weak breaker
- Blown fuse(s)

External open circuits generally involve broken or corroded cables, though, on occasion, the groundbed may be consumed.



Circuit Diagrams

Each rectifier should be supplied with its own specific circuit diagram that can be consulted to establish the electronic configuration of the unit. This is a code requirement in some areas.

Electrical Damage

Note that testing, using visual inspection must be performed with the rectifier off and AC power disconnected and locked out.

Electrical damage, such as from lightning or power surges, might be diagnosed by looking at and smelling the rectifier components. Electrical damage often shows as burnt, melted, or charred marks or the smell of burnt insulation may be present. If any of these are observed, electrical tests using a voltmeter and ohmmeter should be performed to see if the component is functioning. Electrically overstressed components will be hot to the touch.

Efficiency Test

The efficiency of a rectifier is calculated with a watt-hour meter and the following formula:

$$\text{Percent Efficiency} = \frac{\text{DC Power Out}}{\text{AC Power In}} \times 100 \quad \text{Eq. 4-2}$$

For example, calculate the efficiency of a rectifier with a DC output of 10 V 25 A DC if the watt meter reads 500 W.

$$\text{DC power out (watts)} = V_{\text{DC}} \times I_{\text{DC}} \quad \text{Eq. 4-3}$$

$$\text{Percent Efficiency} = \frac{10 \text{ V}_{\text{DC}} \times 25 \text{ A}_{\text{DC}}}{500 \text{ W}} \times 100$$

$$\text{Percent efficiency} = 50\%$$

If a watt-hour meter is used to determine the input power, the following formula is used:

$$\text{AC Input Power} = \frac{3,600 \text{ K N}}{T} \quad \text{Eq. 4-4}$$

where



K = meter constant (shown on face of meter as kh)

N = number of revolutions of the disk (observe for 60 seconds minimum)

T = time in seconds of observation

If the efficiency is below what is expected or DC output voltage is about half that expected, the following can be responsible:

- Output voltage is too low for the rectifier rating
- Input voltage may be lower than it should be
- Half the stacks or plates are open-circuited making the unit operate as a half wave rather than a full-wave rectifier
- Badly aged stacks
- In a 3-phase unit:
 - One phase may be open-circuited
 - One phase may have stacks that are more aged than the others

Filters

Filters are used to improve efficiency and for noise interference control. They consist of capacitors and chokes. If the choke is suspected to be defective, it can be removed from the circuit with a heavy jumper placed across the choke leads.

Capacitors usually fail by shorting. The capacitors should be fused. If the fuse is blown, replace it and turn on the rectifier. If the fuse blows again, the capacitor is defective and should be replaced.

Detection of Cable Breaks

Wire connections within the rectifier can become disconnected or loose (e.g., broken solder joint, burned connection, pulled spade lug). These can be checked with a multimeter or gentle pull at the connection. Note: Turn off and lock out rectifier before testing.

Broken cables outside the rectifier are also a possibility. Causes of external cable breaks include: construction damage, broken bond connection to the structure, broken anode connection, or broken anode wire due to exposure of the metallic wire to the electrolyte at a fault in the insulation.

Testing Transformers

If AC voltage is present to the primary but not the secondary, check to see whether there is an audible hum coming from the transformer. If so, the primary is operating, but the secondary is probably open. Check the above conclusions by electrically isolating the transformer and checking the DC resistance of the windings with an ohmmeter. The secondary should have generally less than one (1) Ω resistance while the primary should have 1 to 10 Ω resistance.

If either value is high, the winding is effectively an open circuit and the transformer will have to be replaced.

Use an AC voltmeter to see if voltage is applied to the stacks. If AC voltage is present, the stacks may be open circuited and should be checked with an ohmmeter. Check the leads between stacks if multiple stacks are used. On silicon stacks, remove each diode and check individually with a diode checker for forward and reverse bias. A bad silicon diode is either open or shorted.

If there is no output voltage or current, the breaker or fuse might be blown. Reduce the output slightly if due to a steady overload. Check for a possible short circuit in some component. Isolate the component and replace or repair.

If the breaker trips occasionally for an unknown reason, the problem could be:

- Temporary overload due to soil moisture changes
- Line voltage surges or wrong line voltage connections
- Intermittent short circuits. Isolate the component. Check for loose connections or brackets. (Check with ohmmeter while moving components – with POWER OFF.)
- Thermal breaker may be affected by sun's heat – install shield or shade.

No AC line voltage. Check with voltmeter. Check the service to the rectifier or check for a:

- Open circuit in some component or connection
- Defective meters or meter switches
- Defective transformer

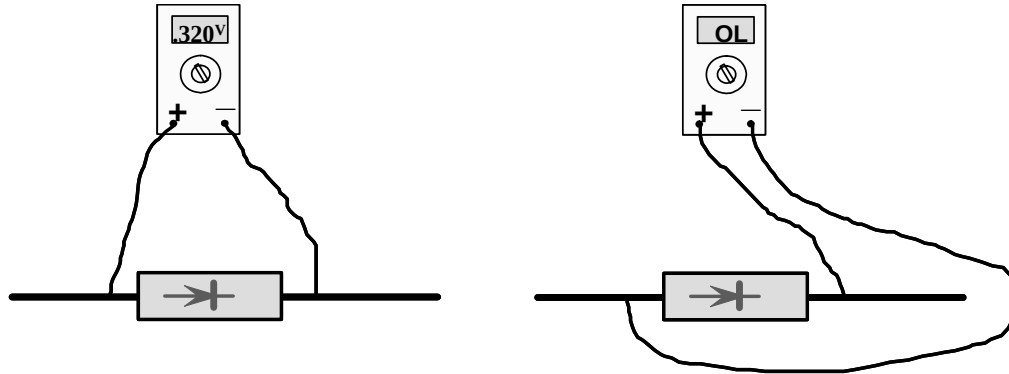
Testing Diodes

To check the diode bias, use the multimeter operated in the diode check mode (Figure 4.26). A functional diode will typically display a voltage 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 functional 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 the power on.



Check diode with power off and at least one lead disconnected from the circuit. Test in forward and reverse bias.

Figure 4.26 Diode Check

Diodes can be tested in a rectifier after it is turned off (locked out) after disconnecting the secondary taps and the DC cables. Each tap and each DC output terminal then represents a connection to a diode. Check the manufacturer's schematic diagram to confirm how the connections are made. Proceed with the diode test described in Figure 4.26. If an open circuit is indicated, check the connection wires and fuses in the circuit also. Connect the diode tester at (A), (B), (C) and (D) as shown in Figure 4.27.

D = Diode Tester

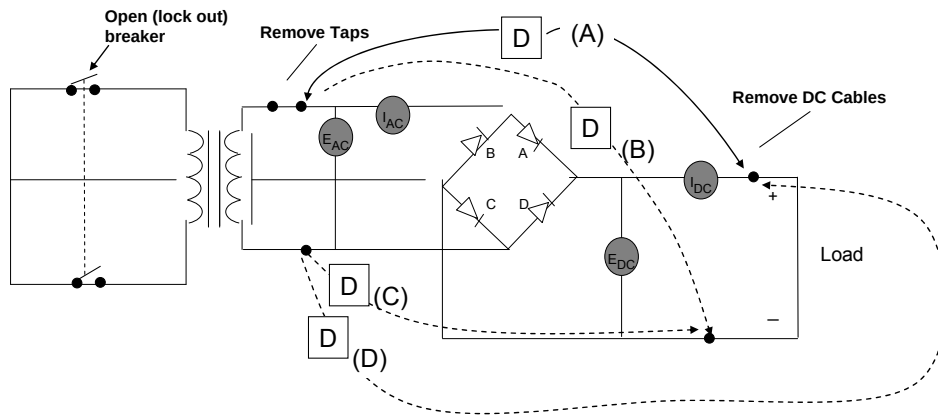


Figure 4.27 Single-phase Bridge Rectifier Circuit Showing Diode Test

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 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.

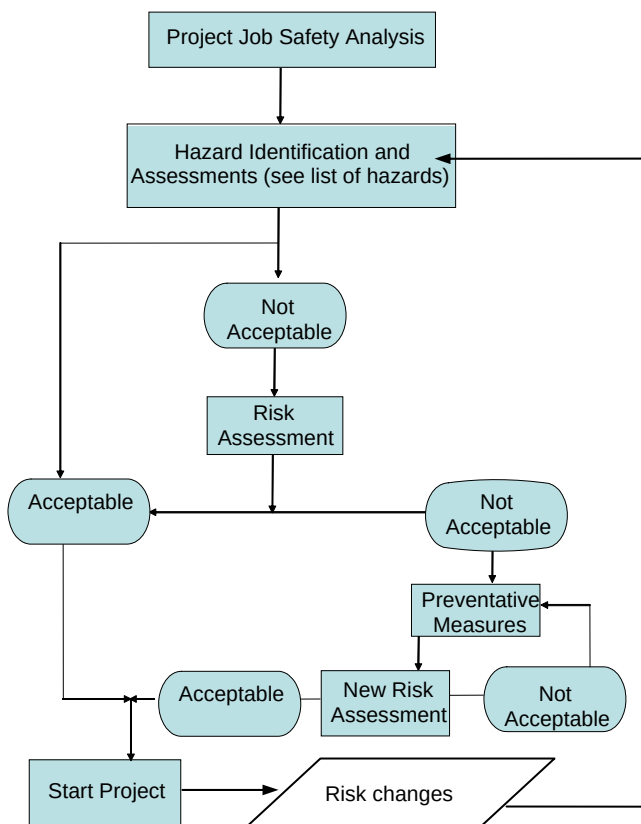


Figure 5.1 Safety Analysis Prior to Commencing Project

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
- Confined space

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.

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 V_{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 tighten.¹ Research indicates the maximum safe current between an arm and a leg is 100 mA at 3 seconds.² 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 V_{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.

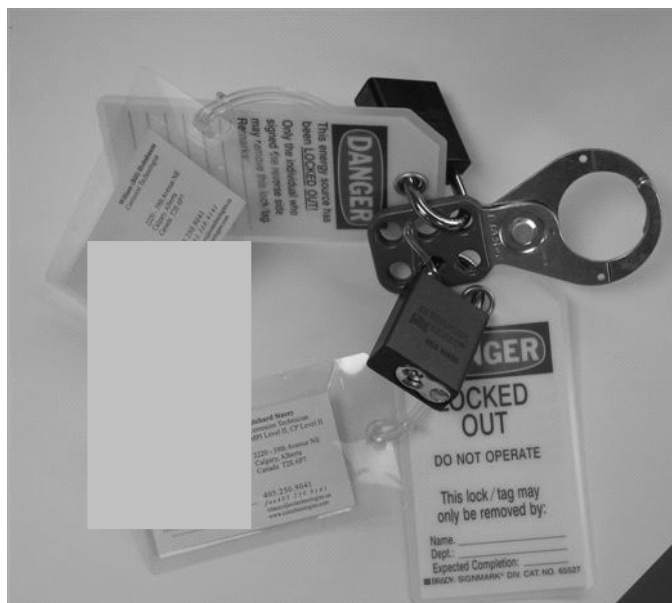


Figure 5.1 Group Scissor Lock Out / Tag Out (LOTO)

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 Standard 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 Standard 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 are 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 work 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.



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.
- 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.

General

Knowledge of proper test procedures is an essential skill for a cathodic protection technician. You must be able to perform tests as they may be required and also be able to teach the procedures to entry level personnel. There is an expectation that students taking this course should have a number of years of field experience performing these tests and conducting surveys. They must know the instrumentation, understand the theory behind the tests, and be familiar with sources of error that can lead to misinterpretation of results.

Measurement of Cathodic Protection Effectiveness

Various techniques may be used to determine the degree to which a structure under cathodic protection (CP) is actually protected against corrosion, including:

- Structure-to-reference potential
- Test coupons
- Current measurements
- Surface potential measurements
- Soil resistivity
- Direct observation
- Leak frequency
- In-line inspection.

Structure-to-Electrolyte Potentials

The definition of a structure-to-electrolyte potential, otherwise referred to as a pipe-to-electrolyte, pipe-to-soil, tank-to-electrolyte, or structure-to-soil 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-electrolyte potential is a measurement taken with the voltmeter connected in parallel in the circuit. The external circuit resistance of this measurement is high, so a high-input resistance voltmeter is required to avoid “shunting” too much current from the structure and therefore achieving inaccurate measurements. In addition, as previously discussed a reference electrode, often referred to as a reference cell, is used to make contact with the soil.

Structure-to-electrolyte potential profile surveys are used to:

- Locate anodic areas on non-cathodically protected pipelines
- Determine the effectiveness of cathodic protection on cathodically protected structures
- Locate stray currents
- Locate electrical shorts and contacts
- Locate coating holidays.

Potential measurements are a common means for determining if adequate protection has been achieved. With the application of current from the environment onto a structure a potential change with respect to the environment will occur. The potential change is a reflection of polarization. Measurements are made to determine whether one of the cathodic protection criteria is met (see Chapter 2 for discussion on CP criteria). According to the NACE standards, voltage drops other than across the structure-to-electrolyte boundary must be considered in order to assess the effectiveness of a CP system using fixed potential measurements. Several methods are used to consider these voltage drops:

- Minimizing the distance between the reference electrode and the surface of the structure

- Measuring the potential when the current flow is interrupted (instant-off potential)
- Measuring the formation of polarization or decay of polarization of the structure when the current is energized or disconnected
- Installing external CP coupons in the vicinity of the structure to replicate a coating holiday

Advantages of the structure-to-reference potential method are that it is relatively straightforward and potential measurements comply with standard criteria. Disadvantages are that all sources of CP current must be interrupted simultaneously, stray currents will affect the readings, polarized potentials of structures with direct-coupled galvanic anodes cannot be obtained, and surface potential measurements actually measure average potentials. The averaging of the actual structure-to-electrolyte potentials means that surface measurements might not detect small corrosion cells that are not being cathodically protected.

The Potential Measurement Circuit and Measurement Error

The intent of the potential measurement is to determine the pipe potential (E_p) accurately at the test location. The measurement circuit can be approximated by the electrical circuit in Figure 6.1.

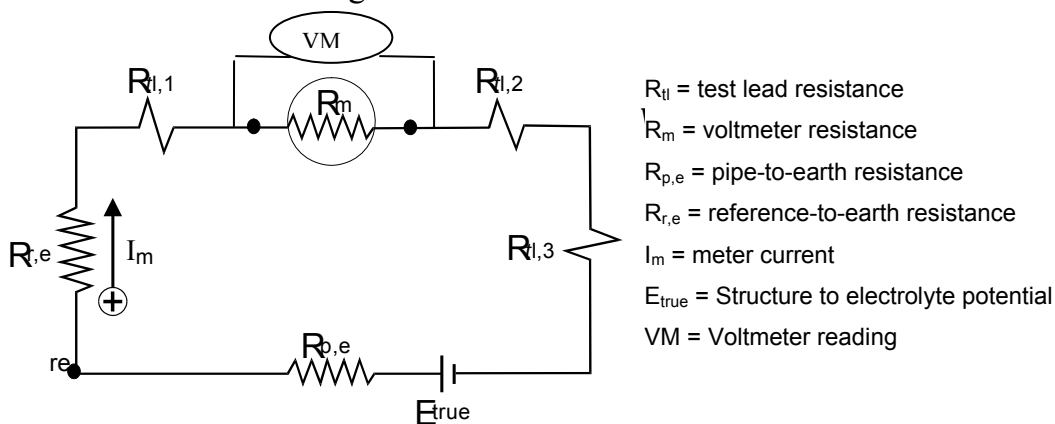


Figure 6.1 Electrical Schematic of the Structure-to-Electrolyte Measurement Circuit

It is the true potential difference (E_{true}) between the pipe and reference electrode that ideally should appear across the meter terminals. Because the meter circuit is a series circuit, the magnitude of the voltage drop that appears across the meter will be proportional to the ratio of the meter resistance to the total meter circuit resistance.

For the measurement circuit, Kirchhoff's voltage law applies and the true potential difference is equal to the sum of the voltage drops around the series circuit.

$$E_{true} = I_m R_t \quad \text{Eq. 6-1}$$

$$E_{true} = I_m [R_{tl,1} + R_{tl,2} + R_{tl,3} + R_{p,e} + R_{r,e} + R_m]$$

$$E_{true} = V_{tl,1} + V_{tl,2} + V_{tl,3} + V_{p,e} + V_{r,e} + V_m$$

$$V_m = E_{true} - [V_{tl,1} + V_{tl,2} + V_{tl,3} + V_{p,e} + V_{r,e}]$$

Let V_{circ} equal all voltage drops in the circuit except for the meter voltage drop

$$V_m = E_{true} - V_{circ}$$

$$\text{but: } E_{true} = I_m R_t \text{ and } V_{circ} = I_m R_{circ}$$

$$\text{and: } R_t - R_{circ} = R_m$$

$$\text{then: } \frac{V_m}{E_{true}} = \frac{R_m}{R_t} \quad \text{Eq. 6-2}$$

Hence, the amount of voltage (V_m) that appears across the meter compared to the true potential difference (E_{true}) is proportional to the ratio of the meter resistance (R_m) compared to the total resistance.

For example: Consider a true potential (E_{true}) of 1,000 mV, each test lead resistance (R_{tl}) of 0.01 Ω , a pipe-to-earth resistance ($R_{p,e}$) of 10 Ω , a reference electrode resistance to earth ($R_{r,e}$) of 100 k Ω , and a meter resistance (R_m) of 1 M Ω . Calculate the voltage that would appear across the voltmeter.

$$\begin{aligned} R_t &= 3R_{tl} + R_{p,e} + R_{r,e} + R_m \\ &= 3(0.01) + 10 + 10^5 + 10^6 \\ R_t &= 1.1 \text{ M}\Omega \end{aligned}$$

From Equation 6-2

$$V_m = \frac{R_m}{R_t} \times E_t$$

$$V_m = \frac{1.0 \text{ M}\Omega}{1.1 \text{ M}\Omega} \times 1,000 \text{ mV} = 909 \text{ mV}$$

This is an error of:

$$\frac{1,000 - 909}{1,000} \times 100 = 9\%$$

If the meter input resistance in the foregoing example is increased to 10 MΩ, the voltmeter would read 990 mV which would reduce the error to 1%.

The voltage across the voltmeter approaches the true potential as the meter resistance becomes much greater than the other resistances in the measuring circuit.

High resistances in the measuring circuit, other than across the voltmeter, should therefore be avoided. Reference electrode contact resistance can be a source of error when the reference is placed on dry soil, well drained gravel, crushed stone, frozen ground, asphalt, or concrete. To minimize this error, the contact conductance can be improved by wetting the area around the reference. In extreme cases, a hole can be drilled from the surface to a depth of permanent moisture and the reference placed in the hole, or an electrolytic bridge can be created between the reference and earth (Figures 6.2a and 6.2b).

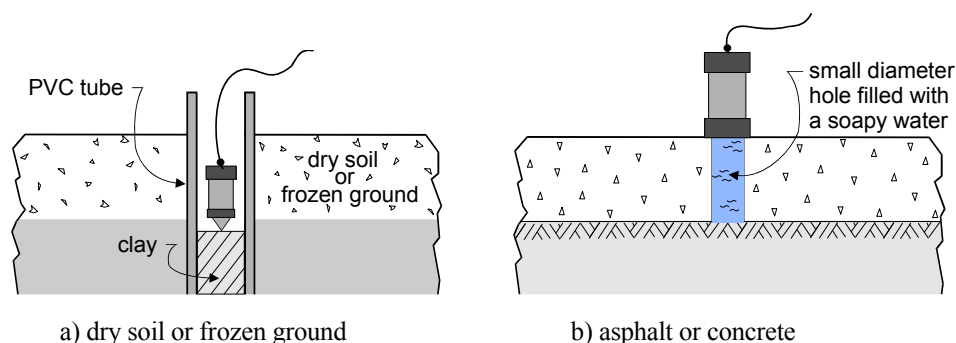


Figure 6.2 Methods of Minimizing Reference Electrode Contact Resistance

In Figure 6.2a, the depth from grade to clay must be below the frost line in frozen soil and to the depth of permanent moisture in dry soil. For asphalt or concrete, a soapy water solution will usually provide sufficient electrolytic contact even if the water level in the hole drops.

High measurement circuit resistance can also occur as a result of broken test leads, test lead connection resistances, and pipe resistance to earth if the pipeline is short and well coated.

When measuring a pipe-to-soil potential, it may not be immediately apparent that a high circuit resistance is present. If the voltmeter has an input resistance selector switch the existence of a high resistance in the measurement circuit can be identified by switching to a lower or higher input resistance. If the potential indicated by the voltmeter differs significantly (i.e., more than 10%) between the two input impedances then there is a high resistance in the measurement circuit. Further by knowing the two input resistances and their corresponding measured voltage, the true potential can be calculated using Equation 6-3.

$$E_{\text{true}} = \frac{V_h (1 - K)}{1 - K \frac{V_h}{V_l}} \quad \text{Eq. 6-3}$$

where:

- E_{true} = true potential (V)
- K = input resistance ratio R_l/R_h
- R_l = lowest input resistance
- R_h = highest input resistance
- V_l = voltage measured with lowest input resistance
- V_h = voltage measured with highest input resistance

For example: If a potential difference (V_l) of $-650 \text{ mV}_{\text{cse}}$ was measured with an input resistance (R_l) of $1.0 \text{ M}\Omega$ and a potential difference of $-800 \text{ mV}_{\text{cse}}$ (V_h) was measured with an input resistance (R_h) of $10 \text{ M}\Omega$, then the true potential (E_{true}) would be calculated as follows:

$$\begin{aligned}
 E_{\text{true}} &= \frac{-800 \text{ mV} (1 - 0.1)}{1 - 0.1 \left(\frac{-800 \text{ mV}}{-650 \text{ mV}} \right)} \\
 &= \frac{-720 \text{ mV}}{1 - 0.123} = \frac{-720 \text{ mV}}{0.877} = -821 \text{ mV}_{\text{cse}}
 \end{aligned}$$

E_{true} is the same as the polarized potential.

In addition, the total circuit resistance (R_t) can be determined using Equation 6-2.

$$\begin{aligned}
 R_t &= \frac{R_m \times E_{\text{true}}}{V_m} \\
 &= \frac{10 \text{ M}\Omega \times 821 \text{ mV}}{800 \text{ mV}} \\
 R_t &= 10.3 \text{ M}\Omega
 \end{aligned}$$

This means that the resistance in the measuring circuit, excluding the meter resistance is:

$$\begin{aligned}
 R_{\text{circ}} &= R_t - R_m \\
 &= 10.3 \text{ M}\Omega - 10 \text{ M}\Omega \\
 R_{\text{circ}} &= 0.3 \text{ M}\Omega \text{ or } 300,000 \Omega
 \end{aligned}$$

As charges flow in the earth to or from the pipe and with earth's resistance, voltage drops occur in the earth creating a voltage gradient around the pipe as illustrated for a bare pipe in Figure 6.3.

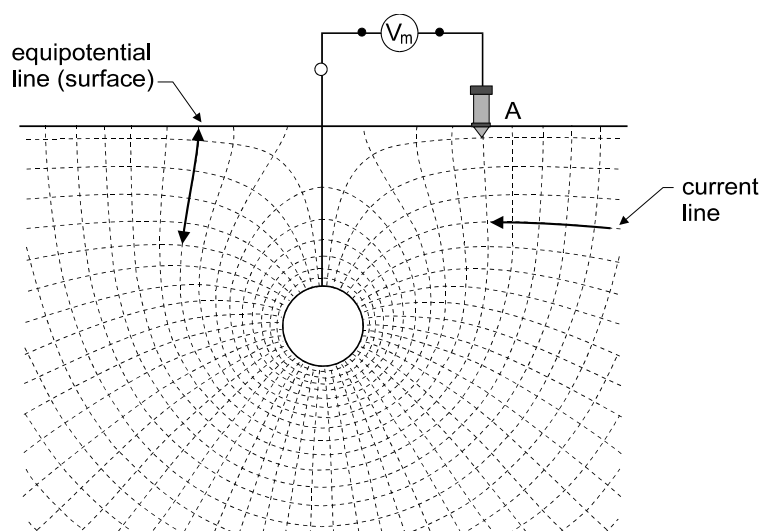


Figure 6.3 Voltage and Current Lines around a Bare Pipeline Receiving Cathodic Protection Current

Source: Parker, Marshall and Peattie, Edward, Pipeline Corrosion and Cathodic Protection, 3rd Edition, Gulf Publishing Co., Houston, TX, p.25

The radial lines denote the current paths while the lines perpendicular to the current lines represent the equipotential surfaces created by the current. The equipotential surfaces, which are perpendicular to the current paths, are not evenly spaced but increase with distance away from the pipe because each successive shell of earth has a larger surface area and hence a lower resistance.

If a potential measurement is taken with the reference electrode located at A and the current direction is toward the pipe (as would be the case in cathodic protection), then there is a voltage drop (V_s) in the soil between the reference electrode and the pipe surface. The soil at point A is more positive than the soil immediately adjacent to the pipe surface. If the potential difference between adjacent equipotential surfaces is 10 mV, the voltage drop in the soil between the pipe surface and the reference location would be 10 lines $\times$ 10 mV = 100 mV. The soil at the pipe surface is -100 mV with respect to the soil at the reference electrode.

For example, if the polarized potential (E_p) of the pipe is $-790 \text{ mV}_{\text{cse}}$ the voltmeter will read:

$$\begin{aligned} V_m &= -790 \text{ mV}_{\text{cse}} + (-100 \text{ mV}) \\ V_m &= -890 \text{ mV}_{\text{cse}} \end{aligned}$$

Thus, there is a 100 mV error in the measurement that makes it appear as if the pipe is better protected than it is.

For a well coated pipeline, the equipotential field forms in close proximity to the holidays as shown in Figures 6.4 and 6.5.

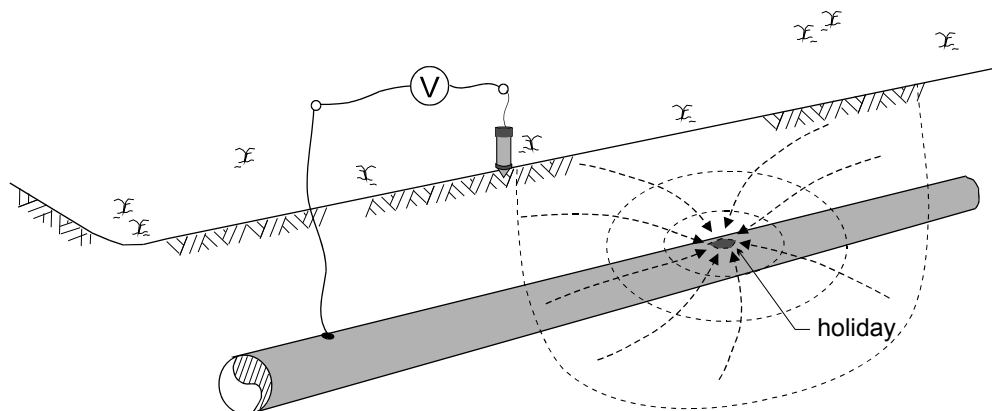


Figure 6.4 *Current and Voltage Lines around a Holiday on a Coated Pipeline*

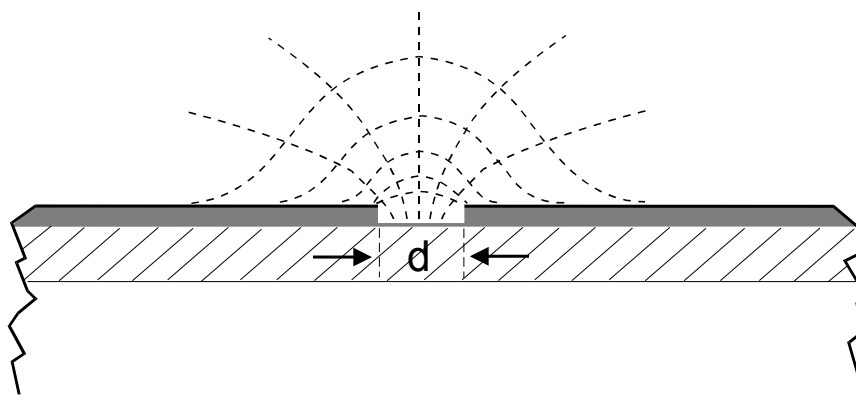


Figure 6.5 *Current and Voltage Lines in Immediate Vicinity of a Holiday*

On a coated pipeline, most of the voltage drop is concentrated in the immediate vicinity of the holiday. Typically 95% of the total voltage drop between the reference and the steel exposed at the holiday is found within about 10 diameters of the holiday (i.e., 10 d). For a 1 cm (0.393 in) diameter holiday, 95% of the voltage occurs within a radius of 10 cm from the holiday.¹

¹ Gummow, R.A., The Cathodic Protection Potential Criterion for Underground Steel Structures, NACE International, CORROSION/93, Paper No. 564, p. 5.

Voltage Drop Errors in the Potential Measurement Due to Current in the Pipeline

Voltage drops also occur in current-carrying metal paths and if the connection to the pipe is remote from the location of the reference electrode, as shown in Figure 6.6, there will be an IR drop error (V_p) in the potential measurement.

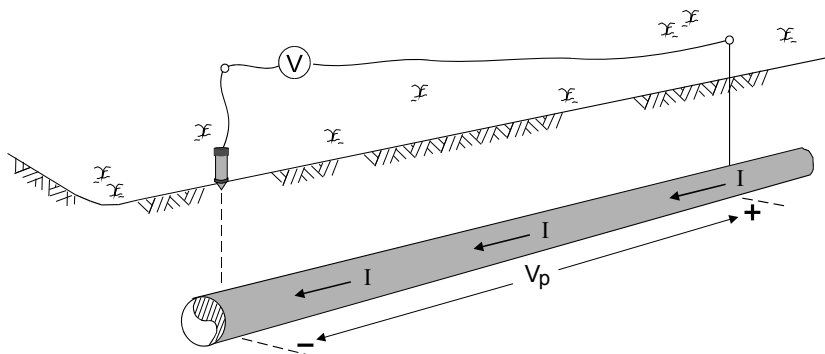


Figure 6.6 Voltage Drop in a Pipeline Carrying Current

IR Drop Error Determination and Correction

Potential measurements often include errors caused by IR drops, particularly in the electrolyte, as discussed previously. Furthermore, the magnitude of IR-drop errors must be determined and appropriately compensated for when measuring and evaluating field data. Accordingly, there are a number of common methods of determining and correcting for IR drop:

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

In some situations, the IR-drop error can be neglected if the current and/or the resistance of a current path that is a function of the path’s cross-sectional area,

resistivity, and length, is small. Before neglecting the IR drop, the magnitude of IR drop should be determined in order to verify its insignificance.

Current Interruption

An effective method of eliminating IR-drop errors is by making the current zero thereby making the IR product equal to zero. Typically, zero IR drop is achieved by temporarily interrupting the flow of current and instantly reading the structure potential. This potential must be read quickly since the structure will begin to depolarize with time (see Figure 6.7).

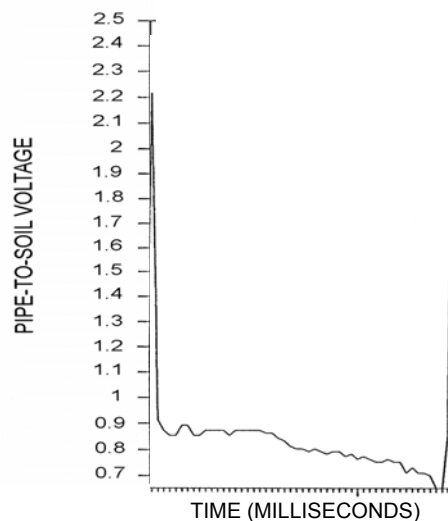


Figure 6.7 Waveprint Illustrating Depolarization During OFF Cycle

However, there may be significant spiking of the potential due to inductive and capacitive effects associated with the interruption of the cathodic protection current. The “instant-off” potential should be measured after this spiking has decayed (see Figure 6.8) but before significant depolarization of the structure has occurred.

