# CP 3–Cathodic Protection Technologist
# COURSE MANUAL

July 2008
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# Acknowledgements

The time and expertise of a many members of NACE International have gone into the development of this course. Their dedication and efforts are greatly appreciated by the authors of this course and by those who have assisted in making this work possible.

The scope, desired learning outcomes and performance criteria were prepared by the NACE Cathodic Protection Subcommittee under the auspices of the NACE Certification and Education Committees. Special thanks go to this subcommittee.

Cathodic Protection Subcommittee

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This group of NACE members worked closely with the contracted course developers, Rob Wakelin, CorrEng Consulting Service, Inc., (Downsview, Ontario), Bob Gummow, CorrEng Consulting Service, Inc., (Downsview, Ontario) and Tom Lewis, Loresco International (Hattiesburg, Mississippi).

# NACE COATINGS NETWORK (NCN)

NACE has established the NACE Coatings 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 Coatings Network, you will be part of an E-mail-driven open discussion forum on topics A-Z in the coatings 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.

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


1. **To Subscribe**, send a blank e-mail to:
   Join-coatings@nacecorrosionnetwork.com

   **To Unsubscribe**, send a blank e-mail to:
   Leave-coatings@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.

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# Instructions for Completing the ParSCORE™ Student Enrollment Sheet/Score Sheet

1. Use a Number 2 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**
   √ LAST NAME:       Your last name (surname)
   √ FIRST NAME:      Your first name (or name by which you are called)
   √ 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 <u>NOT</u> 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.

# WEB INSTRUCTIONS
# FOR ACCESSING STUDENT GRADES

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.  The following are instructions for this process:

To access grades on the NACE Web site go to:  www.nace.org

Choose:      **Education**
                 **Students Only**
                 **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**
      (Normally the last four digits of the telephone number entered on your exam form)
Click on **Search**

<u>Prior to leaving the class</u>, write down your course and student information in the spaces provided below:

| |
|---|
| **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.

Any questions, please contact Carol Steele at [carol.steele@nace.org](mailto:carol.steele@nace.org) or at 281-228-6244.

# Audience (Who Should Attend)

This course is designed for an individual who has extensive CP field experience and a strong technical background in cathodic protection and who intends to become a certified Cathodic Protection Technologist.

# Prerequisites

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

**PATH 1**

8 years **Cathodic Protection** work experience with progressively increasing technical responsibilities

**PLUS**

High school diploma or GED

**PLUS**

Algebra and logarithm training
CP 2–Cathodic Protection Technician certification or equivalent training

**PATH 2**

6 years **Cathodic Protection** 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

**PLUS**

CP 2–Cathodic Protection Technician certification or equivalent training

**PATH 3**

3 years **Cathodic Protection** work experience with progressively increasing technical responsibilities

**PLUS**
4-year physical science or engineering degree

**PLUS**
CP 2–Cathodic Protection Technician or equivalent training

# Length

The course begins on Sunday at 10:00 am and concludes on Friday at 5 pm.

# Examination

This course will conclude with a written final examination. This examination consists of 2 parts–Part A and Part B. Part A is multiple choice format and Part B is essay format. A combined score (Part A and Part B combined) of **70%** or greater is required for successful completion of this course.

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

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

# Certification Application

Successful completion of the written examination and approval of the CP 3–Cathodic Protection Technologist certification application is required for certification.

# Cathodic Protection Certification Application
# CP3 - Cathodic Protection Technologist
**(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:

**CLASSROOM TRAINING - CP3-Cathodic Protection Technologist**
**or**
**EXAM ONLY OPTION - CP 3-Cathodic Protection Technologist 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                    FAX TO:  281-228-6311**
**CERTIFICATION DEPARTMENT**
**1440 SOUTH CREEK DRIVE**
**HOUSTON, TX  77084**

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 standing 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. 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: _____

**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:    _____

NAME: _____

PLEASE CHECK APPROPRIATE BOX (choose only one):

☐  I AM APPLYING FOR CP TECHNOLOGIST **CLASS & EXAM** SCHEDULED FOR:

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

✦ Click here for <u>COURSE </u>SCHEDULE

**<u>OR</u>**

☐  I AM APPLYING FOR CP TECHNOLOGIST **EXAM ONLY** SCHEDULED FOR:

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

✦ Click here for <u>EXAM ONLY</u> SCHEDULE

### REQUIREMENTS FOR CATHODIC PROTECTION TECHNOLOGIST

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.

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### <u>CP TECHNOLOGIST CLASSROOM TRAINING OR  CP TECHNOLOGIST EXAM ONLY</u>

**<u>Path #1</u>**
**8 years CP work experience with progressively increasing technical responsibilities**
**PLUS**
**high school diploma or GED**
**PLUS**
**algebra and logarithm training**
**CP Technician certification or equivalent training**

**<u>Path #2</u>**
**6 years CP work experience with progressively increasing technical responsibilities**
**PLUS**
**2 year post high school training from an approved math or science technical/trade school including algebra and logarithm training**
**PLUS**
**CP Technician certification or equivalent training**

**<u>Path #3</u>**
**3 years CP work experience with progressively increasing technical responsibilities PLUS**
**4 year physical science or engineering degree PLUS**
**CP Technician certification or equivalent training**

---

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

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: _____

**CATHODIC PROTECTION WORK EXPERIENCE**
**FORM 2:  INDIVIDUAL JOB EXPERIENCE**          Page _____ of _____

Use one of these forms for each period of **cathodic protection** work experience ("job") you wish to document.  Make and use as many copies of this form as you need.  Please provide the information requested per the directions and definitions provided.

_____

**Job Information**

Applicant's Name: _____          Who can NACE contact to verify this experience

Job Title: _____          Name: _____

Company: _____          Company: _____

From:  Month _____     Year _____          Address: _____

To:     Month _____     Year _____          State/Province: _____

                                                         Zip/Postal Code: _____

Phone: _____

Fax: _____          E-mail: _____

___

**C.2     CATHODIC PROTECTION WORK EXPERIENCE**
**FORM 2:  INDIVIDUAL JOB EXPERIENCE**          Page ___ of ___

Describe in detail what are/were your **cathodic protection** related duties in this job.  (Do not write on the back of this form).  You may attach additional single sided sheets)

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

_____

_____

_____

_____

_____

_____

_____

_____

_____

_____


Signed: _____Date: _____

# Education and Training For CP 3 – CP Technologist

NAME: _____

Please check applicable statement of qualification:

☐ **Path #1**
**8 years CP work experience with progressively increasing technical responsibilities**
**PLUS**
**high school diploma or GED**
**PLUS**
**algebra and logarithm training**
**CP Technician certification or equivalent training**

## OR

☐ **Path #2**
**6 years CP work experience with progressively increasing technical responsibilities**
**PLUS**
**2 year post high school training from an approved math or science technical/trade school including algebra and logarithm training**
**PLUS**
**CP Technician certification or equivalent training**

## OR

☐ **Path #3**
**3 years CP work experience with progressively increasing technical responsibilities**
**PLUS**
**4 year physical science or engineering degree**
**PLUS**
**CP Technician certification or equivalent training**

### 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 (please include certified copy of diploma with this application)

| Name of College or University | Degree Received | Date Awarded | Student ID Number |
|---|---|---|---|
| _____ | _____ | _____ | _____ |
| _____ | _____ | _____ | _____ |

D.    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 <u>must</u> 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: _____

**REFERENCE**: The applicant is applying for CATHODIC PROTECTION recognition by NACE International.  Applicants for certification must meet specific requirements; please see the list of these requirements on the following page.  Evaluation of an applicant's qualifications also depends on assessment of professional CATHODIC PROTECTION experience by references.  It is requested that you complete Items D.4 through D.13 on this form and return it directly to NACE.

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.)**

D.8     Based on this personal knowledge, I know that the quality of the applicant's work in the field of **CATHODIC PROTECTION** is
Excellent ☐                    Average ☐                    Below average ☐

D.9     The applicant is proficient in the following phases of **CATHODIC PROTECTION**:
_____
_____

D.10    Would you employ, or recommend the employment of, the applicant for employment in the phase of **CATHODIC PROTECTION** work you have described in Item D. 9?
Yes ☐                    No ☐

D.11    Please describe any major projects/activities in which the applicant has been involved in the field of **CATHODIC PROTECTION** work.  Describe only those where you had personal knowledge of the applicant's work.  Please indicate the degree of responsibility exercised by the applicant, the complexity of the project/activity, the degree of knowledge/skill required, etc.  (Attach a separate sheet)

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** <u>one</u> 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** <u>one</u> 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** <u>one</u> 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

D.    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: _____

**REFERENCE**: The applicant is applying for CATHODIC PROTECTION recognition by NACE International. Applicants for certification must meet specific requirements; please see the list of these requirements on the following page.  Evaluation of an applicant's qualifications also depends on assessment of professional CATHODIC PROTECTION experience by references.  It is requested that you complete Items D.4 through D.13 on this form and return it directly to NACE.

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.)**

D.8 Based on this personal knowledge, I know that the quality of the applicant's work in the field of **CATHODIC PROTECTION** is

Excellent ☐          Average ☐          Below average ☐

D.9 The applicant is proficient in the following phases of **CATHODIC PROTECTION**:

_____

_____

D.10 Would you employ, or recommend the employment of, the applicant for employment in the phase of **CATHODIC PROTECTION** work you have described in Item D. 9?

Yes ☐          No ☐

D.11 Please describe any major projects/activities in which the applicant has been involved in the field of **CATHODIC PROTECTION** work. Describe only those where you had personal knowledge of the applicant's work. Please indicate the degree of responsibility exercised by the applicant, the complexity of the project/activity, the degree of knowledge/skill required, etc. (Attach a separate sheet)

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** <u>one</u> 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** <u>one</u> 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** <u>one</u> 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

D.   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 <u>must</u> 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: _____

**REFERENCE**: The applicant is applying for CATHODIC PROTECTION recognition by NACE International. Applicants for certification must meet specific requirements; please see the list of these requirements on the following page.  Evaluation of an applicant's qualifications also depends on assessment of professional CATHODIC PROTECTION experience by references.  It is requested that you complete Items D.4 through D.13 on this form and return it directly to NACE.

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.)**

D.8 Based on this personal knowledge, I know that the quality of the applicant's work in the field of **CATHODIC PROTECTION** is

Excellent ☐ Average ☐ Below average ☐

D.9 The applicant is proficient in the following phases of **CATHODIC PROTECTION**:

D.10 Would you employ, or recommend the employment of, the applicant for employment in the phase of **CATHODIC PROTECTION** work you have described in Item D. 9?

Yes ☐ No ☐

D.11 Please describe any major projects/activities in which the applicant has been involved in the field of **CATHODIC PROTECTION** work. Describe only those where you had personal knowledge of the applicant's work. Please indicate the degree of responsibility exercised by the applicant, the complexity of the project/activity, the degree of knowledge/skill required, etc. (Attach a separate sheet)

D.12 Additional remarks or amplifying information:

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Signature: _____   Date: _____

Printed Name: _____
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CP Technician certification or equivalent training **PLUS** <u>one</u> 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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3. 3 years CP work experience with progressively increasing technical responsibilities **PLUS** 4 year physical science or engineering degree

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CP Technologist certification or equivalent training **PLUS** <u>one</u> of the following:
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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

D.    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.)**

D.8    Based on this personal knowledge, I know that the quality of the applicant's work in the field of **CATHODIC PROTECTION**  is
Excellent ☐          Average ☐          Below average ☐

D.9    The applicant is proficient in the following phases of **CATHODIC PROTECTION**:
_____
_____

D.10   Would you employ, or recommend the employment of, the applicant for employment in the phase of **CATHODIC PROTECTION** work you have described in Item D. 9?
Yes ☐          No ☐

D.11   Please describe any major projects/activities in which the applicant has been involved in the field of **CATHODIC PROTECTION** work.  Describe only those where you had personal knowledge of the applicant's work.  Please indicate the degree of responsibility exercised by the applicant, the complexity of the project/activity, the degree of knowledge/skill required, etc.  (Attach a separate sheet)

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_____

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**CP 3 – Cathodic Protection Technologist must have:**
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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

**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**

## 1.1   Thermodynamic Considerations

*Corrosion* is the deterioration of a material that results from a reaction with its environment. For a metal in contact with an aqueous solution, the reaction is an electrochemical one involving the transfer of electrical charge (electrons) across the metal/solution interface.

The energy that exists in metals and causes them to corrode spontaneously results from the process of converting ore to metal. A measure of the energy available in a metal (Gibbs free energy) to power the corrosion reaction is given in Table 1-1 listing the free energy of formation of some metal oxides.

**Table 1-1**[1]
**Standard Free Energy (-ΔG°) of Formation of Some Oxides
in kcal/mole of Oxide at 27°C**

| | |
|---|---|
| $Ag_2O$ ...... | 2.55 |
| $Cu_2O$ ...... | 34.6 |
| $PbO$ ...... | 45.0 |
| $NiO$ ...... | 51.4 |
| $FeO$ ...... | 54.6 (at 227°C) |
| $ZnO$ ...... | 76.2 |
| $MgO$ ...... | 136.5 |
| $Al_2O_3$ ...... | 377.6 |

This energy, imparted on the metal during the refining process, is available as potential energy ($-\Delta G^o$) to power the corrosion reaction when the metal is placed in an aqueous environment. This process for iron is illustrated in Figure 1-1.

---

[1] *Scully, J.C., Fundamentals of Corrosion, Pergamon Press, Oxford, 1966, p.7.*
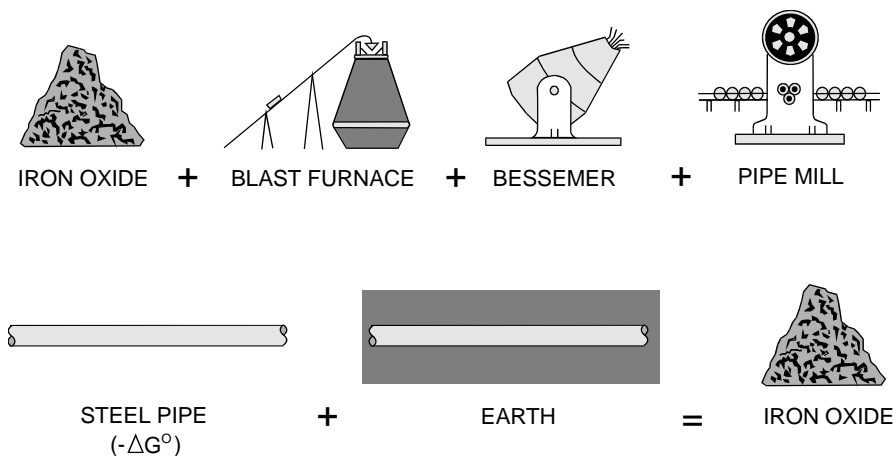
**Figure 1-1: Iron Oxide to Steel to Iron Oxide Cycle**

This illustrates that iron (or its alloys) will tend to transform to a lower energy state spontaneously. The transformation is produced by a change in free energy $(-\Delta G°)$.

Metals are crystalline structures in which individual atoms are held together by the electrical attraction of each atom's bonding or conduction electrons (outer electrons) to the positive nucleus of adjacent atoms. The crystal lattice is composed of atoms arranged in repeating unit cells with characteristic arrangements such as body-centered cubic (BCC), face-centered cubic (FCC), or hexagonal close packed (HCP) as illustrated in Figure 1-2.[2]



body centered cubic
(BCC)

face-centered cubic
(FCC)

hexagonal close packed
(HCP)
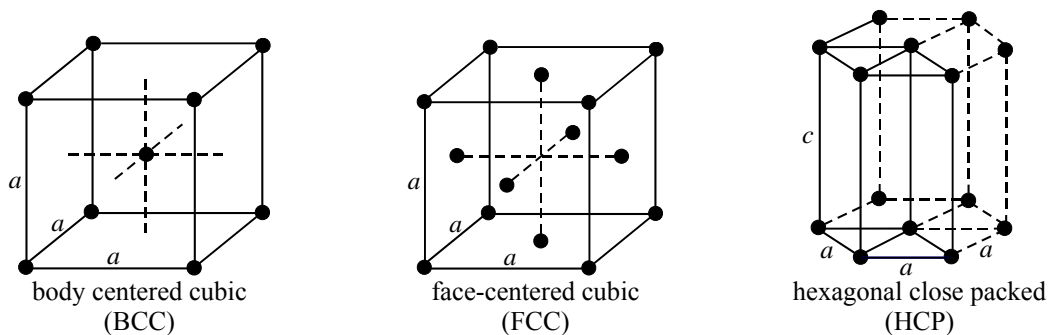
**Figure 1-2: Unit Cell Atomic Arrangement in Metal Crystal Structures**

---

[2] *Moffatt, W.G.; Pearsall, G.W.; and Wulff, J., Structure, John Wiley & Sons, Inc., New York, 1964, p.47.*

For a metal atom to leave the crystal structure, it must overcome the bonding energy with adjacent atoms in the crystal matrix. Metal atoms are not motionless but have vibrational energy depending on their temperature, since temperature is just an indication of atomic or molecular motion. As temperature increases above absolute zero (-273°C or 0°K), the atomic motion increases and the interatomic bonds can be thought of as being elastic. Therefore, at the melting point, atomic motion is so great that the interatomic bonding forces can no longer maintain a crystal structure.

Similarly, at ambient temperatures, surface atoms that have fewer interatomic bonds than internal atoms have a better chance of leaving the crystal structure. This is especially true for atoms at surface impurities, crystal dislocations, or slip planes where there are even fewer interatomic bonds and where the thermal vibrational energy of some poorly bonded atoms may be sufficient to escape the lattice structure. If a metal atom leaves the crystal structure, it leaves behind some of its bonding electrons ($ne^-$) according to the following oxidation reaction:

$$M^o \; \rightarrow \; M^{n+} + ne^- \qquad\qquad [1\text{-}1]$$

*Oxidation* is defined as a reaction in which an atom, ion, or molecule becomes more electropositive. The metal atom has now become a metal ion, with a net positive charge, taking with it most of the atomic mass residing primarily in the nucleus. It is also possible for the metal ion to return to the atom crystal structure, so the reaction can be reversible.

When a metal is placed in an aqueous solution, other possibilities for the metal ion arise because of the presence of the polar water molecule and other cations as illustrated in Figure 1-3 for iron. Water, being a polar molecule, is attracted to the metal interface. A small number of water molecules (1 in $10^7$ at pH 7) will ionize to produce a hydrogen ion ($H^+$) and hydroxyl ($OH^-$) ion.

The metal can now react anodically in two ways other than Reaction 1-1, either to produce a metal hydroxide, as in Figure 1-4, or an aqueous ion as indicated in the following reactions.

$$M^o + nH_2O \; \rightarrow \; M(OH)_n + nH^+ + ne^- \qquad\qquad [1\text{-}2]$$

$$M^o + mH_2O \; \rightarrow \; MO_m^{\,n\text{-}2m} + 2mH^+ + ne^- \qquad\qquad [1\text{-}3]$$
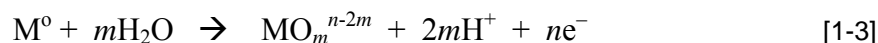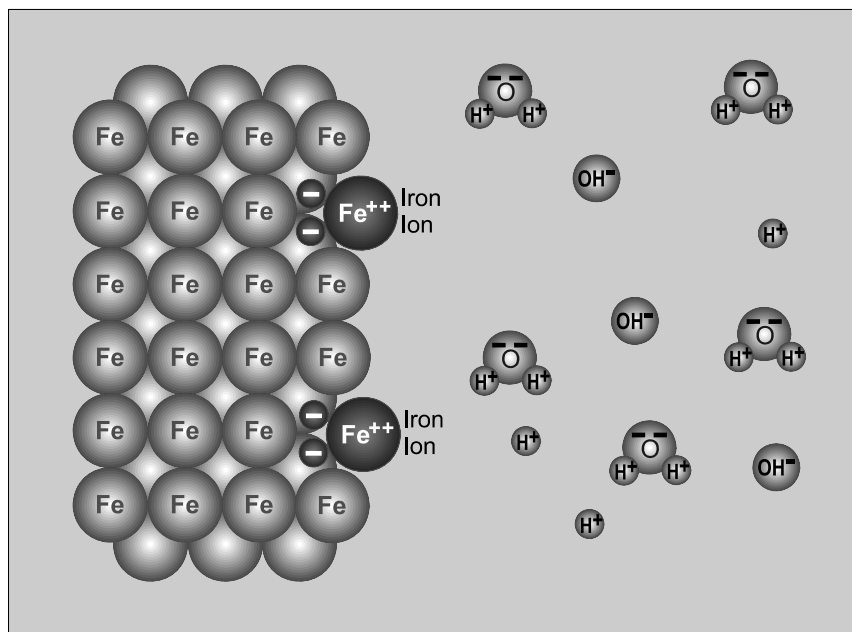
**Figure 1-3: Metal/Aqueous Solution Interface**
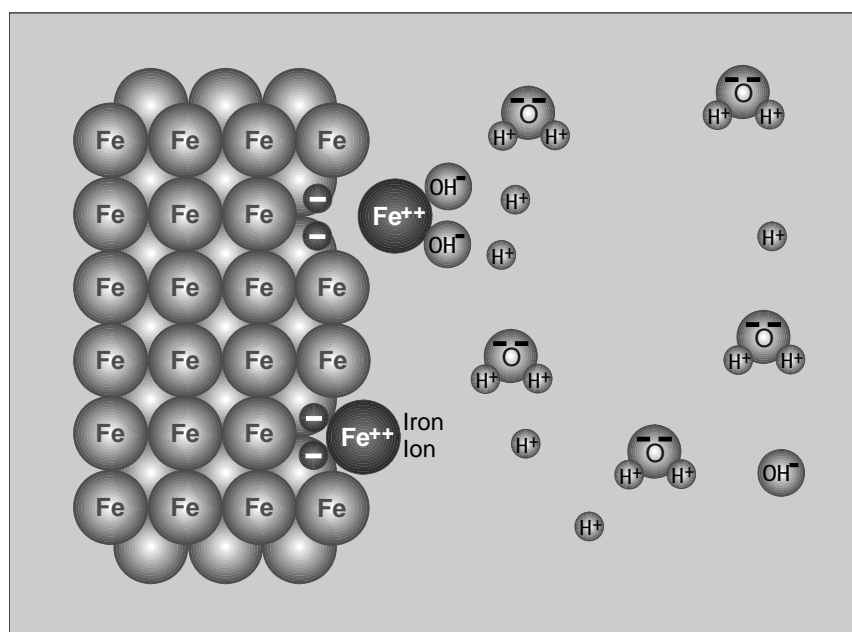


**Figure 1-4: Corrosion Forming Ferrous Hydroxide**

In each case, the reactions produce positive charges on the solution side of the interface and leave behind negative charges in the metal. Clearly, then, a metal in contact with an aqueous solution will develop a potential difference (E) across the interface, as illustrated in Figure 1-5.
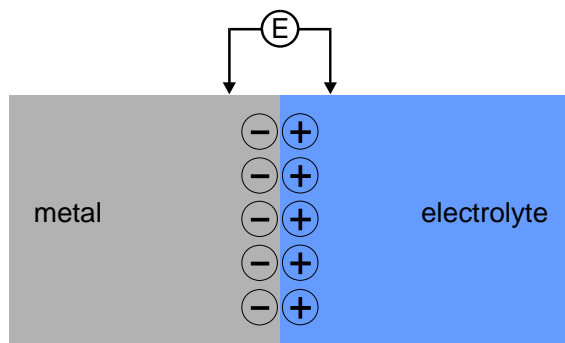


**Figure 1-5:  Potential Difference Across Metal/Water Interface due to Corrosion**

## 1.2   The Pourbaix Diagram

The potential E developed across the interface is a function of the metal involved and the pH (i.e., the relative concentration of H+ and OH– ions at the surface). The thermodynamic tendency for the metal to corrode by one or more of the three reactions above can be calculated using basic energy relationships. For iron, a potential-pH diagram (called a Pourbaix diagram) results as shown in Figure 1-6.[3]
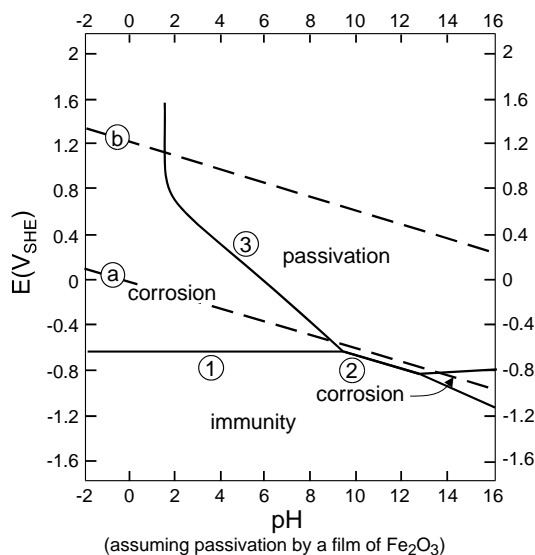


**Figure 1-6:  Theoretical Conditions of Corrosion, Immunity, and Passivation of Iron
– Simplified pH Pourbaix Diagram for Iron in Water at 25ºC**

---

[3] *Pourbaix, M., Atlas of Electrochemical Equilibria in Aqueous Solutions, National Association of Corrosion Engineers, Houston, TX, 1974, p.314.*

Lines 1, 2, and 3 in Figure 1-6 relate to the following reactions:

$$\text{Line ①:} \qquad\qquad Fe^o \;\rightarrow\; Fe^{++} + 2e^- \qquad\qquad \text{[1-4]}$$

$$\text{Line ②:} \qquad\qquad Fe + 2H_2O \;\rightarrow\; Fe(OH)_2 + 2H^+ + 2e^- \qquad\qquad \text{[1-5]}$$

$$\text{Line ③:} \qquad\qquad Fe^{++} + 3H_2O \;\rightarrow\; Fe(OH)_3 + 3H^+ + e^- \qquad\qquad \text{[1-6]}$$

These lines define three distinct regions of relative stability of the ferrous ion $(Fe^{++})$–corrosion, passivation, and immunity. In energy terms, an iron electrode with a potential/pH in the corrosion zone indicates corrosion can occur but doesn't necessarily mean it will happen. In the immunity zone, the ferrous ion is relatively insoluble and hence corrosion is unlikely. In the passivation zone, iron hydroxides and oxides are formed on the metal surface inhibiting further corrosion. Essentially, the hydroxide or oxide passive film forms a barrier between the substrate iron and the water.