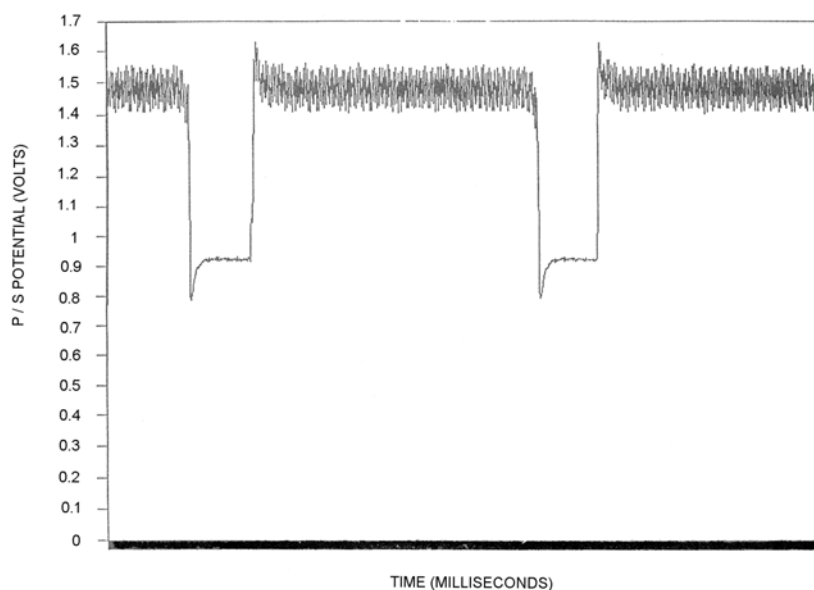


Figure 6.8 Structure-to-Electrolyte Potential “Waveprint” Illustrating the “Spike” During Current Interruption

To measure the “OFF” structure-to-electrolyte potential, all sources of current influencing the area under investigation must be interrupted. This can be accomplished by installing a current interrupter in all current sources influencing the system in the area under investigation. The interrupters are essentially a mechanical or electronic relay connected to a very precise chronometer. Multiple units can be synchronized to cycle in unison, allowing multiple current sources to be interrupted simultaneously, effectively removing all current from the structure at the same instant. With no current flowing, the voltage drops go to zero and the measured potential is the polarized potential of the pipeline.

$$\text{Potential Measured (E}_m\text{)} = E_{\text{corr}} + \text{Polarization} + \text{IR Drop} \quad \text{Eq. 6-4}$$

This is illustrated in Figure 6.9.

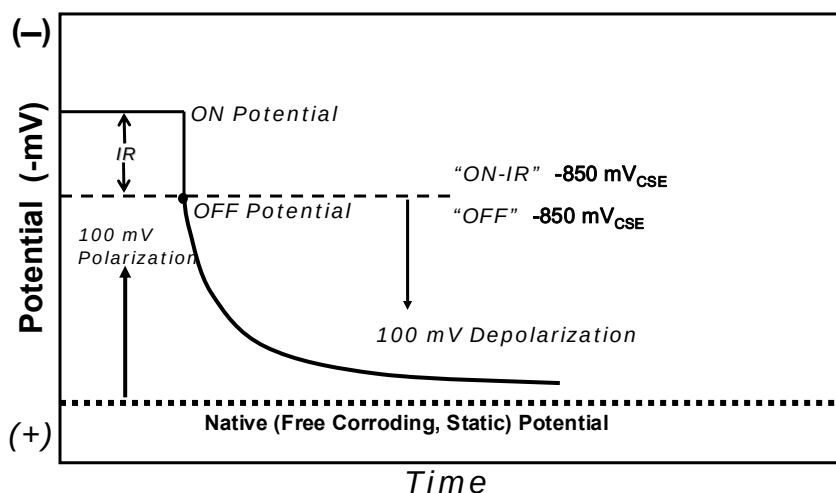


Figure 6.9 Elimination of IR Drop by Current Interruption and Subsequent Depolarization

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

Interruption cycles vary based upon the type of structure-to-electrolyte potential survey that is being conducted. Key factors in selecting an interruption cycle include:

- Minimizing depolarization during the day
- Minimizing depolarization during the OFF period
- Maintaining polarization over the duration of the survey project
- Ability to measure accurate OFF potential data after the “spike” has dissipated.

Maintaining an 80%/20% or 75%/25% “duty cycle” is important to minimize depolarization during the day and over the duration of the survey project. The duty cycle is the percentage of ON time to OFF time. An example would be 3 seconds ON and 1 second OFF.

In addition, it is important to turn off the current interrupters at night. This will reduce the amount of time the current sources are being cycled and help rebuild any polarization which may have been lost during the day when the current sources were cycling ON and OFF.

Maintaining the synchronization of the current interrupters is accomplished by several means. Current interrupters available today include quartz crystal timing devices which, once synchronized together, will maintain the timing for a period of time. The United States government's Global Positioning Satellites (GPS) system also provides precise timing and is available at no charge to the public. GPS-synchronized interrupters which maintain precise timing indefinitely as they "resynchronize" themselves at predetermined times throughout the day are available. Note that some will fail in the on position if they lose their satellite signal and then restart when it comes back. Unless there is a stationary datalogger monitoring the data, this event can go unnoticed and true polarized potentials will not be taken.

One method of verifying interruption synchronization and of checking the magnitude and duration of the inductive/capacitive spike is by recording a "wave print" or waveform. A wave print is a graph of hundreds or thousands of structure-to-electrolyte potentials recorded every second for the duration of an interruption cycle. The data is graphed versus time and can be reviewed in the field to review:

- Interrupter synchronization (see Figure 6.10)
- Depolarization during the OFF period (see Figure 6.7)
- Spiking magnitude and duration (see Figure 6.8)
- Dynamic stray currents (see Figure 6.11)

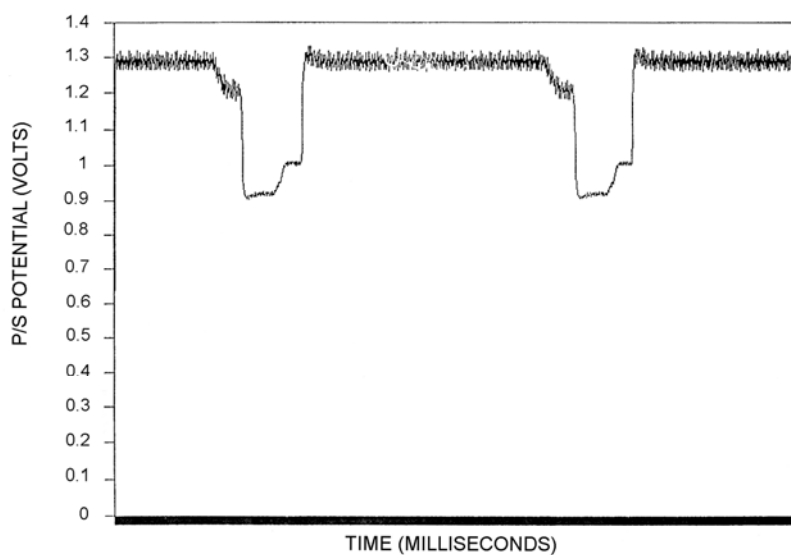


Figure 6.10 Waveprint Illustrating Non-Synchronized Current Interrupters

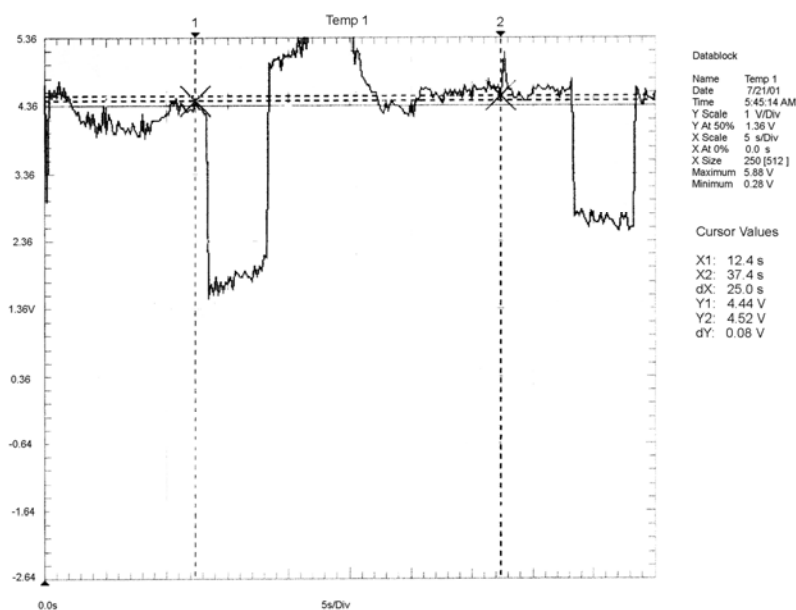


Figure 6.11 Waveprint Illustrating Dynamic Stray Current Interference

Reference Electrode Near the Structure

To minimize the IR-drop error associated with the electrolyte, the reference electrode should be positioned as near to the structure as possible. This may not eliminate all IR drop.

When dealing with underground piping or tanks, the ideal position of the electrode would be at the bare structure surface or at a coating holiday. There are times, however, when the electrode is purposely placed at some distance from the structure; this is discussed later under the section “Remote Earth.”

Inside 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.

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 or the tank is large in diameter. Stationary reference electrodes under the tank bottom yield the best data. Alternately, if a perforated plastic tube is installed under the tank and filled with water, a reference electrode can be pulled through it and potentials measured at intervals underneath (see Figure 6.12).

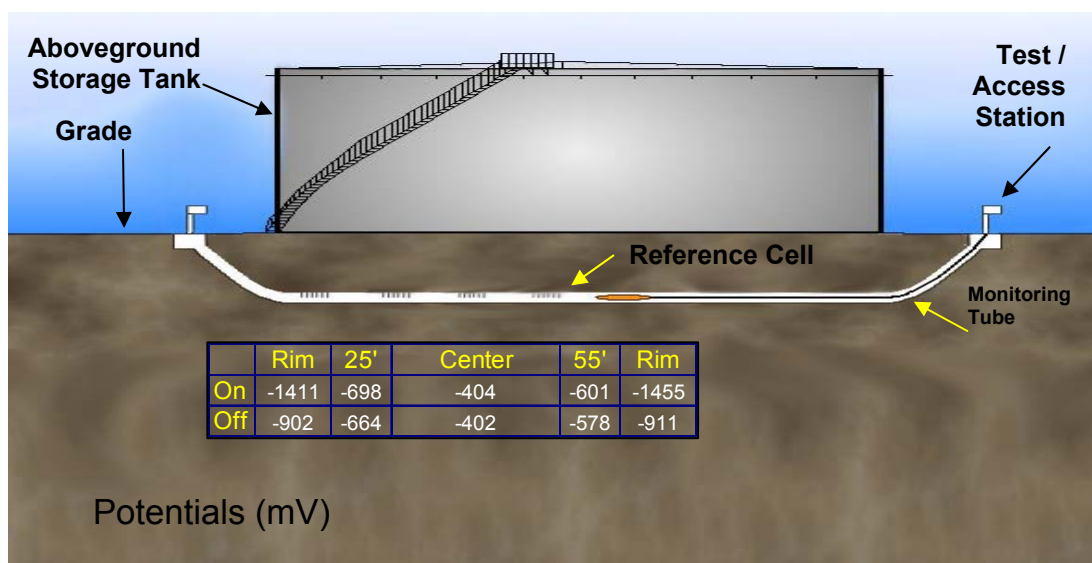


Figure 6.12 Reference Cell Under AST

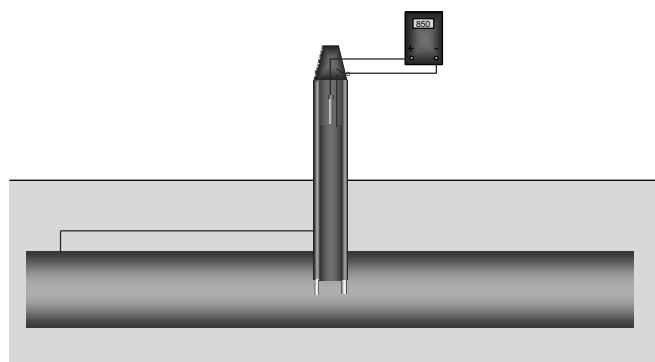
Placing the reference electrode close to the structure minimizes the IR-drop error in the electrolyte in proportion to the electrode's closeness of the electrode to the surface. Unfortunately, for underground structures, this is not a practical technique except at points of structure-to-soil entry and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

immediately outside the coating, and it is across the coating where much of the IR drop exists (Figure 6.4).

External CP Coupons

Evidence that cathodic protection is working can be obtained by using coupons of the same metal as that of the protected structure. These coupons are weighed carefully beforehand, and then electrically connected to the protected structure. The coupons should be placed where they receive the same exposure to cathodic protection current as the structure receives; then, after a known exposure time, they are removed and weighed. Corrosion rate is the weight loss per time.

External CP coupons can also be used to monitor cathodic protection criteria. This is particularly useful on well-coated structures where few coating holidays exist. The coupon serves as a surrogate holiday and polarizes to the same structure potential (Figure 6.13).



9 cm² Coupon

Figure 6.13 External CP Coupon

Advantages of using CP coupons are that IR-drop-free potentials can be obtained without interrupting multiple power sources, structure-to-reference potentials can be measured on structures with direct-connected galvanic anodes, and depolarization tests can be conducted on the structure without de-energizing the CP system.

It should be understood that there can be a discrepancy between the polarized potential of the coupon and that of the structure.

A number of special cathodic protection monitoring test stations are available. These are constructed with a steel coupon connected through the test station

wiring to the structure that is under cathodic protection. The test station is positioned so that the coupon rests near the structure in the same backfill around the structure.

To permit measurement of the coupon to electrolyte potential, a reference electrode is placed in the test station riser, in the soil near the coupon, or at grade. The coupon is momentarily disconnected from the structure and its potential with respect to the electrolyte is read. This measured value is essentially an IR-drop-free reading of the coupon potential to the reference electrode.

The IR-drop-free potential of the coupon is similar to the instant off potential of the structure, if a holiday of similar size were to exist on the structure at that location. If the coupon meets a criterion, then it is inferred that the structure would also meet this criterion.

Some of these test stations are available with resistance-type corrosion probes located in the foot of the test station. The element is connected to the structure and is under the same level of cathodic protection as the structure. If corrosion is occurring, the resistance probe will reflect the condition by showing a higher resistance over time. Figure 6.14 illustrates one type of special test station that includes the features described.

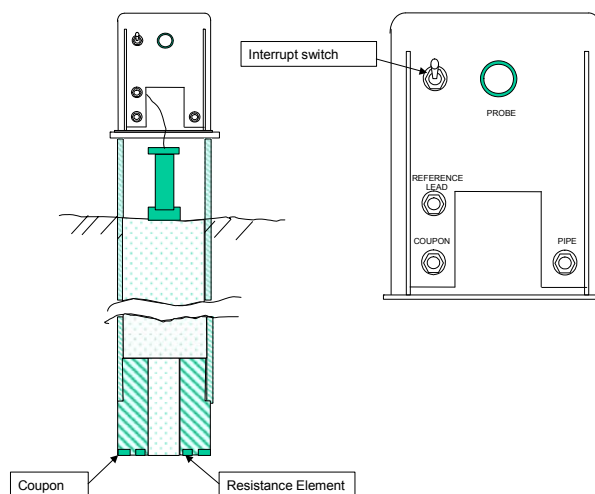


Figure 6.14 Special Test Station for Monitoring Cathodic Protection

Figure 6.15 shows a coupon test station designed to monitor cathodic protection levels on pipelines or other buried structures. Coupons can also be used for submerged structures (such as water tanks, clarifiers, dock structures, and

offshore structures), in reinforced concrete structures, or in any other structure being cathodically protected.

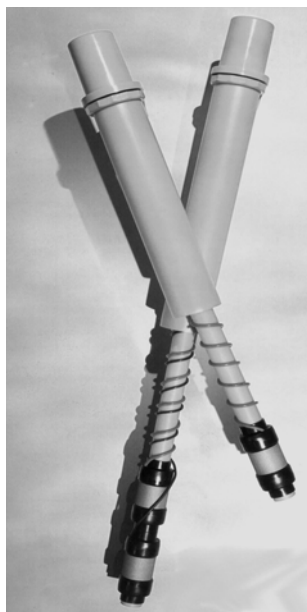


Figure 6.15 Two Types of Coupon Test Stations
(Courtesy of Cott Manufacturing Company)

Resistance probes are available that will monitor corrosion rate directly without being removed from the environment. As a metal corrodes, its volume is reduced, which causes its electrical resistance to increase. These probes work by sensing the increase in resistance of the probe (made of the metal being tested) as the metal corrodes. An instrument at a test station measures the resistance changes, which are then used to determine the corrosion rate. The corrosion rate of the probe on a cathodically protected structure will be zero. The probes can also be used for potential and polarization measurements.

Reference Electrode at Remote Earth

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

Remote earth may be determined by a series of structure-to-electrolyte potential measurements made as one moves away from the structure. Typically, these measurements are made at consistent intervals and presented in graphical form. Figure 6.16 indicates that at points some distance from the structure, there is little increase in the magnitude of the potential. Beyond this distance may be considered electrically remote for practical purposes.

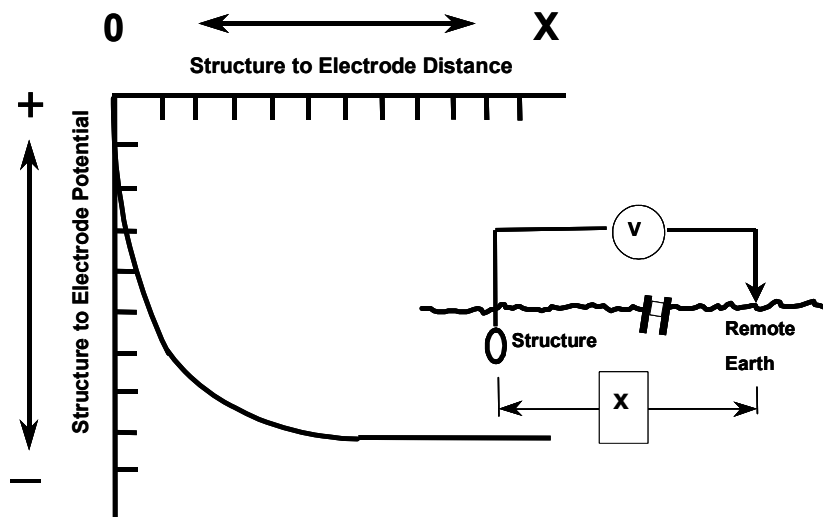


Figure 6.16 *Determination of Remote Earth from Structure*

The distance to remote earth is not necessarily the same at all points on a structure. Both soil resistivity and current density have an effect. In high-resistivity soil areas, the distance to remote earth tends to be greater than in low-resistivity soils.

Stepwise Current Reduction Method

The stepwise current reduction technique involves recording the potential shift in the structure-to-electrolyte potential measurement and a side drain potential measurement as the cathodic protection current is reduced. The test arrangement is illustrated in Figure 6.17.

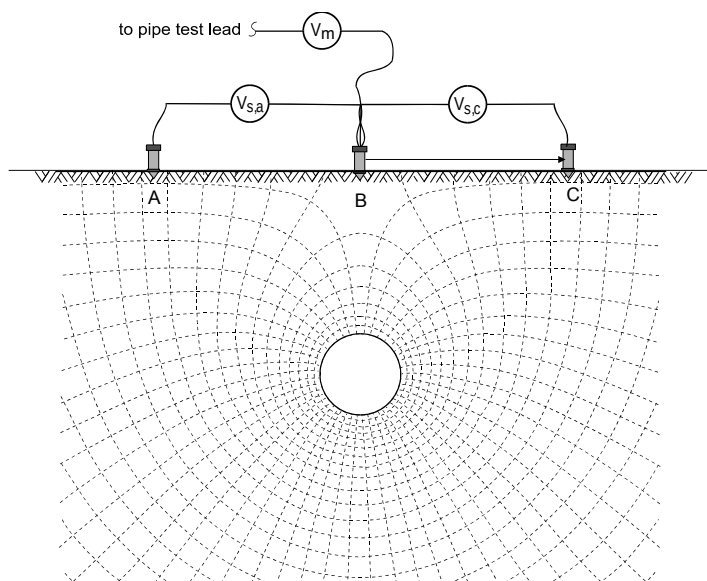


Figure 6.17 Field Test Arrangement for the Stepwise Current Reduction Method of Determining the Amount of IR drop in the On-Potential

The on-potential recorded on the voltmeter (V_m) is

$$V_m = E_p + I_{cp} \cdot R_e \quad \text{Eq. 6.5}$$

If the I_{cp} current was reduced the on-potential would decrease because the earth voltage drop ($I_{cp}R_e$) would decrease. If the stepwise reduction in cathodic protection current was continued until $I_{cp} = 0$, then $V_m = E_p$ and the IR drop would also be zero. Further, the side drain potentials $V_{s,c}$ and $V_{s,a}$ should also approach zero as I_{cp} approaches zero. Assuming the earth voltage drop $I_{cp}R_e$ and the side drain voltages obey Ohm's law, then these parameters should be linearly related.

By reducing the cathodic protection current in increments and measuring V_{on} , $V_{s,c}$, and $V_{s,a}$, the data can then be used to construct the graph of Figure 6.18.

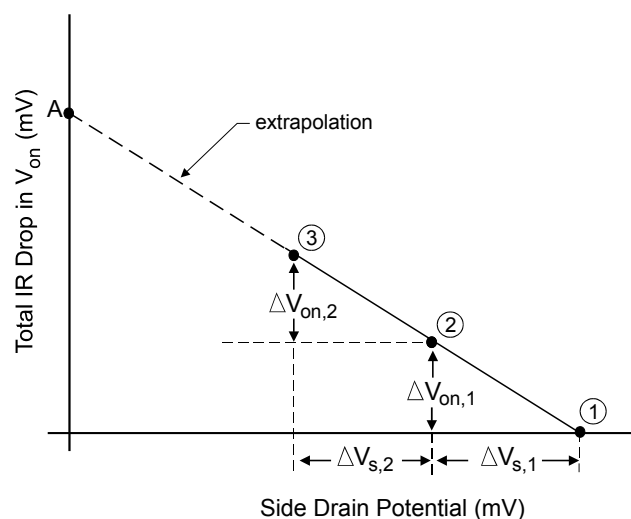


Figure 6.18 Data Plot for Stepwise Current Reduction Technique

- Step ① Plot $V_{s,a}$ or $V_{s,c}$ on the abscissa with full current
- Step ② Reduce I_{cp} , calculate ΔV_{s1} , and $\Delta V_{on,1}$;
plot ΔV_{s1} and $\Delta V_{on,1}$ to obtain point ②
- Step ③ Repeat Step ② and plot ΔV_{s2} and $\Delta V_{on,2}$ to obtain point ③
- Step ④ Draw a best fit straight line through the data points and extrapolate the line until it intersects the ordinate at A.

“A” on the “y” axis is then the amount of IR drop in the original on-potential measurement. The polarized potential (E_p) is then determined by subtracting the IR drop at A from the on-potential measured at location B i.e.,

$$E_p = V_{m,b} - A \quad \text{Eq. 6.5}$$

Two lines could be plotted for both side drain measurements that should give the same intercept A if the current and soil resistivity is symmetrical around the pipe.

Current reduction time intervals should be kept as short as possible, otherwise the polarized potential (E_p) will reduce as well as the earth IR drop and result in a larger IR drop indication. If the potential changes are recorded quickly, this technique can be used in the presence of dynamic stray currents.

The technique is time consuming and seldom used since if it is possible to reduce the cathodic protection current it is possible to interrupt the current and use the current interruption technique.

Theoretically, this method could be used on piping with attached galvanic anodes by applying a test current in increments. This would then be a stepwise current increase technique.

On very well coated pipelines, the side drain potential may be small which would increase the angle of the line such that a small error in plotting would result in a large change in the point of interception. Hence, its accuracy for well coated pipelines may be compromised.

Surface Potential Surveys

Surface potential surveys are used for many purposes and can be broken down into structure-to-electrolyte surveys, coating defect surveys, and earth current surveys.

A structure-to-electrolyte potential is the potential difference between the structure and a standard reference electrode. There are four elements that must be recorded including the value, the polarity, the units, and the reference electrode used.

Since this measurement is often used to determine if a criterion for cathodic protection is met, the readings must be IR-drop free and sufficient readings must be taken to be confident that a representative number of locations have been tested to provide an accurate picture of the status of protection throughout the structure.

Potentials are taken at intervals close enough to provide a clear understanding of the status of protection. Where potentials may vary quickly along a pipeline, a close interval potential survey (CIS) should be conducted.

Close Interval Potential Survey

A series of structure-to-electrolyte potentials determine if adequate cathodic protection is achieved at all points along the structure. Figure 6.19 illustrates a close interval potential profile.

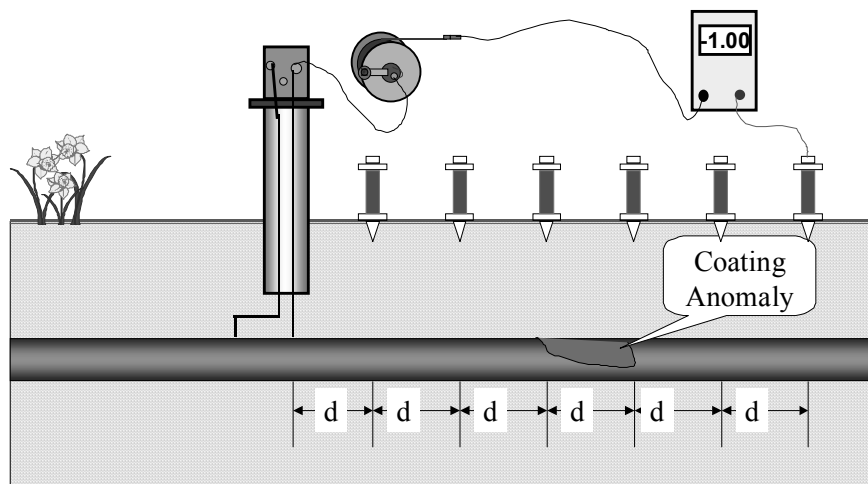


Figure 6.19 Close Interval Potential Survey

In a close interval survey (CIS), the structure-to-electrolyte potential data are collected at close spacing [1 to 5 m (3 to 15 ft)]. This is usually done by carrying a voltmeter or datalogger and a wire-dispensing device. Some wire dispensing devices are equipped with distance measuring capability so that the technician knows where they are when the data is entered into the data logger. Others simply use a measuring chain or calibrated rope and “station” the pipeline using the company’s pipeline as-built information.

A close interval potential survey can be completed on both cathodically protected and non-cathodically protected structures.

One or two reference electrodes, mounted at the end of a short pole(s), are used. A small-gauge wire, usually 30 to 34 AWG size, is attached to a test station or other abovegrade electrically continuous structure and the operator walks over the pipeline, making contact between the electrode(s) and the earth at closely spaced intervals. The operator records abovegrade appurtenances and other identifying items along the way so the location of the data can be pinpointed. During the survey, the data is downloaded into a computer and often printed in graph form (Figure 6.20).

If a single reference electrode is used the operator signals the datalogger to save the readings after a good reference contact is made. Where soil conditions are favorable a “walking electrode” procedure can be used where one reference electrode is in contact with the soil at all times and the datalogger saves the readings based on an odometer input determined from the wire passing through it.

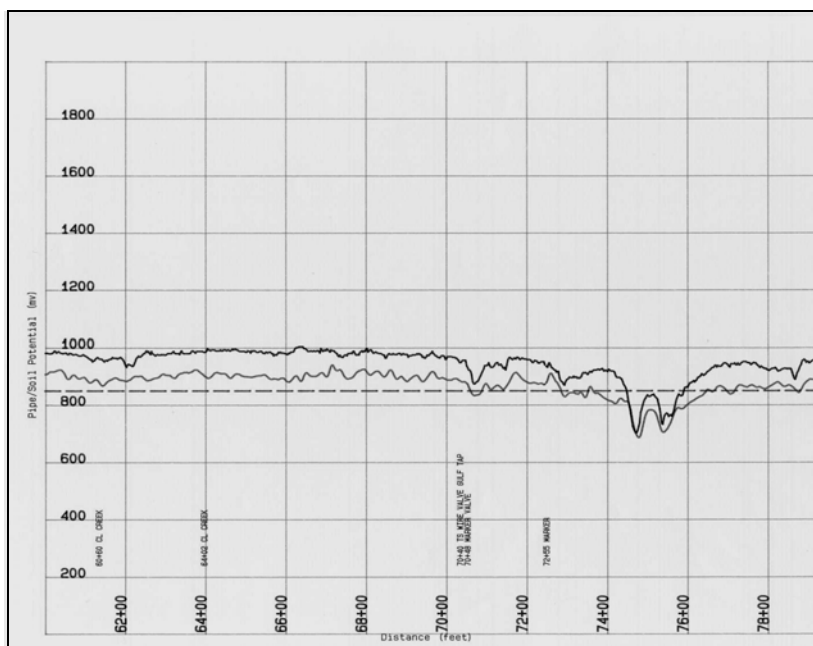


Figure 6.20 On/Off Pipe-to-Electrolyte Potential Profile

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

If the target CP criteria is the $-0.850 \text{ V}_{\text{CSE}}$ polarized potential criteria, then typically an interrupted CIS where the influencing current sources are interrupted and both ON and IR-drop-free (“instant-off”) potentials are completed. For the 100 mV polarization criteria, after the ON/OFF potential data has been collected, the current sources are de-energized and a period of time allowed for the structure to depolarize. Once depolarized, a second CIS is completed collecting depolarized pipe-to-electrolyte potentials at the exact reference electrode locations as during the initial CIS. This data can then be overlaid on the same graphs with the ON/OFF data to confirm whether or not the 100 mV criteria has been satisfied (Figure 6.21).

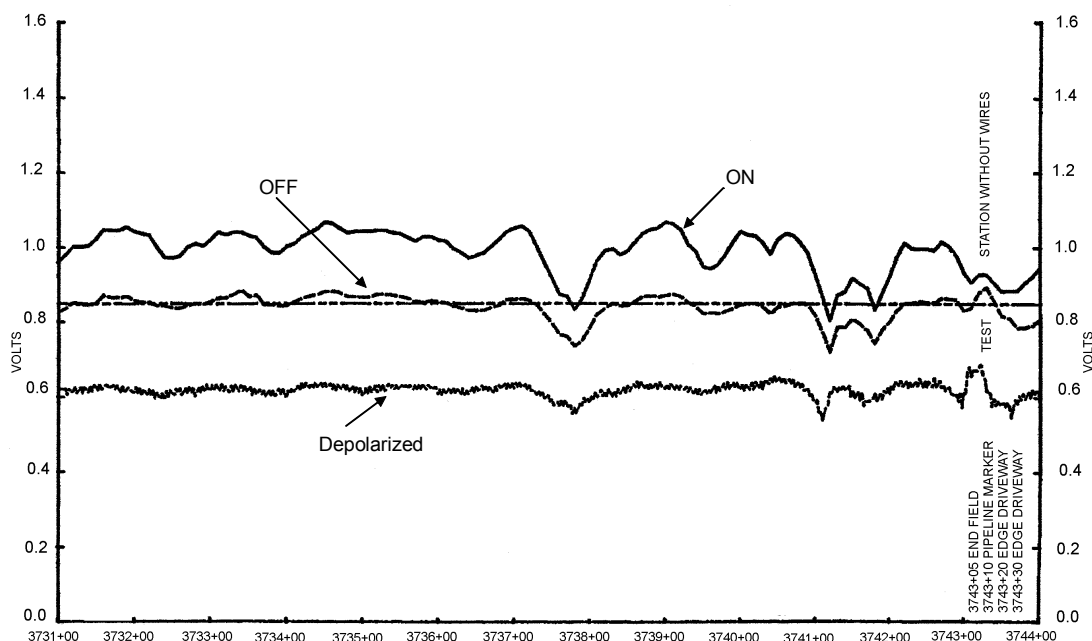


Figure 6.21 ON/OFF Close Interval Survey Showing a Depolarized Potential

Analysis of Surface Potential Surveys

Surveys on Cathodically Protected Structures

The completed pipe-to-electrolyte potential data can be plotted on a graph versus distance for ease of viewing (Figures 6.22 and 6.23). Often, a line is drawn across the graphed pages to easily identify the $-0.850 \text{ V}_{\text{CSE}}$ cathodic protection criteria. A structure-to-electrolyte potential plot where the pipe meets the cathodic protection criterion will have all of the structure-to-electrolyte potentials more negative than the line drawn at $-0.850 \text{ V}_{\text{CSE}}$ (if that is the criterion). If the 100 mV polarization criteria is being used, then the polarized potentials will be 100 mV more negative than the static (native or depolarized) structure-to-electrolyte potential profile (Figure 6.21). Alternately, plot the actual polarization.