Lines ⓐ and ⓑ represent the thermodynamic stability boundaries for a water molecule, which is potential and pH dependent. Between lines ⓐ and ⓑ water is considered thermodynamically stable but dissociates at these lines.

Line ⓑ called the oxygen line, corresponds to the breakdown of a water molecule to produce oxygen gas and hydrogen ions resulting in the transfer of four electrons across the interface as in Reaction 1-7.

$$2H_2O \;\rightarrow\; O_2 + 4H^+ + 4e^+ \qquad\qquad \text{[1-7]}$$
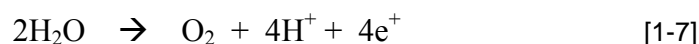
At line ⓐ, called the hydrogen line, for every two molecules of water, a molecule of hydrogen gas and two hydroxyl ions are produced as in Reaction 1-8.

$$2H_2O + 2e^- \;\rightarrow\; H_2 + 2OH^- \qquad\qquad \text{[1-8]}$$

Both of these lines have important implications for operating cathodic protection systems, as will be seen in later chapters.

Line ①, representing the stability of iron ions between corrosion and immunity, can be expanded regarding relative solubility of the ferrous ion as shown in Figure 1-7.[4]

---

[4] *Pourbaix, M., Atlas of Electrochemical Equilibria in Aqueous Solutions, National Association of Corrosion Engineers, Houston, TX, 1974, p.312.*
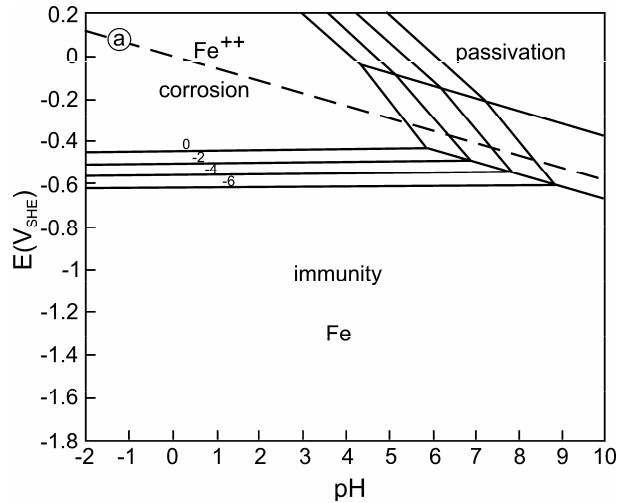
**Figure 1-7: Pourbaix Diagram for Iron in Water at 25ºC Showing Fe++ Solubility Lines**

Line ① in the simplified Pourbaix diagram is replaced by a series of lines each representing a different solubility of the ferrous ion ranging from $10^0$–$10^{-6}$ of moles per liter of water. Hence as the iron potential becomes more electro-negative, the solubility of the ferrous ion decreases. Although theoretically it does not reach zero, for all practical purposes the corrosion rate is reduced to negligible values. The anticipated corrosion rate (mm/y) of iron in water at 25°C can be represented on the Pourbaix diagram as shown in Figure 1-8.[5] The decreasing corrosion rate with increasingly negative potentials is a result of the decreasing solubility of the ferrous ion.
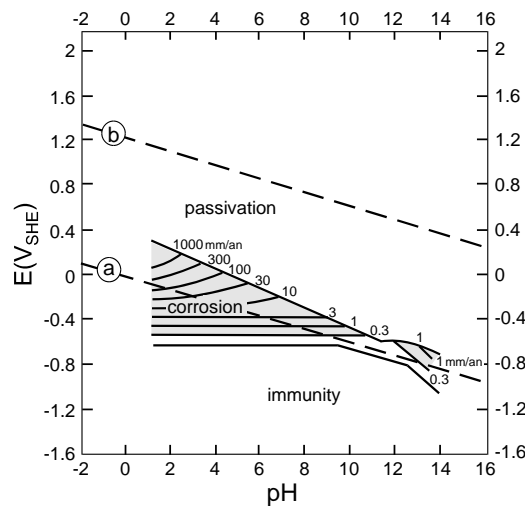


**Figure 1-8: Pourbaix Diagram for Iron in Water at 25ºC Showing Corrosion Rates**

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[5] *Pourbaix, M., Atlas of Electrochemical Equilibria in Aqueous Solutions, National Association of Corrosion Engineers, Houston, TX, 1974, p.316.*

## 1.3  The Electrode Potential

The absolute potential across a metal/solution interface cannot be determined, by measurement, and can only be measured with respect to a second electrode called a *reference electrode*. For the Pourbaix diagram, a particularly stable electrode called a hydrogen electrode is used.
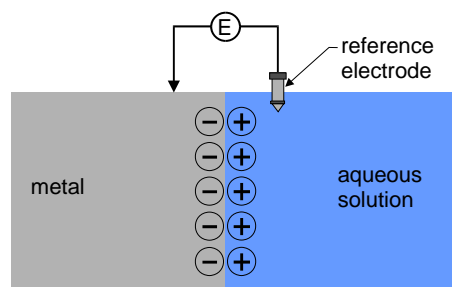


**Figure 1-9:  Measurement of Metal Potential Using a Reference Electrode**

The hydrogen reference electrode is composed of a platinum wire surrounded by a solution with 1 molar concentration of hydrogen ions (e.g., $H_2SO_4$ at pH0) through which hydrogen gas is bubbled. The solution is kept at 25°C.

The platinum surface acts as a catalyst for the following reversible reaction:

$$H^+ + e^- \leftrightarrow H^O \qquad\qquad\qquad [1\text{-}9]$$

Under the particular conditions surrounding the platinum, this results in the electrode maintaining a very stable potential. Because of this and the nature of the reversible reaction, the electrode is called a *standard hydrogen electrode* (SHE), illustrated in Figure 1-10. The SHE's potential $E_{H^O/H^+}$ is used as the zero from which all other electrode potentials are measured. For instance, it is used to measure the standard potential of pure metals to produce the Electromotive Series (Table 1-2).
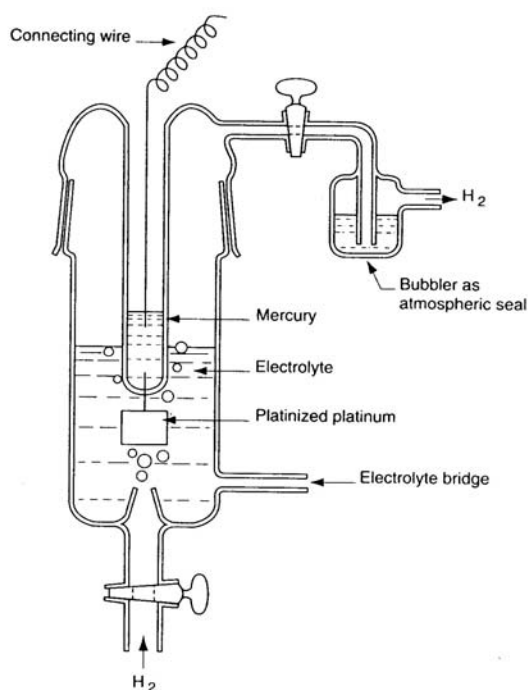


**Figure 1-10:**
**Standard Hydrogen Electrode**
Source: Jones, D., Principles and Prevention of Corrosion, MacMillan Publishing Co. 1992, p.64.

## 1.3.1    The Electromotive Force Series

**Table 1-2[6]**
**The Electromotive Series at 25°C (77°F)**
**(also called EMF Series)**

| Electrode | Standard Potential, $E^o$ (Referred to the SHE) Volts | |
|---|---|---|
| $K^+ \mid K$ | –2.92 | |
| $Na^+ \mid Na$ | –2.71 | |
| $Mg^{++} \mid Mg$ | –2.34 | |
| $Al^{+++} \mid Al$ | –1.67 | |
| $Zn^{++} \mid Zn$ | –0.76 | |
| $Fe^{++} \mid Fe$ | –0.44 | |
| $Pb^{++} \mid Pb$ | –0.13 | |
| $Fe^{+++} \mid Fe$ | –0.04 | Less Noble Potentials |
| $H^+{}_1, H_2 \mid M^*$ (SHE) | 0.00 | |
| KCl (sat.), $Hg_2Cl_2 \mid Hg$ (SCE) | (+0.245)** | More Noble Potentials |
| $Cu^{++} \mid Cu$ | +0.34 | |
| $I^-, I_2 \mid M$ | +0.53 | |
| $Ag^+ \mid Ag$ | +0.80 | |
| $Br^-, Br_2 \mid M$ | +1.07 | |
| $H^+, H_2O, O_2 \mid M$ | +1.23 | |
| $Cl^-, Cl_2 \mid M$ | +1.36 | |
| $Au^{+++} \mid Au$ | +1.50 | |
| $F^-, F_2 \mid M$ | +2.87 | |

*M in this table denotes an inert metal electrode that acts merely as a donor or acceptor of electrons.  Platinum is often used for that purpose.
**This is not a standard potential since the SCE is not a standard state electrode.  The potential of the standard state calomel electrode is +0.268 volts.

The standard potentials ($E^o$) (often referred to as "redox" potentials) of various pure metals are measured only under specific (standard) conditions. These conditions are a temperature of 25°C, a solution of 1 molar concentration of the metal ions, and a measuring circuit where no current is drawn from the pure metal specimens. The resulting table not only indicates the standard potentials of the pure metal but relates the corrosion tendency of each—the more electronegative the potential, the greater the tendency to corrode. The EMF series arrangement of metals is similar to that of Table 1-1, a reflection that the tendency to corrode corresponds to the energy available in a metal to produce an oxide.

---

[6] *deBethune, A. J., "Fundamental Concepts of Electrode Potentials", Corrosion, Vol. 9, Oct. 1953, p.339.*

## 1.3.2   The Nernst Equation

The need to maintain a 1 molar solution of metal ions indicates the importance of metal ion concentration in determining the magnitude of a metal electrode potential. When the ion concentration is not 1 molar (or unit activity) the metal potential will change according to the Nernst equation:

$$E_M = E_M^o + \frac{RT}{nF} \ln \frac{a^{(M^{n+})}}{a^{(M^o)}}$$   [1-10]

*where:*

$E_M^o$ = metal potential at standard conditions
R = gas constant (8.31 J/mol – °K)
T = absolute temperature
n = number of electrons transferred
F = Faraday's constant (96,500 coulomb)
$a^{(M^{n+})}$ = metal ion activity $a = \gamma m$, where $\gamma$ is the activity coefficient (always <1) and m is the molar concentration of the metal ion
$a^{(M^o)}$ = metal activity (assumed to be 1)
$\gamma$ = activity coefficient

The Nernst equation indicates that a metal electrode potential is a function of the metal ion activity, which is related to the metal ion concentration. As the metal ion concentration ($M^{n+}$) increases the metal electrode potential becomes more electropositive.

## 1.3.3   Common Reference Electrodes

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 number of secondary reference electrodes such as saturated copper-copper sulfate (CSE), saturated calomel (SCE), and silver-silver chloride (SSC) are used routinely in the corrosion and cathodic protection industry. As revealed by the Nernst equation, the metal ion concentration is important in maintaining the stability of the reference electrode potential. These secondary references have specific ion concentrations and corresponding potentials with respect to the standard hydrogen electrode as indicated in Table 1-3.

**Table 1-3: Common Reference Electrodes and Their Potentials and Temperature Coefficients**

| Reference Electrode | Electrolyte Solution | Potential @ 25°C (V/SHE) | Temperature Co-efficient (mV/°C) | Typical Usage |
|---|---|---|---|---|
| Cu/CuSO$_4$     (CSE) | Sat. CuSO$_4$ | +0.316[3] | 0.9[5] | soils, fresh water |
| Ag/AgCl (SJ)   (SSC) | 0.6M NaCl (3 ½%) | +0.256[1] | 0.33[1] | sea water, brackish[4] |
| Ag/AgCl (LJ)   (SSC) | Sat. KCl | +0.222[6] | 1.00[2] | --- |
| Ag/AgCl (LJ)   (SSC) | 0.1N KCl | +0.288[3] | 0.43[3] | --- |
| Sat. Calomel   (SCE) | Sat. KCl | +0.241[6] | 0.66[3] | water, laboratory |
| Zn              (ZRE) | Saline Solution | −0.79±0.1[2] | --- | sea water |
| Zn              (ZRE) | Soil | −0.80±0.1[2] | --- | buried |

SJ – solid junction        LJ – liquid junction

[1] Peterson, M.H. and Groover, R.E., "Tests Indicate the Ag/AgCl Electrode Is Ideal Reference Cell in Sea Water", Materials Protection, Vol. 11(5), May 1972, p.19-22.

[2] von Baeckmann, W., Schwenk, W., and Prinz, W., Handbook of Cathodic Protection, Gulf Professional Publishing, 1997, p.80.

[3] Uhlig, H.H., Corrosion and Corrosion Control, John Wiley & Sons, 2$^{nd}$ Edition, 1971, p.33-36.

[4] Potential becomes more electropositive with increasing resistivity.  See monograph for correction in waters of varying resistivity in NACE SP0176, latest edition, or (1).

[5] Ansuini, F., and Dimond, J., Factors Affecting the Accuracy of Reference Electrodes, Materials Performance, Vol. 33(11), Nov. 1994, p.14-17.

[6] Jones, D., Principles and Prevention of Corrosion, MacMillan Publishing Co., 1992, p.65.

## *1.3.4   Effect of Temperature on Reference Electrode Potentials*

The effect of temperature on the reference potential can be expressed by the following equation:

$$E_t = E^o_{25°C} + k_t(T-25°C) \qquad [1\text{-}11]$$

*where:*

$k_t$ = temperature coefficient

$E_t$ = reference potential at temperature (t)

Therefore, for a copper-copper sulfate reference at 5°C, its potential would be:

$$
\begin{aligned}
E_{CSE/SHE} @5°C &= +0.316 \text{ V}_{SHE} + 0.0009\text{V/°C} (5°C - 25°C) \\
&= +0.316 \text{ V}_{SHE} - 0.018 \text{ V}_{SHE} \\
&= +0.298 \text{ V}_{SHE}
\end{aligned}
$$

or at 40°C, its potential would be:

$$
\begin{aligned}
E_{CSE/SHE} @40°C &= +0.316 \text{ V}_{SHE} + 0.0009\text{V/°C} (40°C - 25°C) \\
&= +0.316 \text{ V}_{SHE} + 0.014 \text{ V}_{SHE} \\
&= +0.330 \text{ V}_{SHE}
\end{aligned}
$$

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### 1.3.5 Converting Measured Potentials between Reference Electrodes

In practice, it is often necessary to convert a potential measured with respect to one reference electrode to one with respect to another reference electrode. Such a conversion can be done either arithmetically or graphically. The graphical method is illustrated using the scale in Figure 1-11 for an original potential of –800 mV measured on a metal "X" with respect to a copper-copper sulfate reference electrode (CSE).
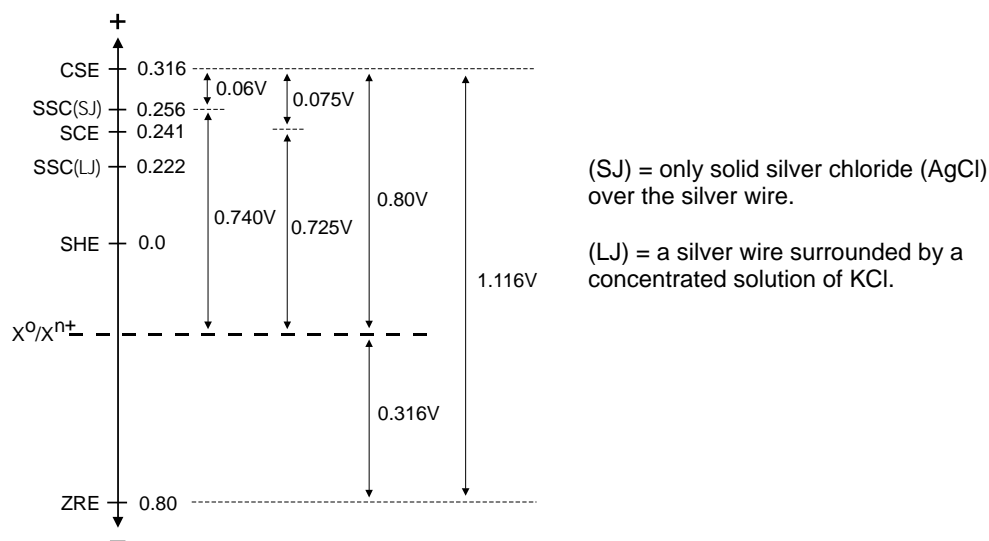


**Figure 1-11:  Reference Electrode Conversion Scale**

For a potential of –0.800 $V_{CSE}$, the measurement of an unknown metal electrode $X^o/X^{n+}$ with respect to a CSE electrode converts to the following potentials with respect to other secondary reference electrodes:

$$X^o / X^{n+} /_{SCE} \quad \text{is} \quad -0.80 \; V_{CSE} - (-0.075 \; V_{SCE}) \quad = \quad -0.725 \; V_{SCE} \qquad \text{[1-12]}$$

$$X^o / X^{n+} /_{SSC} \quad \text{is} \quad -0.80 \; V_{CSE} - (-0.060 \; V_{SSC}) \quad = \quad -0.740 \; V_{SSC \, (SJ)} \qquad \text{[1-13]}$$

$$X^o / X^{n+} /_{ZRE} \quad \text{is} \quad -0.80 \; V_{CSE} - (-1.116 \; V_{ZRE}) \quad = \quad +0.316 \; V_{ZRE} \qquad \text{[1-14]}$$

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 +75mV to SCE).

2. Add the original potential difference to obtain the converted potential.

$$\textit{e.g.,} \quad X^o / X^{n+} / SCE \quad = \quad +75 \; mV + (-800mV_{CSE})$$
$$= \quad -725 \; mV_{SCE}$$

# 1.4  The Corrosion Cell

An electrochemical reaction either produces or consumes electrons. Equations 1-1, 1-2, and 1-3 all produce positive charges on the solution side of the interface and leave behind negative charges (electrons). When hydroxides or oxides are formed, as in Reactions [2] and [3], electrical neutrality in the water and in the metal is disturbed. The formation of ferrous hydroxide leaves two excess positive charges in the water and two excess electrons in the metal. This results in the flow of electrons away from the corrosion site to an adjoining surface where there is a natural attraction to the positive hydrogen ions. The hydrogen ion will pick-up an electron to form an atom of hydrogen ($H^o$), often called nascent hydrogen, as in the following reaction:

$$H^+ \; + \; e^- \; \rightarrow \; H^o \qquad\qquad [1\text{-}15]$$

As both the corrosion reactions forming either hydroxides or oxides continues there will be a related reaction between the excess charges to maintain electrical neutrality as shown in Figure 1-12.
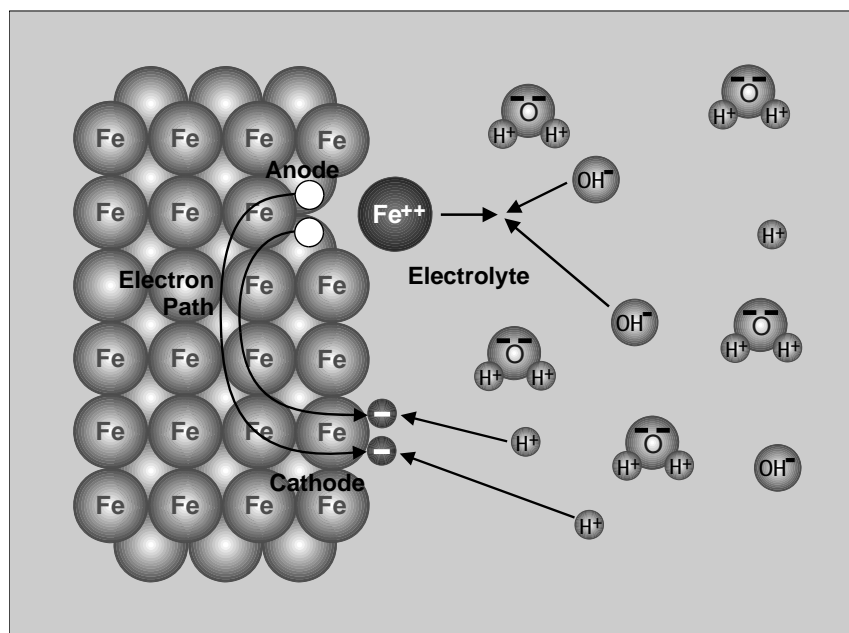


**Figure 1-12:  Iron Corrosion Cell**

The location on the iron surface where corrosion occurs is called the *anode*. Corrosion is defined as an oxidation reaction since the material being oxidized, iron atoms in this case, becomes more electropositive as a result of the corrosion process. Hence a corrosion reaction is an oxidation reaction.

The location where excess electrons transfer across the surface to be picked up by the positive hydrogen ions is called the *cathode*. The cathode is defined as the surface where a reduction reaction occurs [1-15]. *Reduction* is a reaction in which the species being reduced, in this case hydrogen ions, becomes more electronegative. Thus the entire corrosion process involves both oxidation and reduction reactions that transfer charges across a metal/electrolyte interface. This process is called an *electrochemical cell*.