Figure 6.22 is data collected using a twelve-second ON and three-second OFF interruption cycle on a pipeline with approximately 300 mV of IR drop. On this section of pipe the OFF potentials are all less negative than $-0.850 \text{ V}_{\text{CSE}}$ indicating adequate levels of cathodic protection do not exist. The polarized potentials in Figure 6.23 are less electronegative than the $-0.850 \text{ V}_{\text{CSE}}$ for the last half. High electronegative potentials through the first half suggest that all current sources may not have been interrupted.

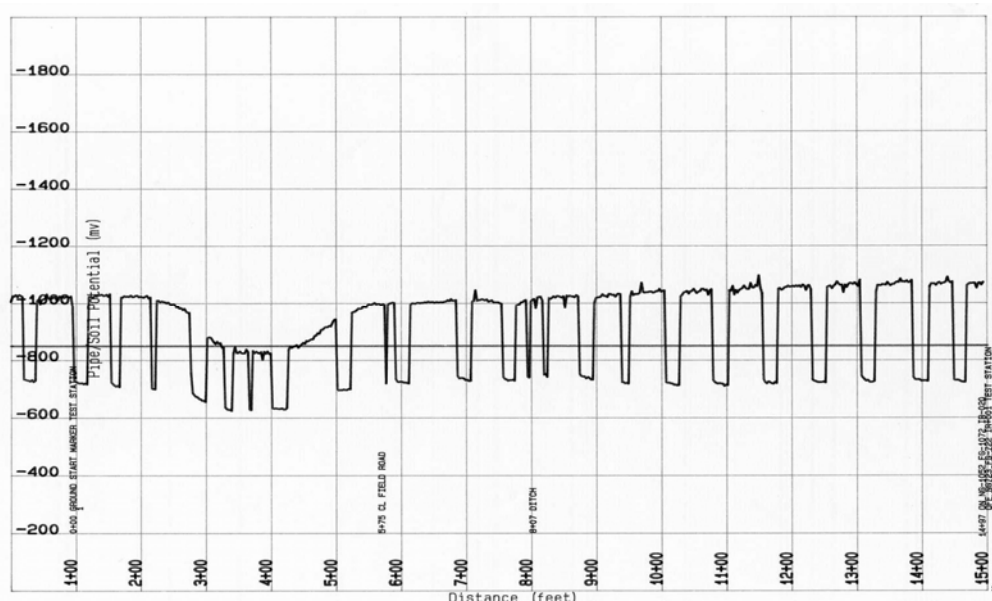


Figure 6.22 On/Off Potential Survey
(Raw data from Datalogger using a Walking Electrode Method)

Figure 6.23 is data collected using a three-second ON and one-second OFF cycle but graphed such that the ON and OFF potentials are separate lines on the plot. Of interest is how the pipe-to-electrolyte potentials change dramatically from having adequate levels of cathodic protection to having inadequate levels and nearly zero IR drop in the ON potential.

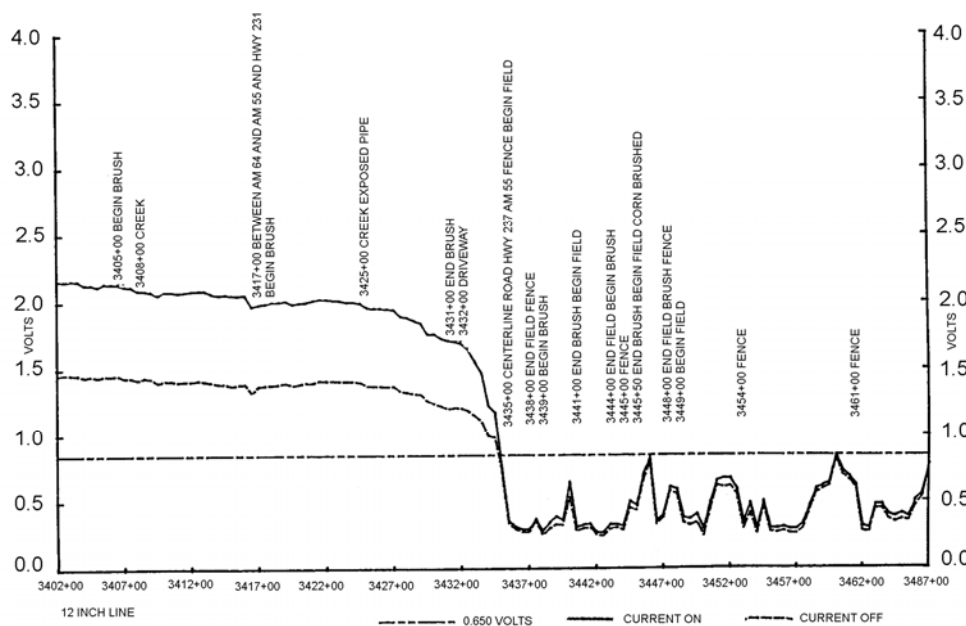


Figure 6.23 ON/OFF Potential Survey Plotted as Two Separate Lines

Figure 6.24 contains data collected on a pipeline with distributed impressed current anodes alongside the pipeline. Again the data was plotted using separate lines for the ON and OFF potentials. The very negative ON potential peaks reveal the locations of the distributed anodes while one can see the OFF potentials in between the anodes are less negative than $-0.850 \text{ V}_{\text{CSE}}$.

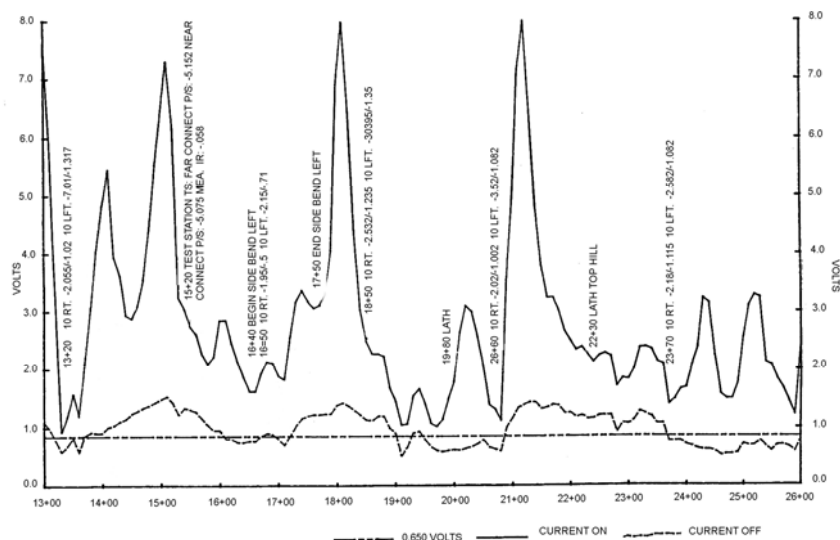


Figure 6.24 ON/OFF Potential Survey Conducted on a Pipeline with Distributed Anodes

Figure 6.25 illustrates data graphed on a larger scale, in this case, 1 in. = 0.50 km, such that 5 km of data fits on a single page. This “big picture” plot may assist in the analysis of pipe-to-electrolyte potentials indicating stray current interference, an electrical short, or inadequate cathodic protection levels.

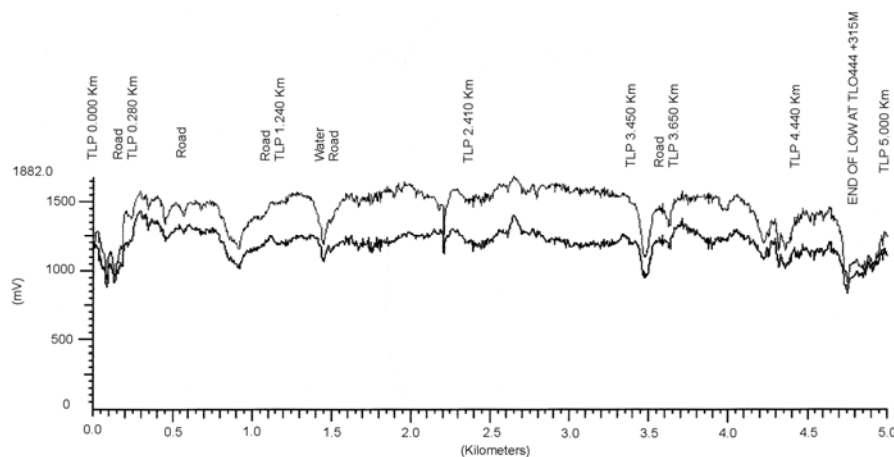


Figure 6.25 ON/OFF Potential Survey on Larger Scale

Lateral/Side Drain Surface Surveys

An additional field test often completed during CIS projects on non-cathodically protected pipes is referred to as a lateral or side drain survey. As structure-to-electrolyte potentials are measured and recorded directly above the pipeline, structure-to-electrolyte potentials are also measured and recorded laterally or to the side of the pipe on one or both sides. The distance is typically 3 m (10 ft) and 7.5 m (25 ft) perpendicular to the pipe.

The benefit of recording this information is that it can be difficult to analyze and draw conclusions from the data measured directly above a pipeline which is not cathodically protected. Anodic locations can appear as both more negative and less negative anomalies, but when compared to the lateral pipe-to-soil potentials, a conclusion can be drawn as anodic locations will only be those areas where the lateral potentials are less negative than the over-the-pipe potentials. Examples of this data can be found in the analysis portion of this chapter.

Current Measurement

Measuring current in the cathodic protection circuit is a necessary procedure in evaluating system performance. Typical current measurements are:

- galvanic anode current
- impressed current system output currents
- current in the structure
- bond current

Both direct and indirect methods of current measurement are available. A direct measurement involves inserting an ammeter into the cathodic protection circuit as illustrated in Figure 6.26.

Using an Ammeter to Measure Current

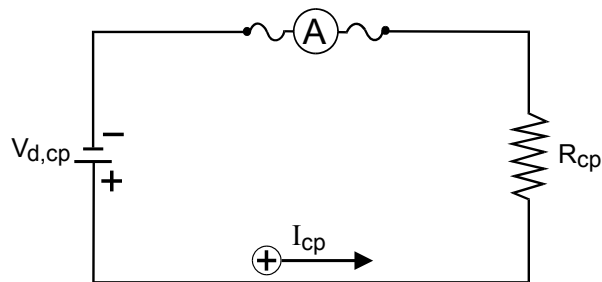


Figure 6.26 Measurement of CP Current Using an Ammeter

An electronic ammeter is typically composed of a voltage measuring device that measures the voltage drop across a low-resistance internal shunt. Ideally, an ammeter should have a low input resistance compared to the circuit resistance (i.e., $R_m \ll R_{cp}$) to prevent measurement error.

For example, in Figure 6.26 from Ohm's law:

$$I_{cp} = \frac{V_{d,cp}}{R_{cp}} \quad \text{Eq. 6-6}$$

but with the ammeter inserted in the series circuit, the current measured on the ammeter (I_m) is given by:

$$I_m = \frac{V_{d,cp}}{R_{cp} + R_m} \quad \text{Eq. 6-7}$$

Hence, the measured current (I_m) will be less than I_{cp} , depending on the resistance of the ammeter.

In many digital multimeters when the mA scale is selected, the ammeter circuit has an input resistance of several ohms. This can lead to significant errors if the ammeter is used to measure the current from a galvanic anode.

Even if a 10 A or 20 A scale is chosen, the input resistance, which may be as low as 0.1 Ω , may still be too high to produce an accurate current measurement in some circumstances. For instance, if the ammeter is placed in series with a

negative drain cable in a parallel set of drain cables, as shown in Figure 6.27, an appreciable error can occur.

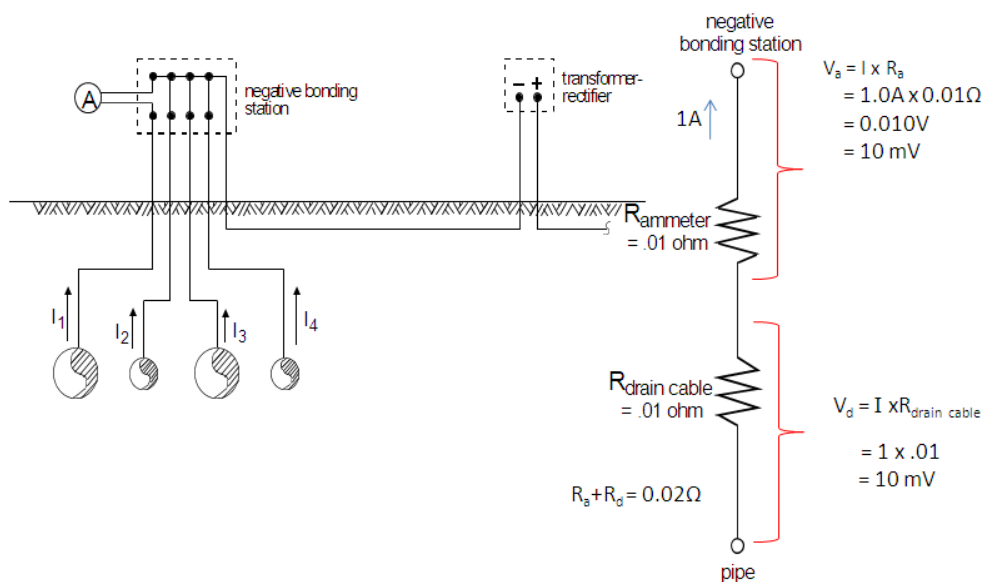


Figure 6.27 Current Measurement in Parallel Drain Conductors

If the shunt resistance inside the ammeter is 0.01Ω and the resistance of the negative return cable is 0.01Ω , insertion of the ammeter has doubled the negative return resistance and possibly reduced the return current (I_1) by half.

In both the above examples a more accurate method is to install an appropriately rated shunt permanently in each circuit and simply measure the voltage drop across the shunt and calculate the current. (see the Shunt Table in the *CP Technician Practical Exam Reference Sheet* provided at the back of the course manual).

Using a Shunt to Determine Current Magnitude

In the parallel negative drain cable example, a shunt of the same rating, hence the same resistance, should be installed in series with each negative drain cable as illustrated in Figure 6.28.

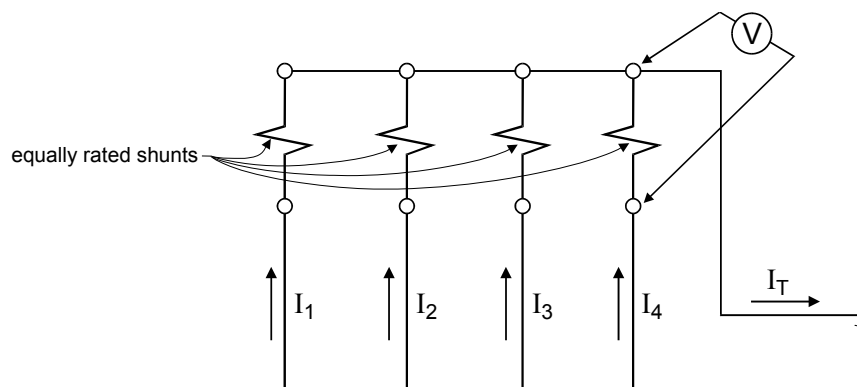


Figure 6.28 Use of Shunts for Current Measurements in Parallel Conductors

When selecting a shunt, its current rating must exceed the anticipated circuit current, and the millivolt drop at the anticipated operating current should be easily measurable on a standard digital multimeter.

For instance, if a shunt rated at 5 A, 50 mV is placed in series with a galvanic anode having an output of 5 mA, the voltage drop across the shunt will be:

$$V_{\text{shunt}} = I_{\text{cp}} \times R_{\text{shunt}} \quad \text{Eq. 6-8}$$

$$= 5 \text{ mA} \times \frac{V_{\text{rating}}}{I_{\text{rating}}}$$

$$= 5 \text{ mA} \times \frac{.050 \text{ V}}{5 \text{ A}}$$

$$V_{\text{shunt}} = 0.05 \text{ mV}$$

This small shunt voltage drop is below the resolution of most digital voltmeters used in the field. For a 5 mA current, a shunt resistance of at least 1 Ω is more appropriate. (See the Shunt Table in the *CP Technician Practical Exam Reference Sheet* provided at the back of the course manual.)

Zero Resistance Ammeter

Sometimes the currents are so small (e.g., < 0.1 mA) they cannot be measured accurately without using very-high-resistance shunts, which can alter the current magnitude because of their resistance. An example is the measurement of coupon current as illustrated in Figure 6.29.



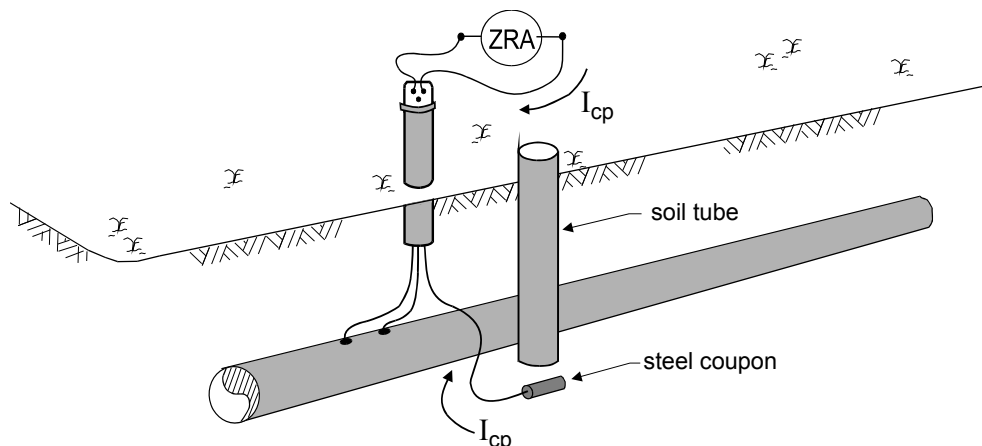


Figure 6.29 Current Measurement Using a Zero Resistance Ammeter (ZRA)

If the coupon has a surface area of 10 cm^2 and a current density of $10 \text{ } \mu\text{A}/\text{cm}^2$ the coupon current (I_{cp}) would be:

$$I_{cpn} = 10 \text{ } \mu\text{A}/\text{cm}^2 \times 10 \text{ cm}^2$$

$$I_{cpn} = 100 \text{ } \mu\text{A} \text{ or } 0.1 \text{ mA}$$

Measurement of such a small current with an ammeter would introduce several ohms of resistance into the circuit as would a shunt since a resistance of $100 \text{ } \Omega$ is required to measure in the 10 mV range. Under these circumstances, a zero resistance ammeter should be used.

Clamp-On Ammeter

A relatively noninvasive method of measuring current in a conductor is by using a clamp-on ammeter as illustrated in Figure 6.30.

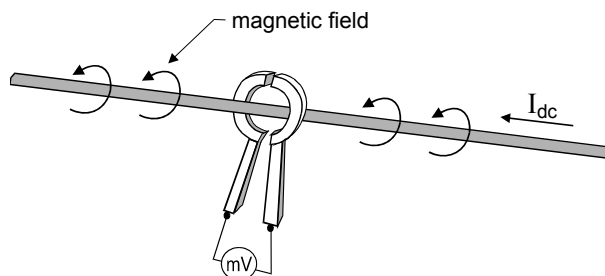


Figure 6.30 Using a Clamp-On Ammeter to Measure Current

The clamp-on ammeter contains a “Hall effect” device that produces a voltage output proportional to the strength of the magnetic field, which is proportional to the magnitude of the current in the conductor.

The Hall effect is illustrated in Figure 6.31 for a fixed meter current (I_m). As electrical charges move perpendicular to the magnetic field (B), a lateral force is exerted on the charges causing a potential difference to appear across the sides of the copper plate.

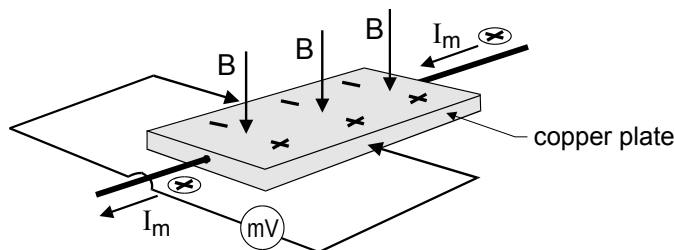


Figure 6.31 Schematic of the Hall Effect for Conventional Current Direction

The magnitude of this voltage is proportional to the magnetic field (B), which in turn is dependent on the magnitude of the current (I_{dc}) in the conductor.

Accuracy of the clamp-on ammeter diminishes at currents of a few mA. When there are multiple current-carrying conductors in a congested area, the accuracy is reduced if there is magnetic interference from adjacent conductors.

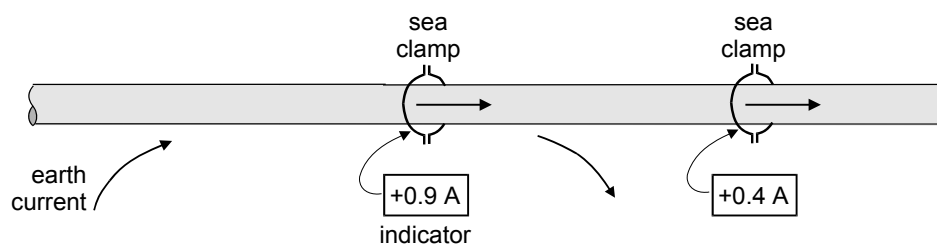
Pipeline Current Measurements

Uses

Pipeline current measurements are used to detect stray current and electrical shorts, and establish current distribution from temporary or permanent cathodic protection systems. Current can be measured by a clamp-on ammeter or by using a section of pipeline of known resistance as a shunt.

Use of a Clamp-On Ammeter

An illustration of the use of clamp-on ammeters is given in Figure 6.32.



Earth current leaving subject pipeline is $0.9 - 0.4 = 0.5$ A.

Figure 6.32 Pipe Current Measurement Using Sensing Loop and Swain Meter

Source: Swain, W.H., *Clamp-On Ammeters Can Watch Cathodic Protection Current Flow*,
Pipe Line & Gas Industry, March 1998, p.38

2-Wire Line Current Test

Current flow on a pipeline is measured by means of an IR drop or calibrated test station such as shown in Figure 6.33 or by using test stations and aboveground appurtenances as a temporary IR-drop test station. In an IR-drop test, the pipe simulates a low-resistance shunt. When properly calibrated, a voltmeter can be used to measure a voltage drop between the two wires or connection points to the pipe. Using Ohm's Law, the current flowing in the pipeline steel can be calculated.

A 2-wire test point span can be used where a known length of pipeline and the diameter and wall thickness or the weight per foot are known. The current flow in the pipe span can be calculated 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 6.33 shows the test setup to measure the mV drop in the section of pipeline.

Table 6.1 provides some resistance values for common pipe sizes. The section of pipe must be continuous with the same diameter and wall thickness without attachments through the pipe span to be used.

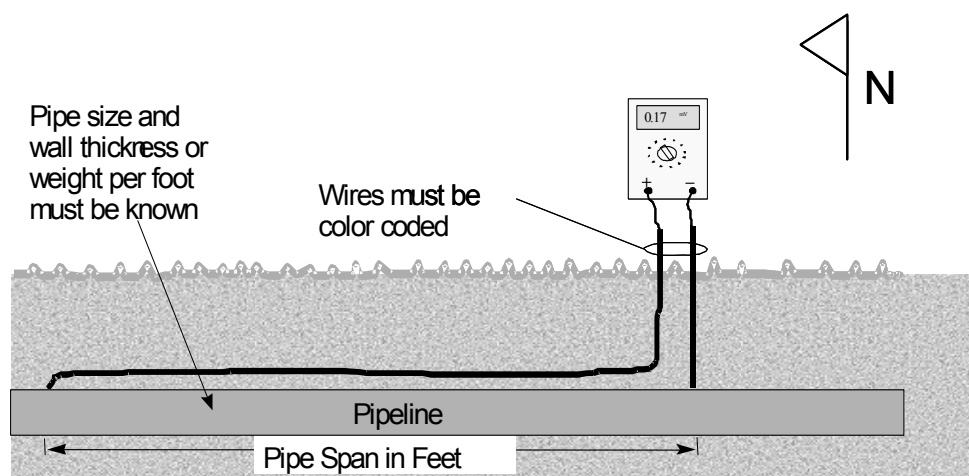


Figure 6.33 2-Wire Line Current Test

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.

For example, if the voltage drop across a 200-ft (61-m) span of 30-in. (762 mm) pipe weighing 118.7 lbs/ft (176.65 kg/m) is 0.17 mV, then current flow is calculated as follows:

$$\begin{aligned}
 \text{Pipe resistance/ft from Table 6.1} &= 2.44 \mu\Omega/\text{ft} \quad (8.01 \mu\Omega/\text{m}) \\
 &= 0.00000244 \Omega/\text{ft} \\
 &\quad (0.00000801 \Omega/\text{m}) \\
 \text{Total resistance} &= 200 \text{ ft} \times 0.00000244 \Omega/\text{ft} \\
 &= 0.000488 \Omega \\
 &\quad \text{OR} = 61 \text{ m} \times 0.00000801 \Omega/\text{m} \\
 &\quad = 0.000488 \Omega \\
 \text{Measured voltage drop} &= 0.17 \text{ mV} \\
 \text{Current (I)} &= \frac{E}{R} \\
 &= \frac{0.00017 \text{ V}}{0.000488 \Omega} \\
 &= 0.348 \text{ A}
 \end{aligned}$$

Table 6.1 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	$\mu\Omega/\text{ft}$	$\mu\Omega/\text{m}$
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	9.25
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 $\mu\Omega\text{-cm}$.

(B) $R = \frac{16.061 \times \text{resistivity in } \mu\Omega\text{-cm}}{\text{Resistance of 1 ft of Weight per foot pipe, } \mu\Omega}$

Refer again to Figure 6.33. 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.

4-Wire Line Current Test

Pipeline current can also be measured using the four-wire span illustrated in Figure 6.34. For accurate measurement, the span is calibrated by injecting a



known DC test current through the pipe using the outside test leads ① and ④ and measuring the resulting voltage drop across test leads ② and ③.

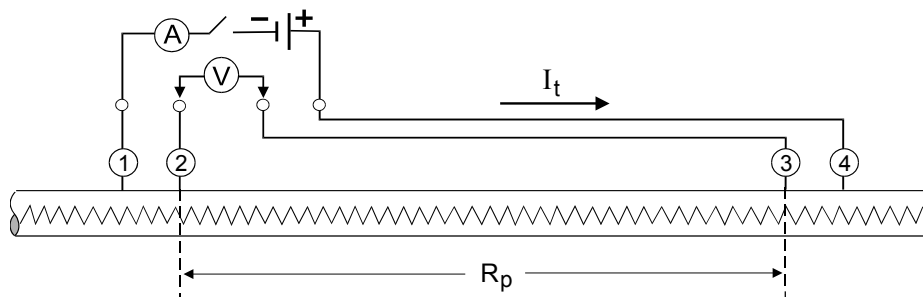


Figure 6.34 Calibrating a Pipeline Current Span

The resistance of the pipe between test leads ② and ③ is calculated from Ohm's law:

$$R_p = \frac{\Delta V_{2-3}}{\Delta I_t} \quad \text{Eq. 6-9}$$

The result can be anticipated prior to the test by referring to Table 6.1.

Attention to polarity is important in this measurement since there will probably be a residual current during the test, and the test current may cause a reversal in the voltage drop polarity.

For example,

$$\begin{aligned} V_{2-3} &= +21 \text{ mV (before test current applied)} \\ V_{2-3} &= -19 \text{ mV (after test current applied)} \\ I_t &= 10 \text{ A} \end{aligned}$$

The resistance (R_p) of the pipe section being tested is:

$$\begin{aligned} R_p &= \frac{+21 \text{ mV} - (-19 \text{ mV})}{10 \text{ A}} \\ R_p &= \frac{+40 \text{ mV}}{10 \text{ A}} = 4 \text{ m}\Omega \end{aligned}$$

The calibration factor is calculated as follows:

$$K = I_{\text{test}} / \Delta E_{\text{test}} \quad \text{Eq. 6-10}$$

where:

K = calibration factor of pipe section (A/mV)

I_{test} = test current applied to section (A)

ΔE_{test} = E with current applied – E with no current applied (mV)

Therefore the current calibration factor is: $\frac{10 \text{ A}}{40 \text{ mV}} = 0.25 \text{ A/mV}$

and the residual current magnitude is:

$$I_{\text{residual}} = 21 \text{ mV} \times \frac{0.25 \text{ A}}{\text{mV}} = 5.25 \text{ A}$$

with a direction from 2 to 3.

Normally, if the pipeline operating temperature is stable, this need only be done once as the calibration factor will remain the same 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.

Once the calibration factor is known, the normal current magnitude can be calculated. First, measure the voltage drop in mV across the measuring span (without the battery current) using the inside test wires. This voltage drop is due to normal pipeline current.

Calculate current flow by multiplying the calibration factor by the voltage drop measured above:

$$I = K \times E_{\text{mV}} \quad \text{Eq. 6-11}$$

where:

I = pipeline current (A)

K = calibration factor of pipe

E_{mV} = voltage drop of pipe section (mV)

The polarity of the voltage drop will 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.

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.

Earth Current Measurements (see also Chapter 7)

A series of potentials measured between two reference electrodes can indicate current flow and its direction in the earth, as shown in Figure 6.35. 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 towards the negative electrode if the value displayed on the voltmeter is positive.

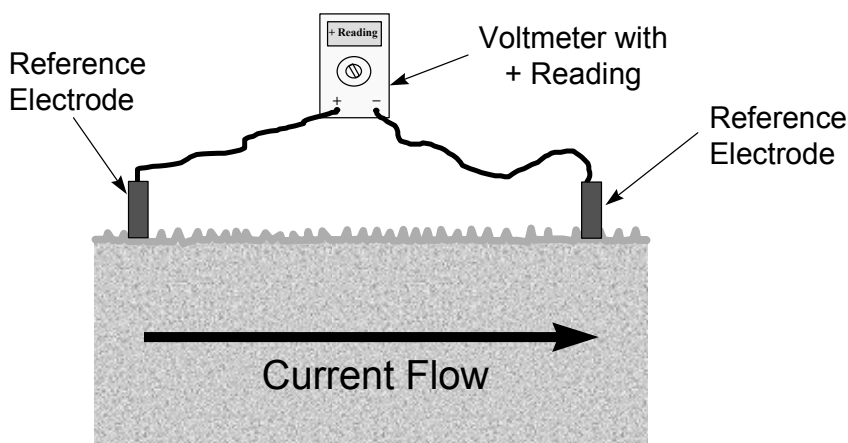


Figure 6.35 Potential Measurement Between Two Reference Electrodes

Non-Cathodically Protected Structures

On lines that are not cathodically protected, corroding areas, or “hot spots,” can be found where the potentials are more negative than the nearby potentials. This is opposite of a cathodically protected structure and is often confusing. In addition, it is beneficial to complete a pipe-to-soil potential survey laterally or to the side of the pipeline. Often, this distance is 15 to 25 ft to one or both sides of the pipe. These surveys are completed on bare unprotected pipelines and pre-stressed concrete cylinder pipe (PCCP).