As corrosion activity continues at the anode positive charges (e.g., hydrogen ions) flow in the water and negative charges flow in the metal towards the cathode site. Current typically flows in the direction of the positive charge (i.e., from the anode to the cathode in the water and from the cathode to the anode in the metal) as shown in Figure 1-13.
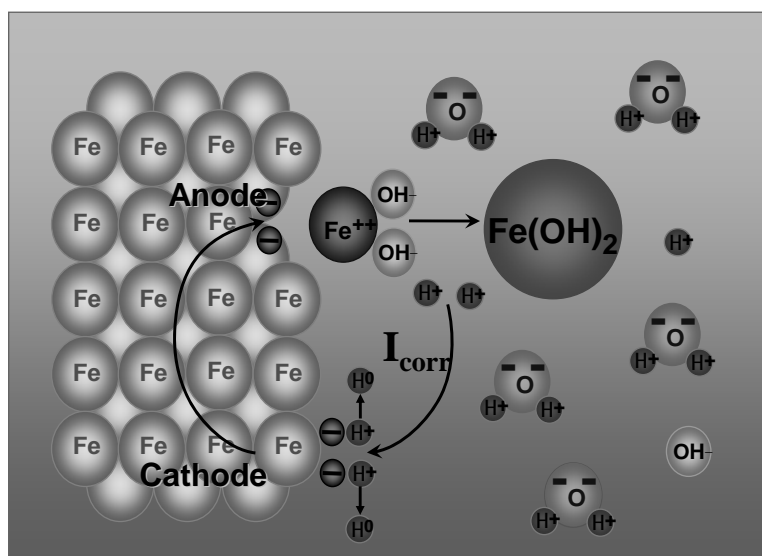


**Figure 1-13:  Direction of Conventional Current
(positive charge flow)**

## 1.4.1   Corrosion Cell Components

All corrosion activity takes place in the context of a corrosion cell that has the following four essential components:

- An anode (where the oxidation reaction occurs)
- A cathode (where the reduction reaction occurs)
- An electronic path that allows electrons to flow from the anode to the cathode (inside the metal)
- An electrolytic path that allows ions to flow between the anode and cathode (in the electrolyte)

Any solution containing ions is an *electrolyte*. Soils typically contain water that has many different ions in solution, not just hydrogen and hydroxyl. In deaerated or non-aerated soils and waters the typical reduction reaction is the reduction of hydrogen as in Reaction 1-15. In aerated soils and waters, where dissolved oxygen is present, the following reduction reaction also transfers electrons across the metal/electrolyte interface.

$$O_2 \ + \ 2H_2O \ + \ 4e^- \ \rightarrow \ 4OH^- \qquad\qquad [1\text{-}16]$$

Oxygen atoms have an affinity for electrons because their outer electron shell has only 6 electrons. A more stable condition would result if there were 8 electrons. Hence an atom of oxygen will pick up 2 electrons at a cathode to fill its outer electron shell. This reduction reaction produces hydroxyl ions that change the pH at the cathode site in the alkaline direction.

When a corrosion cell is established, other ions in solution will tend to migrate toward either the anode or cathode. Positively charged ions, such as $Na^+$, $K^+$, $Ca^{++}$, and $Mg^{++}$, migrate toward the cathode as do hydrogen ions. Hence all positively charged ions are called *cations* because they move towards the cathode.

Similarly, negatively charged ions, such as $Cl^-$, $SO_4^=$, $NO_3^-$, $CO_3^=$, and $HCO_3^-$, migrate toward the anode as do hydroxyl ions. Therefore all negatively charged ions are called *anions*, because they move towards the anode.

An operating corrosion cell showing direction of charge movement is shown in Figure 1-14.
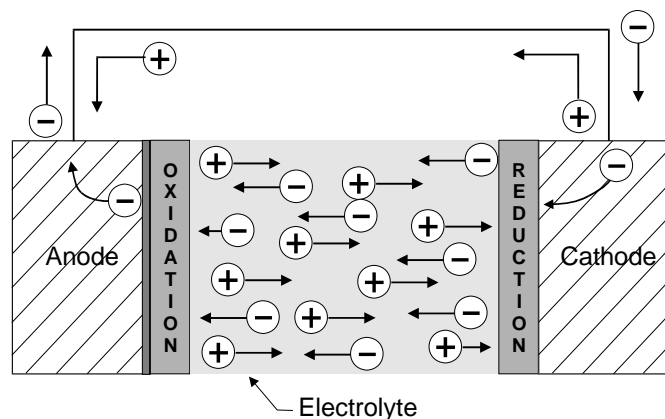
**Figure 1-14:  Charge Movement in a Corrosion Cell**

Charge flow as illustrated in Figure 1-14 produces a corrosion current. The international convention adopted for the direction of current (i.e., conventional current direction) assumes current direction is the direction in which positive charges flow.  Hence the direction of corrosion current in a corrosion cell is from anode to cathode through the electrolyte and from cathode to anode in the external or metal paths as illustrated in Figure 1-15.
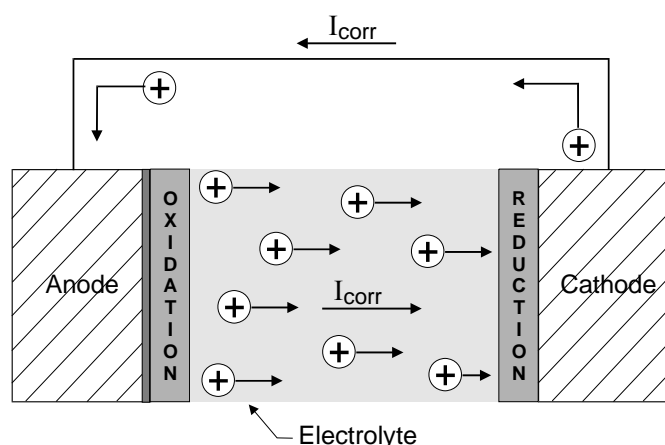


**Figure 1-15:  Direction of Conventional Current (+ve Charges) in a Corrosion Cell**

## *1.4.2   Corrosion Cell Kinetics (Polarization)*

If the electronic path of the corrosion cell could be interrupted, the cell would be open-circuited and the corrosion current ($I_{corr}$) would be zero. After allowing time for equilibrium to be established at the anode and cathode interfaces, their open circuit potentials, $E_{a,oc}$ and $E_{c,oc}$ respectively, could be measured with respect to a

reference electrode placed at the respective interfaces. This open circuit condition is illustrated in Figure 1-16.
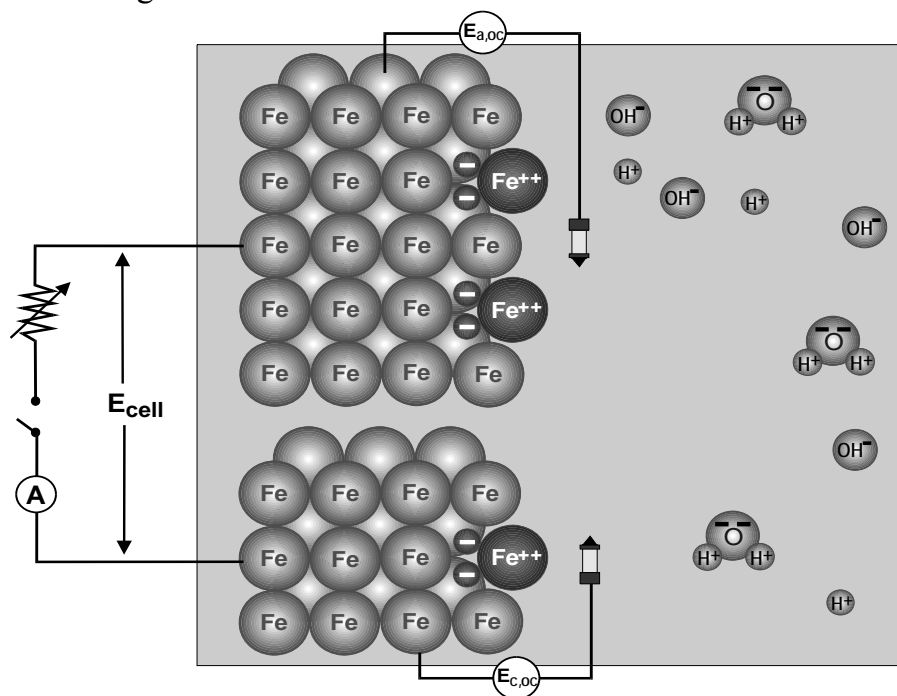


**Figure 1-16:  Open Circuit Corrosion Cell**

The potential difference between the anode and the cathode is the cell EMF ($E_{cell}$) which equates to the Gibbs free energy ($\Delta G^o$) of the metal in the following relationship.

$$E_{cell} \ = \ \frac{-\Delta G^o}{nF} \qquad\qquad [1\text{-}17]$$

*where:*

$E_{cell}$ = corrosion cell potential (volts or joules/coulomb)
n = number of charges transferred in the oxidation reaction
F = Faraday's constant – 96,500 coulombs of charge
$\Delta G^o$ = Change in Gibbs free energy (joules)

This cell voltage is the electrical energy source, which when the switch is closed, causes charges to flow in the corrosion cell circuit (i.e., the corrosion current). With the insertion of an ammeter and a variable resistor and with the switch closed as in Figure 1-17, the corrosion current ($I_{corr}$) can be measured as well as the potential at the anode ($E_{a,cc}$) and cathode ($E_{c,cc}$).
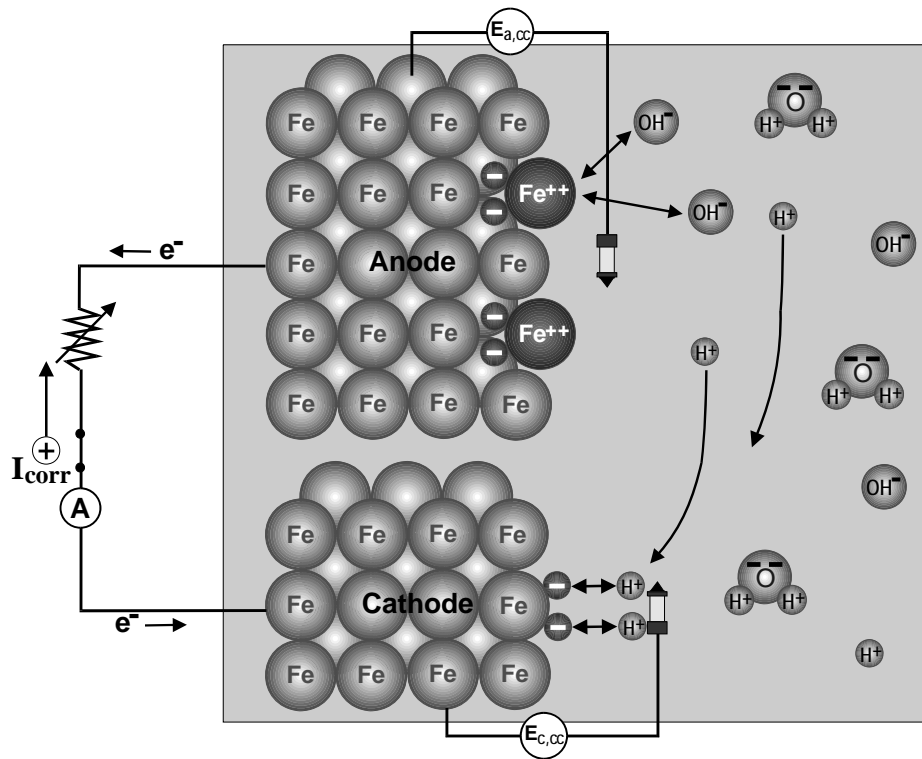
**Figure 1-17: Closed Circuit Corrosion Cell**

If the variable resistor is gradually reduced, the current will increase while the anode and cathode closed circuit potential will change. The change in potential can be expressed as follows:

$$E_{cc} = E_{oc} \pm \Delta E_p \qquad \text{[1-18]}$$

*where:* $\Delta E_p$ is the change in potential due to $I_{corr}$ across the interface.

The anode potential will become more electropositive ($+\Delta E_p$) while the cathode potential will become more electronegative. Hence the potential relationship can be expressed as follows:

*For the anode:* $\qquad E_{a,cc} = E_{a,oc} + \Delta E_{p,a} \qquad \text{[1-19]}$

*For the cathode:* $\qquad E_{c,cc} = E_{c,oc} - \Delta E_{p,c} \qquad \text{[1-20]}$

The operation of the corrosion cell can be illustrated on an Evans diagram (named after U.R. Evans[7]), which compares the potential to the corrosion current.

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[7] *Evans, U.R., Metallic Corrosion, Passivity and Protection, Eduard Arnold & Co., 1948, p.343.*

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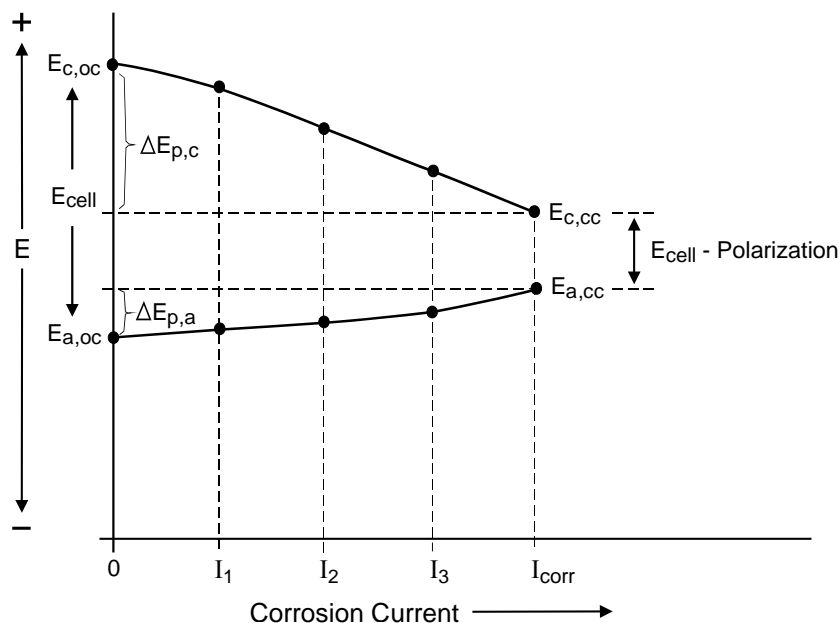
**Figure 1-18: Evans Diagram for a Corrosion Cell Under Cathodic Control**

The change in potential $\Delta E_{p,c}$ and $\Delta E_{p,a}$ that occurs at the cathode and anode interface respectively is due to the electrical energy used up in the transfer of charge across the respective metal/electrolyte interfaces. This change is called *polarization*. Charge transfer processes, although described in a singular oxidation or reduction reaction, are usually multi-step processes.

The slowest step in the process requires the most electrical energy and hence produces the most polarization. It can be seen from Figure 1-18 that there is greater polarization at the cathode than at the anode ($\Delta E_{p,c} > \Delta E_{p,a}$) even though the rate of charge transfer is the same (i.e., the corrosion current is the same). The slowest charge transfer step is, therefore, at the cathode site, and in these circumstances the corrosion cell is said to be under cathodic control (i.e., most polarization occurs at the cathode).

A polarization analogy is the movement of people to and from work using public transit. The walk to the bus stop requires less energy per unit length traveled than does climbing up the steps into the bus. There may be an accumulation of people at the bus stop as well as inside the bus causing a wait to get on or off the bus. If the bus door is analogous to the metal/electrolyte interface, the slowest step in the flow of people to and from the office is at the bus stop.

Furthermore, if people getting on the bus is analogous to cathodic polarization and people getting off the bus is analogous to anodic polarization, it is apparent

that more energy is required to step up into the bus than down from the bus. Also as the flow rate of people increases, as at rush hour, the increased accumulation of people waiting to get on and off the bus is analogous to an increase in current in a corrosion cell. Hence as the flow rate increases, the change in potential (i.e., people arriving at the bus stop) increases.

Most corrosion cells on iron or steel structures in contact with soil or water are under cathodic control. In some specific environments, the corrosion cell can be under anodic or mixed control as illustrated in Figure 1-19.



(a) Anodic Control                                        (b) Mixed Control
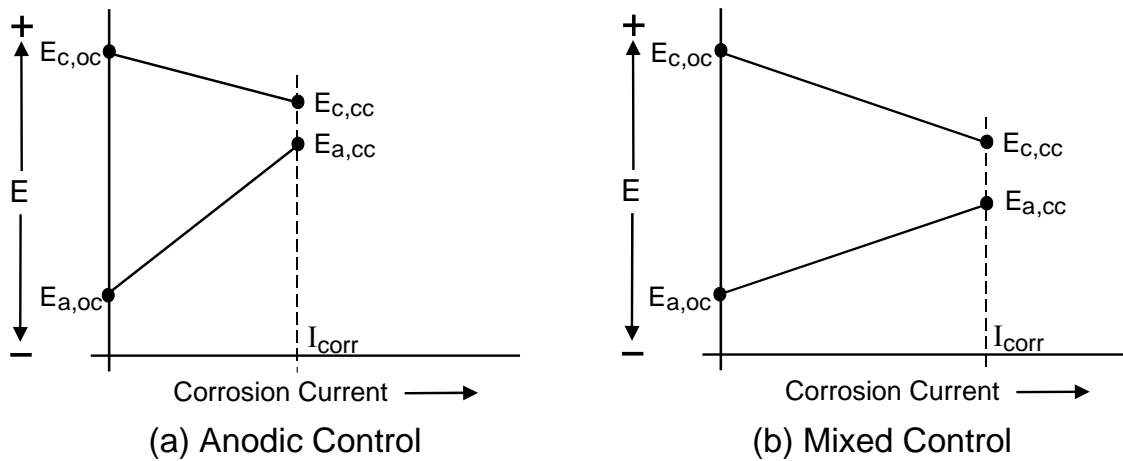
**Figure 1-19:  Evans Diagram for a Corrosion Cell Under Anodic Control and Mixed Control**

The corrosion cell depicted in Figure 1-17 forms a series electrical circuit as illustrated in the following simple DC circuit (Figure 1-20).



where:

$R_m$ = resistance of metal path between anode and cathode

$R_e$ = resistance of electrolytic path between anode and cathode

$V_m$ = voltage drop in metal path

$V_e$ = voltage drop in electrolyte
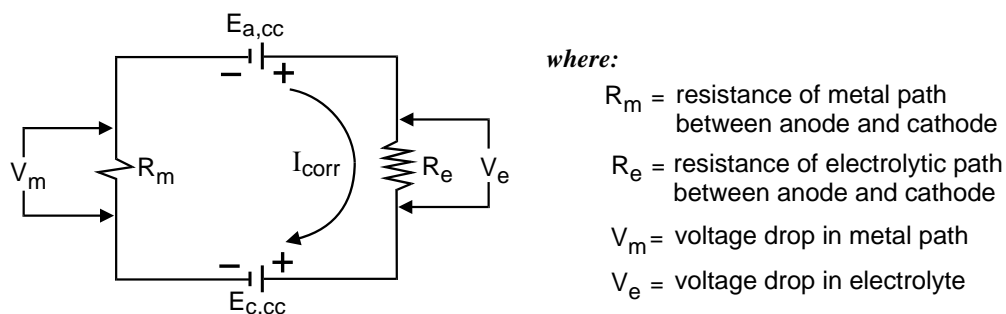
**Figure 1-20:  Simple DC Circuit Representing a Corrosion Cell**

In a series circuit the sum of the voltage drops must equal the sum of the electrical sources (e.g., from Kirchhoff's law for series circuit). Since the two sources oppose each other, the difference in potential between the closed circuit anode and cathode potentials is equal to the total voltage drop in the circuit as shown in Equation 1-22 and Figure 1-21.

$$E_{c,cc} - E_{a,cc} = V_m + V_e \qquad [1\text{-}21]$$

*then:* $\qquad E_{c,cc} - E_{a,cc} = V_t$ (total voltage drop)

*substituting:* $\qquad$ Equation 1-19 for $E_{a,cc}$ and Equation 1-20 for $E_{c,cc}$

*gives:* $\qquad E_{c,oc} - \Delta E_{p,c} - (E_{a,oc} + \Delta E_{p,a}) = V_T$

$$E_{c,oc} - E_{a,oc} = V_T + \Delta E_{p,a} + \Delta E_{p,c}$$

*but:* $\qquad E_{c,oc} - E_{a,oc} = E_{cell} \qquad [1\text{-}22]$

*therefore:* $\qquad E_{cell} = V_T + \Delta E_{p,a} + \Delta E_{p,c} \qquad [1\text{-}23]$
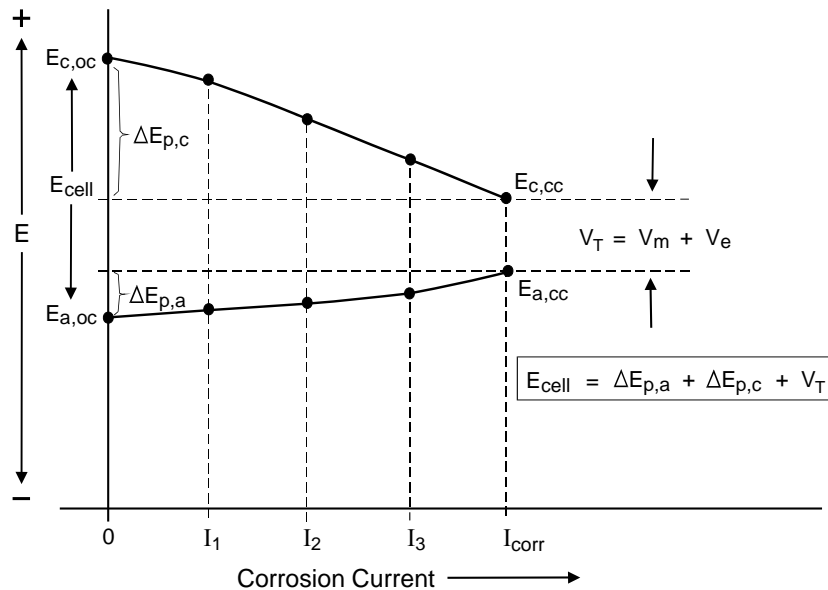


**Figure 1-21: Polarization Diagram for a Corrosion Cell**

This equation relates the original voltage ($E_{cell}$) arising from a change in Gibbs free energy to the total voltage drop in the circuit and the sum of the polarization potential changes occurring at the metal/electrolyte interface (i.e., the source energy is equal to the sum of the energy losses in the circuit).

**Experiment 1-1:**
To Demonstrate Polarization in a Corrosion Cell

## 1.5  Faraday's Law

The amount of material lost at the anode or deposited at the cathode is a function of the atomic weight of the metal or substance, the number of charges transferred, and the corrosion current ($I_{corr}$). This relationship (Equation 1-24) was developed by Michael Faraday while working as Sir Humphry Davy's assistant at the Royal Institute in London, England in 1833.[8]

$$W_t \ = \ \frac{M}{nF} t I_{corr} \qquad\qquad \text{[1-24]}$$

*where:*

$W_t$ = total weight loss at anode or weight of material produced at the cathode (g)

$n$ = number of charges transferred in the oxidation or reduction reaction

$I_{corr}$ = the corrosion current (A)

$F$ = Faraday's constant of approximately 96,500 coulombs per equivalent weight of material (where equivalent weight = $\frac{M}{n}$ )

$M$ = the atomic weight of the metal which is corroding or the substance being produced at the cathode (g)

$t$ = the total time in which the corrosion cell has operated (s)

If Equation 1-24 is multiplied by $\frac{1}{t}$ then the expression becomes:

$$\frac{W_t}{t} \ = \ \frac{M}{nF} I_{corr} \ = \ K_m I_{corr} \qquad\qquad \text{[1-25]}$$

*where:*

$K_m$ …………constant for each metal or substance.

This indicates that the weight loss per unit time (i.e., the consumption rate) for any metal is directly proportional to the corrosion current. Hence, the theoretical consumption rate of any metal can be calculated on an ampere-year (A-y) basis as listed in Table 1-4.

---

[8] *Thomas, John M., Michael Faraday and the Royal Institution, Institute of Physics Publishing, Bristol, UK, 1991, p.24.*

**Table 1-4:  Theoretical Consumption Rates of Various Metals and Substances on an Ampere-Year Basis**

| Reduced Species | Oxidized Species | Molecular Weight, M (g) | Electrons Transferred (n) | Equivalent Weight, M/n (g) | Theoretical Consumption Rate (Kg/A-y) |
|---|---|---|---|---|---|
| Al | $Al^{+++}$ | 26.98 | 3 | 8.99 | 2.94 |
| Cd | $Cd^{++}$ | 112.4 | 2 | 56.2 | 18.4 |
| Be | $Be^{++}$ | 9.01 | 2 | 4.51 | 1.47 |
| Ca | $Ca^{++}$ | 40.08 | 2 | 20.04 | 6.55 |
| Cr | $Cr^{+++}$ | 52.00 | 3 | 17.3 | 5.65 |
| Cu | $Cu^{++}$ | 63.54 | 2 | 31.77 | 10.38 |
| $H_2$ | $H^+$ | 2.00 | 2 | 1.00 | 0.33 |
| Fe | $Fe^{++}$ | 55.85 | 2 | 27.93 | 9.13 |
| Pb | $Pb^{++}$ | 207.19 | 2 | 103.6 | 33.9 |
| Mg | $Mg^{++}$ | 24.31 | 2 | 12.16 | 3.97 |
| Ni | $Ni^{++}$ | 58.71 | 2 | 29.36 | 9.59 |
| $OH^-$ | $O_2$ | 32.00 | 4 | 8.00 | 2.61 |
| Zn | $Zn^{++}$ | 65.37 | 2 | 32.69 | 10.7 |

*Example:*  Using Equation 1-24 to calculate the weight consumed by 1 ampere of stray DC current discharging from an iron structure in 1 year.

$$W_t = \frac{M}{nF} \times t \times I_{corr}$$

*where:*

$t$  =  1 year  =  60 s/min $\times$ 60 min/h $\times$ 8,760 h/y  =  $31.5 \times 10^6$ s
M  =  55.85 g *(from Table 1-4)*
n  =  2
F  =  96,500 coulombs

*then:*

$$W_t = \frac{55.85 \text{ g} \times 31.5 \times 10^6 s \times 1 \text{ A}}{2 \times 96,500 \text{ coulombs}} = 9115 \text{ g} = 9.12 \text{ kg}$$

Note that the weight of hydrogen produced at the cathode of a corrosion cell or the weight of oxygen produced at an inert impressed current anode can also be calculated.

Electric current is the flow rate of charge which can be expressed as

$$I = \frac{Q}{t} \qquad\qquad [1\text{-}26]$$

*where:*

Q........ charge in coulombs
*t* ......... time in seconds
I ......... electric current in amperes

substituting Equation 1-26 into the Faraday relationship (Equation 1-24) yields the following relationship:

$$W_t = \frac{M}{n\text{F}} Q_{corr}$$  [1-27]

This indicates that the total weight of material lost at the anode or produced at the cathode is directly proportional to the total charge passed in the corrosion cell.

Similarly, if the Faraday equation is multiplied by the term:

$$\frac{1}{A \times t}$$  [1-28]

*where:*

A........ surface area of the anode or cathode
*t* ......... time in seconds

*then the following relationship results:*

$$\frac{W_t}{A \times t} = \frac{M}{n\text{F}} \times \frac{I_{corr}}{A}$$  [1-29]

Because $\dfrac{I_{corr}}{A}$ is equal to the corrosion current density ($i_{corr}$) then:

$$\frac{W_t}{A \times t} = \frac{M}{n\text{F}} i_{corr}$$  [1-30]

Therefore the weight loss per unit time per unit area is directly proportional to corrosion current density, which is corrosion rate ($r_{corr}$) expressed in units such as $mg/cm^2/day$. Therefore, corrosion rates for metals are often expressed in terms of the corrosion current density.

If Equation 1-30 is divided by the density (d) of the alloy, then the corrosion penetration ($r_{corr}$) can be expressed as mm/y as in Equation 1-31.

$$r_{corr} = \frac{M}{n\text{F}} \times \frac{i_{corr}}{d}$$  [1-31]

*where:*

M = atomic weight (g)
n = number of charges transferred in corrosion reaction
$i_{corr}$ = corrosion current density ($A/cm^2$)

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$$d = \text{density (g/cm}^3)$$
$$r_{corr} = \text{penetration rate in (cm/s)}$$

*Example:*  Using the Equation 1-31 to calculate the penetration rate for iron based on a current density of 1 A/m$^2$.

*where:*

$$M = 55.85 \text{ g} \qquad\qquad i_{corr} = 10^{-4} \text{ A/cm}^2$$
$$n = 2 \qquad\qquad\qquad\quad d = 7.87 \text{ g/cm}^3$$
$$F = 96,500 \text{ coulombs}$$

*then:*  $$r_{corr} = \frac{55.85\text{g} \times 10^{-4}\text{A/cm}^2}{2 \times 96,500\text{ coulombs} \times 7.87\text{g/cm}^3}$$

$$r_{corr} = 3.68 \, x10^{-9} \frac{cm}{s}$$

Now, convert the units to the more common form of mm/yr by multiplying by the penetration rate by the number of seconds per year and by the number of mm per cm.

$$r_{corr} = 3.68 \, x10^{-9} \frac{cm}{s} \, x \, 3.15 \, x10^{7} \frac{s}{yr} \, x10 \frac{mm}{cm} = 1.16 \frac{mm}{yr}$$

The penetration rate in mpy (0.001 in/y or $25 \times 10^{-3}$ mm/y) is equivalent to a current density of 1$\mu$A/cm$^2$ for a number of common pure metals as given in Table 1-5.

**Table 1-5:  Electrochemical and Current Density Equivalence with Corrosion Rate**

| Metal/Alloy | Element/ Oxidation State | Density (g/cm$^3$) | Equivalent Weight (gm) | Penetration Rate Equivalent to 1 $\mu$A/cm$^{2[1]}$ | |
|---|---|---|---|---|---|
| | | | | (mpy) | $10^{-3}$ mm/y$^{[2]}$ |
| **Pure Metals** | | | | | |
| Iron | Fe/2 | 7.87 | 27.93 | 0.463 | 11.5 |
| Nickel | Ni/2 | 8.90 | 29.36 | 0.431 | 10.8 |
| Copper | Cu/2 | 8.96 | 31.77 | 0.463 | 11.6 |
| Aluminum | Al/3 | 2.70 | 8.99 | 0.435 | 10.87 |
| Lead | Pb/2 | 11.3 | 103.6 | 1.20 | 29.9 |
| Zinc | Zn/2 | 7.14 | 32.7 | 0.598 | 14.95 |
| Tin | Sn/2 | 7.26 | 59.35 | 1.07 | 26.7 |
| Titanium | Ti/2 | 4.51 | 23.93 | 0.69 | 17.3 |
| Zirconium | Zr/4 | 6.52 | 22.81 | 0.457 | 11.4 |

Note:  [1] A current density of 1 $\mu$A/cm$^2$ is approximately = 1 mA/ft$^2$
         [2] 1 mm = 40 mils

# 1.6  Corrosion Potential

If the potential measurement in the previous corrosion cell was made to a single reference electrode placed remote from either the anode or cathode site as shown in Figure 1-22, the potential recorded is considered a "corrosion" potential ($E_{corr}$) or mixed potential.
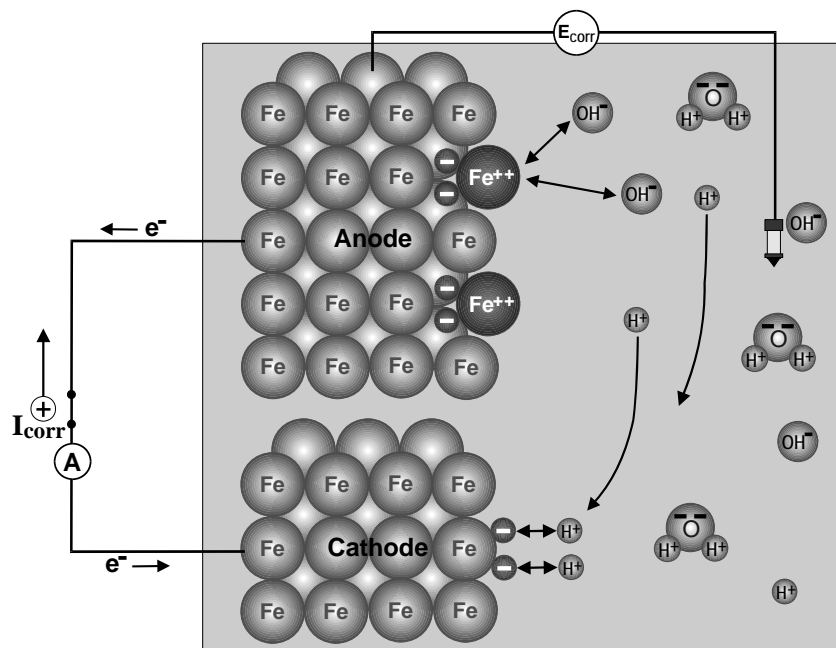


**Figure 1-22:  Corrosion Potential Measurement to a Remote Reference Electrode**

The measured potential is a weighted geometric and electrical average of the anode polarized potential ($E_{a,p}$) and the cathode polarized potential ($E_{c,p}$). The value of this potential will depend on the relative size of the anodes and cathodes, the location of the reference electrode with respect to the anode and cathode, and the resistance of the electrolyte path between the reference electrode and the anode and cathode. For the example in Figure 1-22, assuming equal anode and cathode surface areas and a very remote reference, the corrosion potential ($E_{corr}$) would be about midway between $E_{c,p}$ and $E_{a,p}$ as illustrated in Figure 1-23.
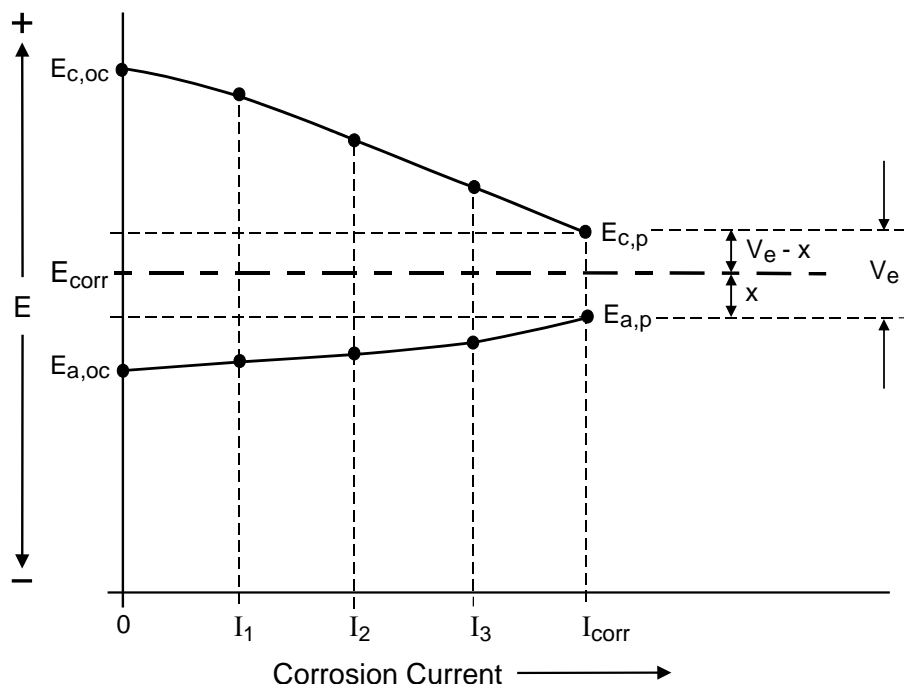
**Figure 1-23: Corrosion Potential Indicated on the Polarization Diagram**

If the reference electrode were moved closer to the anode site, the measured corrosion potential would become more electronegative. Conversely, if it were moved closer to the cathode site, the measured corrosion potential would become more electropositive.

The difference between $E_{c,p}$ and $E_{a,p}$ in a short circuited corrosion cell is simply the voltage drop in the electrolyte ($V_e$) since $V_m = 0$. Therefore the corrosion potential contains a voltage drop component. That is, the corrosion potential is more positive than the anode polarized potential by *x* millivolts and more negative than the cathode polarized potential by $V_e - x$ millivolts.

On an underground bare steel pipeline in the absence of a cathodic protection system, numerous corrosion cells will form, all having different anode and cathode polarized potentials. A potential measurement with the reference placed on grade will be a mixed potential of all the individual surface potentials within the influence of the reference electrode. The corrosion potential consists primarily (about 90%) of the polarized potentials on the pipe surface falling inside a 120° angle[9] from the reference electrode as shown in Figure 1-24 plus a voltage drop

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[9] *Pearson, J.M., Concepts and Methods of Cathodic Protection Part 2, The Petroleum Engineer, April, 1944, p.200.*

component due to corrosion currents in the earth between the reference and the respective anodes and cathodes.
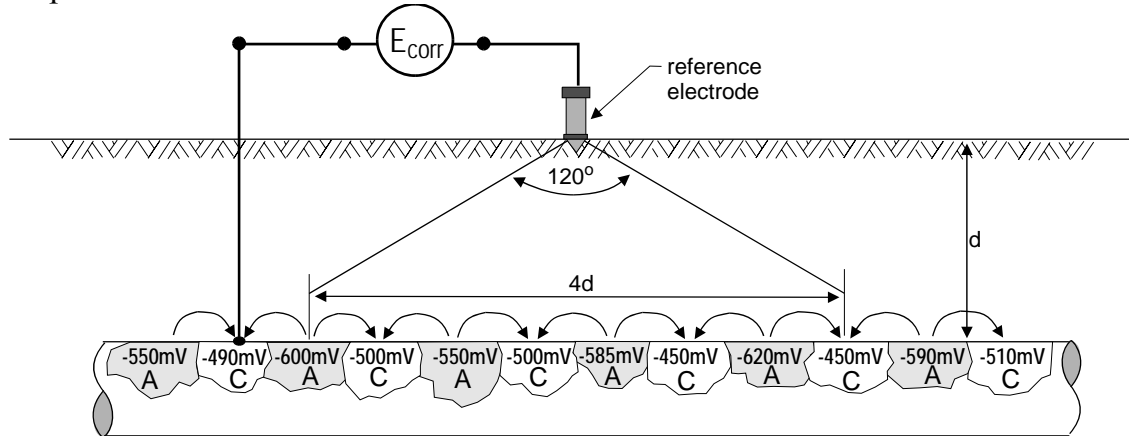


**Figure 1-24:  Measurement of Corrosion Potential (Mixed Potential)**

Measurement of the corrosion potential on a coated pipeline with holidays as illustrated in Figure 1-25 presents a more complex situation.
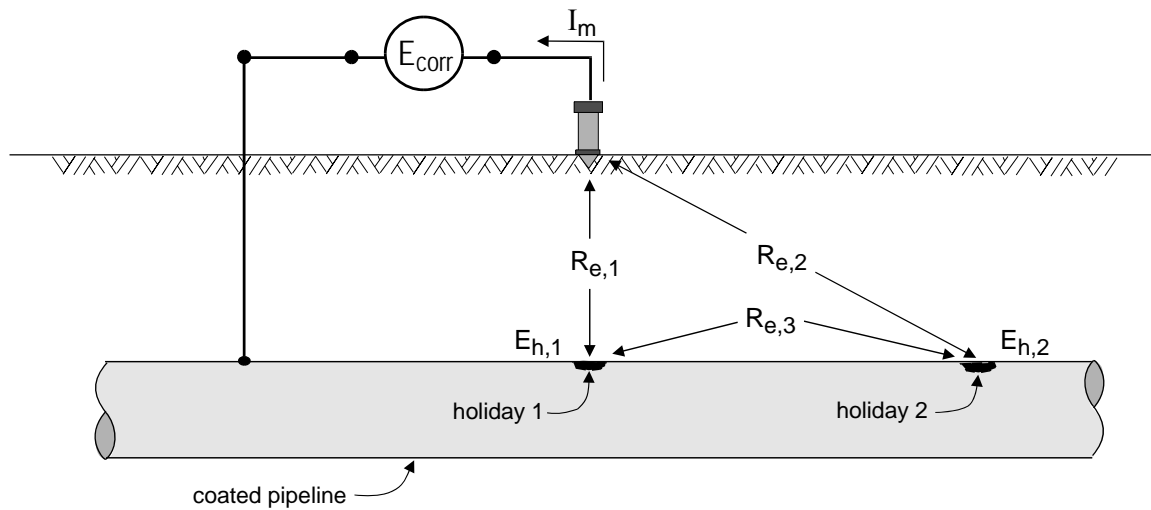


**Figure 1-25:  Measurement of Corrosion Potential on a Pipeline with Two Holidays**

Assuming the coating is a perfect insulator (which it is not), the corrosion potential is given by the following expression:

$$E_{corr} \ = \ E_{h2} \ + \ \frac{\Delta E}{R'} \Big[ R_{e,2} R_{e,3} \ + \ R_{h2} \big( R_{e,1} + R_{e,2} + R_{e,3} \big) \Big] \qquad \text{[1-32]}^{10}$$

---

[10] *Barlo, T.J. and Fessler, R.R., Investigation of Techniques to Determine the True Pipe-to-Soil Potential of a Buried Pipeline, American Gas Association Catalog #L51394, May 1980, p.1-63.*

*where:*        $\Delta E$  =  $E_{h1} - E_{h2}$
                $E_{h1}$  =  potential of holiday 1
                $E_{h2}$  =  potential of holiday 2
                $R'$  =  $(R_{h1} + R_{h2} + R_{e,3})(R_{e,1} + R_{e,2} + R_{e,3}) - R_{e,3}^2$
                $R_h$  =  resistance of soil in volume element of the holiday
                $R_e$  =  resistance in the electrolyte between the holiday
                          and reference electrode
                $R_{e,3}$  =  resistance in the electrolyte between the holidays

For a situation where the reference electrode is midway between two holidays Equation 1-32 reduces to

$$E_{corr} = \frac{E_{h1}R_2 + E_{h2}R_1}{R_T} \qquad \text{[1-33]}$$

*where:*        $R_1$  =  $R_{h1} + R_{e1}$
                $R_2$  =  $R_{h2} + R_{e2}$
                $R_T$  =  $R_{e1} + R_{e2} + R_{h1} + R_{h2}$

If  $R_2 = R_1$,  then the corrosion potential will be primarily influenced by the magnitude of the potential at each individual holiday.

Example:
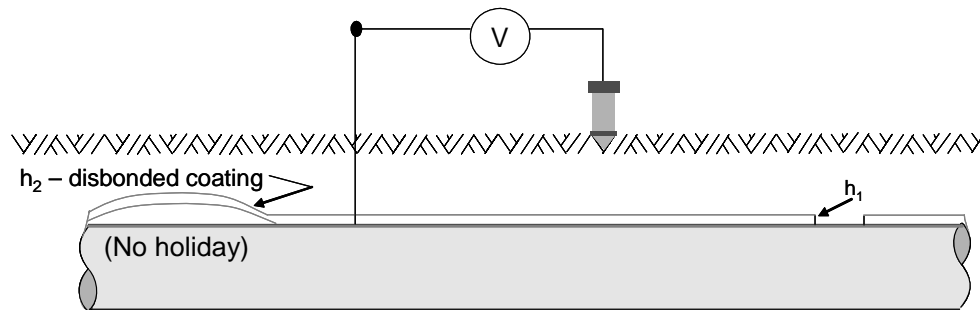


Given:

$E_{h1}$  =  $-900\ \text{mV}_{CSE}$          $d_{h1}$  =  1 cm                    $t_{ctg}$ = 0.1 cm
$E_{h2}$  =  $-500\ \text{mV}_{CSE}$          $A_{h2}$  =  $1\text{m}^2 = 10^4\ \text{cm}^2$     $d_{ref}$=2cm
$\rho_{soil}$  =  $10^4\ \Omega\text{-cm}$          $\rho_{ctg}$  =  $10^{10}\ \Omega\text{-cm}$

$$Em = \frac{E_{h1}R_2 + E_{h2}R_1}{R_T}$$

*where* $R_T = R_{e1} + R_{e2} + R_{h1} + R_{h2}$

$$R_{h1} = \frac{\rho_s}{2d} = \frac{10^4 \Omega - cm}{2cm} = 5 \times 10^3 \Omega$$

$$R_{h2} = \frac{\rho_{ctg} t_{ctg}}{A_{h2}} = \frac{10^{10} \Omega - cm \times 0.1 \, cm}{10^4 \, cm^2} = 10^5 \Omega$$

$$R_{e,1} = R_{e,2} = \frac{\rho_s}{2d_{ref}} = \frac{10^4 \Omega - cm}{2 \times 2 \, cm} = 2.5 \times 10^3 \Omega$$

$$R_1 = R_{h1} + R_{e1} = 5 \times 10^3 \Omega + 2.5 \times 10^3 \Omega = 7.5 \times 10^3 \Omega$$

$$R_2 = R_{h2} + R_{e2} = 10^5 \Omega + 2.5 \times 10^3 \Omega = 102.5 \times 10^3 \Omega$$

$$E_m = \frac{900 \, x \, 102.5 \, x \, 10^3 + 500 \, x 7.5 \, x \, 10^3}{2.5 \, x 10^3 + 2.5 \, x 10^3 + 5 \, x \, 10^3 + 100 \, x 10^3}$$

$$= \frac{92.3 \, x \, 10^6 + 3.75 \, x \, 10^6}{110 \, x \, 10^3} = \frac{96 \, x 10^6}{110 \, x 10^3}$$

$$E_m = -873 \, mV_{CSE}$$

## 1.7 Factors Affecting the Operation of a Corrosion Cell

The primary factors affecting the magnitude of the corrosion current, and hence the corrosion rate are:

- polarization characteristics at the anode and cathode interface
- circuit resistances
- cell EMF (driving voltage); and
- time
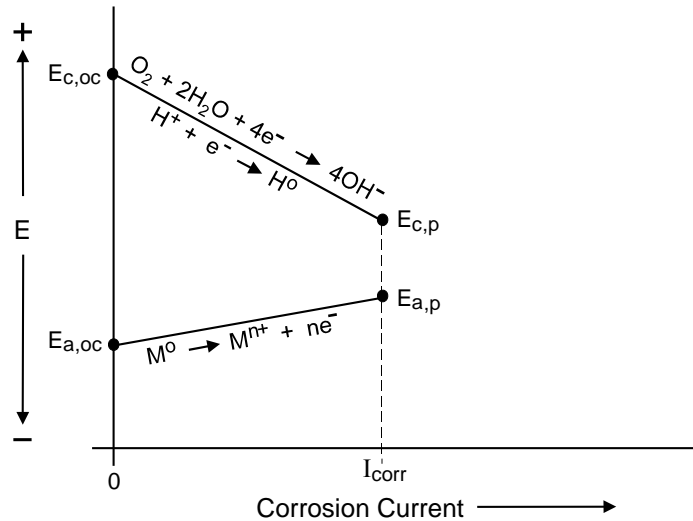
**Figure 1-26: Polarization Diagram Showing Charge Transfer Reactions**

As illustrated in Figure 1-26, the polarization that occurs at the corrosion cell anode results from a slow step in the oxidation reaction ($M^o \rightarrow M^{n+} + ne^-$) and at the cathode, from a slow step in either of the two reduction reactions ($H^+ + e^- \rightarrow H^o$ or $O_2 + 2H_2O + 4e^- \rightarrow 40H^-$) that transfer charge across the interface.