Figure 6.36 illustrates an example of stray current interference as detected by an over-the-line and lateral pipe-to-soil potential survey. In this example, one area of current discharge was found. Stray current interference is identified when the over-the-line potential becomes positive in relation to nearby potentials and the lateral potential is more positive than the over-the-line potentials. This area should be analyzed to determine if corrective action in the form of cathodic protection or

mitigation bonds should be used. Stray current control is discussed in Chapter 7 “Stray Current and CP Interference.”

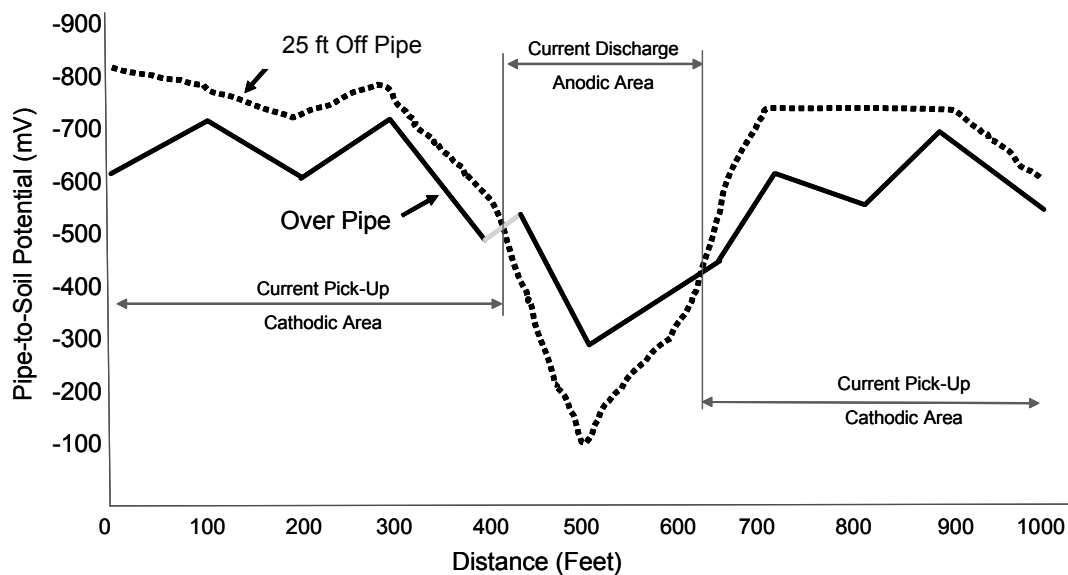


Figure 6.36 *Potential Profile of Pipe Subject to Exposure from Cathodic Protection Interference*

Figure 6.37 illustrates the type of data that would be seen where galvanic corrosion activity is affecting a non-cathodically protected pipe.

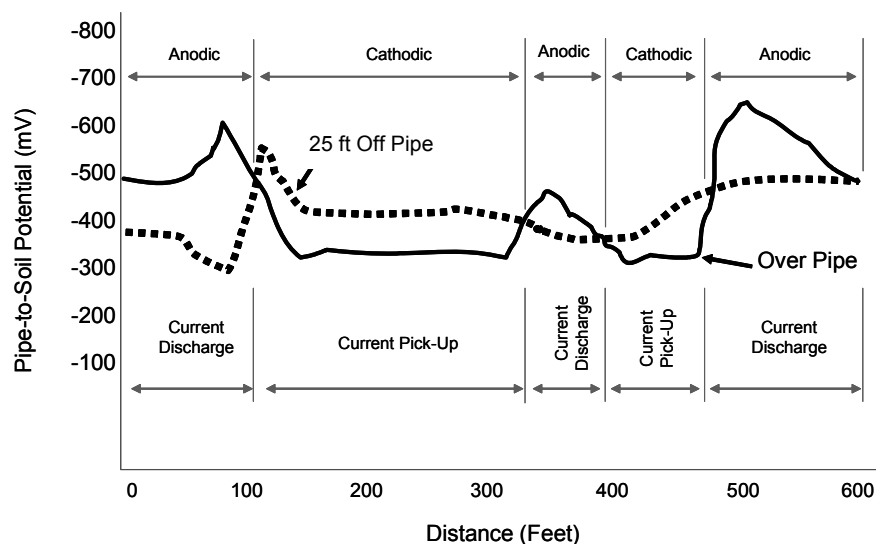


Figure 6.37 *Potential Profile of Pipe Subject to Galvanic Corrosion Activity*

The anodic areas are those locations where the over-the-line potentials become more negative with respect to nearby potentials and when the potentials away from the pipe (lateral) are less negative than the over-the-line potentials. The cathodic areas of the pipe are where the lateral potentials are more negative than the over-the-line potentials. The exact location of each anodic area can be defined by repeating the survey over that area while progressively decreasing the spacing of the electrodes and taking measurements to both sides.

Figure 6.38 illustrates a close interval survey completed above and laterally to the pipe where a bimetallic couple exists. The over-the-line potential becomes less negative with respect to nearby potentials and the lateral potentials are less negative than the over-the-line potentials.

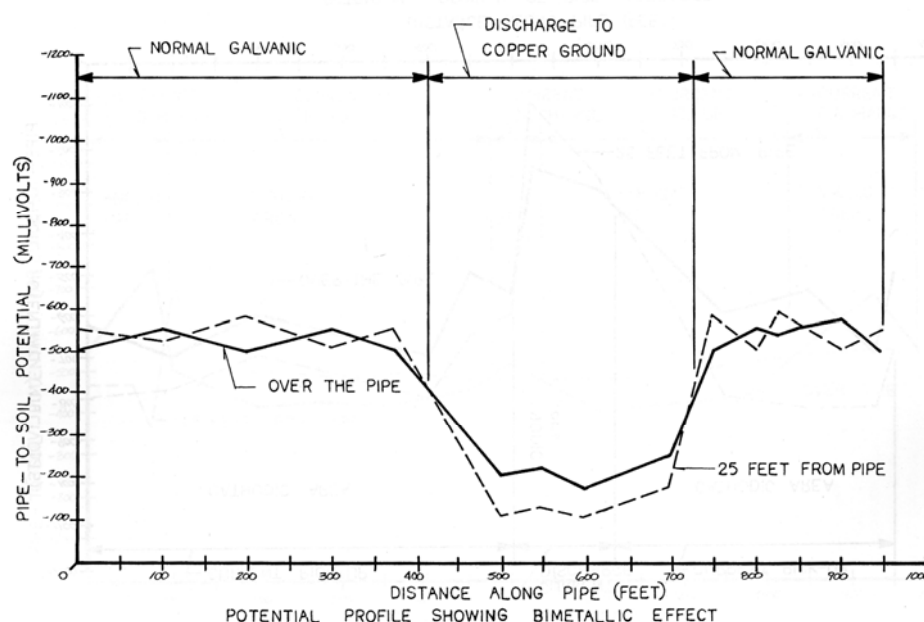


Figure 6.38 Potential Profile Showing Bimetallic Effect

Surface Coating Evaluation Techniques on Buried Pipelines

This section will discuss the various techniques used to evaluate the condition of pipeline coatings once buried. These techniques are:

- Pearson Survey
- DCVG Survey
- Pipeline Current Mapper
- Coating Resistance

Pearson Survey

A Pearson Survey is a method used to detect holidays in a pipe coating after the pipe is buried. In this method, an AC audio signal is impressed onto the pipe using a transmitter. The transmitter is connected to the pipeline (making it a conductive locator) and to a temporary ground. The better the ground, the stronger the signal. Two individuals, each having grounding spikes attached to their shoes, walk directly over the line. The individuals are electrically connected together and one carries a radio receiver. As the location of the coating holiday is reached, the radio signal becomes stronger on the receiver. As the two individuals continue walking, the signal will then “null” and when the back or second person approaches the holiday, the signal will again peak. The point of the “null” is the location of the coating holiday. Figure 6.39 shows this method schematically.

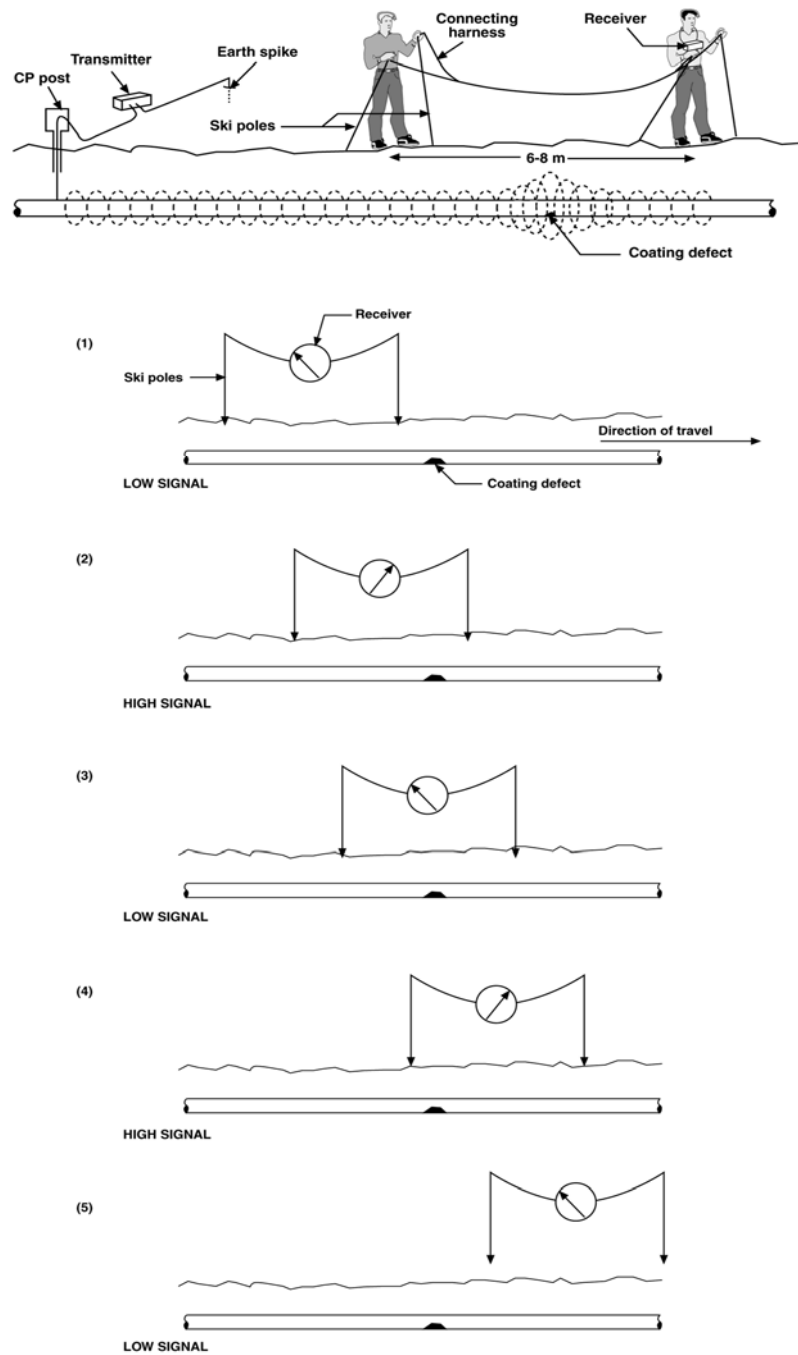


Figure 6.39 Illustration of Pearson Method of Holiday Detection

Direct Current Voltage Gradient (DCVG) Survey

DCVG is a method for detecting cathodic protection current pickup at coating holidays. The DCVG system consists of an analog strap-on voltmeter, connection cables, and two probes with electrodes filled with water. This technique is accomplished by installing a current interrupter in an existing rectifier unit or by using a temporary CP system. The interrupter is installed in series in either leg of the DC output of the rectifier or by installing it in the AC circuit. The interrupter is set to cycle at a very fast rate with the ON period less than the OFF period, such as a 1/3 second ON and 2/3 second OFF. This short cycle allows for a quick deflection measurement by the analog voltmeter (Figure 6.40).



Figure 6.40 DCVG Survey

The analog voltmeter (Figure 6.41) is a very sensitive meter with the ability to adjust the input impedance and the scale with which the meter is displaying the data. Deflections of less than 1 mV are easily noticeable on this voltmeter. In addition, the needle has the ability to deflect in both the positive and negative directions from the zero point which assists in determining the direction the current is flowing in the soil.



Figure 6.41 Analog Voltmeter

The survey method consists of measuring the “ON” and “OFF” potentials at all encountered test points, valves, and risers to determine the signal strength (i.e., difference between ON and OFF readings). The numerical potential difference is the signal strength. An example can be seen below.

ON potential	=	-1.45 V
OFF potential	=	-0.95 V
Signal Strength	=	1.45 – 0.95 V
	=	0.5 V or 500 mV

While walking along the pipeline route the probes are used as walking sticks making sure one electrode tip is in contact with the ground at all times. One probe is always kept near the pipeline centerline while the other is held laterally at 1 to 2 m. Where there is no coating defect, the analog voltmeter needle does not register movement. When a coating defect is approached a noticeable swing can be observed on the voltmeter at the same rate as the interrupter switching cycle. The amplitude of the needle swing will increase as the defect is approached and decreases when passed. The estimated signal strength can be illustrated by using the data represented in Figure 6.42 where:

Signal strength at TS A	=	200 mV
Signal strength at TS B	=	300 mV
Defect from TS A	=	1,500 yds (1,372 m)
Defect from TS B	=	500 yds (457 m)

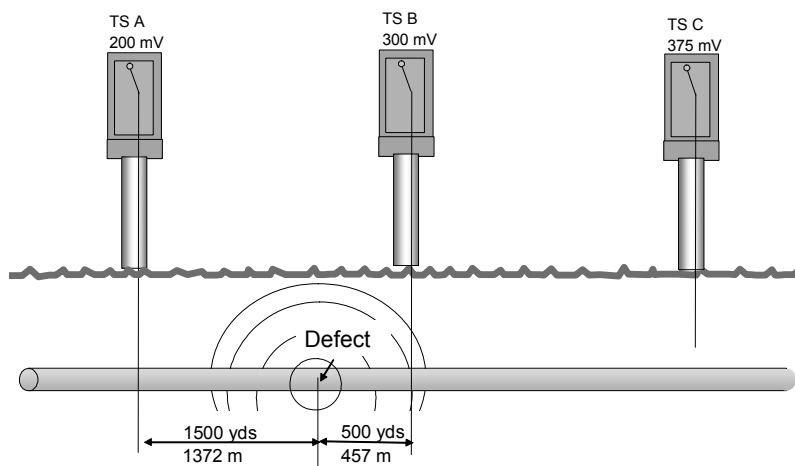


Figure 6.42 Signal Strengths

Estimated signal strength at defect:

$$S_D = S_A + \left[\left(\frac{d_A}{d_A + d_B} \right) (S_B - S_A) \right] \quad \text{Eq. 6-12}$$

where:

S_D = signal strength at defect (mV)

S_A = signal strength at Point A (mV)

S_B = signal strength at Point B (mV)

d_A = distance from A

d_B = distance from B

$$\begin{aligned} S_D &= 200 \text{ mV} + \frac{1500 \text{ yds}(1372 \text{ m})}{1500 \text{ yds}(1372 \text{ m}) + 500 \text{ yds}(457 \text{ m})} (300 \text{ mV} - 200 \text{ mV}) \\ &= 275 \text{ mV} \end{aligned}$$

A straight-line attenuation effect is assumed between test locations to calculate the signal strength at intermediate defect locations.

Centering the defects is achieved by marking the approximate location of the defect at the area where the maximum amplitude is indicated. At two separate locations (A and B in Figure 6.43), offset from the line by approximately 4 m, the probes are placed along the voltage gradient to obtain a null (zero) on the meter. A right-angle line through the center of the probe locations will pass over the coating defect epicenter. This geometrical procedure repeated on opposite sides of the pipeline will locate the exact point above the defect. This procedure is illustrated in Figure 6.43.

Having detected the epicenter of the coating defect, a series of lateral readings are measured moving towards remote earth. Lateral readings near the defect will yield maximum voltage differences where gradients are at a maximum. Readings at remote earth will indicate zero to 1 mV deflections. The summation of these readings is commonly referred to as the over-the-line to remote earth voltage. The expression “percentage IR” has been adopted to give an indication of defect size. For instance, if a series of lateral millivolt readings to remote earth are as follows, 25, 15, 6, 4, 3, 1, 1, 0, then the percentage IR can be calculated as follows:

$$\begin{aligned}
 \text{Pipe-to-Remote Earth} &= \Sigma \text{Earth Gradients} \\
 &= 25+15+6+4+3+1+1 \text{ mV} \\
 &= 55 \text{ mV}
 \end{aligned}$$

$$\text{Percentage IR} = \frac{\text{Pipe-to-remote earth} * 100\%}{\text{Signal strength at defect}} \quad \text{Eq. 6-13}$$

$$= \frac{55 \text{ mV}}{275 \text{ mV}} * 100 = 20\%$$

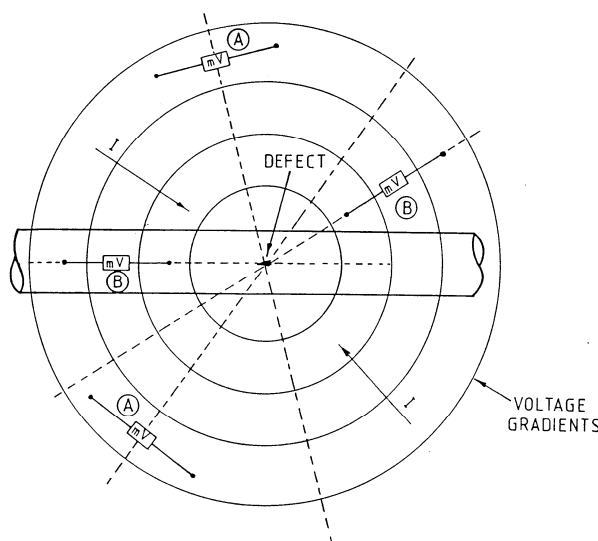


Figure 6.43 Voltage Gradients

Theoretically, this percentage IR is used to predict the reduction in protection levels ignoring polarization effect. Therefore, knowing the ON potential of the pipeline system one can multiply the percentage IR by the known potential to get the theoretical structure-to-electrolyte potential reading of the defect area.

Pipeline Current Mapping

Pipeline current mapping is a method of evaluating and mapping cathodic protection current pickup. It was developed to non-intrusively and accurately measure a near DC current temporarily impressed on the structure and therefore distributed along the pipeline. The PCM system consists of a two-part system; a portable transmitter that applies a special near-DC signal to the pipeline and a hand-held receiver that locates and displays the current magnitude and direction of the near DC signal. If the mainline or repair coatings are damaged causing holidays, or if there is an electrical contact between the pipeline and another metallic structure, this will result in a sufficient pickup of the induced near-DC signal. This is illustrated in Figure 6.44.

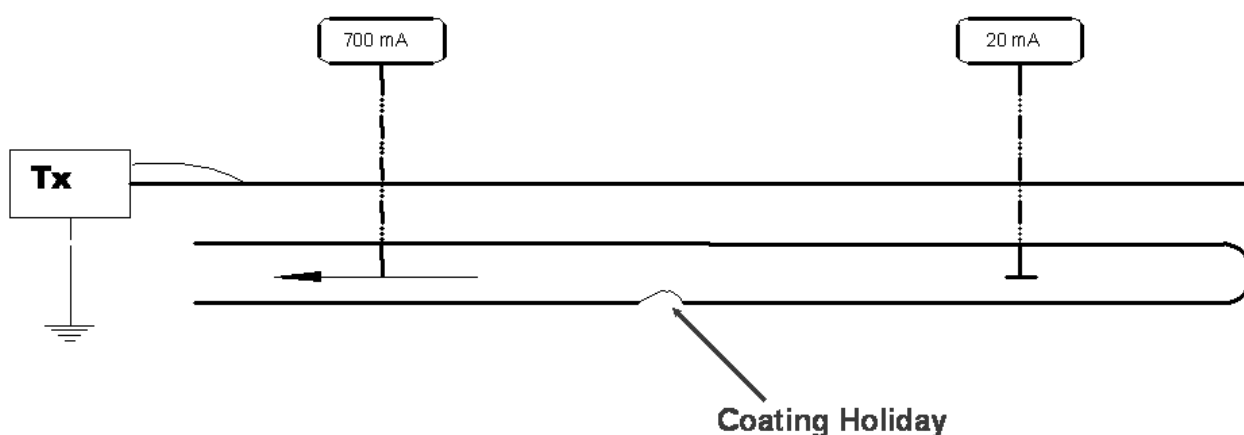


Figure 6.44 Current Pickup

Coating Resistance Calculations

Coating resistance measurements are a means of establishing a coating's ability to provide a dielectric barrier between the structure and the environment. The better barrier a coating provides the higher the coating resistance. The coating resistance is simply the resistance of the structure to the environment multiplied by the surface area of the structure. Units are therefore $\Omega\text{-ft}^2$. Coating resistance measurements years apart can reveal the long-term performance of a coating and if anything has occurred that detrimentally affected the overall structure coating (e.g., electrical shorts, construction damage, and abnormal soil stress).

Test data are obtained from the pipeline section under investigation which can be of any length, though typically three to five miles in length. Pipe-to-electrolyte potential readings (with current ON and OFF) and line current measurements are obtained using an interrupter to cycle the nearest rectifier or a

temporary power source. The resistance of the pipe section is calculated and the coating resistance calculated with the known pipe surface area. For example (see Figure 6.45):

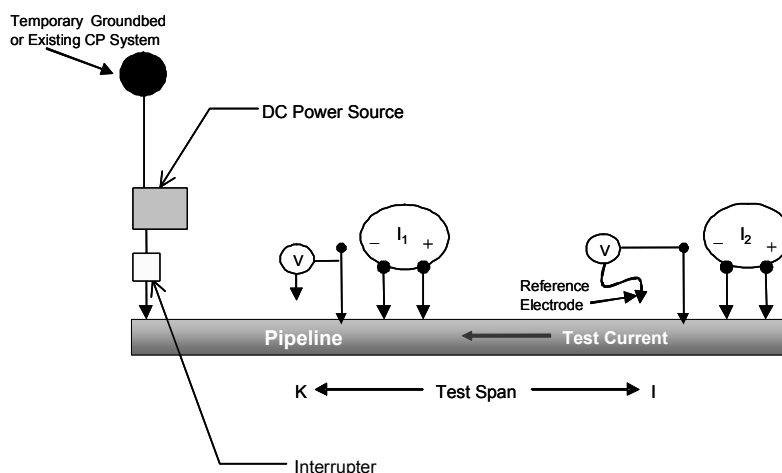


Figure 6.45 Set-Up for Coating Resistance Measurement

Assume the following field data:

Size of Pipe: 24-in. dia. (610 mm, 61 cm or 0.61 m)

Length of Test span: 1 mile = 5,280 ft (1609 m or 1.609 km)

$E_{ON_{TS1}} = -2.00 \text{ V}$
 $E_{OFF_{TS1}} = -0.90 \text{ V}$
 $\Delta E_{TS1} = 2 \text{ V} - 0.9 \text{ V} = 1.10 \text{ V}$

$I_{ON_{TS1}} = 3.00 \text{ A}$
 $I_{OFF_{TS1}} = 0.20 \text{ A}$
 $\Delta I_{TS1} = 3.0 \text{ A} - 0.20 \text{ A} = 2.80 \text{ A}$

$E_{ON_{TS2}} = -1.70 \text{ V}$
 $E_{OFF_{TS2}} = -0.85 \text{ V}$
 $\Delta E_{TS2} = 1.7 \text{ V} - 0.85 \text{ V} = 0.85 \text{ V}$

$I_{ON_{TS2}} = 2.80 \text{ A}$
 $I_{OFF_{TS2}} = 0.10 \text{ A}$
 $\Delta I_{TS2} = 2.80 \text{ A} - 0.10 \text{ A} = 2.70 \text{ A}$

$$\text{Total Pipe Surface Area} = d \times \pi \times L \quad \text{Eq. 6-14}$$

$$= \frac{24 \text{ in}}{12 \text{ in/ft}} \times \pi \times 5,280 \text{ ft} = 33,158 \text{ ft}^2$$

$$\text{Or in metric} = 0.61 \text{ m} \times \pi \times 1,609 \text{ m} = 3080 \text{ m}^2$$

$$\Delta E_{ave} = \frac{\Delta E_{TS1} + \Delta E_{TS2}}{2} \quad \text{Eq. 6-15}$$

$$\Delta E_{ave} = \frac{1.10 \text{ V} + .85 \text{ V}}{2} = 0.975 \text{ Volt}$$

Now that the average potential change caused by the current is known, the current that affects only that section of pipe must be calculated. To accomplish this, the current “entering” the test section is subtracted from the current exiting the test section. It is this value of current that the pipe is picking up in this test section.

$$\begin{aligned} I_C &= \text{current on pipe section of interest} \\ &= \Delta I_{TS1} - \Delta I_{TS2} \\ &= 2.80 \text{ A} - 2.70 \text{ A} = 0.10 \text{ A} \end{aligned} \quad \text{Eq. 6-16}$$

Pipe-to-earth resistance or the pipe coating resistance

$$\begin{aligned} &= R_C = \frac{\Delta E_{ave}}{I_C} \\ &= \frac{0.975 \text{ V}}{0.1 \text{ A}} = 9.75 \Omega \end{aligned} \quad \text{Eq. 6-17}$$

$$\text{Specific coating resistance} = r_{CE} = A_{\text{pipe}} \times R_C \quad \text{Eq. 6-18}$$

$$\begin{aligned} &= 33,158 \text{ ft}^2 \times 9.75 \Omega \\ &= 323,291 \Omega\text{-ft}^2 \end{aligned}$$

Or in metric

$$\begin{aligned} r &= 3080 \text{ m}^2 \times 9.75 \Omega \\ r &= 30030 \Omega\text{-m}^2 \end{aligned}$$

An assumption is made that the change in structure potential as a result of the current is linear and that the average change in structure potential over the test span is the average of the beginning and ending test point potential changes. A more representative value might be obtained by averaging multiple structure potential changes measured at various locations along the test span.

When discussing coating resistance, often the terminology “coating conductance” is used. Conductance (G) is the reciprocal of resistance (R) and the units used are typically Siemens (S) or microSiemens (μS).

$$G = 1 \div R$$

Conductance is normally defined in terms of a unit of surface area that is called specific conductance (g) which is the reciprocal of specific resistance (r). Using Equation 6-19:

$$\text{Metric: } g_C = \frac{1}{r_C} = \frac{1}{30030 \Omega - m^2} = 0.0000333 \frac{S}{m^2} = 33.3 \frac{\mu S}{m^2}$$

$$\text{Imperial: } g_C = \frac{1}{r_C} = \frac{1}{323,291 \Omega - ft^2} = 0.00000309 \frac{S}{ft^2} = 3.09 \frac{\mu S}{ft^2} \quad \text{Eq. 6-19}$$

where: g_C = specific coating conductance (S/m²) or (S/ft²)
 r_C = specific coating resistance (Ω-m²) or (Ω-ft²)

The overall conductance would be

$$G_C = 1/R_C = 1 / 9.75 \Omega = 0.102 \text{ S}$$

For further information refer to NACE Standard TM0102, “Measurement of Protective Coating Electrical Conductance on Underground Pipelines.”

Current Requirement Tests

When a structure is in place in its final configuration, it is possible to perform current requirement tests. Such tests have the advantage of producing data on the actual structure and its environment and do not involve assumptions as to effectiveness of the protective coating and other factors. Structures which have been designed for the application of cathodic protection can be tested in their entirety or broken down into sections.

Current requirement testing involves installation of either a permanent or test anode system. The purpose is to introduce current into the earth at the site where the permanent cathodic protection system (groundbed) will be located. For large structures, a representative area can be chosen for the initial test phase. A suitable power supply (batteries, test rectifier, or motor generator system) is then connected between the structure and test groundbed as illustrated in Figure 6.46. Test current is applied between the groundbed and the structure and the effects on the structure are measured.

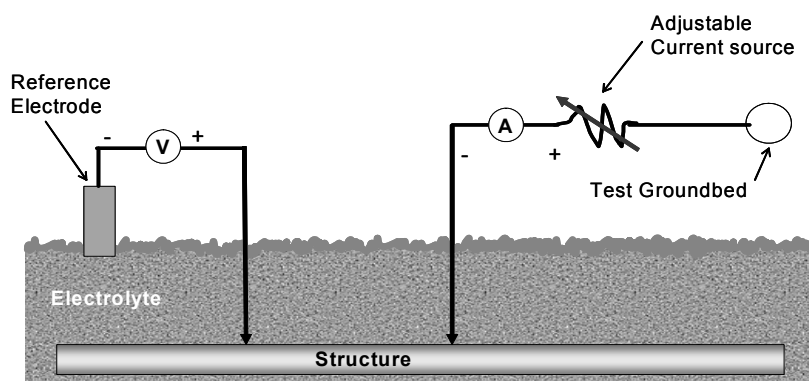


Figure 6.46 Test Circuit for Current Requirement Test

With this circuit, controlled amounts of current can be applied to the structure from the anode.

The potential measured includes the following:

- The electrochemical potential between the structure and the reference electrode
- An “IR drop” produced between the point in the electrolyte where the reference electrode is located and the structure

Calculation:

$$I_{req} = \frac{\Delta E_{preq} * I_{test}}{\Delta E_{ptest}} \quad \text{Eq. 6-20}$$

where:

I_{req} = Estimated current requirement (A)

ΔE_{preq} = Polarization required (V)

= [-0.850 V – E_{native}] for -0.850 V_{CSE} (-850 mV_{CSE}) polarized potential criterion OR

= [-0.100 V] for 100 mV polarization criterion

ΔE_{ptest} = Polarization from test (V) [E_{OFF} – E_{native}]

The formulas used for these calculations consider:



The value of resistance producing IR drop

$$R = (E_{ON} - E_{OFF})/I_{ON} \quad \text{Eq. 6-21}$$

The IR drop can be calculated for other intermediate levels of current using an average value for R:

$$\text{IR drop} = I_{\text{applied}} R$$

Following is an example of a current requirement calculation:

- | | | |
|----|---|---------------------------|
| 1. | Native (Static) pipe-to-soil potential | = -0.645 V _{CSE} |
| 2. | Desired polarized p/s potential | = -0.850 V _{CSE} |
| 3. | Test current | = 0.050A (50 mA) |
| 4. | Polarized potential due to test current | = 0.775 V _{CSE} |

From Equation 6-20:

$$I_{\text{req}} = \frac{[0.850 \text{ V} - 0.645 \text{ V}] 0.050 \text{ A}}{(0.775 - 0.645)}$$

$$= 0.0788 \text{ A or } 78.8 \text{ mA}$$

Electrical Isolation

Indication of Problems

Electrical isolation is important to the success of cathodic protection except where the system being protected cannot be electrically isolated and the CP system is designed to take this into account. In an isolated system, the failure of the CP system to maintain a satisfactory level of cathodic protection might be caused by an electrical short to another metallic structure including other pipelines, power grounds, station grounding, etc.