## 1.7.1   Depolarization in a Corrosion Cell

If the charge transfer reactions are sped up, there will be less polarization for a given amount of current and therefore more driving voltage available to push charges through the circuit resistances, hence more current ($I'_{corr}$). This effect is termed *depolarization* and is illustrated in Figure 1-27.
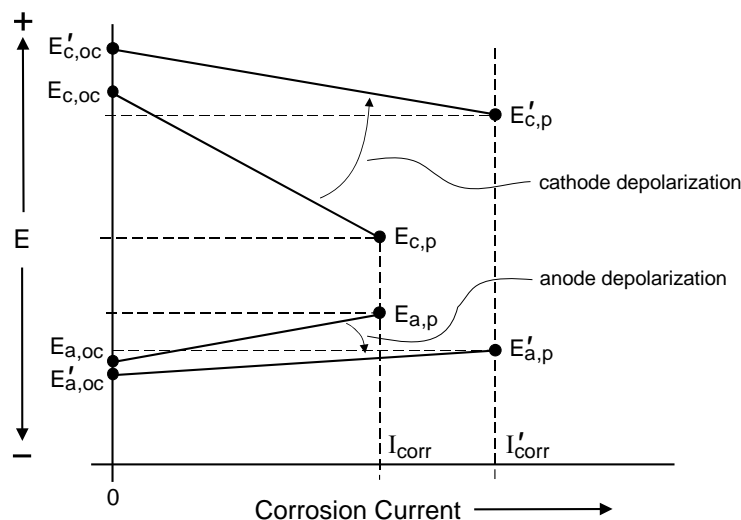


**Figure 1-27:  Effect of Depolarization at Both Anode and Cathode**

This figure shows the effect of depolarization at both the anode and cathode, although they can occur independently. Depolarization at both the anode and cathode results in increased corrosion current ($I'_{corr}$), a more electropositive cathode polarized potential ($E'_{c,p}$), and a more electronegative anode polarized potential ($E'_{a,p}$). Also, the open circuit potentials are often affected by the depolarization with a resultant increase in cell EMF.

## 1.7.1(a)  Cathode Depolarization

In general, factors that increase the rate of charge transfer across the interface result in depolarization. An increase in the concentration of reactants at the cathode interface increases the rate of charge transfer.  For instance, an increase in the dissolved oxygen concentration speed ups the oxygen reduction reaction ($O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$). Also, an increase in hydrogen ion concentration ($H^+$) speeds up the hydrogen reduction reaction ($H^+ + e^- \rightarrow H^o$). These effects are shown in Figure 1-28.
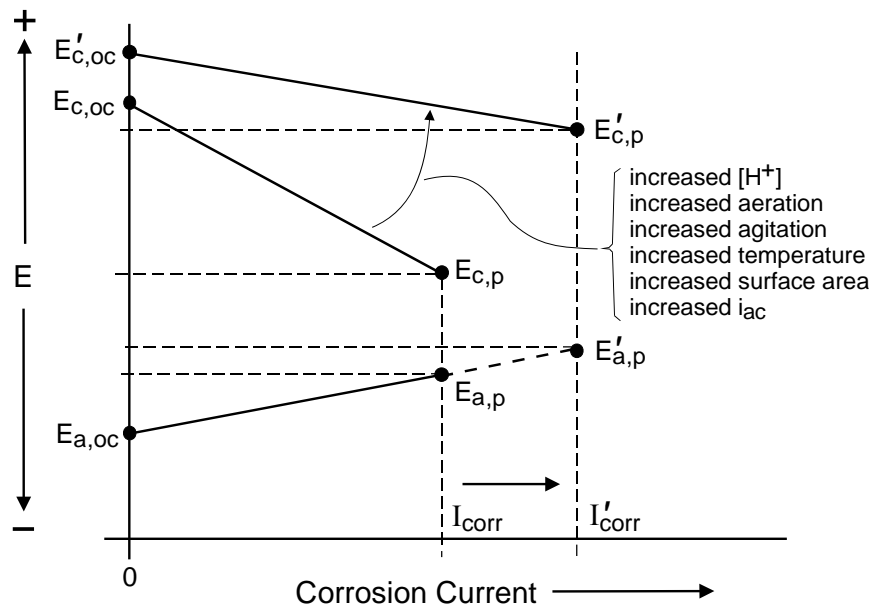


**Figure 1-28:  Cathode Depolarization in a Corrosion Cell**

Cathode depolarization can also be caused by the removal of reduction reaction products (i.e., $OH^-$ and $H^o$) as would occur if there were increased agitation in the electrolyte. As with most chemical reactions, an increase in temperature increases the reaction rate and therefore the rate of depolarization increases. If the cathode surface area increases, perhaps due to coating failure, charges can transfer more

readily (i.e., with less energy required). Cathodic depolarization results in an increased corrosion current, an electropositive shift in both the open circuit and polarized potential at the cathode, and an electropositive shift in the anode polarized potential. This is assuming there is no depolarization effect at the anode. A superimposed alternating current density on the cathode can also cause depolarization.[11]

## 1.7.1(b)  Anode Depolarization

Anything that increases the rate of the oxidation reaction will result in anode depolarization. One cause of anode depolarization is the removal of the oxidation products that are the dilution of the metal ion concentration or removal of the oxidation products formed on the surface.

For steel, a ferrous hydroxide corrosion product is formed over the anode surface. If the pH decreases, the ferrous hydroxide becomes more soluble thus exposing more surface. Similarly, chloride ions can attack corrosion films and depolarize anode surfaces. Increased temperature and agitation also will cause anode depolarization. The effect of anode depolarization is illustrated in Figure 1-29.
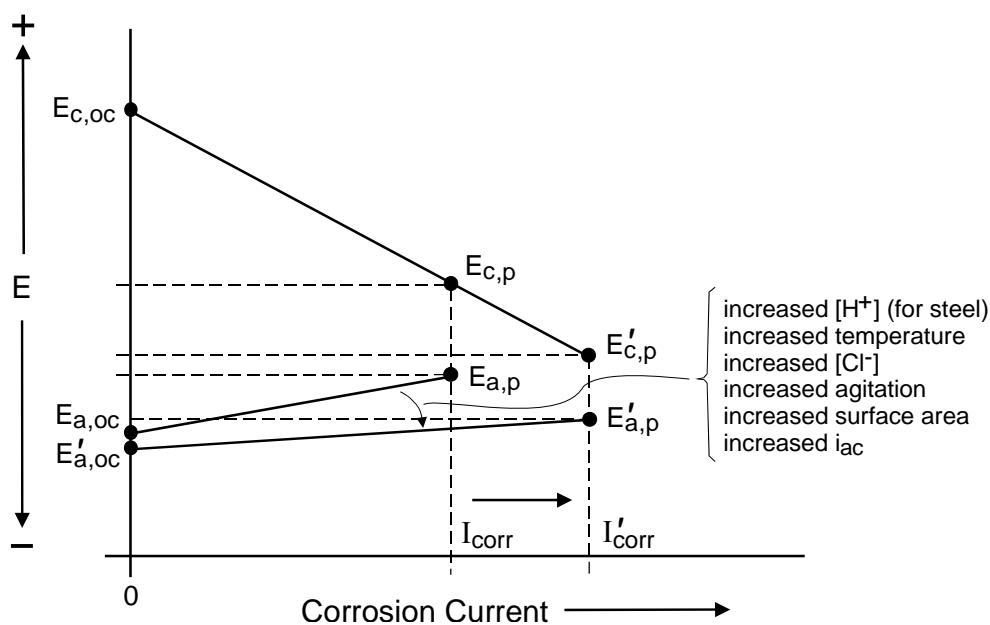


**Figure 1-29:  Anode Depolarization in a Corrosion Cell**

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[11] *Bolzoni et al., Laboratory Testing on the Influence of Alternated Current on Steel Corrosion, CORROSION /2004,  paper no. 208 (Houston, TX: NACE, 2004).*

Anode depolarization causes the corrosion current to increase to $I'_{corr}$, the anode polarized potential to shift electronegatively to $E'_{a,p}$, the anode open circuit potential to shift electronegatively to $E_{a,oc}$ and the cathode polarized potential to shift electronegatively to $E'_{c,p}$. Note that for an increase in temperature at the anode or an increase in anode surface area, the open circuit potential ($E_{a,oc}$) of the anode could shift electropositively instead of electronegatively.

## *1.7.2   Increased Polarization in a Corrosion Cell*

If conditions at the anode and cathode interface cause the rate of charge transfer to slow down, this will increase the polarization since it will require more electrical energy to transfer the charge. An increase in polarization of both the anode and cathode is illustrated in Figure 1-30.
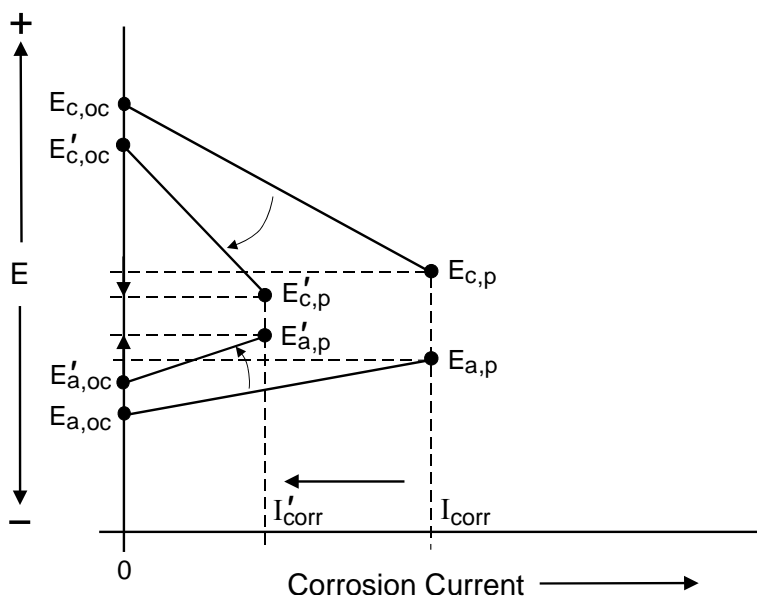


**Figure 1-30:  Increased Polarization at Both the Anode and Cathode of a Corrosion Cell**

Increased polarization at both the anode and cathode results in less corrosion current, an electronegative shift in the cathode open circuit and polarized potential, and an electropositive shift in anode open circuit and polarized potential.

A depletion of reactants, a lower temperature, less agitation, and a buildup of reaction products can cause this combined effect which results in less corrosion. Increased polarization can occur independently at the cathode or anode.

## 1.7.2(a)  Increased Polarization at the Cathode of a Corrosion Cell

If only the speed of the reduction reaction is reduced, the resulting polarization characteristics will be as shown in Figure 1-31.
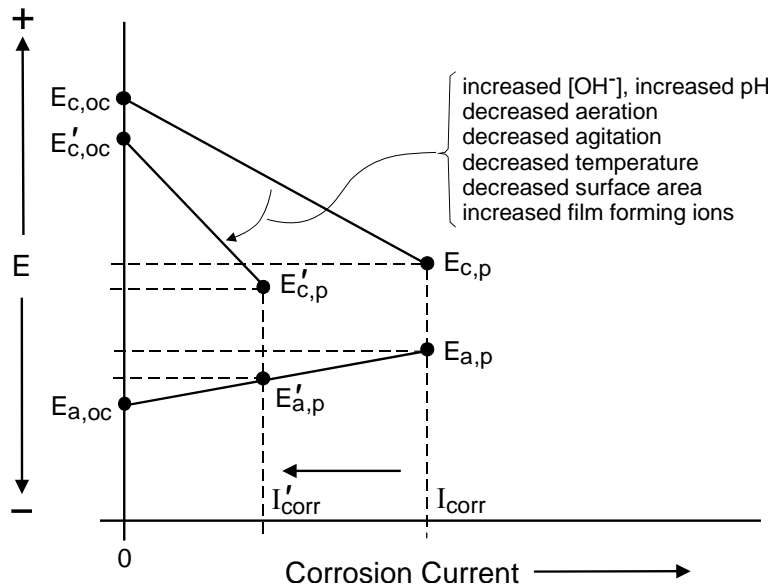


**Figure 1-31:  Increased Polarization at the Cathode in a Corrosion Cell**

Such an increase in polarization can be due to a number of factors localized at the cathode such as an increase in the pH, decrease in aeration, decrease in agitation, decrease in temperature, and decrease in surface area. The result is less corrosion current, an electronegative shift in the cathode open circuit potential, and polarized potential, and the anode polarized potential.

Note that an increase in pH would occur with time as the products of the oxygen reduction reaction ($OH^-$ ions) build up.

## 1.7.2(b)  Increased Polarization at the Anode of a Corrosion Cell

If the oxidation reaction at the anode is inhibited, it will require more electrical energy to transfer charge and thus a greater polarization shift in potential will be observed as depicted in Figure 1-32.

The diagram shows a plot of $E$ (potential) on the vertical axis (with + at top and − at bottom) versus Corrosion Current on the horizontal axis. Points labeled $E_{c,oc}$, $E'_{c,p}$, $E_{c,p}$, $E'_{a,p}$, $E_{a,p}$, $E'_{a,oc}$, $E_{a,oc}$ are shown. Vertical dashed lines mark $I'_{corr}$ and $I_{corr}$. A bracket on the right lists:

increased [OH⁻], increased pH
decreased agitation
decreased temperature
decreased surface area
increased passivating ions
increased $M^{n+}$ concentrations

**Figure 1-32:  Increased Polarization at the Anode in a Corrosion Cell**

An increase in polarization at the anode can result from an increase in the pH of the electrolyte if the anode metal is steel, a decrease in agitation, a decrease in temperature, a decrease in anode surface area, or an increase in ions that will form a passive film on the anode surface (e.g., nitrates, phosphates, etc.).

If the anode polarizes due to localized conditions, then the corrosion current is reduced and the anode open circuit potential and polarized potential both shift electropositively as does the cathode polarized potential.

Increased polarization at either the anode or cathode of a corrosion cell results in less corrosion.

## 1.7.3  Circuit Resistance Changes

As shown in Equation 1-21 the difference in potential between the polarized potential of the anode and cathode $[E_{c,p} - E_{a,p}]$ is equal to the sum of the voltage drops in the metallic and electrolytic current paths. The operating driving voltage (that is, the driving voltage remaining after subtracting anode and cathode polarization) is therefore equal to the total voltage drop in the corrosion cell.

The voltage drops are a product of the corrosion current multiplied by the path resistance, sometimes called the IR drop. If the resistance of either the metallic or electrolytic current paths changes and the corrosion cell open circuit driving voltage remains unchanged, from Ohm's Law the corrosion current will change.

## 1.7.3(a)  Increase in Resistance in a Corrosion Cell

Consider an increase in either the metallic or electrolytic path resistance on the corrosion cell operation as illustrated in Figure 1-33.
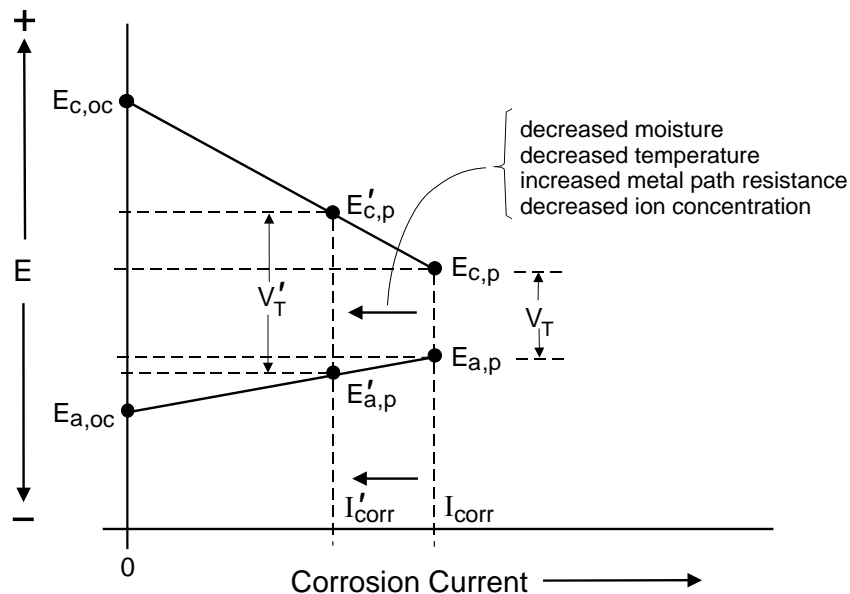


**Figure 1-33:  Increase in Resistance in a Corrosion Cell**

As would be expected, an increase in resistance decreases the corrosion current, which results in a more electropositive cathode polarized potential and a more electronegative anode polarized potential.

An increase in resistance of a soil is typically due to either a decrease in moisture or freezing of the soil, both of which can appreciably change the soil resistivity as illustrated in Figure 1-34 and Figure 1-35.
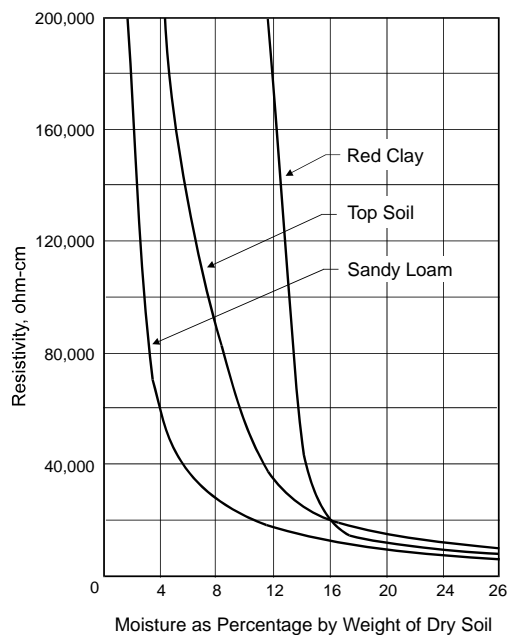
**Figure 1-34:  Soil Resistivity vs. Moisture Concentration**
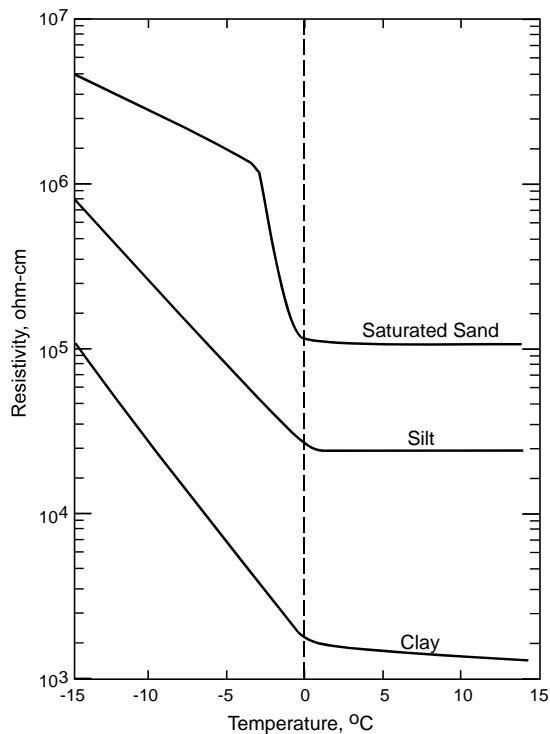


**Figure 1-35: Typical Resistivity vs. Temperature for Three Soil Types**

Source:  Earth Resistances, G.F. Tagg**,** Pitmann Publishing, 1964, p.5

As shown in Figure 1-34 the resistivity of red clay increases from 20,000 Ω-cm to 180,000 Ω-cm (a factor of 8 times) with only a 4% reduction in moisture content (16 to 12%). Moisture content greater than about 16% does not significantly change the resistivity of any of the soils.

A decrease in temperature from 0 to –10°C results in at least an order of magnitude increase in resistivity for the three soil types shown in Figure 1-35. Yet above 0°C there is relatively little decrease in resistivity with increasing temperature.

## 1.7.3(b)  Decrease in Resistance in a Corrosion Cell

A decrease in resistance of either the metallic or electrolytic path between the corrosion cell anode and cathode results in an increase of corrosion current as shown in Figure 1-36.
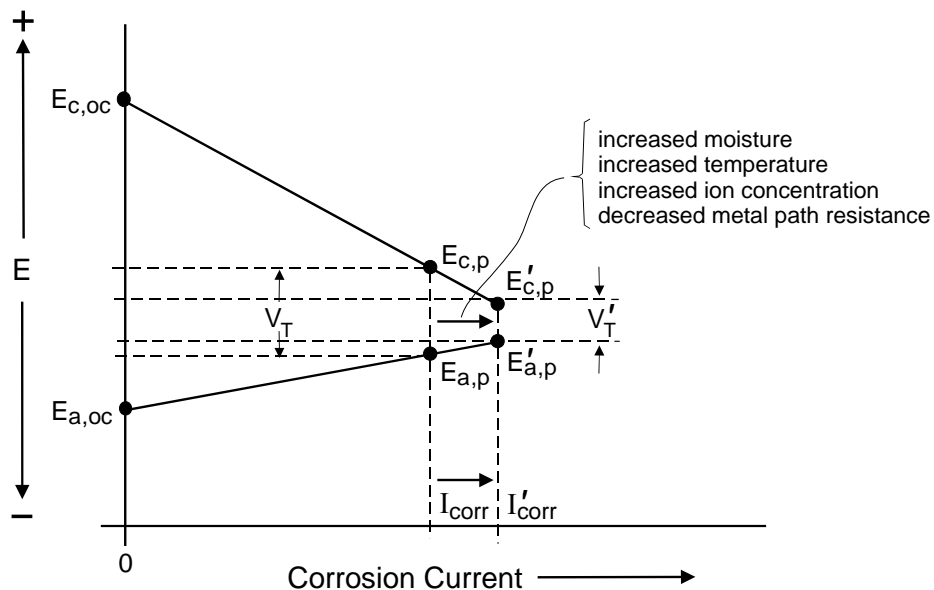
**Figure 1-36: Decrease in Resistance in a Corrosion Cell**

Even though the corrosion current increases, the total IR drop in the circuit is less. Both the cathode and anode polarized potentials have moved closer to one another resulting in more anodic and cathodic polarization because of the larger corrosion current.

Changes in electrolyte resistance are common in corrosion cells in contact with the earth due primarily to seasonal variations in moisture or temperature.

## 1.7.4   Effect of Driving Voltage on a Corrosion Cell

From Ohm's Law it is clear that the greater the driving voltage, the greater the corrosion current will be, as illustrated in Figure 1-37.
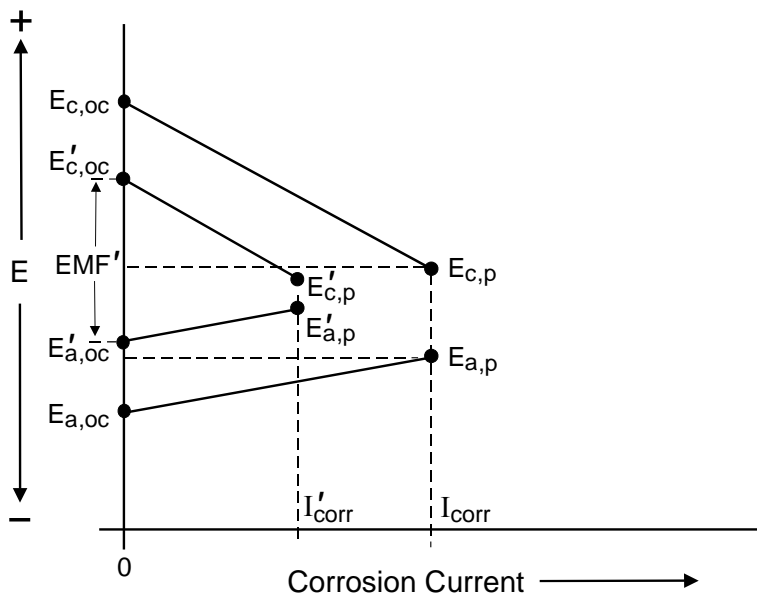
**Figure 1-37:  Effect of Driving Voltage (EMF) on a Corrosion Cell**

Referring to Figure 1-24, the corrosion current would be greater in the  –620 mV/ –450 mV corrosion cell than the –550 mV/–500 mV corrosion cell, since the operating EMF of the former is 170 mV compared to 50 mV for the latter.

## 1.7.5   *Effect of Time on a Corrosion Cell*

As corrosion continues with time, where there is limited electrolyte agitation, oxidation and reduction reaction products will build up at their respective interfaces. In the case of the reduction reactions this means an increasing concentration of hydroxyl ions, and it is apparent from Figure 1-31 that an increase in pH will result in increased polarization.