Locating the Problem

There are many methods to locate an electrical isolating device and/or tests to determine if the device is functioning properly:

- Pipeline/cable locators
- Isolation testing instrument
- Structure-to-electrolyte potential
- Interrupted structure-to-electrolyte potential
- DC line current measurements
- Fixed cell to moving ground
- Current response test
- Isolation resistance test.

Each technique has advantages and disadvantages including whether or not the particular test can be used under the circumstances and if the test is conclusive under those circumstances.

Use of a Pipeline/Cable Locator for Isolation Testing

A pipeline or cable locator can be used to locate the pipe as well as locate electrical short circuits or discontinuities on a structure. The AC signal is placed onto the structure using either a conductive or an inductive locator. The signal placed onto the structure will stay only on the structure unless there is an electrical contact with a foreign structure. If the AC signal is not detected on the foreign structure or portion of the structure meant to be electrically isolated, then the two are electrically isolated.

If the signal continues past the electrical isolating device, then the isolating device is not functioning and the two metallic structures are electrically continuous.

Most locators include a transmitter and receiver. The transmitter is a source of AC radio frequency 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 and/or visual signal. The sound of the signal, such as the frequency and rate of the pulse, can be controlled by the transmitter.

There are two types of pipe locators—conductive and inductive. Some locators contain both types in one unit. The conductive pipe locator is of most use in locating shorts.

Conductive Pipe Location

The conductive locator uses a audio frequency AC signal and is electrically connected to the structure under investigation 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 signal is connected between ground and the structure to be traced.

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 6.47 illustrates the principle of the conductive locator.

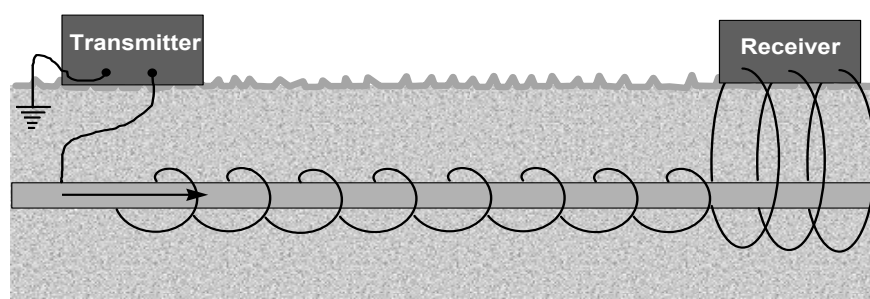


Figure 6.47 Conductive Pipe Locator Principle

Inductive Pipe Location

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 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 6.48 illustrates the principle of the inductive locator. Signals can be induced on both sides of an isolation giving a false indication of a short.

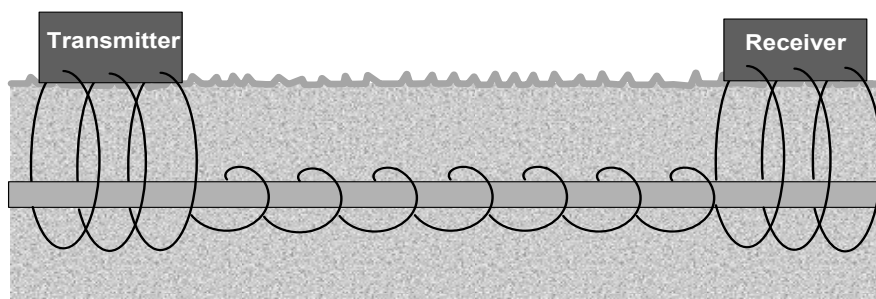


Figure 6.48 Inductive Pipe Locator Principle

Testing Above Grade Isolating Flange/Unions

An “isolation checker” is an instrument specifically built to check both below grade as well as abovegrade isolation devices (see Figure 6.49). For abovegrade 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.

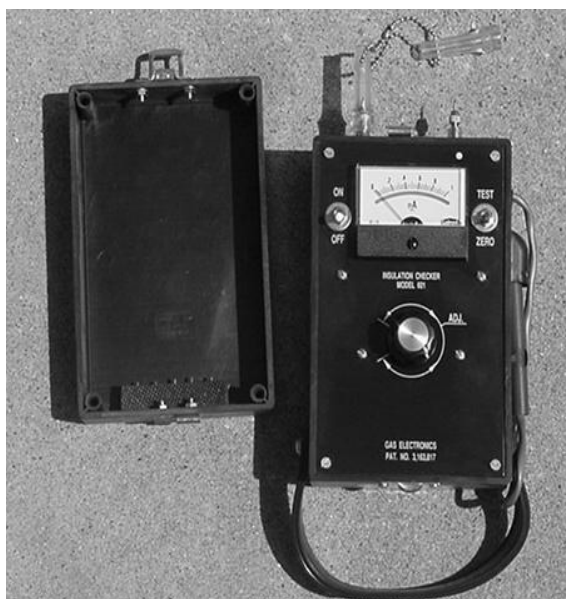


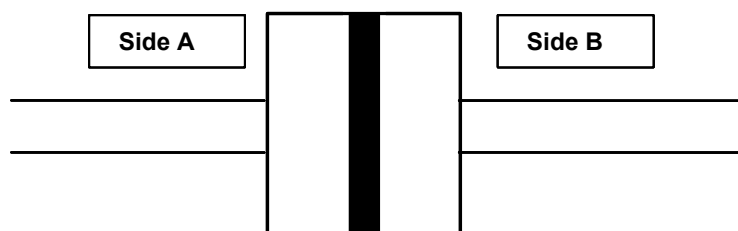
Figure 6.49 Isolation Checker

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. It can be used to test for a shorted isolating bolt or stud if it has double isolating washers.

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. 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	Shorted
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 not functioning properly, the ON and OFF potentials will be the same on each side of the isolating device and the potentials on both sides will be swinging with 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	$-0.950 V_{cse}$	$-0.948 V_{cse}$	$-0.875 V_{cse}$	$-0.750 V_{cse}$

DC Line Current to Test Isolation

Measuring DC pipeline currents can help locate an electrical short and help determine if an isolating device is functioning properly. These tests can be run many ways. First, two electrical connection points to the pipeline that are separated by at least several hundred feet must exist. These can be two test stations, an IR-drop (calibrated) test station, two valves, or two probe bars. Figure 6.50 illustrates the principle behind this test which is discussed in more detail later in this chapter. In addition, examples are given for calculating the pipe resistance and current magnitude.

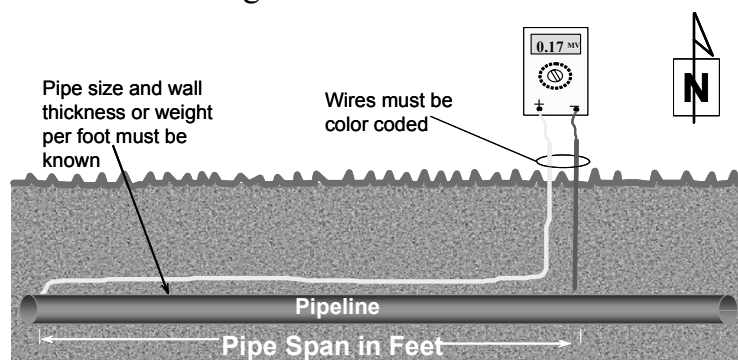


Figure 6.50 Two-Wire Line Current Test

By measuring the magnitude and direction of current flow in the pipeline steel, one can trace the direction the current is taking to return to its source (Figure 6.51). If current is flowing towards an electrical isolating device and there are no current sources or interference bonds located between where you are measuring the current and the isolating device, then the device is not functioning properly and is shorted.

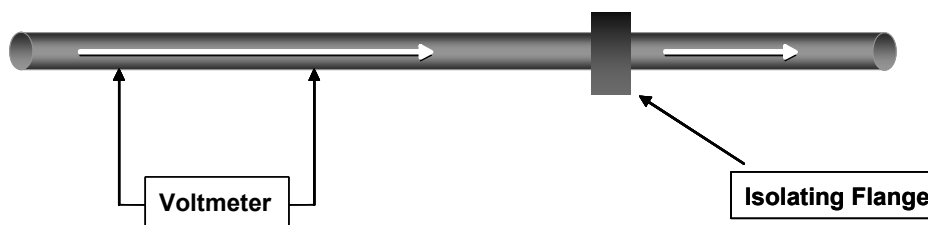


Figure 6.51 Shorted Isolating Buried Flange

Fixed Cell to Moving Ground for Continuity Test

In this test, a reference electrode is connected to one lead from a multimeter and placed at a fixed location while the second 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 point of electrical contact, continuity is indicated (Figure 6.52). 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 then other tests outlined in this chapter should be completed.

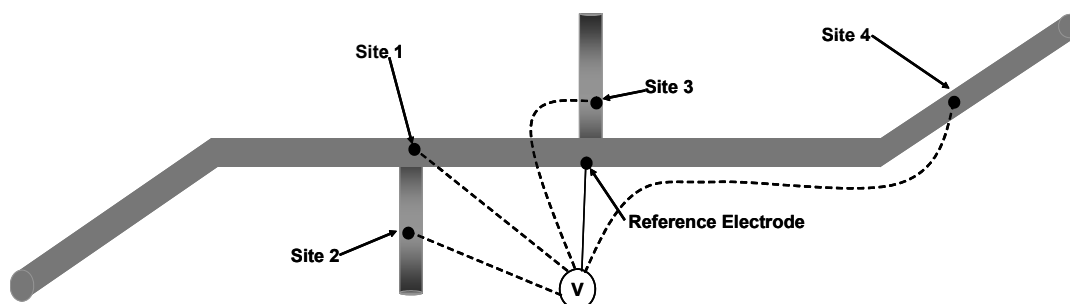


Figure 6.52 Fixed Cell to Moving Ground Technique

Example

Site No.	Electrically Continuous	Electrically Discontinuous
1	-1.560 V _{CSE}	-1.560 V _{CSE}
2	-1.560 V _{CSE}	-1.456 V _{CSE}
3	-1.560 V _{CSE}	-1.652 V _{CSE}
4	-1.560 V _{CSE}	-1.488 V _{CSE}

Current Response

Applying a temporary current to one side of an electrical isolation device can determine if the device is functioning properly. Using the setup illustrated in Figure 6.53 below, the side of the isolating device which has the temporary current applied to it will become more negative with the application of current while the pipe on the opposite side will remain the same. If the electrical isolating device is not functioning properly, the shift in potential will be the same on both sides of the isolating device.

In addition, cycling the temporary current using a current interrupter will confirm electrical isolation in the same manner as previously stated. If the two structures are isolated, the far side of the isolating device will not have “cycling” potentials.

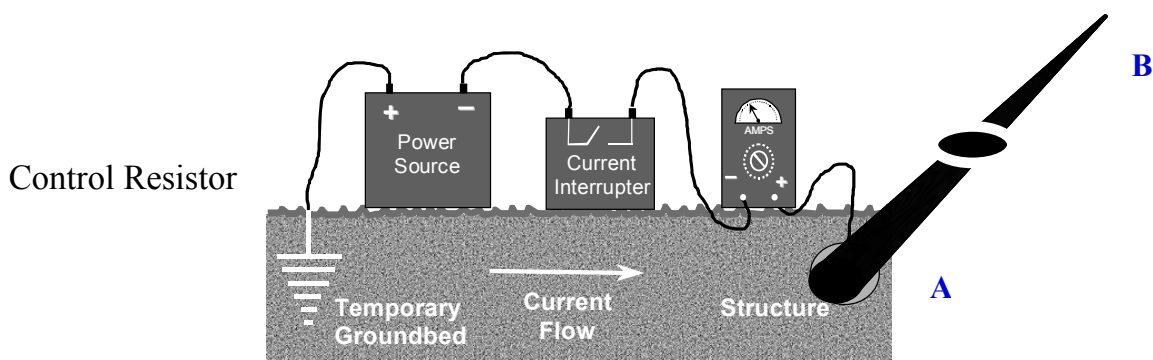


Figure 6.53 Current Response

Example

Flange Side	Electrically Isolated		Electrically Shorted	
	ON	OFF	ON	OFF
A*	$-1.650 \text{ V}_{\text{CSE}}$	$1.345 \text{ V}_{\text{CSE}}$	$-1.650 \text{ V}_{\text{CSE}}/-$	$1.345 \text{ V}_{\text{CSE}}$
B	$-1.300 \text{ V}_{\text{CSE}}/-$	$1.300 \text{ V}_{\text{CSE}}$	$-1.650 \text{ V}_{\text{CSE}}/-$	$1.345 \text{ V}_{\text{CSE}}$

* Flange side with temporary current applied cycling ON and OFF.

Casings

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 attenuation in the pipe-to-electrolyte potential in the area of the casing. The potential might attenuate, for example from $-950 \text{ mV}_{\text{CSE}}$ to $-750 \text{ mV}_{\text{CSE}}$. The electropositive attenuation is especially pronounced if the casing is bare. Discovery of such a change in the usual pipe-to-electrolyte potential should lead you to suspect a shorted casing. 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.

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.

Indication of Problems

A casing which is shorted to the carrier pipe is typically detected when one or all of these circumstances occur:

- Low structure-to-electrolyte potential profile in vicinity of a casing
- Sudden overall deterioration of cathodic protection levels
- Annual test station survey reveals the pipeline and casing have nearly the same structure-to-electrolyte potentials.

Locating the Problem

The following are methods used to detect casings shorted to carrier pipes.

1. Structure-to-Electrolyte Potential Survey

Place the reference electrode as close to the end of the casing as possible. Measure the pipe-to-electrolyte and casing-to-electrolyte potential as shown in Figure 6.54. The values should be significantly different if the carrier pipe is cathodically protected. If the difference between the two potentials is less than 100 mV, the casing might be shorted to the carrier pipe or, coincidentally, be at similar potentials and further testing is required.

Care should be taken as conclusions have been incorrectly drawn from structure potentials that were measured on test wires assumed to be casing wires when in reality they were attached to either a foreign structure or to the carrier pipe. Confirmation of test wires should take place and can include using the casing vents to check test wire continuity.

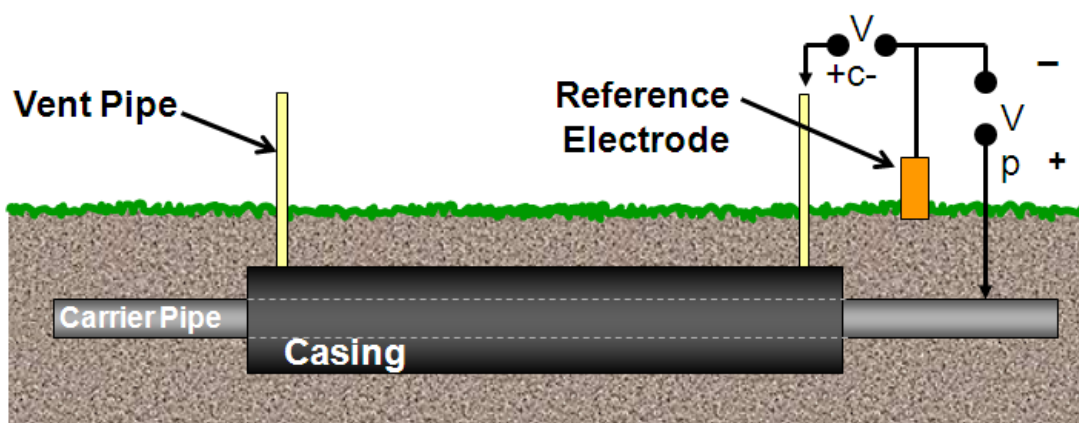


Figure 6.54 Set-Up for Measuring the Pipe-to-Electrolyte and Casing-to-Electrolyte Potential

Example

	Shorted	Isolated
C/S	$-0.900 V_{CSE}$	$-0.750 V_{CSE}$
P/S	$-0.900 V_{CSE}$	$-0.910 V_{CSE}$

2. Interrupted Structure-to-Electrolyte Potential Survey

Temporarily interrupting the nearest cathodic protection system will assist in testing casing/carrier pipe shorts and test wire continuity. With the nearest source interrupted, 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 are shifting the same magnitude between the ON and OFF, then the casing and carrier pipe are likely electrically shorted. If the casing potentials are shifting in the opposite direction or are shifting only slightly between the ON and OFF, then the two structures likely are not shorted. Again, the reference electrode should be located near the end of the casing pipe and should not be moved during these sets of measurements.

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.

Example

	Shorted		Isolated	
	ON	OFF	ON	OFF
C/S	$-1.56 V_{CSE}$	$-1.00 V_{CSE}$	$-1.00 V_{CSE}$	$-1.00 V_{CSE}$
P/S	$-1.56 V_{CSE}$	$-1.00 V_{CSE}$	$-1.56 V_{CSE}$	$-1.00 V_{CSE}$

3. Structure-to-Electrolyte Potential Change (Current Response Test)

Measure the structure-to-electrolyte potential and casing-to-electrolyte potential with respect to reference electrode placed on the soil directly above the structures. Use the vent, test wires on the casing, or a probe bar to contact the casing. Impress a current on one of the two structures using an interruptible DC power supply and a temporary anode bed (Figure

6.55). Measure E_{ON} and E_{OFF} structure-to-electrolyte potential readings on both structures. If the potentials of the two structures become more negative by the same magnitude and in the same direction when the current is on, they are shorted. If the potential of the structure that the temporary CP current is being impressed upon becomes more negative while the potential of the other structure decreases or stays the same, the two structures are electrically isolated.

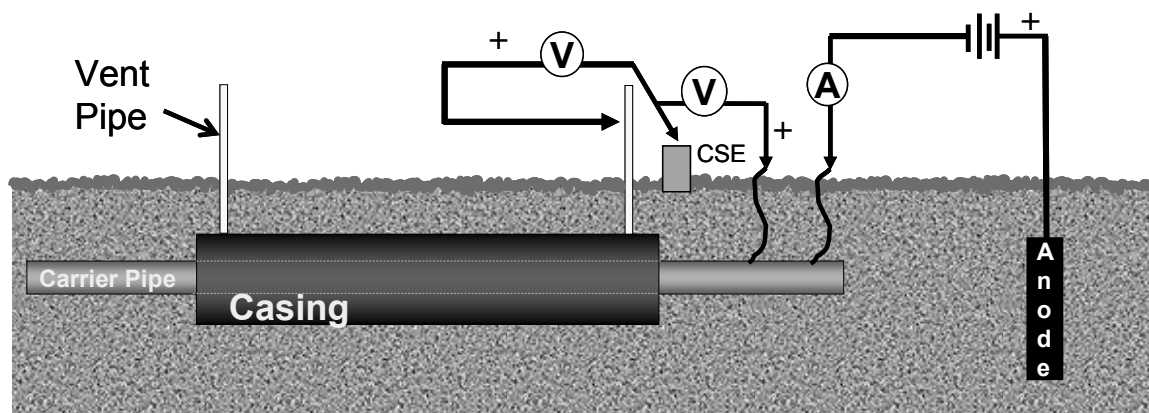


Figure 6.55 Illustration of Structure-to-Soil Potential Change Measurements

Example

	Shorted (ON/OFF)		Isolated (ON/OFF)	
	ON	OFF	ON	OFF
C/S	$-1.50 V_{CSE}$	$-1.25 V_{CSE}$	$-1.25 V_{CSE}$	$-1.25 V_{CSE}$
P/S	$-1.51 V_{CSE}$	$-1.25 V_{CSE}$	$-1.51 V_{CSE}$	$-1.25 V_{CSE}$

4. Resistance Between the Casing and Pipe

The resistance between the pipe and casing can be measured using an ammeter, voltmeter, and external DC power supply. Do not use a volt-ohmmeter due to the influence of the voltage between the structures. NACE Standard SP0200, “Steel-Cased Pipeline Practices”, describes the measurement technique.

5. Voltage or IR Drop Method

This method can be used to estimate the location of the electrical short between the carrier pipe and casing. The procedure calls for impressing a current between the casing and pipe from two different locations and measuring the resulting voltage drop. A ratio of the voltage drops

compares to a ratio of the distance from the end to the contact. NACE Standard SP0200 describes the procedure and analysis.

6. Casing Depolarization Test

The casing is depolarized by showing a temporary current between it and a temporary electrode with the casing connected to the positive side of the current source. Potentials are measured on the pipe and casing at different amounts of current. The procedure is described in NACE Standard SP0200.

Corrosivity Evaluations

Electrolyte resistivity and pH are two of the factors that determine the corrosivity of an electrolyte. Electrolyte resistivity is a measure of the ability of the electrolyte to support electrochemical corrosion, and electrolyte pH is a measure of the acidity or alkalinity of the electrolyte. Both influence the corrosion rates of metals placed underground or that are submerged.

Resistivity and pH are not the only factors affecting corrosion since total acidity, aeration, moisture content, soil type, soil permeability and composition, and heterogeneity play a role in determining the corrosivity of a given soil. Because of the natural heterogeneity of soil, there is no single value of soil resistivity that represents a particular site. Instead, for a given site a range of values are measured and calculations made to determine the “layer” resistivities.

Soil Resistivity Testing

Purposes

Soil resistivity is one factor that can determine the corrosivity of an environment. Resistivity is also essential in the design of cathodic protection systems.

Measurement Techniques

Various means of measuring electrolyte resistivities are used. These include the Wenner Four-Pin Method as described in ASTM Test Method G57, Collins Rod, and electromagnetic induction methods.

Wenner Four-Pin Method

The four-pin resistivity method developed by Wenner involves the use of 4 pins driven into the ground (Figure 6.56). Current is applied to the outer pins, and the voltage drop between the inner pins is measured. The resistivity is a function of the current, voltage drop, and spacing of the electrodes (which is equal to the depth of the test). The current is usually applied using an instrument that supplies alternating current; otherwise, polarization effects occur at the electrodes that can alter the reading. If a DC current is used, “instant” current and potential measurements must be taken. Stray earth currents can also affect the readings if these effects are not separated from the data.

Instruments can use current generated from batteries by a vibrator (e.g., Vibroground or Nilsson), or current generated by hand cranking (e.g., Meggar). The Nilsson uses a voltage of 12 V and a frequency of 97 Hz and the Vibroground uses a voltage of 100 V and 97 Hz. The LEM is an automated, microprocessor-controlled instrument and uses a range of frequencies (50 to 128 Hz) and 48/20 V.

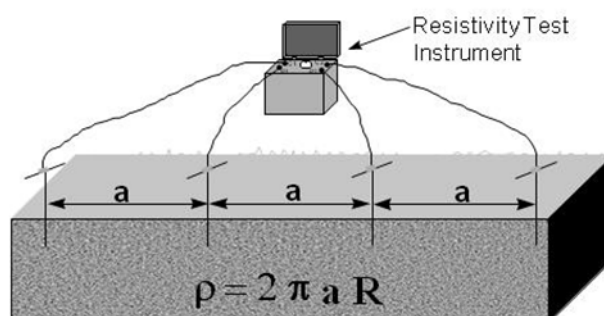


Figure 6.56 Wenner Four-Pin Soil Resistivity Measurement

The first step is to determine the resistance in Ω between the center pair of pins. Using the commercially available equipment detailed above, the resistance is indicated directly by the soil resistance meter. Resistivity is then calculated using the following formula:

$$\rho = 2 \pi a R$$

Eq. 6-22

where:

ρ = Resistivity, Ω -cm

π = Constant Pi (3.1416)

a = Spacing, cm

R = Resistance, Ω

or, if spacing is measured in feet, with the resistivity still in Ω -cm, use the following formula:

$$\rho = 191.5 a R \quad \text{Eq. 6-23}$$

ρ = Resistivity, Ω -cm

a = Spacing, ft

R = Resistance, Ω

For example,

If the resistance reading from the meter is 8 Ω at a pin spacing of 3.048 m (304.8 cm), then the average resistivity to an approximate depth of 3 m is

$$\rho = 2 \times \pi \times 304.8 \text{ cm} \times 8 \Omega = 15,320 \Omega\text{-cm}$$

or, similarly if the resistance reading is 8 Ω at a pin spacing of 10 ft, then the average resistivity to a depth of 10 ft is

$$\rho = 191.5 \times 10 \text{ ft} \times 8 \Omega = 15,320 \Omega\text{-cm}$$

If the line of soil pins runs closely parallel to a metallic structure, the presence of the structure may cause the indicated soil resistivity values to be lower than is actually the case. This is because a portion of the test current will flow along the metallic structure rather than through the earth. For this reason, this situation should be avoided. When taking soil resistivity measurements along a structure, it is good practice to place the line of pins perpendicular to the structure, with the nearest pin no closer than 15 ft from the structure.

Layer Resistivity Calculations

The resistance, R , at each given spacing (S), is the resistance from ground level to a depth equal to the spacing of the two inside pins. Figure 6.57 shows the average and layer resistivity.



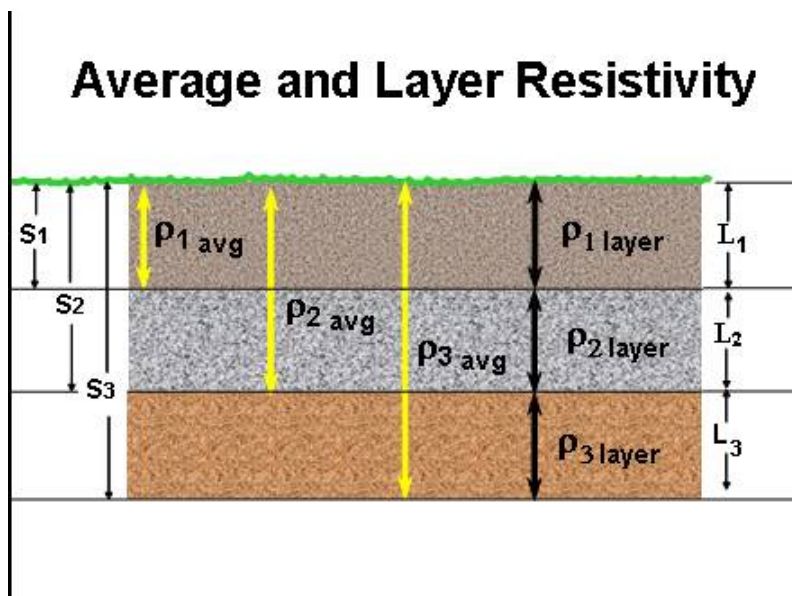


Figure 6.57 Average and Layer Resistivity

Using the Wenner Method, the soil resistivity, whether average or layer, is determined by Equations 6-24 or 6-25:

When calculating average resistivity, “R” is the resistance measured and “a” is the spacing of the pins. In determining layer resistivity, the resistance “R” for the layer can be calculated based on Barnes Layer Analysis which assumes the layers are in parallel and ‘a’ is the thickness of the layer. Begin with the parallel resistance formula:

$$1 / R_T = 1 / R_1 + 1 / R_2 + 1 / R_3 + \dots + 1 / R_N \quad \text{Eq. 6-24}$$

If there are only two parallel resistances then Equation 6-24 becomes:

$$R_2 = \frac{R_1 R_T}{(R_1 - R_T)} \quad \text{Eq. 6-25}$$

Therefore, based on the above illustration and equations, the following is true if the measured resistances are R_1 , R_2 , and R_3 with respect to spacings S_1 , S_2 , and S_3 . Note that the subscripts for the resistances in Equation 6-25 are now changed in Equation 6-26 to the layers in Figure 6.57.

$$R_{L2} = \frac{R_1 R_2}{(R_1 - R_2)} \quad \text{Eq. 6-26}$$

Where:

R_{L2} Resistance of Layer 2 (Ohms)

R_1 Resistance measured to depth S1 (Ohms)

R_2 Resistance measured to depth S2 (Ohms)

To calculate the average resistivity to a certain depth and the resistivity of each layer:

$$\rho_{1 \text{ avg}} = 2\pi S_1 R_1 \quad (191.5 S_1 R_1)$$

$$L_1 = S_1$$

$$R_{L1} = R_1$$

$$\rho_{L1} = 2\pi L_1 R_{L1} \quad (191.5 L_1 R_{L1})$$

$$\rho_{2 \text{ avg}} = 2\pi S_2 R_2 \quad (191.5 S_2 R_2)$$

$$L_2 = S_2 - S_1$$

$$R_{L2} = (R_1 R_2) / (R_1 - R_2)$$

$$\rho_{L2} = 2\pi L_2 R_{L2} \quad (191.5 L_2 R_{L2})$$

$$\rho_{3 \text{ avg}} = 2\pi S_3 R_3 \quad (191.5 S_3 R_3)$$

$$L_3 = S_3 - S_2$$

$$R_{L3} = (R_2 R_3) / (R_2 - R_3)$$

$$\rho_{L3} = 2\pi L_3 R_{L3} \quad (191.5 L_3 R_{L3})$$

The results of sample soil resistivity calculations shown below that may be derived from data acquired using the Wenner Method and the Barnes Layer calculations.

Table 6.3 Examples of Layer Resistivity Calculations

SPACING (ft) [cm]	RESISTANCE R (Ω)	RESISTIVITY AVERAGE ρ_{ave} (Ω-cm)	LAYER RESISTANCE $R_L(\Omega)$	RESISTIVITY LAYER ρ_{layer} (Ω-cm)
5.22 [159.1]	10.0	10,000	10.0	10,000
10.44 [318.2]	7.4	14,795	28.46	28,450
15.66 [477.3]	3.1	9,295	5.33	5,328

The “Resistivity Average” data in Table 6.3 is calculated below.

$$\rho_{ave} = \frac{2 \pi a R}{\ln 4}$$

$$\begin{aligned}\rho_{1ave} &= 2 \pi \times 159.1 \text{ cm} \times 10 \Omega \\ &= 10,000 \Omega\text{-cm}\end{aligned}$$

Or in feet

$$\begin{aligned}\rho_{1ave} &= 191.5 \times 5.22 \text{ ft} \times 10 \Omega \\ &= 10,000 \Omega\text{-cm}\end{aligned}$$

$$\begin{aligned}\rho_{2ave} &= 2 \pi \times 318.1 \text{ cm} \times 7.4 \Omega \\ &= 14,795 \Omega\text{-cm}\end{aligned}$$

Or in feet

$$\begin{aligned}\rho_{2ave} &= 191.5 \times 10.44 \text{ ft} \times 7.4 \Omega \\ &= 14,795 \Omega\text{-cm}\end{aligned}$$

$$\begin{aligned}\rho_{3ave} &= 2 \pi \times 477.3 \text{ cm} \times 3.1 \Omega \\ &= 9,295 \Omega\text{-cm}\end{aligned}$$

Or in feet

$$\begin{aligned}\rho_{3\text{ave}} &= 191.5 \times 15.66 \text{ ft} \times 3.1 \Omega \\ &= 9,295 \Omega\text{-cm}\end{aligned}$$

The “Layer Resistance” and the “Resistivity Layer” data in Table 6.3 are calculated as follows:

ρ 1 layer

$$\rho_{L1} = \rho_{1\text{ave}} \text{ as they are the same layer of soil.}$$

ρ 2 layer

$$\rho_{L2} = 2\pi L_2 R_{L2} \text{ (with } L_2 \text{ in cm)}$$

where

$$\begin{aligned}L_2 &= S_2 - S_1 \\ &= 318.2 \text{ cm} - 159.1 \text{ cm} \\ &= 159.1 \text{ cm}\end{aligned}$$

Or

$$\begin{aligned}L_2 &= 10.44 \text{ ft} - 5.22 \text{ ft} \\ &= 5.22 \text{ ft}\end{aligned}$$

and

$$\begin{aligned}R_{L2} &= (R_1 R_2) / (R_1 - R_2) \\ R_{L2} &= (10\Omega \times 7.4\Omega) / (10\Omega - 7.4\Omega) \\ &= 28.46\Omega \\ \rho_{L2} &= 2\pi L_2 R_{L2} \\ &= 2 \pi \times 159.1 \text{ cm} \times 28.46\Omega \\ &= 28,450\Omega\text{-cm}\end{aligned}$$

Or in feet

$$\begin{aligned}\rho_{L2} &= 191.5 L_2 R_{L2} \\ &= 191.5 \times 5.22 \text{ ft} \times 28.46\Omega \\ &= 28,450\Omega\text{-cm}\end{aligned}$$

ρ₃ layer

$$\rho_{L3} = 2\pi L_3 R_{L3} \text{ (with } L_3 \text{ in cm)}$$

where

$$\begin{aligned} L_3 &= S_3 - S_2 \\ &= 477.3 \text{ cm} - 318.2 \text{ cm} \\ &= 159.1 \text{ cm} \end{aligned}$$

Or in feet

$$\begin{aligned} L_3 &= 15.66 \text{ ft} - 10.44 \text{ ft} \\ &= 5.22 \text{ ft} \end{aligned}$$

and

$$\begin{aligned} R_{L3} &= (R_2 R_3) / (R_2 - R_3) \\ &= (7.4 \, \Omega \times 3.1 \, \Omega) / (7.4 \, \Omega - 3.1 \, \Omega) \\ &= 5.33 \, \Omega \end{aligned}$$

$$\begin{aligned} \rho_{L3} &= 2\pi L_3 R_{L3} \\ &= 2\pi \times 159.1 \text{ cm} \times 5.33 \, \Omega \\ &= 5328 \, \Omega\text{-cm} \end{aligned}$$

Or in feet

$$\begin{aligned} \rho_{L3} &= 191.5 L_3 R_{L3} \text{ (with } L_3 \text{ in ft)} \\ &= 191.5 \times 5.22 \text{ ft} \times 5.33 \, \Omega \\ &= 5,328 \, \Omega\text{-cm} \end{aligned}$$

Single Rod Method

Another instrument mounts the electrodes on a single rod. An alternating current is supplied, and the resistivity is measured using a galvanometer (e.g., Collins Rod). These techniques measure local volumes of soil, making them useful for that very reason. They fit into confined spaces, such as next to tanks and between pipes, where the standard Wenner Four Pin method would not provide accurate results.

The probe-type device consists of a metal probe rod, which can be pushed into the ground to the desired depth. Typically, the tip of the rod is isolated from the remainder of the rod so that the resistance between the rod tip and rod body can be measured. The resistance measured is a function of the soil resistivity. This permits calibrating the resistance measuring device directly in $\Omega\text{-cm}$ or measuring the resistance and multiplying the observed value by some factor to obtain a value of soil resistivity. Figure 6.58 shows this device.

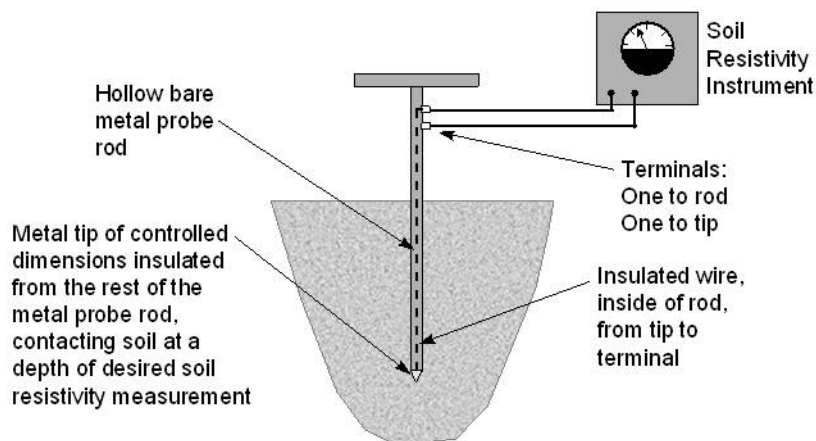


Figure 6.58 Probe Type Resistivity Meter

Soil/Electrolyte Box

Another method of measuring resistivity does not rely on contact with the ground at all.

Soil or electrolyte box measurements of resistivity involve placing water or a soil sample in a container having electrodes. These electrodes are then connected to a power supply and a voltage measuring device, and the resistance of the soil between two potential electrodes is measured. There are two different methods of preparing the soil for testing using this measurement technique. ASTM G51 provides a method for testing the soil in the as-received state and saturated with ground water, distilled water, or tap water. AASHTO T288 calls for drying the sample, sieving it, and then adding water. The measurement is made in a specially designed box having two electrodes. All of these methods measure a “minimum” resistivity of a relatively small soil sample that may not represent the in-situ soil in terms of compaction, pressure, temperature, permeability, or moisture content. These test methods should not, therefore, be expected to replicate field measurements.

A soil/electrolyte box, shown in Figure 6.59, can be made or a commercial model purchased. The commercial models are usually a clear, plastic box constructed with end plates for current input and pins through the side for potential measurements.

The formula for resistivity is:

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

Eq. 6-27

If a soil box is constructed such that the cross-sectional area and the length are equal, then the calculated value of resistivity would equal the measured resistance. That is,

If $L = A$

then

$\rho = R$

but

ρ = soil resistivity (Ω -cm)

R = resistance from test (Ω).

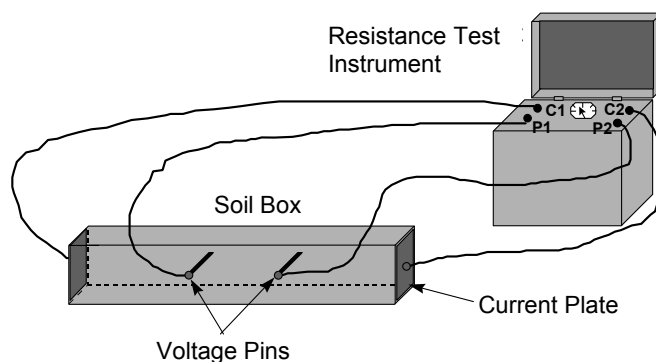


Figure 6.59 Soil Box Resistivity Test

Some commercially available soil boxes are sized for this straight one-to-one conversion but remember the units for resistance (Ω) and resistivity (Ω -cm) are different. Without the correct units the result is incorrect.

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, a pH meter, or a pH test kit. 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 antimony electrode and copper-sulfate reference electrode are placed close together with the electrode tips in the soil and connected to a voltmeter. It does not 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 mV and pH. Once the potential difference between the two electrodes is obtained, the pH can be determined from the scale.

Concrete Structures

The following discussion pertains primarily to atmospherically exposed reinforced concrete structures, such as bridges and buildings. Reinforced concrete structures requiring cathodic protection are found in immersed situations as well, such as prestressed concrete pipes, prestressed concrete pilings, and cement-mortar-coated steel pipes.

Since cathodic protection requires a continuous structure, and since reinforcing is usually only connected through tie wires, electrical continuity must be verified. Items such as drains, railings, and expansion joints must also be continuous with reinforcing to avoid interference. Electrical continuity can be

evaluated using AC-resistance measurements. Connections to two widely spaced points on the structure are made through the AC instrument. A resistance of less than $0.100\ \Omega$ indicates continuity.

Continuity can also be estimated by measuring the rebar-to-reference cell potential between several locations using a constant reference cell location. Rebar-to-structure potentials within $\pm 0.001\ \text{V}$ of each other suggest that the points are continuous. Measurements greater than $\pm 0.001\ \text{V}$ but less than $\pm 0.003\ \text{V}$ indicate uncertain continuity, and measurements greater than $\pm 0.003\ \text{V}$ indicate that the structure is discontinuous.

Depth of concrete cover is important when an impressed current cathodic protection system is to be installed. The anode must not come into contact with the rebar or any other metallic component of the structure, otherwise a short circuit will occur rendering the system useless. Depth of cover is measured using a Pachometer.

Metal reinforcing-to-reference electrode potentials are taken on concrete structures to determine the probability of corrosion of the embedded metal. Details of this procedure are provided in ASTM Test Method C876, "Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete."

A high-impedance voltmeter is connected between the reinforcing steel and a reference electrode placed on the surface of the concrete. The most commonly used reference electrode is the copper-copper sulfate half-cell. Excavation of the concrete to expose the reinforcing steel might be required to obtain the structure contact. Because of the high resistance inherent in the measurement circuit, the voltmeter must have sufficient input impedance to accurately measure the half-cell potentials. The minimum voltmeter impedance should be $10 \times 10^6\ \Omega$ and be selectable to higher values in order to identify significant resistances in the circuit.

To reduce the contact resistance between the concrete surface and the half-cell, a moist sponge is placed between the half-cell and the surface. It is also desirable to pre-moisten the entire surface with clean potable water. This will reduce instabilities, but will result in a "leveling" of the measured potentials.

Half-cell potential measurements can be interpreted as follows:



Potential	Probability of Corrosion
More positive than -200 mV	< 5 percent
-200 to -350 mV	About 50 percent
More negative than -350 mV	> 95 percent

Potential measurements on concrete that is completely saturated, e.g., submerged piling, may be more negative than -350 mV yet have little corrosion activity because the water saturation limits oxygen diffusion which reduces corrosion.

Potential measurements are usually taken in a grid pattern, for example, one reading every 2 to 5 ft (0.6 to 1.5 m). The resulting data is plotted on a contour map showing areas that are corroding.

Direct Inspection

Direct inspection involves physical inspection of the structure itself. The surface of the structure must be exposed; it is then cleaned and examined for corrosion. Measurements of general corrosion and pitting can be made and compared to previous data. There should be no new or future corrosion if the cathodic protection system is working.

Leak Frequency

Comparing the cumulative frequency of leaks vs. time often identifies the effect of corrosion. It is typical of corrosion that the cumulative frequency increases logarithmically with time. Leaks that occur from purely mechanical causes would not behave with such regularity. The effect of cathodic protection is to slow down or flatten the leak rate curve.

Figure 6.60 is an example of a leak vs. time curve before and after the application of cathodic protection. Figure 6.60 comes from actual data on the leak history of a cast iron water main before and after cathodic protection was installed. The leaks occurring before 1984 show the logarithmic increase in the number of leaks with time. The leaks are shown to have essentially stopped after cathodic protection was installed.

Maintaining leak record curves is a method that can be used to prove the effectiveness of cathodic protection. It is particularly useful for owners of structures that are not regulated by a government agency.

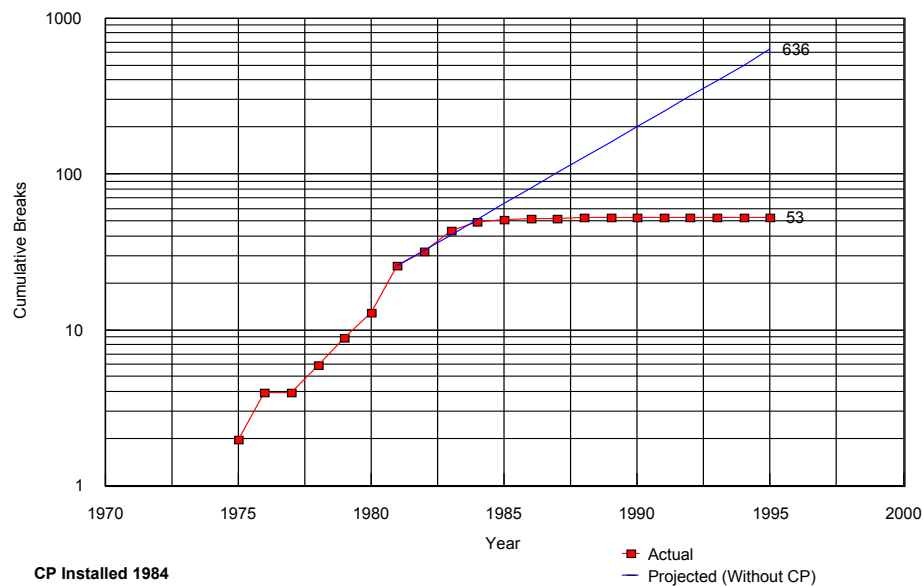


Figure 6.60 Cumulative Leaks vs. Time Before and After Cathodic Protection

In-Line Inspection

Instrumented or “smart” pigs using ultrasonic, eddy current, or mechanical measuring instrumentation can be used to measure corrosion from the inside of a pipe. Instrumented pigs contain sensing devices that scan the pipe wall searching for defects. Ultrasonic devices work by measuring the time it takes a high-frequency sound wave to travel across the pipe thickness and back to the transducer. The instrument is calibrated to measure this time as thickness of the pipe wall. Magnetic or eddy-current devices work by sensing deviations in a magnetic flux field caused by corrosion pits or other defects that distort the flux field.

CHAPTER 7

Stray Current and CP Interference

Stray Current

Stray currents are currents through electrical paths other than the intended circuit. Stray current is not the galvanic corrosion current between anodes and cathodes on the same structure. Stray currents, or interference currents, can be classified as being either static or dynamic.

Stray current can refer to either alternating current or direct current. AC stray current is more of a safety hazard than a corrosion problem. The exception is that AC can cause significant corrosion of aluminum. DC stray current causes significant corrosion of most metals.

Stray current is especially damaging because large currents, often involving many amperes, might be involved. On the other hand, even small amounts of stray currents can be highly damaging if discharged over a small surface area. In some areas, particularly around older rail rapid-transit systems or in the vicinity of underground mine railroads, pipelines may carry hundreds of amperes of stray current. For every ampere discharged from a structure, a certain amount of metal is lost. Faraday's Law allows us to relate the corrosion lost to the amount of current discharged. For ferrous metals (cast iron, ductile iron, steel), copper, and lead the loss rates are:

Ferrous	9.1 Kg / A-yr	(20 pounds / A-yr)
Copper	10.4 Kg / A-yr	(23 pounds / A-yr)
Lead	33.85 Kg / A-yr	(74.64) pounds / A-yr)

It is apparent that, if not controlled, stray current can destroy a structure very rapidly or at least to a potentially catastrophic situation. Structures in environments that normally would not be considered extremely corrosive will be subjected to accelerated corrosion when exposed to stray current conditions. Further consideration must be given to the current density for total penetration of the metal.



Stray current, being from an external source, enters the pipe or other structure through the soil (or other electrolyte) but does not cause corrosion at that point. Some amphoteric metals such as aluminum and lead may suffer “cathodic corrosion” in stray current “pick up” areas. Many structures, in fact, receive “free” cathodic protection from stray currents at the point of entry. The damaging effect of stray current typically occurs if the current *leaves* the structure through the electrolyte where corrosion will be accelerated.

The objective of stray current analysis is to determine:

- The source of the stray current.
- Where and over what area does the stray current enter the structure?
- Where and over what area does the stray current leave the structure?
- What is the magnitude of the stray current?
- How can the stray current be mitigated?

Dynamic Currents

Dynamic stray currents are those currents that vary in amplitude and/or change in the direction of current flow. These currents can be manmade or natural in origin.

Sources of Dynamic Stray Currents

Dynamic stray current can originate from any of the following sources:

- Transit systems
- Mining
- DC welding machines
- Electric power transmission
- Industrial plants (aluminum and chlorine production facilities)
- Telluric current



Examples of manmade sources are DC welding equipment, mining operations, and DC electrical railway systems. Telluric currents are naturally occurring stray currents that are caused by disturbances in the Earth's magnetic field by sun spot activity. Figure 7.1 shows stray currents from a DC railway. These are commonly called *stray traction currents*.

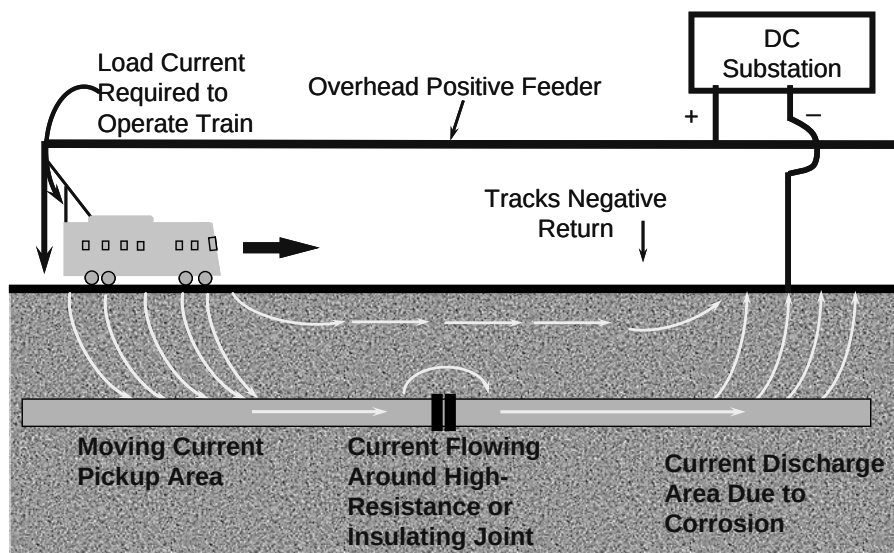


Figure 7.1 Illustration of Dynamic Stray Currents from a Transit System

Natural (Telluric) Currents

Telluric current is generated by the interaction of the solar wind (high-energy particles given off by the sun), the Earth's magnetic field, and metal structures at the surface of the Earth. The current generated shifts in magnitude and direction with time. It generally occurs during times of increased sun spot activity. Telluric currents create significant monitoring difficulties but have not been conclusively demonstrated to cause corrosion.

Detecting Dynamic Stray Currents

Dynamic stray currents can be readily detected from structure-to-electrolyte potentials and/or line current measurements. Dynamic stray currents can be indicated by a structure-to-electrolyte potential that is changing with time with the reference electrode in a stationary position in contact with the electrolyte. These potential changes are a direct result of current changes at the source of the interference.

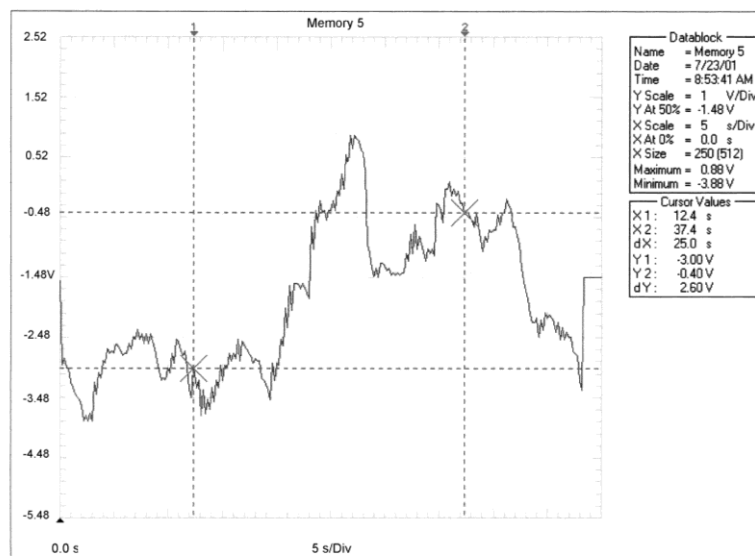


Figure 7.2 Pipe Potential Fluctuating Due to Dynamic Stray Current

Varying voltage gradients in the earth can be detected using two reference electrodes spaced ten to twenty-five feet apart. Reference electrodes placed on the soil over the existing pipeline or proposed pipeline route will show the voltage gradients that the pipe is (or will be) exposed to between the two cells.

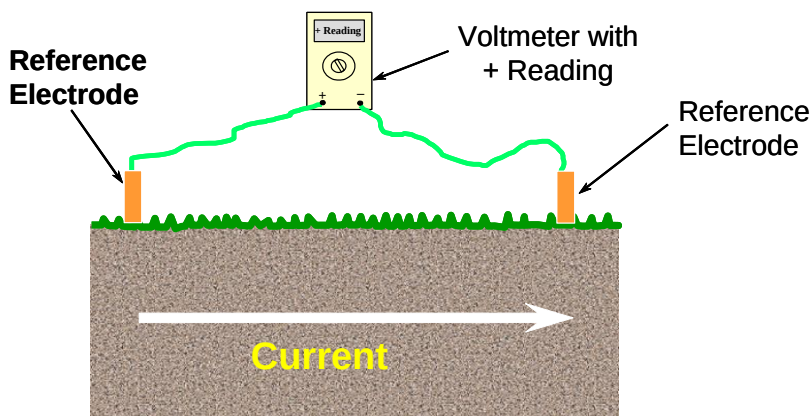


Figure 7.3 Potential Measurement Between Two Electrodes

The analysis of dynamic stray currents may require the use of correlations, or comparisons, of currents or voltages from one point on the structure to another. It is necessary to have sufficient test facilities on the structure to measure structure-to-soil potentials and current on the structure. If the structure has few or no test facilities and stray currents are detected, then install additional test facilities to permit a meaningful analysis.

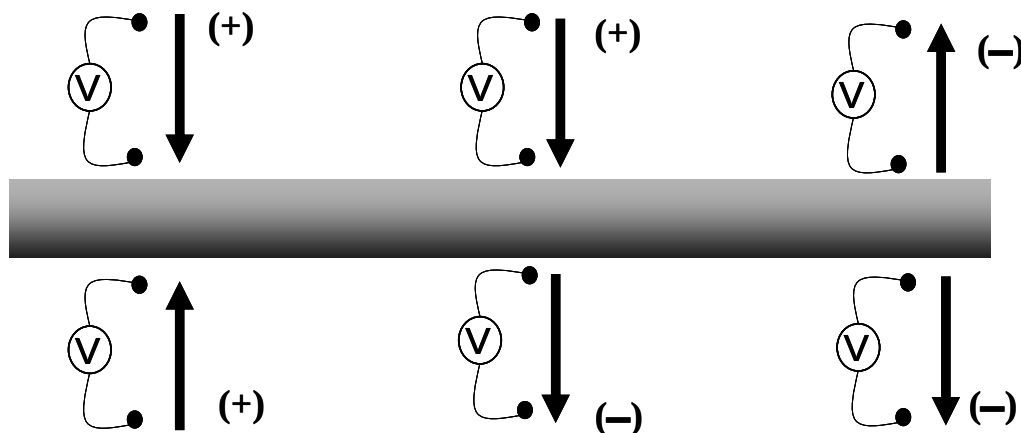


Figure 7.4 Potential Measurement Between Two Electrodes

Continuous Data Recording

The above analysis provides valuable information about where stray current enters and discharges from a structure. But it does not provide information on the value of the maximum stray current affecting the structure, does not show whether the stray current voltages observed during the test period are significant, and does not document the predominant *direction* of voltage or current. To perform this function, data about the stray current magnitude over time is needed. This data is obtained using a long term (24 hours or more) voltage or current recording. A strip chart recorder or data logger can be used for this purpose.

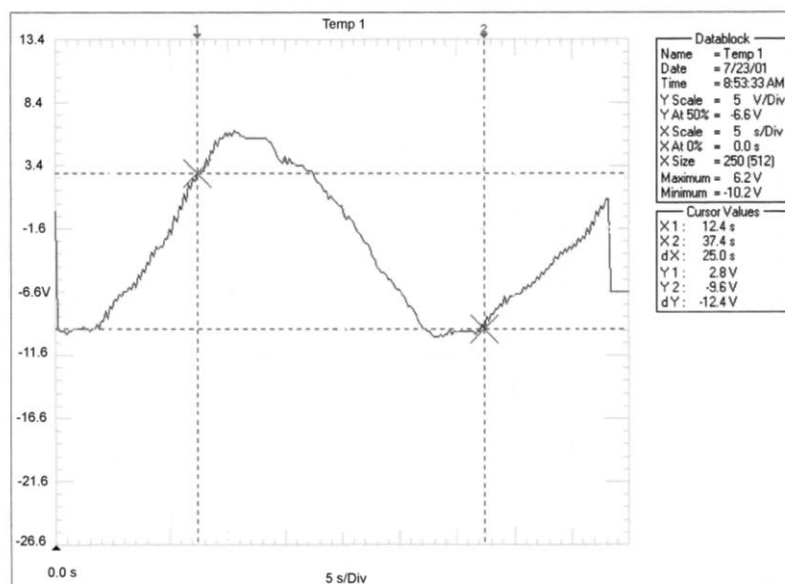


Figure 7.5 Data Logger Plot Illustrating Dynamic Stray Currents

Select the location to be tested using the results of the correlations, the best location being the one of most importance. The location of the recording should obviously be one of the test points used in the correlations as long as the voltages in the long term recording can be correlated back to the other test points using the correlations. However, almost any location will do. Select a location where the recording device will be safe and out of the way of traffic, pedestrians, and vandals. Note: The recording device should be identified with the company name, address, and telephone number.

More than one recording device might be needed.

Finding the Source of the Stray Current

Engineering solutions to stray current problems can be complex. Frequently, more than one source of current is involved. Transit systems, which are often the culprit, do not operate from a single substation; rather they are supplied by a number of substations operating in parallel and feeding many different lines simultaneously. Such transit systems operate with many thousands of amperes of current, and the effects can be seen for many miles on underground structures. If stray current is to be successfully drained from the structure of interest to the source, two conditions must be met.

The source must tend to pick up stray current at the point where the mitigation bond is to be installed. This is point determined using the correlations described above.

The structure must tend to discharge stray current at the point where the mitigation bond is to be installed. This point is also determined using the correlations described above.

Sufficient current must be drained to clear (mitigate) the most severe stray current exposure. This is determined by measuring or calculating the maximum current flow through the proposed bond or other mitigation system.

Static (Steady State) Currents

Static, or steady state, interference currents are defined as those that maintain constant amplitude and constant geographical paths. Examples include High-Voltage Direct Current (HVDC) ground electrodes and cathodic protection systems. Figure 7.6 shows how interference can occur from a cathodic protection system on a foreign pipeline.

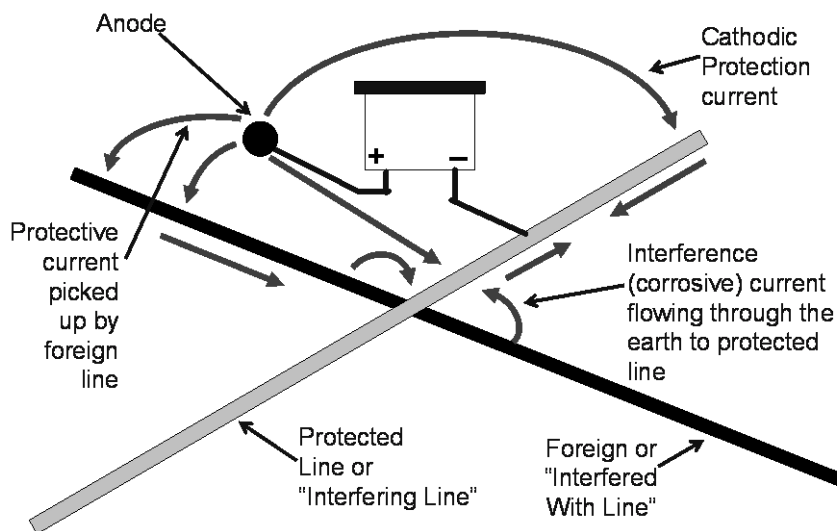


Figure 7.6 Static Stray Current Interference from a CP System

The polarity of the voltage gradients to remote earth affecting the foreign structure determines the type of interference. Interference can be either of the following two types or a combination of the two.

Cathodic Interference

When a voltage gradient overlaps a foreign structure and is negative with respect to remote earth, it promotes current discharge from the foreign structure in the area of influence. The cathodic gradient could be considered as the controlling factor in this situation. If current discharges from a structure,

then it must pick up current outside the area of influence. This is *cathodic interference* and is illustrated in Figure 7.7.

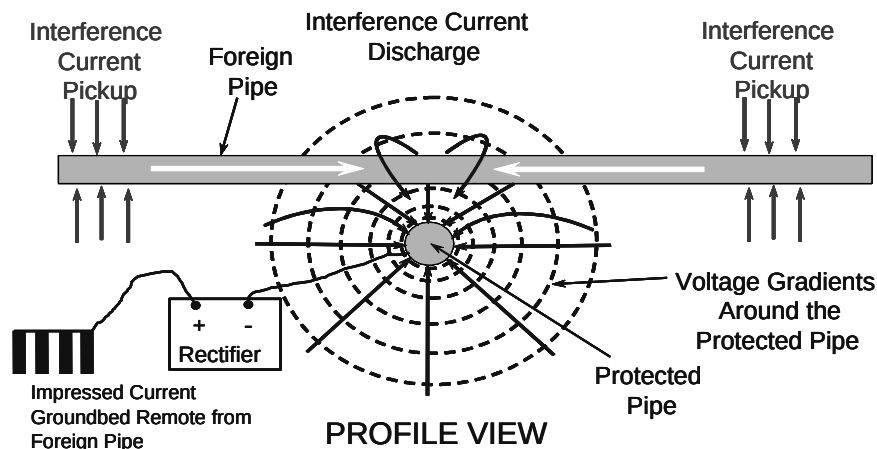


Figure 7.7 Cathodic Interference

Anodic Interference

Anodic interference is the opposite of cathodic interference. If a foreign structure crosses a voltage gradient that is positive with respect to remote earth, then it will promote current pickup on the foreign structure within the area of influence. The anodic gradient could be considered as the controlling factor in this case. Because current is picked up on the foreign structure, then current must discharge outside the area of influence. Anodic interference is illustrated in Figure 7.8.

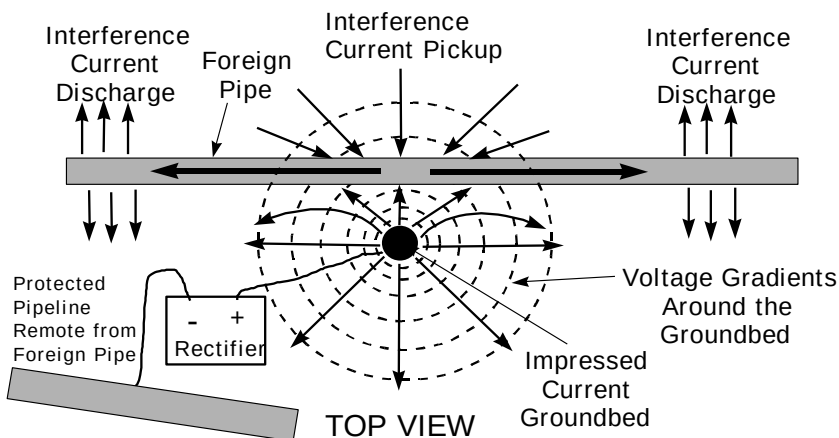


Figure 7.8 Anodic Interference

In certain conditions, a foreign structure may cross voltage gradients that promote anodic and cathodic interference from a single current source. For

example, a foreign structure could cross the cathodically protected structure at one location and its impressed current groundbed at another location.

Detection of Static Interference Currents

Certain changes and/or conditions in the system indicate the presence of interfering currents, including:

- Structure-to-electrolyte potential changes on the affected structure caused by the foreign cathodic protection current source
- Changes in line current magnitude or direction caused by the foreign cathodic protection current source
- Localized pitting in areas near or immediately adjacent to a foreign structure
- Breakdown of protective coatings in a localized area near a foreign anode bed or near any other source of stray direct current

Static interference is detected by analysis of structure-to-electrolyte potential surveys. The corrosion technician can sometimes misinterpret a structure-to-electrolyte potential survey because of static stray currents. In an unprotected pipeline, the corroding (anodic) areas exhibit a potential that is more negative when measured against a reference electrode, while the non-corroding (cathodic) areas yield a more positive (less negative) potential. Consider the case where stray current is flowing toward the pipe in a protective direction. In this case, the stray current makes the soil more positive than the pipe, and a more negative area appears on the structure-to-electrolyte potential profile, giving a false indication of a corroding area. The reverse is true in areas where stray current leaves the structure. Surface potential profiles may be misleading, as they represent a composite of current leaving the structure being surveyed and close to a crossing structure.

Static interference effects are detected similarly on protected pipelines. In this instance, however, the interpretation of the potentials is opposite to that described above for an unprotected pipeline. Figures 7.9 and 7.10 show examples of *close-interval surveys* (CIS) and the effect of static stray current on pipe-to-soil potentials for coated and uncoated cathodically protected structures. The key points to consider in detecting static interference effects on a pipeline are:



- Potential profiles show abnormal variation from previous surveys.
- Large negative values are noted remote from any cathodic protection system on the pipeline or are noted on unprotected piping.
- Unusual currents are measured along the pipeline.
- Low negative or positive potentials are present.
- Changes in the current output of a nearby cathodic protection system may cause changes in the structure-to-electrolyte potential of the pipeline.