Similarly, as the metal corrodes at the anode, the metal ion concentration will increase anode polarization as indicated in Figure 1-32. Accordingly, polarization increases at both the anode and cathode and with time corrosion current will reduce as shown in Figure 1-38.
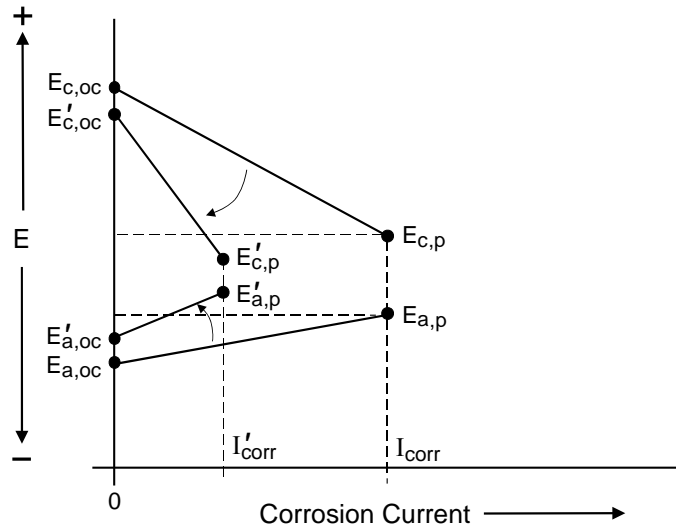
**Figure 1-38:  Effect of Time on a Corrosion Cell**

Anything that increases polarization (i.e., slows down charge transfer reactions) in a corrosion cell will reduce the corrosion current and is therefore beneficial.

## 1.7.6  Randle's Circuit Model for an Electrode Interface in a Corrosion Cell

The electrode/electrolyte interface can be modeled electrically as shown in Figure 1-39.
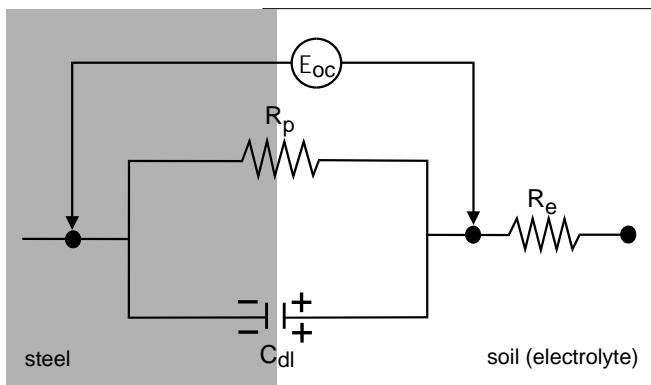


*where:*

$C_{dl}$ = double layer capacitance $(1\text{-}200\,\mu F/cm^2)$

$R_p$ = polarization resistance $(1\text{-}10^4\,\Omega\text{-}cm^2)$

$R_e$ = resistance of steel surface to remote earth

$E_{oc}$ = potential difference (volts)

**Figure 1-39:  Randle's Electrical Circuit Model of a Metal/Electrolyte Interface**

This model shows that the interface is not simply a resistance but a parallel combination of the polarization resistance ($R_p$) and a capacitor ($C_{dl}$) called the

*double layer capacitance*. The potential E across the parallel combination can be considered the open circuit potential. Therefore the potential at more electro-negative (anodic) sites on a structure will be greater than at cathodic (more electropositive) sites. When coupled, as shown in Figure 1-40, charges move from the most highly charged capacitor to the least highly charged capacitor, changing the potential of each in the process. The anode capacitor is being discharged while the cathode capacitor is being charged. These changes in potential ($\Delta E$) as a result of charge transfer is polarization, and the resulting potential across the metal/electrolyte interface is called the *polarized potential* ($E_{a,p}$ and $E_{c,p}$) for the anode and cathode site respectively.
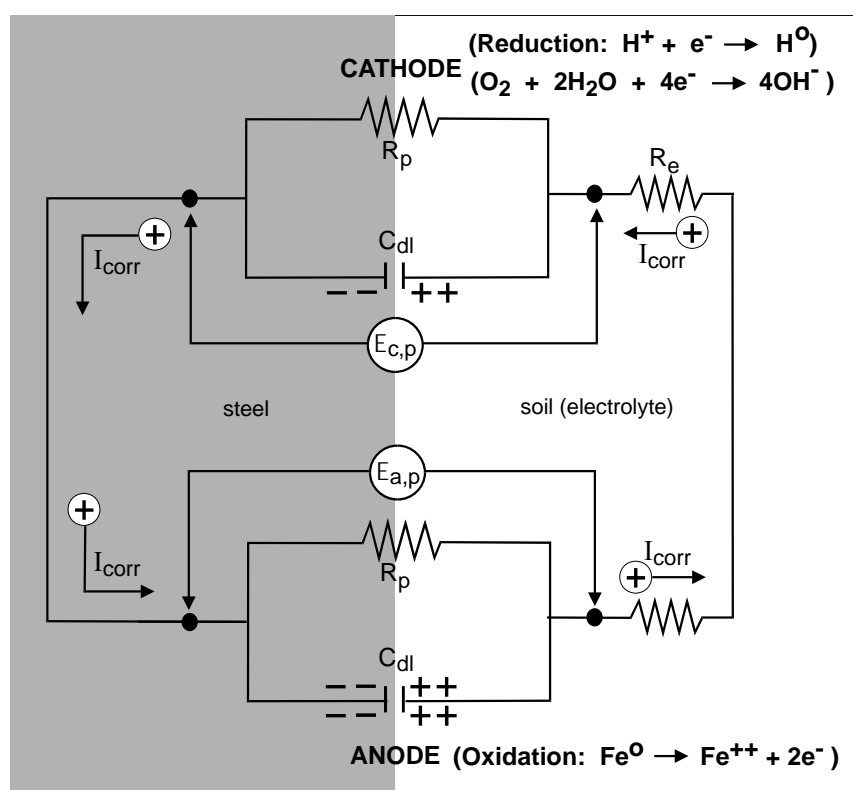


**Figure 1-40:  Randle's Electrical Circuit Model for a Typical Corrosion Cell on an Unprotected Steel Surface**

## *1.7.7 Types of Corrosion*

Corrosion always occurs in the form of a corrosion cell where an anode site, a cathode site, and an electronic and electrolytic current path between the anode and cathode sites exist. However the conditions of the metal and its environment may vary widely leading to the characterization of different types of corrosion activity as listed below.
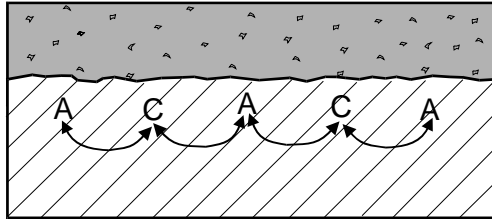


**Figure 1-41a**

**Uniform Corrosion** – anodes and cathodes change locations resulting in general metal loss (e.g., atmospheric corrosion).
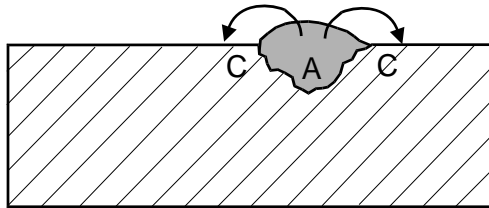


**Figure 1-41b**

**Pitting Corrosion** – the anode site remains fixed and corrosion is localized (e.g., stainless steels in the presence of chlorides).
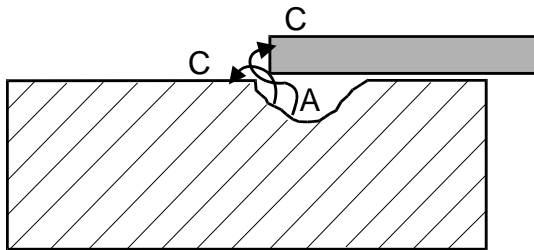


**Figure 1-41c**

**Crevice Corrosion** – the surface area in the crevice is oxygen starved but the surrounding surfaces have access to dissolved oxygen (e.g., overlapping seams on surface storage tank floors).
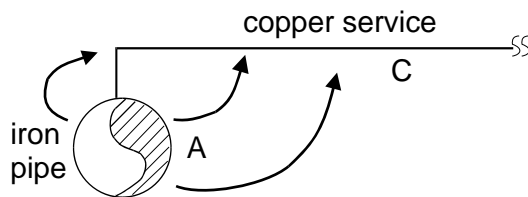


**Figure 1-41d**

**Galvanic Corrosion** – dissimilar metals are interconnected and exposed to a common environment (e.g., cast iron water main with copper services).

stress cracking    fatigue cracking
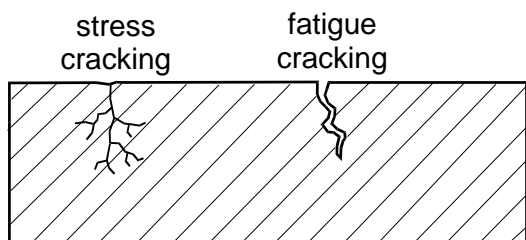
**Figure 1-41e**

**Environmentally Induced Cracking** – there is a brittle fracture of a ductile metal alloy in the presence of modest corrosion and a static or cyclic stress. This includes stress corrosion cracking (SCC), fatigue cracking, and hydrogen induced cracking (HIC).

Typically the crack tips are anodic to the crack walls.

graphite flakes & iron corrosion product
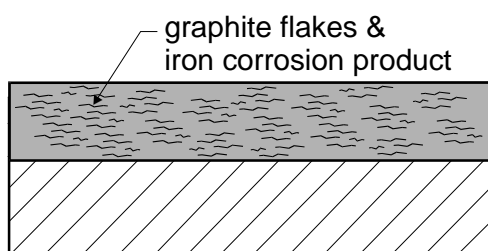
**Figure 1-41f**

**Dealloying and Dezincification** – one of the alloying elements is more active than another resulting in the selective corrosion (sometimes called leaching) of the more active element (e.g., graphitic corrosion of gray cast iron).

turbulent flow
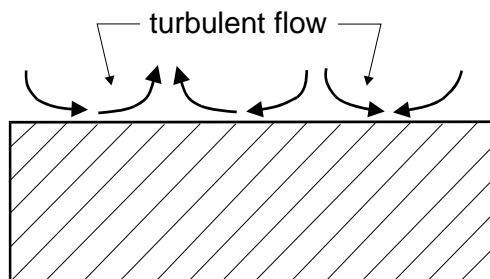
**Figure 1-41g**

**Erosion-Corrosion and Fretting** – corrosion product is removed from the metal surface by fluid flow or abrasion accelerating the corrosion reaction (e.g., pipelines transporting slurries).

Except for hydrogen-induced cracking and fatigue cracking, cathodic protection can be effective in mitigating all of these forms of corrosion if the structure is buried or immersed.

## 1.7.7(a)  Galvanic Corrosion

Galvanic corrosion is one of the more common forms of corrosion because of the many different materials of construction available for use. As shown in Figure 1-42, not only can there be considerable corrosion potential difference between different alloys but also there is a range of possible corrosion potentials for each alloy, even in a relatively homogenous seawater environment. When any two metals are coupled, the more electronegative alloy will become the anode of a corrosion cell. Further, the greater the potential difference between these metals, the higher the corrosion current will be.

A number of alloys such as the stainless steels, which depend on a passive film for their corrosion protection, have relatively noble (electropositive) potentials when passive but electronegative potentials if the passive film is damaged. Hence stainless steel is strongly cathodic to low-alloy steel when passive but only mildly cathodic when active. Magnesium, zinc, and aluminum are all more electronegative than low mild steel and cast iron, which makes them effective galvanic anode materials for the cathodic protection of ferrous structures.

Volts versus saturated calomel reference electrode

| (Active) | | | | | | | | | | (Noble) |
|---|---|---|---|---|---|---|---|---|---|---|
| -1.6 | -1.4 | -1.2 | -1.0 | -0.8 | -0.6 | -0.4 | -0.2 | 0 | 0.2 | |

Graphite
Platinum
Ni-Cr-Mo alloy C
Titanium
Ni-Cr-Mo-Cu-Si alloy G
Nickel-iron-chromium alloy 825
Alloy 20 stainless steels, cast and wrought
Stainless steel-types 316, 317
Nickel-copper alloys 400, K-500
Stainless steel - types 302, 304, 321, 347
Silver
Nickel 200
Silver-bronze alloys
Nickel-chromium alloy 600
Nickel-aluminum bronze
70-30 copper nickel
Lead
Stainless steel - type 430
80-20 copper-nickel
90-10 copper-nickel
Nickel silver
Stainless steel - types 410, 416
Tin bronzes (G & M)
Silicon bronze
Manganese bronze
Admiralty brass, aluminum brass
50Pb-50Sn solder
Copper
Tin
Naval brass, yellow brass, red brass
Aluminum bronze
Austenitic nickel cast iron
Low-alloy steel
Low-carbon steel, cast iron
Cadmium
Aluminum alloys
Beryllium
Zinc
Magnesium

**Figure 1-42:  Galvanic Series for Seawater**
**(Dark boxes indicate active behavior of active-passive alloys)**

Source:  ASM Handbook, Vol.13, Corrosion, 9th Ed. of Metals Handbook, p.234

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## *Experiment 1-1*
## To Demonstrate Polarization in a Corrosion Cell
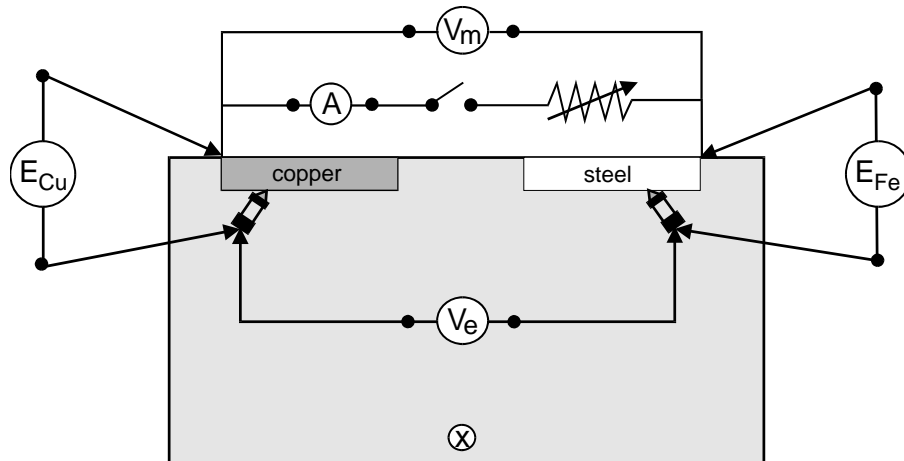


**Experiment Schematic**

## Procedure

**Step:**

A. Fill plastic tub with cold water to a depth of 5cm, add a cap full of salt, and place copper and steel sheets along one side of tub, making sure they are not touching.

B. Measure open circuit potential of steel and copper.

C. Connect an ammeter and a 10,000 ohm resistor in series with the copper and steel sheet as shown in the schematic.

D. With the switch in the open position, measure and record the potential of the copper and steel sheets with respect to a copper-copper sulfate reference electrode (CSE) placed next to the surface of each sheet.

E. Measure and record the potential difference between the steel and copper sheet ($V_m$).

F.  Measure and record the potential difference ($V_e$) between the two
    reference electrodes.

G.  Close the switch and wait 2 minutes before repeating steps C, D, E, and
    measuring and recording the corrosion cell current ($I_{corr}$) and direction.

H.  Reduce resistance to 1,000 ohms and repeat Step F.

I.  Reduce resistance to 100 ohms and repeat Step F.

J.  Reduce resistance to 10 ohms and repeat Step F.

K.  Reduce resistance to 0 ohms and repeat Step F.

L.  Measure and record the potential of the corrosion cell ($E_{corr}$) with reference
    placed at "x."

M.  Plot the cathodic and anodic polarization curves on the semi-log graph
    paper with potential on the ordinate and current on the abscissa (see Figure
    1-21).

N.  Leave current connected as in Step J in preparation for Experiment 2-1 and
    2-2.

## Results

| Step | Status | Potentials (mV$_{cse}$) | | Voltage Drop (mV) | | $I_{corr}$ | Calc. | Calc. |
|------|--------|-------------------------|--|-------------------|--|------------|-------|-------|
|      |        | $E_{Fe}$ | $E_{Cu}$ | $V_m$ | $V_e$ | ($\mu$A) | $E_{Fe} - E_{Cu}$ | $V_m + V_e$ |
| C,D,E | 0C | | | | | | | |
| F | 10 k$\Omega$ | | | | | | | |
| G | 1 k$\Omega$ | | | | | | | |
| H | 100 $\Omega$ | | | | | | | |
| I | 10 $\Omega$ | | | | | | | |
| J | 0 | | | | | | | |
| K | $E_{corr}$ | | | | | | | |

## Conclusions

1.  The difference between the open circuit (OC) potentials of the steel and copper electrode equals the corrosion cell initial EMF ($V_m$).

2.  The difference between the closed circuit potentials of the steel and copper electrodes equals the sum of external and electrolyte voltage drops since Kirchhoff's voltage law applies to this series circuit (e.g., for Steps F through J).

3.  The corrosion potential ($E_{corr}$) recorded in Step K is about midway between the polarized potential of the steel and copper.

4.  More polarization occurs at the cathode (copper electrode) than at the anode (steel electrode), i.e., $\Delta E_{p,Fe} < \Delta E_{p,Cu}$.

5.  Both the cathodic and anodic polarization curves are nonlinear.

6.  As corrosion current ($I_{corr}$) increases, the amount of polarization increases.

7.  The operating EMF ($E_{p,Fe} - E_{p,Cu}$) is always less than the initial EMF and decreases with increasing current.

8.  The corrosion current ($I_{corr}$) direction is from copper to steel in the external circuit and from steel to copper in the electrolyte.

## 2.1 Definition

Although the concept of cathodic protection finds its roots in the experiments and works of Sir Humphrey Davy and Michael Faraday, it was not until 1938 that Mears and Brown offered the following theory of cathodic protection:

> *…in cases where corrosion is entirely electrochemical in nature it is necessary to polarize the cathodes in the corrosion cell to the open circuit potential of the local anodes in order to obtain complete cathodic protection.[1]*

The theory of cathodic protection is best understood by first considering a simple corrosion cell consisting of one anode and one cathode on a structure. The driving force for corrosion current is the difference in potential between the anode and cathode. The magnitude of the corrosion current, as determined by Ohm's law, is directly related to this potential difference and inversely related to the resistance of the current path. After the corrosion cell has reached a steady state condition, the driving potential is the potential difference between the polarized potential of the anode and the polarized potential of the cathode, as seen in Equation 2-1.

$$I_{corr} = \frac{E_{a,p} - E_{c,p}}{R_a + R_c}$$ [2-1]

*where:*

$I_{corr}$ = Corrosion current (A)
$E_{a,p}$ = Potential of polarized anode (V)
$E_{c,p}$ = Potential of polarized cathode (V)
$R_a$ = Resistance of anode to electrolyte ($\Omega$)
$R_c$ = Resistance of cathode to electrolyte ($\Omega$)

As seen in the electrical equivalent of this simple corrosion cell in Figure 2-1, the current discharged by the anode is exactly the same as the current collected at the cathode, Equation 2-2.

$$I_a = I_c = I_{corr}$$ [2-2]

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[1] *R. B. Mears and R. H. Brown, "A Theory of Cathodic Protection," Transactions of the Electrochemical Society, presented October 15, 1938, vol. 74, pp. 519-531.*

*where:*  $I_a$ = Anode current (A)
$I_c$ = Cathode current (A)
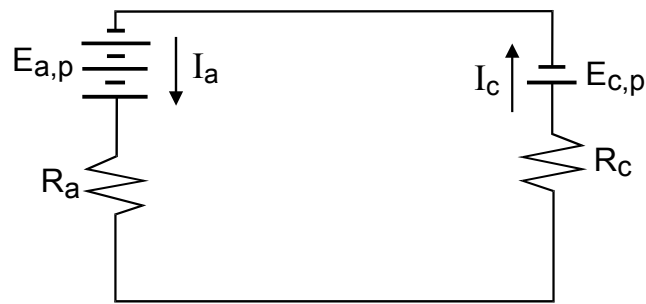


$$I_a = I_c = I_{corr} \qquad I_{corr} = \frac{E_{a,p} - E_{c,p}}{R_a + R_c}$$

**Figure 2-1: Simple Corrosion Cell**

With the application of cathodic protection, positive charge flows from an external source toward the structure (single corrosion cell), as seen in Figure 2-2. Now, the corrosion current or anodic current is no longer equal to the cathodic current. From Kirchhoff's current law, Equation 2-3 indicates that the anodic or corrosion current is equal to the cathodic current from the corrosion cell minus the applied current.
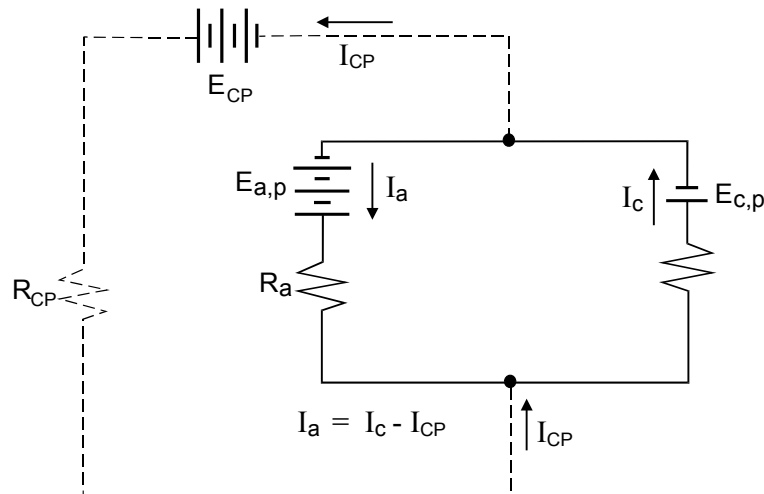


**Figure 2-2: Application of CP Current**

$$I_a = I_c - I_{CP} \qquad\qquad [2\text{-}3]$$

*where:*  $I_{CP}$ = cathodic protection current (A)

The corrosion cell must reach a new steady state condition. Since the cathode on the structure is at a more electropositive potential than the anode, the current collects at the cathode site first, assuming equal resistance paths. This collection of current at the cathode site causes the cathode to polarize more in the electronegative direction (reduction). Because of the increased polarization of the cathode, the potential difference between the anode and cathode in the corrosion cell decreases. This causes a decrease in the magnitude of the corrosion current. With a smaller corrosion current discharging into the electrolyte at the anode, the anode depolarizes becoming less electropositive. A new steady state condition is reached with a smaller corrosion current due to the applied cathodic protection current.

With each additional increment of applied cathodic protection, the corrosion current decreases further and the anode depolarizes more until the anode reaches its open circuit potential. At this point, the anode cannot depolarize further; therefore, the potential difference between the anode and cathode is zero. With zero potential difference, the anodic current becomes zero, the anode ceases to exist (i.e., ceases to function as an anode), and the cathodic current is equal to the applied cathodic protection current, as seen in Figure 2-3. Applying additional current serves only to polarize the two sites, which are now both cathodes, more electronegatively.
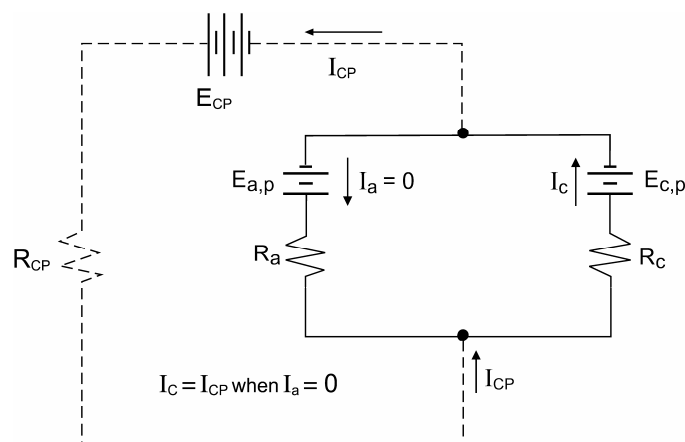


**Figure 2-3:  Corrosion Stopped**

Now consider a real corroding structure with many anodes and cathodes. As cathodic protection current is applied, the current enters the structure at the cathodes and causes polarization of the cathodes in the electronegative direction. As more and more cathodic protection current is applied, the potentials of the cathodes approach the potentials of the more active anodes. As the potential

differences decrease, more and more anodes convert to cathodes. When the structure polarizes to the open circuit potential of the most negative (most active) anode, no further anodes exist on the structure, and complete cathodic protection is achieved.