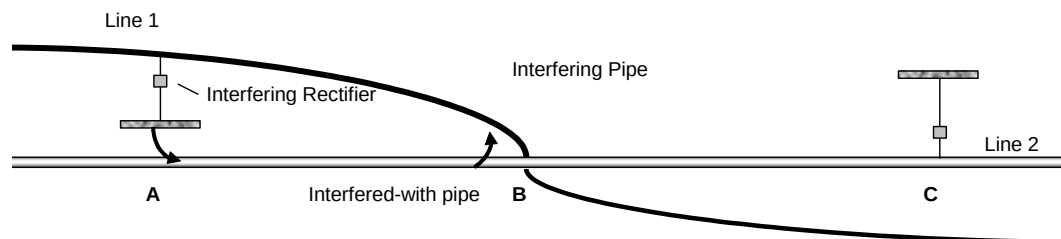
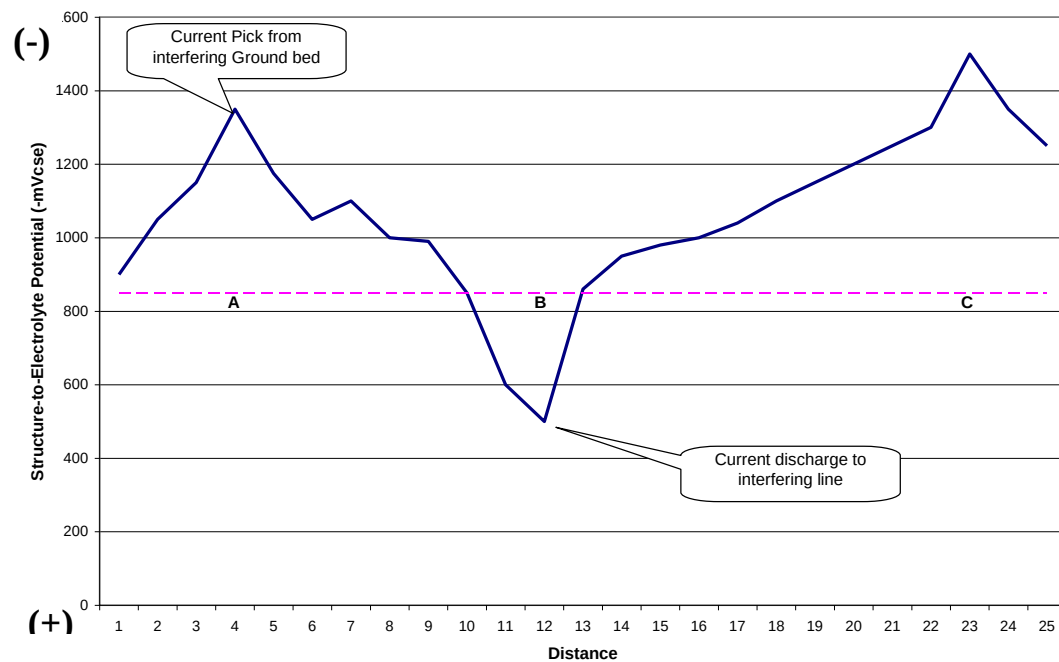


Figure 7.9 Effect of Static Stray Current on Pipe-to-Soil Potentials for Coated Cathodically Protected Structure (Interfered-with line) (Line 2)

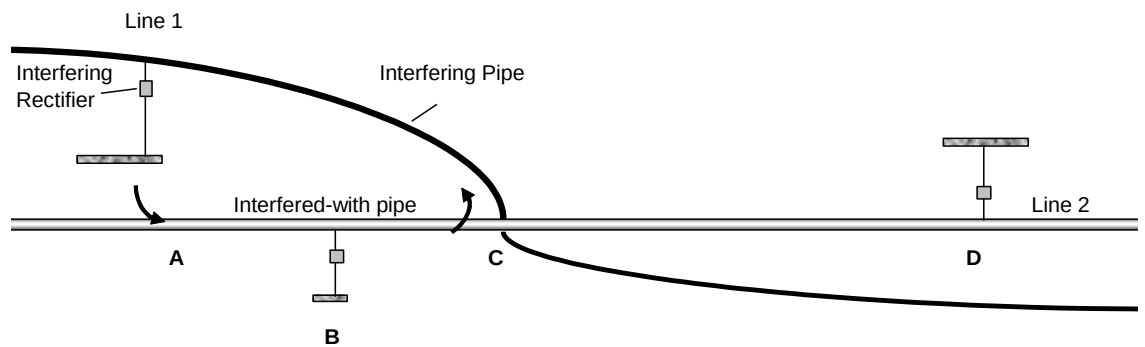
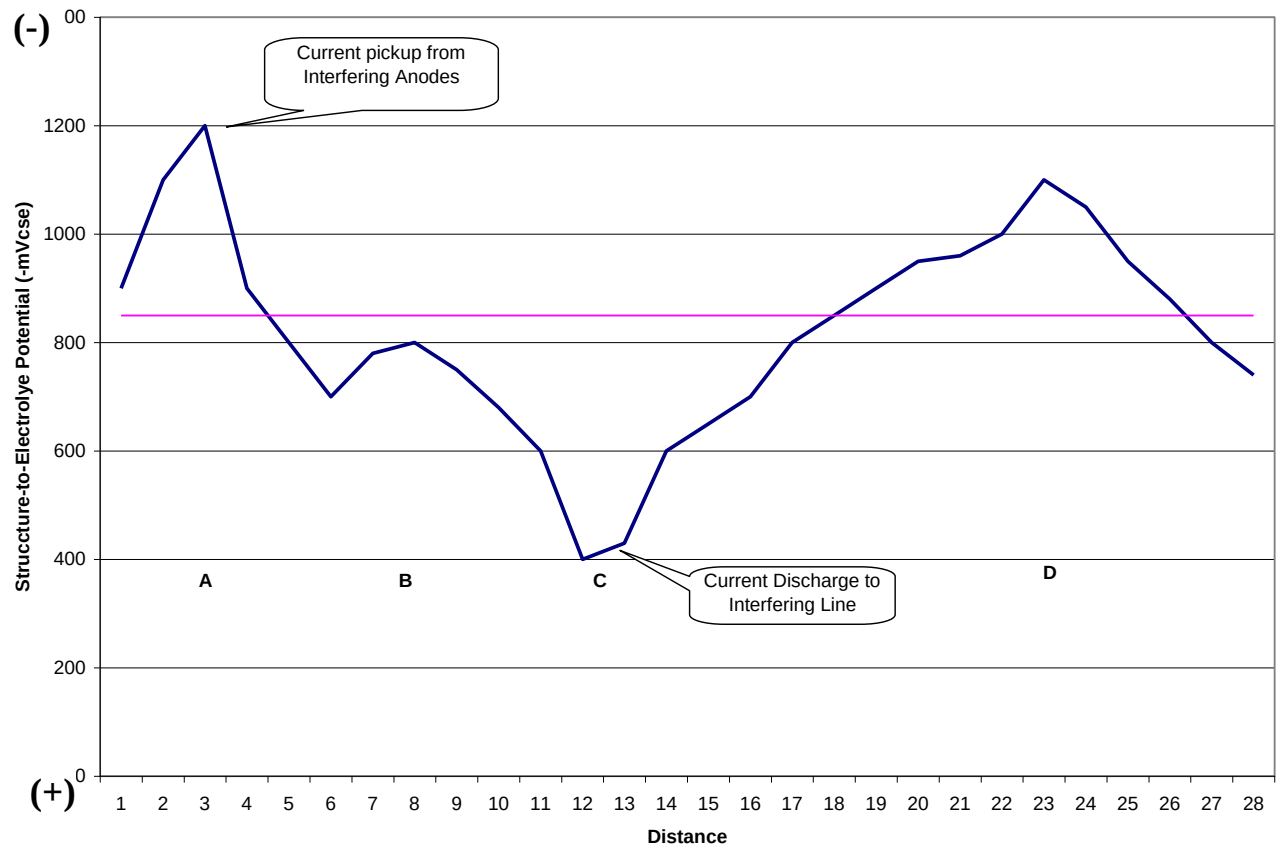


Figure 7.10 Effect of Static Stray Current on Pipe-to-Soil Potentials for Uncoated Cathodically Protected Structure (Interfered-with line) (Line 2)

Sample Field Data

Structure-to-Electrolyte Potentials

When testing for stray current interference with an interrupter installed in the suspected source of interference it is critical that the ON and OFF structure-to-electrolyte potentials be identified by the length of the interrupter cycles and the assumption that the ON potential is the most negative value must NOT be made.

Consider an example where two structures are protected by independent CP systems and the structure designated as the “Foreign” Structure is afforded a new system that adversely affects the other structure (Affected Structure). The data from three test locations along the Affected Structure are shown in Table 7.1

Table 7.1 Sample of Data Indicating Cathodic and Anodic Interference

LOCATION	AFFECTED STRUCTURE	
	ON	OFF
X	-1600	-1100
Y	-400	-1050
Z	-1000	-1000

A negative change in potentials as the current comes ON indicates possible current pick-up. In some cases, a negative shift on a structure when the foreign CP system is energized can be attributed to voltage gradients in the environment that don't result in current pick-up. A potential shift in the positive direction (less negative) with the foreign structure CP system energized can be indicative of an overall reduction in CP current collected on the affected structure, or can indicate current discharge. Current discharge is indicated when the potential shifts to a less negative value than the free corrosion potential of the affected structure.

In the example data shown in Table 7.1, Anodic Interference is likely indicated at Point “X” on the affected structure and suggests that it is in an anodic gradient of the foreign structures CP anodes. Cathodic Interference and current discharge is indicated at Point “Y” on the affected structure as the potentials become less negative than the free corrosion potential when the foreign structure's CP system comes ON. There is no current pickup or discharge at Point “Z” on the affected discharge.

Current Measurements

Current measurements within a structure such as a pipeline can be used to predict current pickup and discharge areas using the principle of Kirchoff's Current Law as illustrated by Figure 7.11.

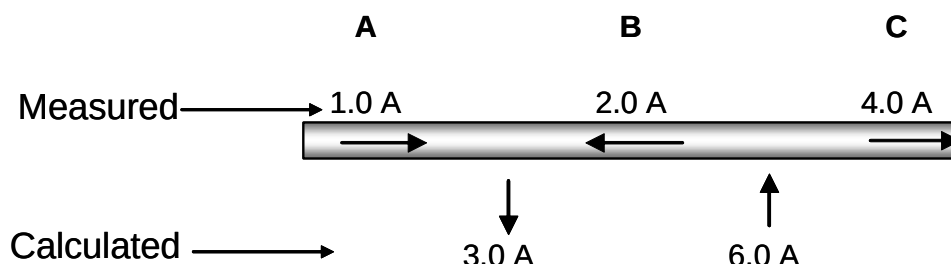


Figure 7.11 *Current Pickup and Discharge Using Pipeline Current*

Current was measured at locations A, B, and C and the current discharge or pickup was determined using Kirchoff's Current Law, that is, the difference in current between the points measured represents a current pickup or discharge. In Figure 7.11, there must be a current discharge between A and B equal to the difference of current ($1.0 - (-2.0) = 3.0$ A) while there must be a current pickup between B and C equal to the current difference between these points ($-2.0 - 4.0 = -6.0$ A).

Resolving Interference Problems

Interference problems are individual in nature, and the resolution should be agreeable to all parties involved. Resolving interference problems generally involves one or more of the following:

- Removal of the detrimental effects of interfering current by installing a metallic return path
- Counteracting the effect of interfering current by applying cathodic protection
- Consultation with utility coordinating committee
- Removing or relocating the interfering current source
- Preventing the pick up or limitation of the flow of interfering current

These general approaches can be translated into some typical specific techniques:

- Adjust current output from the interfering systems.
- Reduce the stray current at the source (e.g., isolation from ground, better conductivity of the negative return paths, or lower voltages).
- Apply coating to current pick-up area(s).
- Install a mitigation bond, or electrical connection, between the structures to drain the stray current back to its source through an electrical conductor rather than the earth.
- Relocate existing structures or re-route proposed structures.
- Properly locate isolating fittings.
- Apply cathodic protection to the affected structure at the interfering current's discharge site.
- Relocate anodes
- Break up the structure of interest into smaller electrically isolated segments to reduce the stray current voltage gradients being traversed by the structure.

Installation of Metallic Bonds to Control Interference

Figure 7.12 illustrates a metallic bond between pipelines. The resistance of the bond must be lower than the parallel path through the soil.

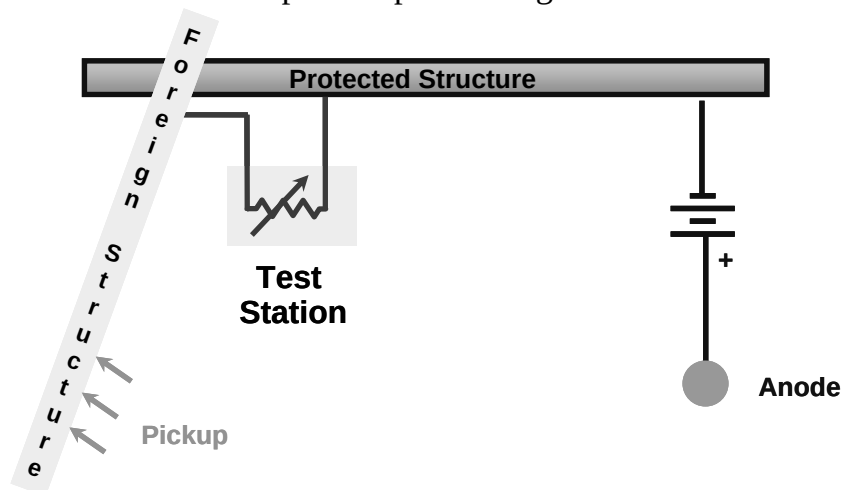


Figure 7.12 Electrical Bonding

Note: Protected structure must be more negative than foreign structure at the bond location to return current safely.

Figure 7.13 illustrates the use of a metallic bond to control stray current interference from a transit system.

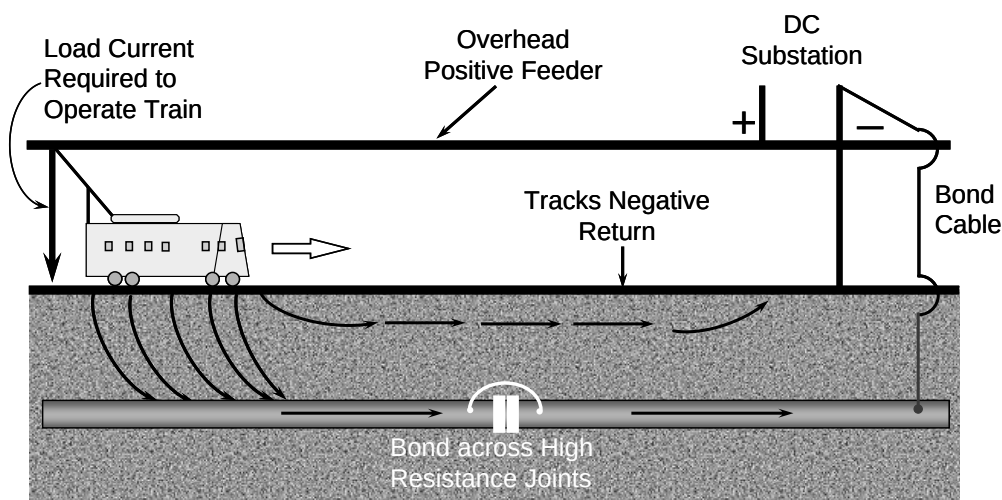


Figure 7.13 Installation of Metallic Bond

When installing metallic bonds, the following should be considered:

- Unidirectional control devices, such as diodes or reverse current switches, may be required in conjunction with the metallic bond if fluctuating currents are present. These devices prevent reversal of current flow.
- A resistor may be needed in the metallic bond circuit to control the flow of electrical current from the affected structure to the interfering structure. At the proper bond resistance, the discharge of interfering current from the structure to electrolyte is stopped.
- If cathodic protection exists on the interfering structure, attaching metallic bonds can reduce the magnitude of protection. Supplementary cathodic protection may then be required on the interfering structure to compensate for this effect.
- A metallic bond may not perform properly in the case of a cathodically protected bare or poorly coated pipeline that is causing interference on a coated pipeline. A metallic bond can increase the current discharge.

Coating the bare pipe or installing local galvanic anodes on the coated pipe may reduce interference effects.

Single Bond Problem

If after doing all that is practical to minimize the accumulation of stray currents on structures it is necessary to control the stray current, a bond may be required. If there is a definite location (i.e., structure such as the substation on the trolley system) of current discharge, it is frequently possible to design a metallic bond through which this current can be returned to the traction system or, in the case of an industrial operation, to the power source (Figure 7.14). This requires accumulating certain data and calculating the needed bond resistance. Mitigation of dynamic interference is not part of this course but is covered in an separate “Interference” course.

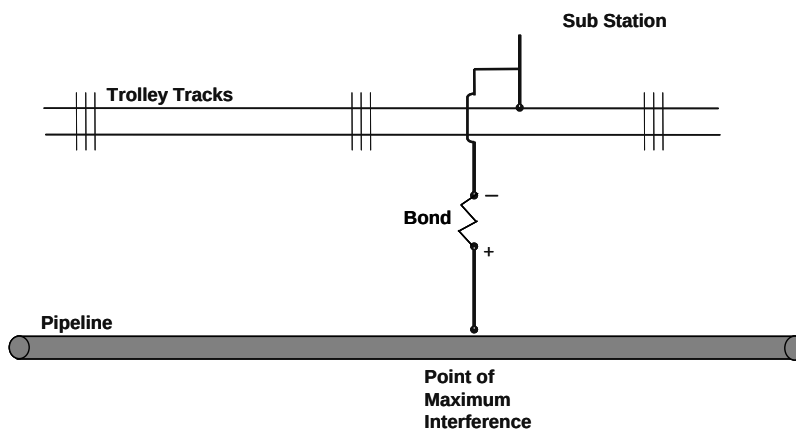


Figure 7.14 Solution of a Single Bond Problem

In relatively simple cases where a single source of stray current is involved, a trial-and-error solution may be possible. If you are only interested in eliminating the corrosive changes in potential caused by the source using a bond connection, then a variable resistor of adequate current-carrying capacity is inserted at the proposed bond location. The value of resistance is slowly reduced while the structure-to-electrolyte at the most critical location is observed. When the structure-to-electrolyte potential of the interfered-with structure at the most critical location is returned to normal, the correct value of resistance for the bond has been set.

Typically, it is desirable to use a resistance bond instead of a solid bond for the following reasons:

- The resistance bond limits the amount of current for the structure being protected.
- The resistance bond must be of low enough resistance to ensure that the stray current return is using this metallic path rather than the electrolyte.
- Resistance bonds are subject to damage by high current surges and therefore must be inspected frequently (see Chapter 8)

Controlling the Direction of Stray Current Through the Bond

Sometimes the direction of stray current through the bond is in the desired direction for much of the time but not all of the time. In these cases, stray current is toward the source when the structure to be protected is discharging current (corroding) and the reverse when the structure is receiving stray current. Stray current flow onto the structure is not desirable since it causes a discharge point at some other location(s). Diodes or reverse-current switches are used to prevent the reverse flow. The resistance to the forward current created by these devices must be included in the bond calculations.

Reverse-Current Switch

With dynamic stray current sources the direction of current through a bond could reverse causing accelerated corrosion. A diode can be installed to prevent this but it may be slow to respond. A relay can be installed that will open or reverse current. A combination of a diode and a relay reduces the disadvantages of each. Another solution may be a potentially controlled rectifier that controls the current in a forced drainage bond as shown in Figure 7.15.

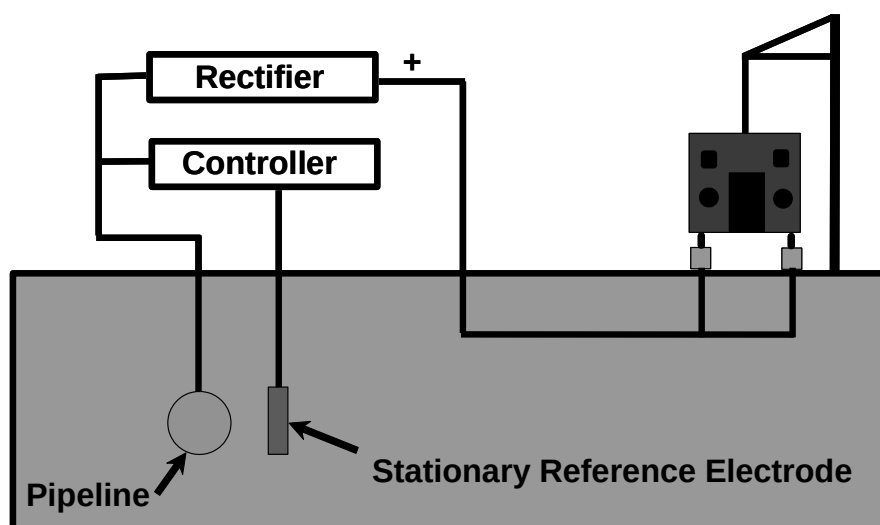


Figure 7.15 Forced Drainage Bond

Controlling Stray Current Through Cathodic Protection

Stray current can safely be returned to its source through a cathodic protection system. An example using a sacrificial (galvanic) anode is shown in Figure 7.16.

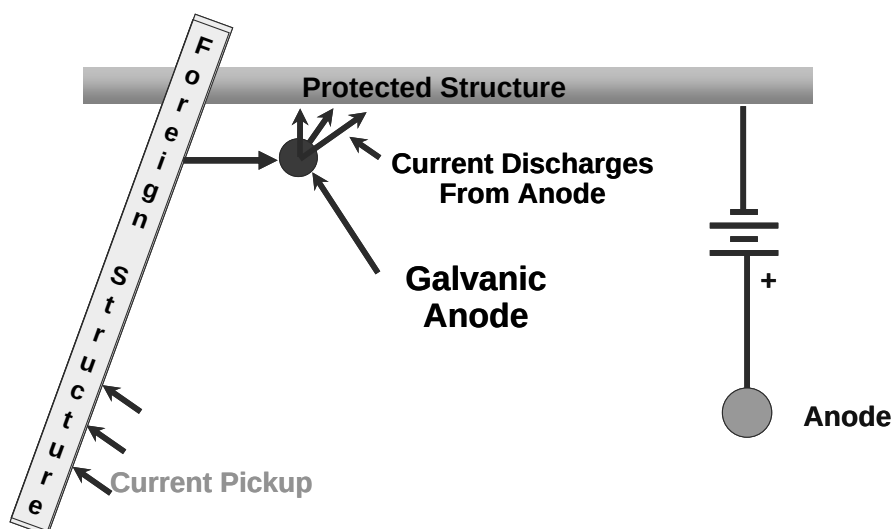


Figure 7.16 Galvanic Anodes

Coating

Coating of a known current pickup area can reduce the amount of stray current but the major portion of the anodic gradient should be coated (see Figure 7.17). Do not coat

areas of current discharge as this will cause accelerated pitting at the small coating holidays.

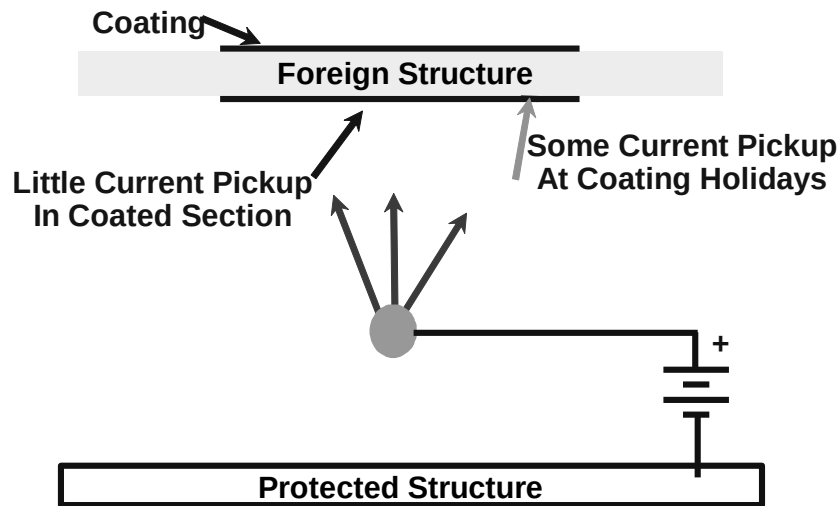


Figure 7.17 Protective Coatings

AC Testing and Mitigation

Introduction

Increased difficulty in obtaining utility rights-of-way and the concept of utility corridors have brought many underground structures, and pipelines in particular, into close proximity with electric power transmission and distribution systems. The electromagnetic field created by the alternating current expands and collapses and changes direction 120 times per second (Figure 7.18).

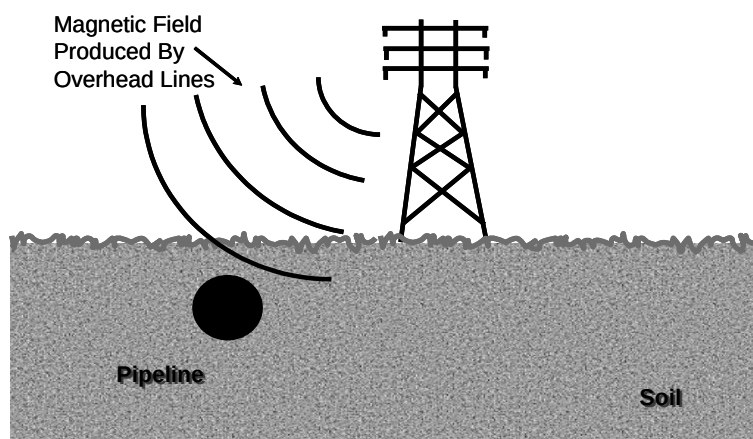


Figure 7.18 AC Interference on Pipeline from Changing Electromagnetic Field

Any metallic object subjected to an alternating electromagnetic field will exhibit an induced voltage. In addition, power conductor faults to ground can cause substantial fault currents in the underground structure.

There are three basic methods by which AC currents and voltages appear on metallic structures near AC power lines. These methods are as follows:

- Electrostatic coupling, where the structure acts as one side of a capacitor with respect to ground. This is only of concern when the structure is abovegrade (e.g., pipeline supported on skids).
- Electromagnetic induction, where the structure acts as the single-turn secondary of an air-core transformer in which the overhead power line is the primary. This type of induction may occur when the structure is either above or below ground.
- Resistive coupling, where AC power is transmitted to ground then flows on and off the underground structure.

Stray alternating currents can cause corrosion on metallic structures, although the amount of metal loss is less than an equivalent amount of DC current discharge would produce. For instance, 1 A DC discharge results in a loss of approximately 20 lbs of steel in one year, while one ampere of AC would consume less than 1 lb. The corrosion weight loss varies depending on the metal and the alternating current density. For instance, aluminum can exhibit a weight loss of approximately 40% of the DC equivalent at AC densities greater than about 40 mA/cm².

Even though the corrosion weight loss for AC currents is less than for equivalent DC currents, the magnitude of AC stray current is often large—hundreds of amperes under electromagnetic induction and thousands of amperes during power line faults. These high current levels can produce a shock hazard for personnel and can damage the structure and related equipment, such as cathodic protection facilities.

Electrostatic or Capacitive Coupling

Any two materials separated by a dielectric material can be considered as a capacitor. Capacitance is the ability to store electrical charge between two conductors relative to the voltage between the conductors. In this case the air is the dielectric and the power line is one conductor while the pipe or equipment is the other conductor.

Injury is more likely from an uncontrolled reaction to a shock rather than electrocution due to this couple.

This coupling is of most concern on aboveground equipment or pipelines such as during construction or maintenance of the pipeline. During these operations a qualified person should be on site to monitor the AC voltage and install grounds or bonds around open sections of pipe as necessary.

Electromagnetic Induction

The most important AC-induced interference current occurs as a result of electromagnetic induction as illustrated in Figures 7.19 and 7.20. Charges in the pipeline are alternately separated toward opposite ends of the pipeline. The resulting stray current magnitude is directly proportional to the phase currents ($I\Phi$) and their relative magnitudes and to the length (L) of mutual exposure; it is inversely proportional to the relative distance (d) between the structure and the power line conductors.

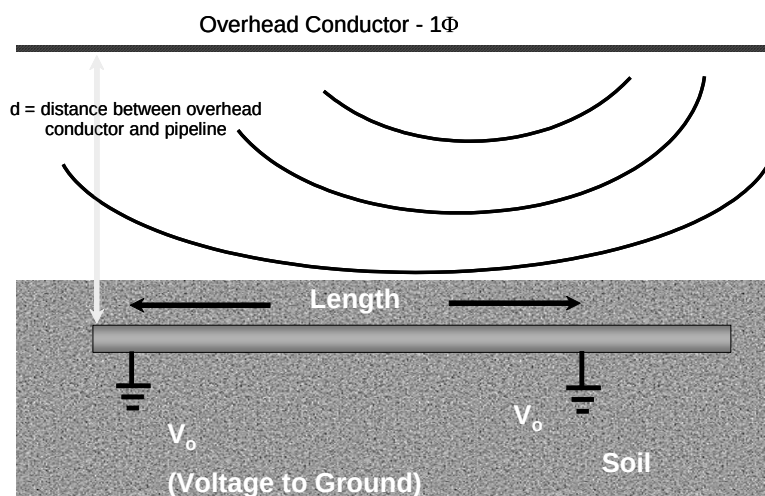


Figure 7.19 Electromagnetically-Induced AC Voltages

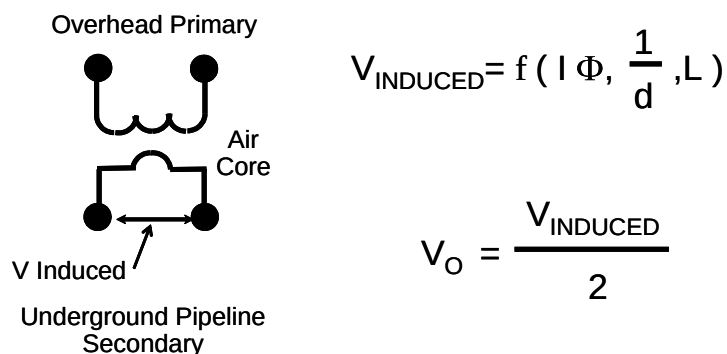


Figure 7.20 Electromagnetically-Induced Voltage Analogy

The induced voltage does not directly depend on the power line voltage; therefore, relatively low voltage AC power systems can produce electromagnetically-induced currents. In particular, single-phase heavily loaded AC power distribution lines can produce significant AC stray-current activity.

The pipe acts as a single-turn secondary of an air-core transformer, and the overhead AC power lines are primary (see Figure 7.21). The induced voltage (V_{induced}) appears across the ends of the pipe. The voltage to ground (V_{ground}) at each end of the structure is one-half the total induced voltage.