Therefore, **the true criterion for complete cathodic protection of a structure is the polarization of the cathodes on the structure to the open circuit potential of the most active anode on the structure.**

Since corrosion current ceases at this point, further addition of protective current is unnecessary and wasteful. Although the true criterion is relatively easy to understand, application of this criterion to real corrosion problems is not possible because the open circuit potential of the most active anode on a structure cannot be accurately calculated or measured in the field. Therefore, surrogate criteria are necessary.

## 2.2  Criteria

The effectiveness of cathodic protection can be determined by methods that show corrosion on the structure is not occurring. Many of these methods involve physically inspecting for corrosion on the surface of the structure, reviewing the environmental conditions and corrosion control operating parameters and/or a reduction in the rate of corrosion leaks. In most cases involving pipelines and other buried structures, it is not practical to routinely and frequently inspect the surface to verify that corrosion is not occurring. In the absence of this kind of specific data that adequate cathodic protection has been achieved, surrogate criteria based on cathodic polarization can be used. These criteria can be applied without waiting for evidence of corrosion.

The purpose of a surrogate cathodic protection criterion is to provide a benchmark against which the level of cathodic protection applied to a specific structure can be compared. Some desirable characteristics of a good criterion include applicability to a wide range of structures and environments, ease of application, sound scientific basis, high probability of mitigation of corrosion to an acceptable level, and low probability of excessive protection.

Although several criteria have been recognized in the past, current versions of NACE Standards SP0169 (pipelines), RP0193 (on-grade tanks), and RP0285 (underground storage tanks) recognize three primary criteria for steel exposed to soil environments: 1) the -850 mV$_{CSE}$ potential criterion with current applied, 2)

the $-850$ mV$_{CSE}$ polarized potential, and 3) the 100 mV polarization criterion. In this text we will refer to the first two criteria as the "potential criterion" and the third criterion as the "polarization shift criterion." Since all three of these standards provide essentially the same criteria with slight variations in order and wording, we will concentrate on SP0169 in the following discussions.

### 2.2.1  Potential Criterion (–850 mV$_{CSE}$)

The current version of NACE Standard SP0169 provides two different statements of the potential criterion. In paragraph 6.2.2.1.1, the criterion is stated as:

> *A negative (cathodic) potential of at least 850 mV with the cathodic protection applied. This potential is measured with respect to a saturated copper/copper sulfate reference electrode contacting the electrolyte. Voltage drops other than those across the structure-to-electrolyte boundary must be considered for valid interpretation of this voltage measurement.*[2]

This statement of the criterion goes on to indicate that *"Consideration is understood to mean the application of sound engineering practice in determining the significance of voltage drops by methods such as: 6.2.2.1.1.1 Measuring or calculating the voltage drop(s)...."* The standard contains other approaches to considering voltage drop significance.[2]

In paragraph 6.2.2.1.2, the potential criterion is stated as *"A negative polarized potential (see definition in Section 2) of at least 850 mV relative to a saturated copper/copper sulfate reference electrode."* In Section 2, the definition of a polarized potential is given as "…*the sum of the corrosion potential and the cathodic polarization."*[3]

In measuring the structure-to-soil potential in the field, the potential measured is the algebraic sum of the corrosion potential, the cathodic polarization ($\eta_c$), and any IR drop present (Equation 2-4).

$$E_{meas} \ = \ E_{corr} \ + \ \eta_c \ + V_{IR} \tag{2-4}$$

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[2] *NACE Standard SP0169, "Control of External Corrosion on Underground or Submerged Metallic Piping Systems," (Houston, TX: NACE, 2002), pp. 12-17.*
[3] *Ibid.2*

*where:*    $E_{meas}$  =  Measured potential (V)
            $E_{corr}$  =  Corrosion potential (V)
            $\eta_c$  =  Polarization (V)
            $V_{IR}$  =  Voltage drop (V)

If the IR drops are removed from the measurement, through interruption of the current or any other valid means, the remaining value represents the polarized potential of the structure as defined by Section 2 in the standard. Since the potential criterion, as stated in paragraph 6.2.2.1.1, requires "consideration of voltage drops other than those across the structure-to-electrolyte boundary" and "consideration" is further defined as "measuring or calculating the voltage drop(s)," the two statements of the potential criterion are exactly the same with one exception. **The potential criterion, as stated in paragraph 6.2.2.1.1, specifically allows the engineer to evaluate IR drop by methods other than actual measurement or current interruption within the confines of "sound engineering practice."**

The –850 mV$_{CSE}$ criterion for the protection of steel in soil was first suggested by Kuhn in 1933 without scientific justification for this specific value.[4] Over the next twelve years, the validity of this criterion was strengthened through actual field experience, as reported by Logan.[5] Through laboratory experimentation Ewing and, at about the same time, Schwerdtfeger and McDorman added further validity to the potential criterion showing that in some cases the –850 mV$_{CSE}$ value was conservative.[6,7]

Schwerdtfeger and McDorman plotted the experimentally measured potentials of steel electrodes in different air free soils versus pH. By drawing a curve through this data and plotting the potential of a hydrogen electrode versus pH on the same graph, they observed that the intersection of the two curves occurred near a pH of 9 and a potential of –770 mV$_{SCE}$ (–846 mV$_{CSE}$). Based on this data and information from Holler, they concluded that since there would be no difference in potential between steel and a hydrogen electrode at this potential, corrosion would be negligible.[8,9]

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[4] *Robert J. Kuhn, "Cathodic Protection of Underground Pipe Lines from Soil Condition," API Proceedings, vol. 14, sec. 4, November 1933, pp. 153-167.*
[5] *Kirk Logan, "Underground Corrosion," Circular C450, NBS, November 1945, pp. 250-279.*
[6] *Scott Ewing, "Potential Measurements for Determining Cathodic Protection Requirements," CORROSION, vol. 7, no. 12, (1951): pp. 410-418.*
[7] *W. J. Schwerdtfeger and O. N. McDorman, "Potential and Current Requirements for the Cathodic Protection of Steel in Soils," CORROSION, vol. 8, no. 11 (1952): pp. 391-400.*
[8] *Ibid. 7.*

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The potential criterion was further enhanced by more recent experimental confirmation that the –850 mV$_{CSE}$ value provided adequate protection in a wide range of soil types, even with varying moisture levels (from approximately 4 % to saturation) and oxygen levels (aerated and deaerated).[10] This research was followed up by field testing in a variety of natural environments to confirm the laboratory results. The researcher selected eleven test sites in three different countries to test the validity of the criterion in varied field environments. Adequate corrosion mitigation assumed a corrosion rate of one mpy or less over the test period. Figure 2-4 shows the interim results for the eleven field test sites. As noted in Figure 2-4, this field testing further strengthened the validity of the –850 mV$_{CSE}$ criterion since all of the eleven sites tested were adequately protected according to the criterion.[11]
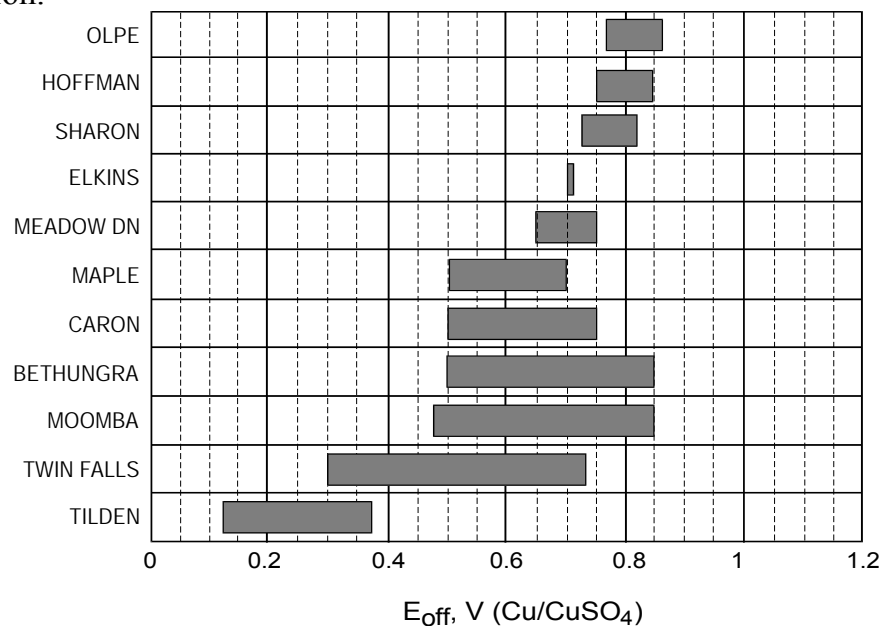


**Figure 2-4: Range of Polarized Potentials for Protection at Each Site**
Source:  Dr. Thomas J. Barlo, "Field Testing the Criteria for Cathodic Protection," Research sponsored by Pipeline Research Committee of American Gas Association, SAIC Interim Report, Dec. 1987, Cat. No. L51546 (Hoffman Estates, IL: AGA) 1988.

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[9] *H. D. Holler, "Studies on Galvanic Couples," Journal of Electrochemical Society, vol. 97, (1950): pp. 277-282.*

[10] *Thomas J. Barlo and Warren E. Berry, "An Assessment of the Current Criteria for Cathodic Protection of Buried Steel Pipeline," MP, vol. 23, no. 9 (1984): pp. 9-16.*

[11] *Dr. Thomas J. Barlo, "Field Testing the Criteria for Cathodic Protection," Research sponsored by Pipeline Research Committee of American Gas Association, SAIC Interim Report, Dec. 1987, Cat. No. L51546 (Hoffman Estates, IL: AGA) 1988.*

Meanwhile, a number of investigators have attempted to calculate a specific value for the potential criterion based on thermodynamic considerations. Beginning with an assumption regarding what constituted "an acceptable corrosion rate," they used the Nernst equation with solubility data in an attempt to calculate a potential value. The values determined varied around the previously established value of -850 mV$_{CSE}$ depending on the specific assumptions.[12,13,14,15,16,17,18]

As indicated in NACE Standard SP0169 and other standards, the data interpreter must consider IR drop when evaluating the protection level of a cathodically protected structure. In the practical application of cathodic protection, Pearson noted as early as 1944 that IR drop in the electrolyte did not significantly reduce corrosion. He concluded, "It is clear that any measurement of the polarization of a buried structure must be made to differentiate between the effects of purely IR drop and the electrochemical results of the current flow. Only the latter is of any use in controlling the rate of corrosion."[19] This concern over elimination of the IR drop error was reiterated by Logan, Ewing, Schwerdtfeger, and McDorman along with many others.[20,21,22]

Although the specific value of –850 mV$_{CSE}$ as a potential criterion for cathodic protection of steel in a soil or water environment is now widely accepted, this has not been the only value offered. Some argued that a more negative potential was required to mitigate corrosion fully. In fact, potential values as electronegative as –1000 mV$_{CSE}$ have been suggested.[23,24,25] Also, a number of investigators report

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[12] *M. Pourbaix, CORROSION, vol. 5, no. 4 (1949): p. 125.*

[13] *C. Wagner, J Journal of Electrochemical Society, vol. 1, (1952).*

[14] *L. P. Sudrabin, CORROSION, vol. 13, no. 5 (1957): p. 87.*

[15] *M. H. Peterson, CORROSION, vol. 15, no. 9 (1959): p. 485t.*

[16] *H. H. Uhlig, Corrosion and Corrosion Control, 2$^{nd}$ Ed. (New York, NY: John Wiley & Sons, 1971), p. 224.*

[17] *U. R. Evans, The Corrosion and Oxidation of Metals (Edward Arnold Publishers, Ltd., 1960), p. 284.*

[18] *J. A. Davis and J. D. Kellner, "Electrochemical Principles Applied to Operating Pipelines,: CORROSION/89 paper no. 412(Houston, TX: NACE, 1989).*

[19] *J. M. Pearson, "Concepts and Methods of Cathodic Protection – Part I," The Petroleum Engineer, (March 1944): pp. 216, 218, 220.*

[20] *Kirk Logan, "Underground Corrosion," Circular C450, NBS, November 1945, pp. 250-279.*

[21] *Scott Ewing, "Potential Measurements for Determining Cathodic Protection Requirements," CORROSION, vol. 7, no. 12, (1951): pp. 410-418.*

[22] *W. J. Schwerdtfeger and O. N. McDorman, "Potential and Current Requirements for the Cathodic Protection of Steel in Soils," CORROSION, vol. 8, no. 11 (1952): pp. 391-400.*

[23] *Robert J. Kuhn, "Cathodic Protection on the 840-Mile Texas Gas Transmission Corporation 26-Inch Pipe Line from Texas to Ohio," American Gas Association Annual Conference, Atlantic City, N.J., Oct. 1950.*

[24] *A. C. Toncre, "A Review of Cathodic Protection Criteria," Proceedings of the 6$^{th}$ European Congress on Metallic Corrosion, (London, England: Society of Chemical Industry, 1977).*

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that a more electropositive potential criterion will provide adequate protection in special cases. This was found to be especially true for aerated, dry soils.[26,27,28,29,30]

Perhaps one of the primary reasons for the disagreement between various investigators regarding a specific potential criterion stems from the level of acceptable corrosion adopted by each. The acceptance of the $-850$ mV$_{CSE}$ potential is based on mitigating corrosion to an economically acceptable level, not stopping corrosion completely.

## 2.2.2    Polarization Shift Criterion (100 mV)

NACE Standard SP0169 also establishes a polarization shift criterion for determining adequate protection for steel structures in Section 6.2.2.1.3, as follows:

> *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.*[31]

The theoretical basis for understanding the polarization shift criterion begins with the assumption that the corrosion cell is operating under cathodic control. Further, it is assumed that the difference in the open circuit potential of the most active anode on the structure and the corrosion potential of the structure is 100 mV or less. Therefore, if the structure is cathodically polarized from an external source by at least 100 mV, there will be no potential difference between the anodes and cathodes on the structure, and corrosion will cease.

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[25] *Komei Kasahara, Taisaku Sato, and Haruhiko Adachi, "Results of Polarization Potential and Current Density Surveys on Existing Buried Pipelines," MP, vol. 19, no. 9 (1980): pp. 49-51.*

[26] *Scott Ewing, "Potential Measurements for Determining Cathodic Protection Requirements," CORROSION, vol. 7, no. 12, (1951): pp. 410-418.*

[27] *Thomas J. Barlo and Warren E. Berry, "An Assessment of the Current Criteria for Cathodic Protection of Buried Steel Pipelines," MP, vol. 23, no. 9 (1984): pp. 9-16.*

[28] *Kirk H. Logan, "Comparisons of Cathodic Protection Test Methods," CORROSION, vol. 10, no. 7 (1954): pp. 206-211.*

[29] *T. J. Barlo et. al., "Investigation of Techniques to Determine the True-Pipe-to-Soil Potential of a Buried Pipeline," Research sponsored by Pipeline Research Committee of American Gas Association, Battelle Annual Report, Feb. 1981.*

[30] *Standard DIN 30676, "Design and Application of Cathodic Protection of External Surfaces," (October 1985).*

[31] *NACE Standard SP0169, "Control of External Corrosion on Underground or Submerged Metallic Piping Systems," (Houston, TX: NACE, 2002), pp. 12-17.*

In addition to his confirmation of the –850 mV$_{CSE}$ criterion, Ewing's experimental work supported the 100 mV polarization shift criterion. He concluded "The change in potential or the polarization necessary for protection of pipe lines is probably always less than 0.1 volt."[32] von Baeckmann and Schwenk provided theoretical justification of the 100 mV polarization by applying the Nernst equation to experimentally determined corrosion rate potential plots.[33] However, the comprehensive testing of various criteria by Barlo and Berry provided convincing support for the wide ranging validity of the 100 mV criterion. They concluded "The 100 mV polarization criterion appears to be the most generally valid and applicable criterion to prevent corrosion in various soils."[34] Again, they further investigated the potential shift criterion through field testing at eleven field sites. As shown in Figure 2-5, the 100 mV criterion was found to be valid for all the field test sites.[35]
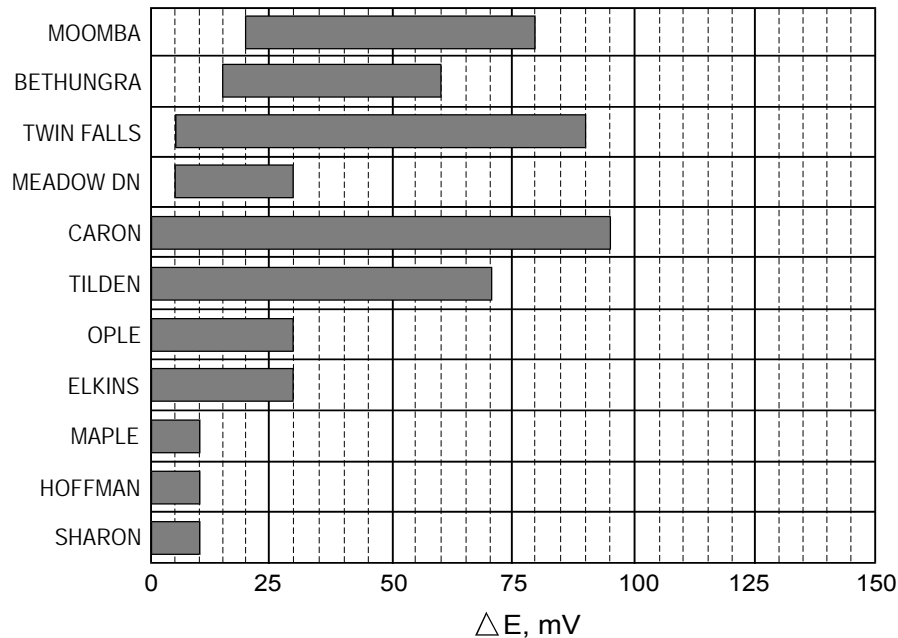


**Figure 2-5: Range of Polarization for Protection at Each Site**
Source:  Dr. Thomas J. Barlo, "Field Testing the Criteria for Cathodic Protection," Research sponsored by Pipeline Research Committee of American Gas Association, SAIC Interim Report, Dec. 1987, Cat. No. L51546, 1988.

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[32] *Scott Ewing, "Potential Measurements for Determining Cathodic Protection Requirements," CORROSION, vol. 7, no. 12, (1951): pp. 410-418.*

[33] *W. von Baechmann and W. Schwenk, Handbook of Cathodic Protection, (Surrey, England: Portcullis Press Ltd., 1975), pp. 37-38, 58-59, 153-173, 185-198, and 208-217).*

[34] *Thomas J. Barlo and Warren E. Berry, "An Assessment of the Current Criteria for Cathodic Protection of Buried Steel Pipelines," MP, vol. 23, no. 9 (1984): pp. 9-16.*

[35] *Dr. Thomas J. Barlo, "Field Testing the Criteria for Cathodic Protection," Research sponsored by Pipeline Research Committee of American Gas Association, SAIC Interim Report, Dec. 1987, Cat. No. L51546 (Hoffman Estates, IL: AGA) 1988.*

## 2.2.3   Factors Affecting Validity of Criteria

Both the potential criterion and the polarization shift criterion are based on soil and natural water environments at ambient temperatures. These criteria have decreasing validity as temperature increases or unusual conditions and chemistries are encountered. Some of the factors that can affect the validity and application of specific criteria include temperature, bacteria, alternating current (AC) interference, type of metal, presence of mixed metals, stress corrosion cracking (SCC), and disbonded coatings.

### 2.2.3.1   Temperature

The $-850$ mV$_{CSE}$ potential criterion and the 100 mV polarization shift criterion have been thoroughly investigated and validated under normal ambient temperature conditions (20 to 25 °C) for steel in soils and natural waters. However, a number of investigators have determined that these criteria become inadequate with increasing temperatures. Most agree that the potential criterion should be adjusted electronegatively to $-950$ mV$_{CSE}$ for temperatures above about 60 °C (140 °F).[36,37,38] According to results reported by Barlo and Berry, the polarization shift criterion should be adjusted from 100 mV to 150 - 250 mV at temperatures of 60 °C (140 °F), while Morgan suggested an adjustment of 2 mV/°C for high temperatures.[36,39]

### 2.2.3.2   Sulfate Reducing Bacteria

The presence of sulfate reducing bacteria (SRB) can affect the criteria necessary for adequate cathodic protection. SRB are anaerobic microbes often found in marine sediments, wet marshy areas, and clay soils. Since these bacteria can use hydrogen adsorbed on steel surfaces to convert sulfates into sulfides and the resultant sulfides react with the iron ion to form iron sulfide, depolarization of the anodes and cathodes on the steel surface results. In the presence of SRB the potential criterion recommended is $-950$ mV$_{CSE}$, and the polarization shift criterion

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[36]*Thomas J. Barlo and Warren E. Berry, "An Assessment of the Current Criteria for Cathodic Protection of Buried Steel Pipelines," MP, vol. 23, no. 9 (1984): pp. 9-16.*

[37]*Standard DIN 30676, "Design and Application of Cathodic Protection of External Surfaces," (October 1985).*

[38]*W. von Baechmann and W. Schwenk, Handbook of Cathodic Protection, (Surrey, England: Portcullis Press Ltd., 1975), pp. 37-38, 58-59, 153-173, 185-198, and 208-217.*

[39]*John Morgan, Cathodic Protection, 2nd Ed. (Houston, TX: NACE, 1987), pp. 37, 152-175, 205, and 254-258.*

becomes 200 mV.[36,37,39,40] Barlo and Berry further suggested the polarization shift criterion should be approximately 200 to 300 mV in the presence of SRB at temperatures of 60 °C (140 °F).[36]

### 2.2.3.3   Alternating Current (AC) Density

The significance of AC current in the corrosion of steel has been investigated since the early 1900s. Several studies in the 1960s concluded that for steel "the corrosiveness of an induced AC current is equal to approximately 0.1% of an equivalent value DC current." Therefore, corrosion engineers ignored AC-induced corrosion as relatively insignificant for many years. However, the significance of AC corrosion re-emerged as the subject of numerous investigations into a pipeline failure in Germany in 1986 attributed to AC corrosion of a cathodically protected pipeline. Investigators have now determined that the presence of AC current at the metal/electrolyte interface of a steel structure can significantly affect the corrosion rate of the structure even with significant cathodic protection applied.[41,42]

German investigators concluded that the risk of AC corrosion on a cathodically protected structure was a function of the AC current density at the metal/electrolyte interface. Up to an AC current density of 20 $A/m^2$ (2 $A/ft^2$), they concluded there was "probably no risk" of corrosion using conventional criteria for cathodic protection. At AC current densities greater than 20 $A/m^2$ (2 $A/ft^2$) and less than 100 $A/m^2$ (10 $A/ft^2$), they indicated conventional CP criteria were unreliable and corrosion was possible. However, with AC current densities greater than 100 $A/m^2$ (10 $A/ft^2$), corrosion damage would be expected.[43]

The level of cathodic protection current density does have a mitigating effect on the AC corrosion up to a point. According to Helm, et al., cathodic protection current densities up to 0.25 $A/m^2$ (25 $mA/ft^2$) had no mitigating effect; however, noticeable effect occurred at densities of 4 $A/m^2$ (400 $mA/ft^2$). Dévay, et al., reported that at AC current densities of 100 and 250 $A/m^2$ (10 and 25 $A/ft^2$)

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[40]*Karl P. Fischer, "Cathodic Protection is Saline Mud Containing Sulfate Reducing Bacteria," MP, vol. 20, no. 10 (1981): pp. 41-46.*

[41]*R. A. Gummow, R. G. Wakelin, and S. M. Segall, "AC Corrosion – A New Challenge to Pipeline Integrity," NACE CORROSION/98, paper 566, (Houston, TX: NACE).*

[42]*J. Dabkowski and A. Taflove, "Mutual Design Considerations for Overhead AC Transmission Lines and Gas Transmission Pipelines – Volume I: Engineering Analysis," EPRI EL-904, (Chicago, IL: IIT Research Institute, 1978), pp. 7/1 – 7/10.*