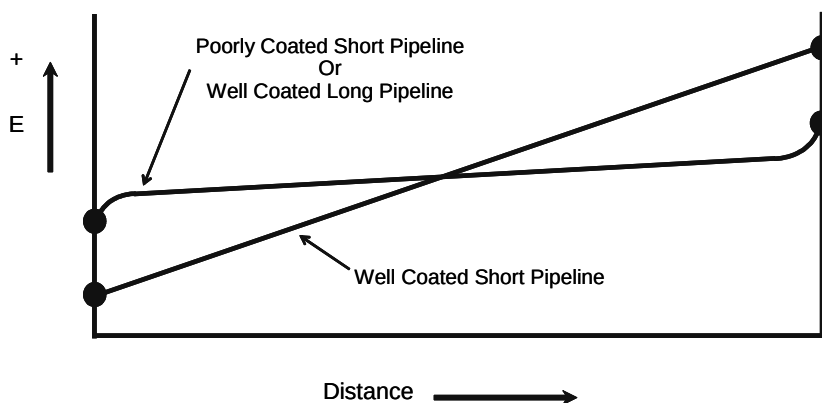


Figure 7.21 *Electromagnetically-Induced Voltages on a Parallel Pipeline*

For a short, well-coated structure that is not electrically lossy (i.e., causing attenuation or dissipation of electrical energy), the induced voltage profile with distance is linear. However, for poorly coated or very long, well-coated structures the voltage profile is nonlinear and the induced voltage peaks are of a lower magnitude. The induced voltage peaks appear at any electromagnetic field or pipeline discontinuity. For example, where a pipeline closely parallels a power line for some distance, induced voltage peaks would be expected where the power line and pipeline separate. Under such circumstances, the induced voltage effect can extend some distance along the pipeline from the power line right-of-way.

Measuring the structure's AC voltage with respect to earth can easily identify interference currents of an AC origin. The reference electrode used for cathodic protection measurements can be used as the ground contact. It is prudent to measure both AC voltage and DC potentials with respect to earth on all structures in close proximity to power lines. Typically, the DC potentials will be more positive at the AC voltage peaks than in the absence of AC interference.

Resistance or Conductive Coupling

During power line faults to ground, large AC currents can be transmitted to the earth through resistance coupling and, subsequently, into nearby underground structures. These currents, which can be several thousand amperes, can cause substantial physical damage to structure coatings; in extreme cases where the AC density is high, steel piping has been known to melt. Normally, these faults occur infrequently and are of short duration; therefore, they do not represent a serious risk to operating personnel.

AC Voltage on Pipelines

Hazardous AC voltages can occur on a structure as a result of induction, ground return currents, or faulted power circuits. In cases where a structure or test leads parallel power transmission circuits, significant AC voltages may be encountered.

If an AC voltage is near or is in excess of 15 V, the structure is considered hazardous and personnel working on the structure must be advised that a hazardous situation exists. The owner or supervisor must also be advised that steps need to be taken to reduce the hazardous voltage.

If the AC voltage is determined to be less than 15 V, no specific action is necessary. However, be aware that unlike DC potentials the AC voltage changes with the load on the power line so that it can increase from when measured to later in the day. Therefore contact the power company to find out what percent of load they were operating at when the readings were taken. This will indicate the AC voltage that can be expected at full load conditions. Whenever an AC voltage is close to 15 V (e.g., 12 V_{AC} to 14 V_{AC}) the same action should be taken as if it were 15 V_{AC} or greater.

Measurement of AC Voltage-to-Ground

The measurement of an AC voltage-to-ground is similar to a DC structure-to-electrolyte potential in that the voltage is measured between the structure and a reference electrode in the ground. There are significant differences including:

- The voltage measured may be hazardous and safety is of great concern. Do not touch any metal directly or through the meter leads/clips until it is established that there is no hazardous voltage.
- The reference electrode can be any bare metal but if a structure-to-electrolyte potential is also to be taken then a standard reference electrode can be used.
- The exposed portions of the reference electrode must not be touched and the electrode is to be installed first. If using a CSE then the top should be taped to prevent accidental contact.
- Induced AC voltage changes with the power line load and/or power line fault conditions.



- AC voltages change on aboveground pipelines under construction as the pipe length increases during the welding operation.
- Induced AC voltages can be expected to be higher at the discontinuities between the pipeline and the power line, that is, where they come together, separate, or cross.
- The measurement should duplicate step voltages. Therefore the electrode should be about one (1) meter away from the closest contact point(s) above ground on the structure. (Unlike structure-to-electrolyte potentials where the reference electrode is to be placed close to the structure where it enters the ground.)

Measure the AC structure-to-ground voltage first to make certain that it is safe to continue to work.

First, place the electrode into the ground approximately one (1) meter from the structure contact point then contact the structure with an insulated probe and turn the meter to AC Volts.

If the AC voltage is 15 V or greater, cease work until the AC voltage has been mitigated or, if qualified, proceed with further investigation into the cause and best means of mitigation. At no time should the structure be contacted under these conditions. Qualified personnel are to install temporary grounds, grids and/or nonmetallic fences at the work area or where the public can contact the structure until permanent protective equipment is installed.

Mitigation of AC Interference

The close proximity of structures to AC power lines and their sharing parallel paths for relatively long distances is the principal cause of stray AC. If the structure is remote from the power line(s), the interference can be virtually eliminated. Obviously, this method of mitigation is practical only at the preconstruction stage of either the power line(s) or the structure. Otherwise, the mitigation must be accomplished by alternative methods.

AC mitigation methods include:

- Significant separation between pipe and HVAC system
- Ground pipe using distributed galvanic anodes



- Grounding pipe using a metal such as zinc, magnesium, steel, or copper. DC decouplers such as a capacitor, polarization cells, or polarization cell replacements (PCR) connected between pipe and a separate “grounding” structure will reduce the CP requirements when a more noble ground is tied directly to the structure. A DC decoupler allows AC current to pass but blocks DC current.
- Protective devices for electrical isolating devices such as flange kits or joints.
- Step-and-touch protection systems (gradient mats or grids)

Figure 7.22 shows that the induced voltage is reduced if the structure becomes electrically conductive to earth. A well-coated structure would normally result in higher induced voltages.

On short lines, this effect can be remedied by using distributed sacrificial anodes on the structure; the anodes will not only be sufficient to provide cathodic protection current but will also simultaneously lower the resistance of the structure with respect to earth. Another approach is to use a zinc strip or ribbon anode parallel to the structure as the grounding method.

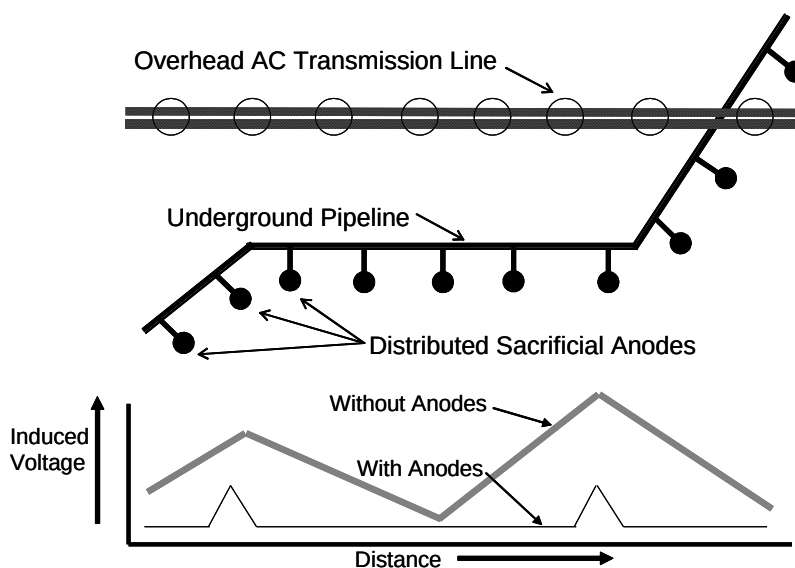


Figure 7.22 Mitigation of AC Interference Using Distributed Galvanic Anodes

On longer lines, the approach is to install grounds at the higher voltage peaks, normally at the discontinuities. In Figure 7.22 a similar effect could likely be achieved by installing larger grounds at the two voltage peaks.

Even with the grounds, hazardous voltages may still exist at other separation points and require more extensive grounds to reduce the AC voltage to 15 V or less.

Corrosion personnel must be aware of the possible shock hazard that can appear on a structure subjected to AC interference. Precautions such as nonmetallic dead-front test stations should be incorporated into the cathodic protection systems, and nearby cathodic protection rectifiers should be protected from AC fault currents with devices such as capacitors, polarization cells, and zinc grounding cells.

Bare casings interconnected through a capacitor bank, polarization cell replacement, or a polarization cell to the structure also are effective in mitigating AC interference.

Polarization Cells

Figure 7.23 shows a polarization cell used as a DC decoupler that allows AC current to pass to a ground while blocking the DC current intended for the cathodic protection of the structure. The cell consists of a container filled with a potassium hydroxide solution (the electrolyte) into which stainless steel plates are immersed and alternately connected to the cell terminals. One of the cell terminals is connected to the structure and the other to ground (or if used to protect an insulating joint from AC, the terminals are connected across the insulating joint).

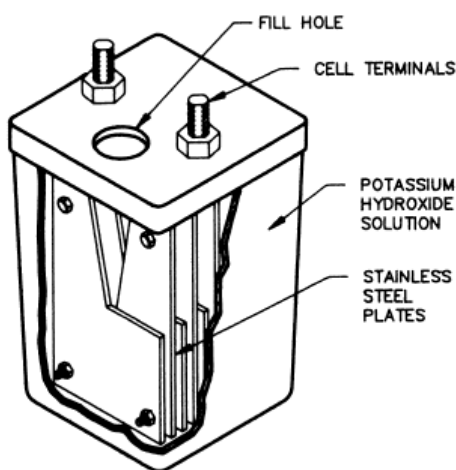


Figure 7.23 Polarization Cell

The cell acts as an electrochemical switch to shunt voltage to ground. Under normal conditions, the plates of the cell polarize and allow normal cathodic protection potentials

to exist. As the applied voltage across the cell increases from either AC or DC, the polarization film on the plates breaks down and the cell shunts current. The cells must be properly vented (to allow gases generated during operation to escape) and periodically inspected to ensure adequate electrolyte levels.

Semiconductor Devices

Solid state devices are available that block the low-potential DC cathodic protection current from leaking across an insulating device while still providing instant protection from high-voltage spikes and induced AC. These devices do not involve caustic liquid electrolytes and are a low-maintenance device. Figure 7.24 shows a semiconductor-type device.



Figure 7.24 Semiconductor Device for AC and High-Voltage Fault Control (courtesy of Dairyland Electrical Industries)

Ground Mats

Ground mats may be required to protect personnel from electric shock while working on well coated pipelines. Induced voltage from AC power lines and lightning strikes can create large voltage gradients between a pipeline and earth.

Ground mats are metal conductors placed in the soil around locations where a person may come in contact with the pipeline. Test station wires, line valves, and other fittings are examples of where a hazard may exist. The ground mat is connected to the pipe thus assuring that the pipe and the ground in the immediate area are at the same electrical voltage. They are not intended to be

an electrical ground as they are installed close to the surface often in high-resistivity soil or frost.

Ground mats can be made from any metal. A more active metal such as zinc or magnesium is used to have minimum impact on the cathodic protection system. Other metal such as copper or steel can be used but will add significantly to the current required for cathodic protection due to their large area of earth contact. If the mats are constructed of copper or other noble alloy or metal, adequate cathodic protection must be applied to eliminate the corrosive galvanic couple or isolated using a DC decoupler. Figure 7.25 illustrates how ground mats are applied with the rings becoming consecutively deeper at about 15° away from the structure.

It should be noted that if zinc or magnesium is used as a gradient mat around a test station, then the instant OFF potential is no longer valid as all sources of DC current have not been interrupted.

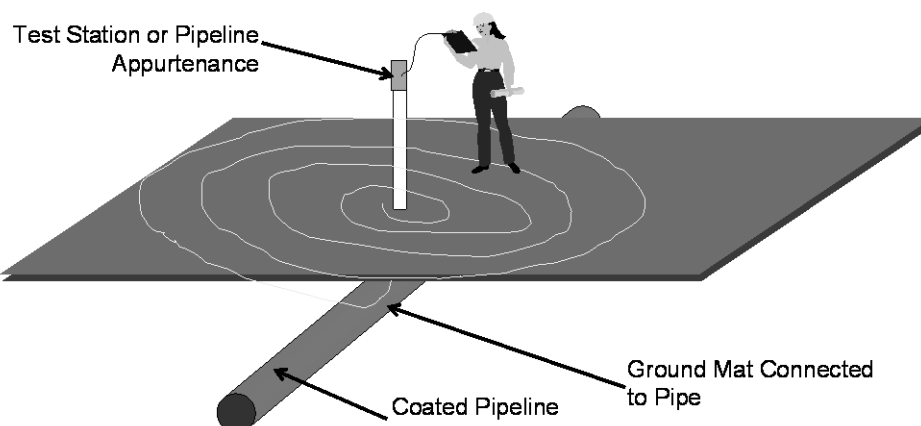


Figure 7.25 Typical Ground Mat Used to Protect Personnel from Electric Shock

AC Corrosion¹

Since at least 1916 AC current discharge from steel has been known to cause corrosion but at a rate that is a small fraction of what would occur for an equivalent amount of DC current. It was also largely believed that AC corrosion effects could easily be overcome by the application of cathodic protection. However, in the 1990s corrosion failures occurring on cathodically

¹ Gummow, R.A., Wakelin, R.G., and Segall, S.M., "AC Corrosion - A New Challenge to Pipeline Integrity," CORROSION/98, paper no. 566 (Houston, TX: NACE, 1998).

protected pipelines began to be attributed to the discharge of steady state AC currents.

While the mechanism of AC corrosion is still not completely understood, there appears to be a relationship between AC current density and corrosion rate, and there may be a current density threshold at which AC corrosion begins to occur, as follows:

$i_{ac} < 20 \text{ A/m}^2$	No Corrosion
$20 \text{ A/m}^2 < i_{ac} < 100 \text{ A/m}^2$	Corrosion Unpredictable
$i_{ac} > 100 \text{ A/m}^2$	Corrosion Expected

The above thresholds are with cathodic protection applied. That is, cathodic protection may be of some benefit at lower AC current densities, but any amount of cathodic protection at higher AC current densities does not mitigate the AC corrosion. The current density is a function of the AC voltage, coating holiday size and the soil resistivity. As the last two are normally fixed, mitigation would be in the form of reducing the structure AC voltage to earth.

Major Objectives of a Cathodic Protection System

The following objectives must be accomplished in a cathodic protection system that adequately prevents corrosion:

- Provide sufficient current to the structure to be protected.
- Distribute this current such that the selected criteria for cathodic protection are efficiently attained.
- Minimize the interference currents on nearby underground structures and from other sources of DC current.
- Have an anode system with life commensurate with the required life of the protected structure, or provide for periodic rehabilitation of the anode system.
- Allow for changes in current requirements with time.
- Ensure anodes are not disturbed or damaged and other structures have not been installed close to them.
- Ensure that the CP system operates continuously.

Monitoring

The objective of a cathodic protection system is to ensure that it continues to operate at the intended levels. Frequent inspections will be the first step in keeping the time without protection to a minimum. The second step is to have a quick response plan to correct trouble as it is found.

A complete monitoring program involves a detailed field survey over the entire system with brief inspections in between. The detail survey ensures that the conditions have not changed, and the current output is still adequate to meet a cathodic protection criterion or, if not, to make the appropriate adjustments.

The routine readings must be adequate to confirm that the system is continuing to operate at the levels expected.

Detailed Field Survey

Electrical measurements are normally taken at the source(s) of cathodic protection and throughout the structure at close enough spacing to confirm that a criterion for protection is met. If a portion of the system is delinquent then additional testing is required to either locate the trouble or to determine the additional current required to meet a criterion.

Regulated industries are required to meet minimum standards and inspection intervals that will vary depending on the country (Table 8.1).

Pre-Survey Planning

Before starting the field survey, all available information about the structure should be assembled and studied. This will furnish valuable data on conditions to be expected during the survey.

The following items of information are typical of those that should be accumulated prior to planning and starting the field survey, especially the first survey:

- Structure material(s): example, steel (including grade of steel), cast iron, wrought iron, or other material and their known electrical resistance.
- Is the structure bare or coated? If coated, what is the coating material and what coating specifications were used?
- If it is an existing structure, is there a leak record? If so, information on the location and date of each leak occurrence may indicate the more serious problem areas.
- Structural dimensions such as wall thickness and weight per foot
- If applicable, sizes of casing pipe with wall thickness or weight per foot; grade of steel used; data on insulators used between pipe and casing; specifications of casing end seals; for coated casing pipe, type of coating, and application specifications.

- Location and construction details of all corrosion test points installed on the structure. If no corrosion test points were installed, determine locations where contact can be made with the structure for test purposes.
- Is the structure all welded construction or are mechanical couplings used?
- Location of branch taps or associated structures
- Location of any electrical isolating flanges or couplings used to sectionalize the structure or to electrically isolate it from other portions of the system or from foreign structures.
- Details and location of the cathodic protection system.
- System maps
 - Location of structures of other ownership that may be affected, including the location of cathodic protection current sources.
 - Location of test stations and other facilities
 - Location of possible sources of manmade stray current (such as DC electric transit systems or mining operations)
 - Location of AC power services if additional current capacity is suggested
- Does any part of the structure closely parallel (within 200 ft or so) high-voltage (HVAC or HVDC) electric transmission lines? If so, what is the length of such exposure? How close is the structure to the towers? What voltages and currents are associated with the AC power line? What method is used for grounding the towers? Is any grounding in place for the pipeline? These factors aid in determining whether AC voltages may be induced on the structure during construction, maintenance or during normal operation of the structure. If induced AC potentials are possible, the structure should be considered a safety hazard and contact with it avoided until measurement of actual AC potential.
- Is the structure operated at elevated temperatures or will it be in the foreseeable future? (High temperatures deteriorate coatings and increase corrosion rates.)

Survey Methods

After obtaining background information on the structure, the actual field survey may be organized to use several or all of the following procedures (either separately or combined). The methods selected and the relative importance of data obtained from each method will depend on the particular situation at hand.

- ON/OFF or ON Structure-to-electrolyte potential survey
- Line current survey
- Location of faulty isolation
- Road/railroad casing tests if applicable
- Coating conductance tests if applicable
- Inspection for corrosion

Sometimes nothing will satisfy the corrosion engineer except having an actual look at the structure being surveyed. Actually, this is an acceptable and desirable procedure for evaluating the severity of corrosive areas detected by abovegrade surveys. “Hot spot” corrosion (local areas of corrosion) found during a survey may be uncovered and inspected.

If areas are found where structure coatings have unusually low resistance values, bellhole inspections may be in order to trace causes of the coating damage. This may be particularly valuable with older coatings to determine the nature of deterioration and as a guide to selecting materials for future coating projects.

- Electrical resistivity of the environment if applicable

In addition to being a valuable aid for interpreting the severity of corrosive areas, a resistivity survey is extremely helpful in later selection of sites for cathodic protection installations.

- Determination of acidity or alkalinity of the environment

In many areas, an environment is approximately neutral (pH 7). Some locations have unusual environmental conditions that could be either alkaline or acidic.

It may be of value to check the soil pH. The results could have considerable effect on the locations selected for future cathodic protection rectifiers or galvanic anodes. A particularly acidic condition could indicate the need for a relatively high current density to maintain cathodic protection. This could make it desirable to locate cathodic protection installations at or near the area of high current requirement.

- Determination of conditions suitable for anaerobic bacterial corrosion

Certain bacteria that exist under anaerobic conditions (absence of oxygen) can reduce sulfates and consume hydrogen in the process. Consumption of hydrogen at the structure surface depolarizes the steel at cathodic areas and permits more rapid consumption of the metal by galvanic corrosion cells. The bacteria then do not directly attack the structure but create conditions conducive to more rapid attack by existing corrosion cells, which, normally, are partially stifled by the development of a polarization film of hydrogen.

Areas where anaerobic corrosion is suspected may be exposed for examination. If anaerobic bacteria are present and active, a layer of black iron sulfide will be found at the structure surface. The deposit would be expected only at coating defects on structures having a bonded coating. If this black substance is iron sulfide and is treated with a dilute solution of hydrochloric acid, hydrogen sulfide gas will be released, which can be recognized by its characteristic rotten egg odor.

The practical effect of anaerobic bacterial activity on the application of cathodic protection is an increase in the amount of current required to maintain cathodic protection.

- Evaluation of current requirements for cathodic protection

During a survey, it may be desirable to conduct a specific test to determine the additional current requirements if a cathodic protection criterion is not achieved. Such a test consists of forcing direct current to flow from a temporary anode bed to the structure being studied and determining how much current will be needed to achieve a specific level of polarization.

- Use of recording instruments to study dynamic stray current conditions

- Earth Gradient Measurements

Routine Readings

The method of routine inspection will vary depending on the type of structure and cathodic protection system. A plan must therefore be developed and tested to ensure that the objectives are met. Such a plan would include:

- The type of cathodic protection system
- The type of measurements to be taken
- The location where the readings are to be taken
- The type of equipment to take the measurements
- The frequency of the readings.

Sacrificial (Galvanic) Anodes

Most sacrificial (galvanic) anode systems can be routinely inspected by taking reference potential measurements at critical locations throughout the system. Since these systems usually provide low current outputs, a problem such as a shorted isolation will have a major impact on the potentials. Reference potentials are essentially a structure-to-electrolyte potential although for this purpose a large unprotected structure can be used as a reference and the data converted to a standard reference electrode. An example may be the use of a large unprotected metal water main by taking a reference potential across an isolating feature between it and a gas distribution system. A reading with a nonstandard reference should not be used to confirm a criterion but can be used to predict a change in the level of protection.

When another large bare structure is accidentally connected to a structure protected by a galvanic anode, the structure-to-electrolyte potential will naturally become less electronegative or more electropositive. This change in potential then increases the difference in potential between the structure and the anode thus increasing the driving voltage and in turn increasing the current.

Impressed Current Systems

A combination of inspections of the DC power source and reference potentials are often employed for impressed current systems. In the case of a transmission pipeline where few external problems are expected, then an inspection of the DC power sources may be sufficient.

Where there is a possibility of shorted isolation or stray currents then reference potentials should also be taken.

The readings taken to confirm that a DC power source is operating properly should include:

- DC Current
- DC Voltage
- Tap Setting

These are described in more detail in Chapter 4. The DC current is the prime measurement but the DC voltage, when used to calculate anode resistance, will help predict future anode failures. The initial increase in resistance is slow but as the few remaining anodes fail, the resistance increases at a greater rate. The tap setting will indicate if someone authorized or has not been adjusting the taps.

If a DC power source is not accessible during portions of the year, then reference potentials taken at a “Control Point” can be taken. A “Control Point” is located such that the DC power source (rectifier) in question has a large influence on the potentials. The influence should be confirmed by either turning all rectifiers influencing the area off in turn and taking ON/OFF potential measurements or by installing interrupters at different cycles in the rectifiers and taking a datalog at the Control Point. In this way a prediction of the operating status of the rectifier can be made by an analysis of the Control Point potentials. Another factor to consider is that structure-to-electrolyte potentials may change with the seasons.

A shorted bare structure will likely exceed the capacity of the impressed current cathodic protection system and cause an electropositive shift in the structure-to-electrolyte potential. Since the anode resistance is the major component of the total resistance in an impressed current system a small reduction in the structure resistance is not likely to have a noticeable change in the current output of the DC power source.

Inspection Intervals

Regulated industries are required to inspect the cathodic protection systems and take sufficient readings at intervals to ensure that it is operating as intended. This practice is of value to any cathodic protection system as it helps ensure that the cathodic protection system continues to operate. The more frequent the reading interval, the more likely the structure will receive protection for more of its life. To illustrate this point, if a rectifier goes off just after it is read and is not discovered for two (2) months and this happens once each year then after twelve (12) years, the pipeline has been without protection for an accumulated period of two (2) years. This possible outage period can be reduced to an accumulated time of one (1) year/twelve (12) years by reading the rectifiers monthly.

A summary of the inspection intervals required by different regulations is given in Table 8.1

Table 8.1 Cathodic Protection Inspection Intervals for Regulated Pipelines

Regulation or Standard	Detailed Survey Frequency	Rectifier Inspection Frequency	Interference Control Drainage Bond Frequency
USA			
DOT 49CFR192 DOT 49CFR195	Once per calendar year not to exceed an 15-month interval	Six times per calendar year not to exceed 2½- month intervals	Six times per calendar year not to exceed 2½- month intervals
Canada			
CSA Z662 (CGA OCC-1)	Annual	Monthly not to exceed 6 weeks	Bimonthly
Europe			
ISO 15589 Part 1	Instant OFF annually except stable systems can extend to every 3 years with ON potentials in between	1 to 3 months depending on conditions such as lightning, stray currents, construction	Monthly
	Less frequent measurements considered based on results of specialized surveys		
Industry Practice			
NACE Standard SP0169	Annually. Longer or shorter periods depending on safety factors, etc.	2-month intervals	2-month intervals

Records

Complete and accurate records are mandatory. There are technical, historical, and legal reasons why records must be kept. You, as a CP Technician, must accept full responsibility for the accuracy and completeness of both your records and those of personnel under your supervision.

A great deal of time and effort has gone into collecting this information and it is of no use if it is not documented properly.

Records for Technical Purposes

These records may be used for:

- Technical support of cathodic protection (CP)
- Data that must stand up to a regulator's scrutiny if a regulated industry
- Evaluations of coatings
- Stray current analysis
- Assessment of CP capacity
- Location of CP equipment relative to structures

Records for Historical Purposes

We must recognize that throughout the life of the system others will be referring to these records. Full and complete explanations are required as they may be reviewed at a time when personnel and conditions have changed. Data that seems obvious today may be confusing at a later date. Regulated industries must keep their records for a specified period of time or for the life of the structure. Regardless, historical information is of great value in:

- an assessment of the life of the CP system
- changes to the operation that have occurred
- troubleshooting
- determining future requirements
- an External Corrosion Direct Assessment (ECDA)¹
- an Internal Corrosion Direct Assessment (ICDA)

Records for Legal Purposes

Although we hope that an incident never occurs, we must be prepared to show due diligence and be prepared for a legal defense. For this reason records must be impeccable with no room for criticism. Some items that are necessary to include before filing the notes include:

- Are the values recorded correctly?
- Has polarity been assigned to all readings?
- Are the units clearly indicated (Volts, Amperes, etc.)

¹ See NACE SP0502, "Pipeline External Corrosion Direct Assessment Methodology," a four-part program to assess external pipeline integrity especially for pipelines that are not suitable for an intelligent tool.

- Where applicable, is the reference electrode clearly noted?
- Are the exact reading locations listed?
- Are the structures on which the readings are being taken described?
- Are drawings and maps accurate and up to date?
- Have descriptions of troubleshooting work been included?
- Has inspection data been documented?

Field Data Sheets

Tester's name, date, time, and weather conditions should always be noted on the data sheets. Weather conditions can affect the data collected and help explain the data collected in the field.

Measurements must include the accurate recording of the:

- Value
- Polarity
- Units
- Type of reference electrode, where applicable

Without all of the above indicated for each measurement, the data is of little use in industry or for legal purposes and will be considered incorrect in this course!

Sketches showing the layout of structure(s) should be completed along with the location of measurements with the polarity of measurements indicated. The name and serial numbers of all instruments used should be included in the data sheets. Always indicate unusual site conditions. 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 met 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 troubleshooting.

If you have been collecting data on a computer datalogger, 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 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 previously discussed above under Data Sheets.

Records of Related Information

Direct Inspection

Whenever an underground structure is exposed an inspection for corrosion should be made and the data recorded even though no corrosion is found. This information can then be used to complete future analysis of the effectiveness of cathodic protection systems and of pipeline integrity.

Leak Frequency

Records of corrosion-related leaks are invaluable in assessing the effectiveness of the program and the integrity of the structure (Figure 6.60). Maintaining leak record curves is a method that can be used to prove the effectiveness of cathodic protection and is also useful for owners of structures that are not regulated by a government agency. All information related to the type and cause of the leak should be recorded and maintained.

In-Line Inspection

The results of in-line inspection and subsequent dig inspections are extremely valuable in confirming the effectiveness of the corrosion control program in addition to confirming the pipeline integrity. Unfortunately, this does not confirm this effectiveness until after corrosion has had an opportunity to proceed therefore it should be used in conjunction with other tests. Once it has confirmed that no corrosion is occurring at the potentials that have existed, then these potentials can be argued as an effective criterion for those particular sections of pipeline.

Storage

Data must be stored in a predefined fashion that allows it to be easily retrieved for future reference. The storage time for regulated industries is defined by their regulations, however, it is recommended that this data be kept for the life of the system for both regulated and unregulated systems. As discussed before this data can be invaluable for ECDA.

Regulatory Requirements for Records

Each country or local region has its own regulations and the CP technician must be familiar with the regulations that apply to the facility in that particular area. For example, those working on regulated systems must be familiar with the following applicable codes and standards.

Leak Records

Structure	Federal Regulation	Storage
USA		
Gas pipeline	Title 49 CFR Part 191.23(a)(1)	Life of pipeline
Gas pipeline	Title 49 CFR Part 192	
Hazardous liquids pipe	Title 49 CFR Part 195.55 (a)(1)	Life of pipeline
Hazardous liquids pipe	Title 49 CFR Part 195.404(c)(1)(2)	
Canada	CSA Z662	Life of pipeline
Europe	ISO 15589 Part 1	Retained

Pipeline Examinations

Structure	Regulation/Standard	Storage
USA		
Gas pipeline	Title 49 CFR Part 192.491	Life of pipeline
Hazardous liquid pipe	Title 49 CFR Part 195	Life of pipeline
Canada	CSA Z662	Life of pipeline
Europe	ISO 15589 Part 1	

Cathodic Protection Facility Locations

Structure	Regulation/Standard	Storage
USA		
Gas pipeline	Title 49 CFR Part 192.491	Life of pipeline
Hazardous liquid pipe	Title 49 CFR Part 195.266(f)	Life of pipeline
Canada	CSA Z662 (CGA cOCC-1)	Life of pipeline

Tests, Surveys, and Inspections

Structure	Regulation/Standard	Storage
USA*		
Gas pipeline	Title 49 CFR Part 192.465(a) and (e)	Life of pipeline
Hazardous liquid pipe	Title 49 CFR Part 195.416(a)	Life of pipeline
Underground tanks	Title 40 CFR Part 280.34	Life of tank
Aboveground tanks	API RP 651	5 years
Canada	CSA Z662 (CGA OCC-1)	Life of pipeline
Europe	ISO 15589 Part 1	Retained for future reference

*Field testing, including soil resistivity, pH, current requirement tests, leak detection surveys, coating inspections, periodic tests of power sources, internal corrosion monitoring devices, stray current control devices, and coating evaluation must be kept for five years per 49 CFR Parts 192.455, 457, 461, 465, 416, 477, and 481. This information is; however, of value in future assessments and for a possible External Corrosion Direct Assessment (ECDA) therefore it is wise to keep it for the life of the system.

Useful Information

Other useful information on a system that should be maintained and updated includes:

- System specifications and practices as applicable
 - Site maps
 - Construction dates
 - Pipe, fittings, etc.
 - Coatings
 - Casings
 - Test stations
 - Electrical insulating devices
 - Electrical bonds
 - Aerial, bridge, and underwater crossings
 - Project budget
- System site conditions
 - Existing and proposed cathodic protection systems
 - Possible interference sources
 - Special environmental conditions
 - Nearby buried metallic structures (including location, ownership, and corrosion control practices)
 - Structure accessibility
 - Power availability
 - Feasibility of electrical isolation from foreign structures
- Field survey, corrosion test data, and operating experience
 - Protective current requirements to meet applicable criteria
 - Electrical resistivity of the electrolyte
 - Electrical continuity
 - Electrical isolation

- Coating integrity
 - Cumulative leak history
 - Interference currents
 - Deviation from construction specifications
 - Other maintenance and operating data
- Other
 - Smart pig data
 - Dig site records
 - Coupon data

Some of the data gathered can be analyzed using graphical or statistical methods to highlight locations needing particular attention. For example, soil resistivity data can be statistically analyzed and plotted to determine areas with particularly corrosive soils. Pit depth data can be statistically analyzed to identify areas that are severely corroded. Leak records can be plotted as cumulative leaks vs. time to identify trends and prioritize areas needing attention.