[43]*G. Helm, H. Heinzen, and W. Schwenk, "Investigation of Corrosion of Cathodically Protected Steel Subjected to Alternating Currents," 3R International, 32, Issue 5, pp. 246-249 (German).*

increasing DC current densities reduced the AC corrosion; however, AC corrosion was still significant with DC current densities as high as 10 A/m$^2$ (1 A/ft$^2$). Considering normal anticipated protective DC current densities of 10 to 30 mA/m$^2$ (1 to 3 mA/ft$^2$) in soil without the presence of AC, the DC current densities required in the presence of AC currents are quite high.[43,44]

Since AC current densities may not be known or easily measured, it is often desirable to convert to AC voltages, a more readily measurable quantity. This can be accomplished by considering the current at the interface of a circular disk holiday with a surface area of 1 cm$^2$, worst case according to Prinz. By combining Ohm's law with the equation for the resistance-to-earth of a circular disk and the equation for the surface area of the disk, Equation 2-5 results.[45,46]

$$V_{ac} = \frac{i_{ac}\, \rho\, \pi\, d}{8} \qquad\qquad [2\text{-}5]$$

*where:*   $V_{ac}$ = AC voltage pipe-to-earth (V)
　　　　　　$i_{ac}$ = AC current density (A/m$^2$)
　　　　　　$\rho$ = soil resistivity (Ω-m)
　　　　　　$d$ = diameter of disk holiday (m)*
　　　　　　　* (d = 0.0113 m for disk with 1 cm$^2$ surface area)

Equation [2-5] is derived as follows:
　　　　Ohm's Law
　　　　$V = IR$
　　　　Current Density
　　　　$I = iA$
　　　　Resistance to Earth of a Circular Disk

　　　　$R = \dfrac{\rho}{2d}$

　　　　Area

　　　　$A = \dfrac{\pi d^2}{4}$

　　　　AC Pipe-to-Earth Voltage
　　　　$V_{ac} = IR$

　　　　$V_{ac} = \dfrac{i_{ac} A \rho}{2d}$

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[44]*J. Devay, et. Al., "Electrolytic AC Corrosion of Iron," Acta Chimica, 52 (1967), pp. 65-66.*
[45] *Ibid 41*
[46]*W. Prinz, "AC Induced Corrosion on Cathodically Protected Pipelines," UK Corrosion 92, vol. 1, (1992).*

$$V_{ac} = \frac{i_{ac}\pi d^2 \rho}{4(2d)}$$

$$V_{ac} = \frac{i_{ac}\pi d\rho}{8}$$

For an AC current of 100 A/m$^2$ (10 A/ft$^2$), Figure 2-6 provides the threshold AC voltages for various soil resistivities and holiday sizes. This figure may be used to determine the likelihood of AC corrosion for a structure based on a specific AC voltage, soil resistivity, and holiday size.[45]
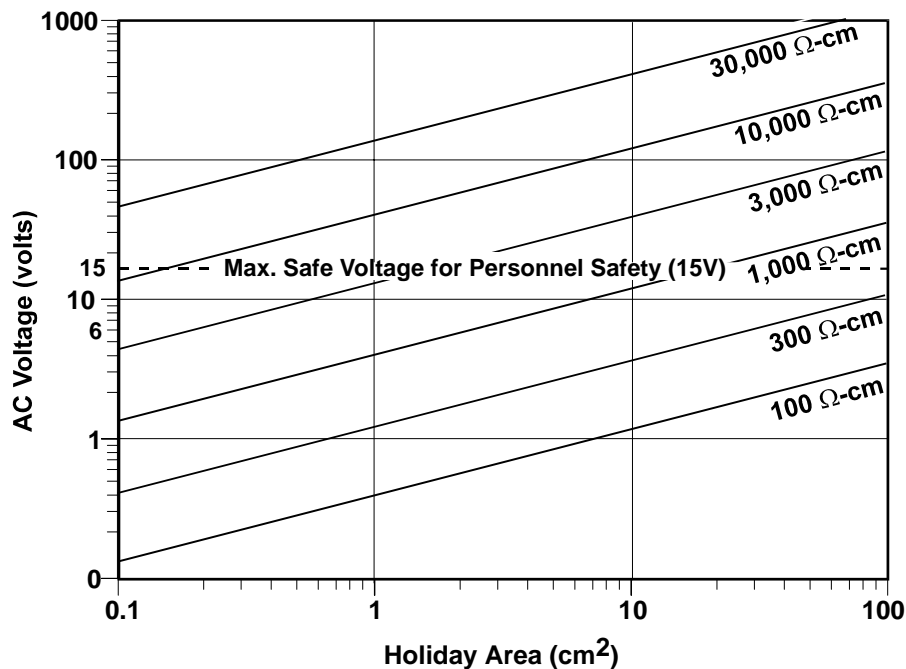


Figure 2-6: AC Voltage vs Holiday Size for i$_{AC}$ = 100 A/m$^2$

Source:  R. A. Gummow, R. G. Wakelin, and S. M. Segall, "AC Corrosion – A New Challenge to Pipeline Integrity," CORROSION/98, paper no. 566, (Houston, TX: NACE, 1998).

### 2.2.3.4   Type of Metal

Different metals exhibit different corrosion potentials. Since the corrosion potential of a metal is a mixed potential based on the weighted average of the polarized anodes and the polarized cathodes on the structure, the potential criterion must change depending on the specific metal involved. This is a result of the need to polarize the cathodes to the open circuit potential of the most active anode according to the true criterion for cathodic protection. Since the potential of the anodes is different for different metals, the potential criterion must be adjusted.

However, assuming cathodic control of the corrosion cell, the polarization shift criterion as established for steel may be sufficient for other metals.

Although NACE Standard SP0169 does not provide a specific potential criterion for aluminum or copper, it does indicate that a cathodic polarization shift criterion of 100 mV would apply. However, a caution is given for excessive potentials (more electronegative than –1200 mV$_{CSE}$) in the case of aluminum, an amphoteric metal[47] In general, caution should be exercised with any amphoteric metal (aluminum, cadmium, lead, tin, zinc) since these metals can undergo significant corrosion at the high pH values encountered with excessive cathodic potentials.

Other standards, such as British standard BS 7361 (Table 2-1) and German standard DIN 30676 (Table 2-2), do provide specific potential criteria for various types of metals.[48]

**Table 2-1:   Potential Criteria from British Standard BS 7361**

| Material | Potential, CSE Soils and Fresh Water | Potential, Silver-silver Chloride Seawater |
|---|---|---|
| Iron and Steel Aerobic environment | –850 mV | –800 mV |
| Iron and Steel Anaerobic environment | –950 mV | –900 mV |
| Lead | –600 mV | –550 mV |
| Aluminum Not to exceed | –950mV –1200 mV | –900 mV –1150 mV |
| Copper Alloys | –500 to –650 mV | –450 to –600 mV |

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[47]*NACE Standard SP0169, "Control of External Corrosion on Underground or Submerged Metallic Piping Systems," (Houston, TX: NACE, 2002), pp. 12-17.*
[48]*C. F. Schrieber and Reece W. Murray, "Effect of Hostile Marine Environments on the Al-Zn-In-Si Sacrificial Anode,"   CORROSION/88, paper no. 32, (Houston, TX: NACE, 1988).*

**Table 2-2:  Potential Criteria from German Standard DIN 30676**

| Material | Temperature, °C or Electrolyte | Potential $V_{CSE}$ |
|---|---|---|
| Unalloyed & low-alloy ferrous materials | Below 40°C (104ºF) | –850 mV |
| Same | Greater than 60°C (140ºF) | –950 mV |
| Same | Anaerobic media | –950 mV |
| Same | Sandy soil, $\rho$>500 Ω-m | –750 mV |
| Stainless steels with Cr≥16% | Soil or fresh water and less than 40°C | –100 mV |
| Same | Soil or fresh water and higher than 40°C | –300 mV |
| Same | Salt water | –300 mV |
| Copper, copper-nickel alloys | | –200 mV |
| Lead | | –650 mV |
| Aluminum | Fresh water | –800 mV |
| Same | Salt water | –900 mV |
| Steel in contact with concrete | | –750 mV |
| Galvanized steel | | –1200 mV |

# 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 mV$_{CSE}$
- Limiting critical potential not more negative than –1,200 mV$_{CSE}$
- Anaerobic soils or sulfate-reducing bacteria (SRB) more negative than –950 mV$_{CSE}$
- High soil resistivity
    - –750 mV$_{CSE}$ for 100 Ω-m < ρ < 1,000 Ω-m
    - –650 mV$_{CSE}$ for ρ > 1,000 Ω-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 mV$_{CSE}$.

## 2.2.3.5   Mixed Metals

When two different metals are electrically coupled, a macroscopic corrosion cell forms where one metal is anodic to the other. However, microscopic corrosion cells also exist on the surfaces of each of the individual metals. Although the corrosion cells on the surface of the cathodic metal may be suppressed by electrically coupling the metals, the corrosion cells on the anodic metal remain active. To mitigate all corrosion including the microscopic corrosion cells on the surface of the anodic metal, the metal couple must be cathodically polarized to the open circuit potential of the most anodic potential on the anodic metal.

In other words, according to NACE Standard SP0169 for dissimilar metals the potential criterion becomes: *"A negative voltage between all pipe surfaces and a stable reference electrode contacting the electrolyte equal to that required for the protection of the most anodic metal should be maintained."*[49]

As indicated previously, the polarization shift criterion is based on cathodic control with 100 mV or less of potential difference between the structure corrosion potential and the open circuit potential of the most active anode. Although this assumption may be correct for an individual metal, when coupled to a more cathodic metal, the corrosion potential of the couple will shift electropositively. The magnitude of this potential shift is a function of the individual corrosion potentials and the surface areas of the two metals. Since validity of the polarization shift criterion requires shifting the potential of the structure from its corrosion potential, the criterion cannot be used unless the open circuit potential of the anodic metal is known, or the surface area of the cathodic metal is insignificant compared with the surface area for the anodic metal. That is, disconnecting the cathodic metal would not significantly change the measured corrosion potential. If this criterion is used, the polarization shift must be from the open circuit potential of the anodic metal.

## 2.2.3.6   Stress Corrosion Cracking (SCC)

Two different forms of stress corrosion cracking (SCC) of pipeline steels have been identified: high-pH (classical) SCC first reported in the mid-1960s and near-neutral (low-pH) SCC identified in the 1980s.[50,51]   High-pH SCC is intergranular

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[49]*NACE Standard SP0169, "Control of External Corrosion on Underground or Submerged Metallic Piping Systems," (Houston, TX: NACE, 2002), p. 12-17.*
[50]*R. L. Wenk, "Field Investigation of Stress Corrosion Cracking," 5th Symposium on Line Pipe Research, Pipeline Research Committee of the American Gas Association, Catalog no. L30174, 1974, p. T-1.*

and identified with a carbonate-bicarbonate environment existing at the structure surface. This environment can exist at a metal surface in soil or water due to the chemical reaction of dissolved carbon dioxide with natural carbonates in the higher pH ground water created by the application of cathodic protection. The susceptibility of steel to high-pH SCC is potential-dependent. The application of cathodic protection can increase the susceptibility of a structure to high-pH SCC if the protective potentials are insufficiently electronegative. The range of possible cracking potentials is larger and becomes more electronegative with increasing temperatures; however, cracking has not been observed at potentials more negative than $-850$ mV$_{CSE}$ (although the cracking range approaches this potential at temperatures near 75 °C).[52,53]

Near-neutral pH SCC, which occurs within the pH range of 6 to 8, is transgranular and linked with corrosion occurring at the crack faces. Near-neutral pH SCC is much less dependent on the interface potential.[52,53]

Due to the potential dependence and the environment required for high-pH SCC, caution must be exercised in application of cathodic protection, especially with the application of the 100 mV polarization shift criterion.[52,53] Under precautionary notes NACE SP0169 warns: *"Caution is advised against using polarized potentials less negative than -850 mV for cathodic protection of pipelines when operating pressures and conditions are conducive to stress corrosion cracking…."*[54]

### 2.2.3.7   Disbonded Coatings

Organic coatings adhere to a metallic substrate due to both mechanical and polar bonding. Mechanical bonding is a result of the anchoring pattern between the solidified coating and the irregular surface roughness of the metallic substrate. Polar bonding is due to the electrical attraction between polar molecules within the coating formulation and the metallic surface.

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[51]*J. T. Justice and J. D. Mackenzie, "Progress in the Control of Stress Corrosion Cracking in a 914 mm OD Gas Transmission Pipeline," Proceedings of the NG-18/EPRG Seventh Biennial Joint Technical Meeting on Line Pipe Research, Pipeline Research Committee of the American Gas Association, Paper no. 28, 1988.*

[52]*J. A. Beavers and K. C. Garrity, "100 mV Polarization Criterion and External SCC of Underground Pipelines," CORROSION/2001, paper no. 1592, (Houston, TX: NACE, 2001).*

[53]*R. A. Gummow, "Cathodic Protection Potential Criterion for Underground Steel Structures," MP, 32, 11 (1993): p. 21-30.*

[54]*NACE Standard SP0169 (latest revision), "Control of External Corrosion on Underground or Submerged Metallic Piping Systems," (Houston, TX: NACE, 2002), p. 12-17.*

For purposes of this discussion, a disbonded coating will mean a coating that does not adhere to the metallic structure surface. A number of other factors such as soil stress, changing soil and/or pipe temperatures, high operating temperatures, tenting, blisters and cathodic (alkaline) disbondment may result in a disbonded coating. Cathodic disbondment is usually associated with areas having a holiday or damaged spot on the coating while blisters usually occur at holiday-free areas.

Soil stress is typically a concern where the soil and pipe move in different directions and result in forces that try to shear the coating away from the pipe surface. This is not uncommon with clay soils that expand and contract when they go through wet-dry cycles. It can also happen due to typical seasonal changes in pipe and/or ground temperatures that cause the pipe to try to elongate or shrink as the temperature changes. High operating temperatures can soften some types of coating; especially those made from polyethylene and mastic, making them more susceptible to soil stress and water permeation. Tenting can occur at a longitudinal or circumferential weld and is a result of a coating that does not conform properly to the 'hump' in the steel surface. This results in a "tent", or air gap, forming adjacent to the weld where dirt and/or water can collect. The problems described below that are associated with blisters and cathodic disbondment are also typical of these other causes of a disbonded coating.

Blisters begin with poor coating adhesion caused by poor surface preparation, improper coating application, or poor coating properties. All organic coatings absorb and transmit moisture to some extent. If the coating does not adhere to the metallic substrate, the hydraulic gradient, osmotic pressure, and, in the case of a cathodically protected structure, electro-osmotic pressure will increase water transmission through the coating. When the coated structure is initially placed in water or water-saturated soil, a hydraulic gradient exists from the outer surface of the coating to the metal substrate. This gradient results in the transmission of water through the coating to the metal surface where it can accumulate between the coating and the metal surface. In addition, if the coating's lack of adhesion is due to poor surface preparation, contaminating ions are likely to be present on the surface of the metal.

Once moisture reaches the metal surface due to the hydraulic gradient, an osmotic pressure can initiate due to the greater ionic concentration at the metal surface. This osmotic pressure will increase the water transmission rate through the coating. Finally, if the structure receives cathodic protection current, electro-osmosis will result. Electro-osmosis moves water molecules through semipermeable membranes in the direction of charge flow. Because of all of these forces, water continues to accumulate between the coating and the metal surface resulting in the formation of a blister.

Blister formation is minimized by proper surface preparation and coating application.[55,56]

Cathodic disbondment results from loss of adhesion between the coating and the metal substrate due to cathodic protection application. The cathodic reduction reactions generate hydroxyl ions at the metal surface. In this case, the hydroxyl ions ($OH^-$) generated at pores or damaged spots in the coating can attack and destroy the polar bonds between the coating and the metal surface causing loss of coating adhesion. Some coatings are more susceptible to cathodic disbonding than others; therefore, proper coating selection is the first line of defense. Higher temperatures also promote cathodic disbondment. Finally, since the susceptibility to cathodic disbonding increases at higher polarization potentials due to the increased alkalinity, cathodic protection potential levels should be limited.[55]

The validity of both the potential and the polarization shift criteria are questionable for metallic surfaces shielded by a disbonded coating regardless of the cause. It is not the criteria themselves that are in question but the ability to make measurements that allow the application of the criteria. Especially in the case of unruptured blisters, the coating electrically shields the environment at the pipeline surface from potential measurements with the reference electrode at ground level above the structure. In fact, to determine the true potential, the reference electrode would have to be on the inside of the disbonded coating. Therefore, surface potential measurements do not provide a true measurement of the potential at the metal surface and a shielded surface can be inadequately protected and undetected by surface potential profiles.[57]

If both cathodic disbondment of the coating and SCC are concerns for a specific structure, what is the appropriate potential range for the steel structure? If susceptibility to SCC is a concern, the potential criterion ($-850\ mV_{CSE}$) should be applied in favor of the polarization shift criterion (100 mV) to avoid placing the structure within the potential range where susceptibility is increased. In applying the potential criterion to a structure, the corrosion engineer should avoid excessively negative potentials if cathodic disbonding of the coating is a concern. Therefore, what is an appropriate electronegative value for a steel structure? The answer to this question, as with many technical questions, is based on good

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[55]*W. von Baechmann and W. Schwenk, Handbook of Cathodic Protection, (Surrey, England: Portcullis Press Ltd., 1975), p. 34-38, 58-59, 153-173, 185-198, and 208-217.*

[56]*CP 4–Cathodic Protection Specialist Course Manual, (Houston, TX: NACE, 2002), p. 1:25-1:27, 3:4-3:14, 3:18-3:33, and 8:34-8:35.*

[57]*T. J. Barlo and R. R. Fessler, "Interpretation of True Pipe-to-Soil Potentials on Coated Pipelines with Holidays," CORROSION/83, paper no. 292, (Houston, TX: NACE, 1983).*

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engineering judgment balancing the needs of competing requirements. On one hand, more electronegative potentials near the power source offset the effects of attenuation resulting in fewer cathodic protection installations. But on the other hand, the maximum level of electronegative potentials must be limited to avoid excessive protection levels.

To evaluate the most electronegative potential allowable, we must first determine what potential values are possible. As the potential becomes more electronegative, the most likely reduction reaction for structures buried in most soils becomes the electrolysis of water. As discussed later in this chapter, evidence suggests a theoretical limit of the most negative true polarized potential of a structure in the presence of sufficient moisture is approximately –1.15 $V_{CSE}$.[57]

To polarize deep crevices created by cathodic disbondment, some investigators suggest limiting the potential below levels where hydrogen generation becomes significant. They suggest that as hydrogen bubbles form at the coating defect, current flow down the narrow passage under the disbonded coating is inhibited. Although the potential where hydrogen gas generation occurs is variable depending on environmental factors such as temperature, pH, and surface condition, the suggested limit is approximately -1.0 to -1.10 $V_{CSE}$.[58,59]

# 2.3  Typical Cathodic Polarization Characteristics

## 2.3.1  Cathodic Polarization Curve

As suggested by the definition of cathodic protection, the polarization characteristics of the cathode and the specific potential of the most active anode determine the current requirement necessary to achieve cathodic protection. Polarization, as defined in Chapter 1, is the potential change due to a charge transfer (current) across a reacting interface. This potential change always occurs with a polarity that opposes the current causing it. Therefore, the potential of a cathode must change in the electronegative direction due to current from the electrolyte.

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[58]*R. R. Fessler, A. J. Markworth, and R. N. Parkins, "Cathodic-Protection Levels Under Disbonded Coatings," CORROSION/82, paper no. 118, (Houston, TX: NACE, 1982).*
[59]*F. M. Song et.al., "Corrosion Under Disbonded Coatings Having Cathodic Protection," MP, 42, 9 (2003): p. 24-26.*

In Chapter 1, we illustrated the polarization or Evans diagrams plotting polarized potential versus current, E vs. I. Both the abscissa, X-axis, and the ordinate, Y-axis, were drawn on linear scales. However, Evans diagrams are commonly plotted with the potential on a linear scale but the current on a logarithmic scale (E log I). As we will discover when we discuss types of polarization, the polarization potential is a function of the logarithm of the current. If E log I plots are constructed, the Evans diagram will often be a straight line. However, when we plot Evans diagrams with current on a logarithmic scale an interesting feature of a logarithmic plot becomes obvious. There is no zero point on the logarithmic scale. As you move toward smaller numbers on the scale, the magnitude changes by a factor of 10 but never reaches zero.

Investigating the types of polarization and the equations describing polarization, we will discover that as the corrosion current decreases a point is reached where it stops decreasing and reverses direction. At this point the Gibb's free energy for a specific reaction to occur in either direction (anodic or cathodic) is equal. Therefore, there is an equal probability the reaction will occur in either direction. Since all atoms, ions, and molecules are constantly in motion due to thermal energy, the thermal (vibrational) energy results in the electrochemical reaction occurring in both directions at once. In other words, at an anode every time an atom loses electrons and begins to go into solution as an ion, a metallic ion captures electrons at the metal interface and becomes a metal atom ("plates out"). Therefore, there is no net reaction and no net charge flow in a specific direction. Both anodic and cathodic reactions occur simultaneously, and charge flow is in both directions at once resulting in zero net current.

This point is the equilibrium condition for the specific reaction involved. At the equilibrium point, the polarization potential is the equilibrium potential for the reaction, as determined by the Nernst equation, and the current is the exchange current at equilibrium conditions. Therefore, on an E log I plot for a specific reaction, the beginning point is the equilibrium potential and the exchange current, as seen in Figure 2-7. In this figure polarization due to the oxidation and reduction reactions is shown for both hydrogen and iron emanating from their respective equilibrium points. The intersection of the oxidation curve for iron and the reduction curve for hydrogen establishes the corrosion potential and corrosion current for the corrosion of iron in a solution containing hydrogen ions (acid). On most polarization plots constructed to illustrate a specific corrosion cell, the polarization curve for oxidation of the reduced species and the polarization curve for the reduction of the oxidized species are not shown. Only the polarization curves determining the corrosion state are shown. However, each of the polarization curves begins at the equilibrium state.
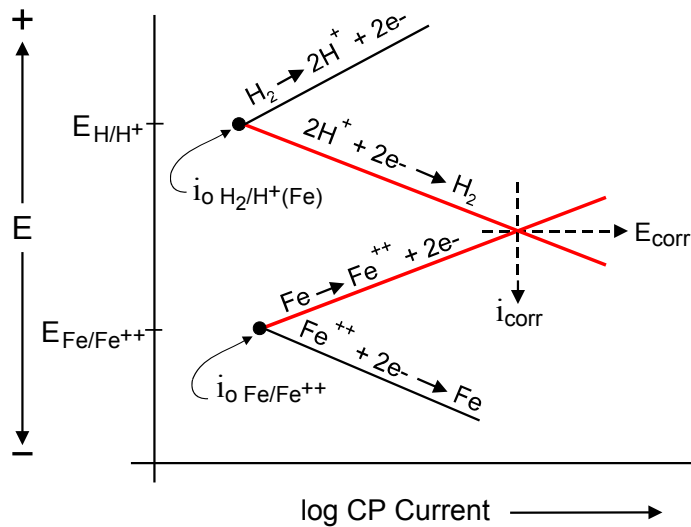
**Figure 2-7:  Polarization Curves for Iron Corrosion in Acid**

Considering a simplified corrosion cell involving one anode and one cathode on a reacting surface (Figure 2-8), the driving potential ($E_{cell}$) for current is the difference between the open circuit potentials of the cathode and anode ($E_{c,oc} - E_{a,oc}$) at the moment of immersion in an electrolyte. At this moment, a complete corrosion cell forms and charge begins to flow from anode to cathode within the electrolyte. As charge movement (current) begins, polarization of the reacting surfaces begins. This polarization results in opposing EMFs across the reacting interfaces thereby reducing the available driving potential. The decreased driving potential reduces the magnitude of current until finally a steady state condition is reached. The changes occurring at the anode and cathode stabilize through polarization to a specific, maintainable reaction rate.
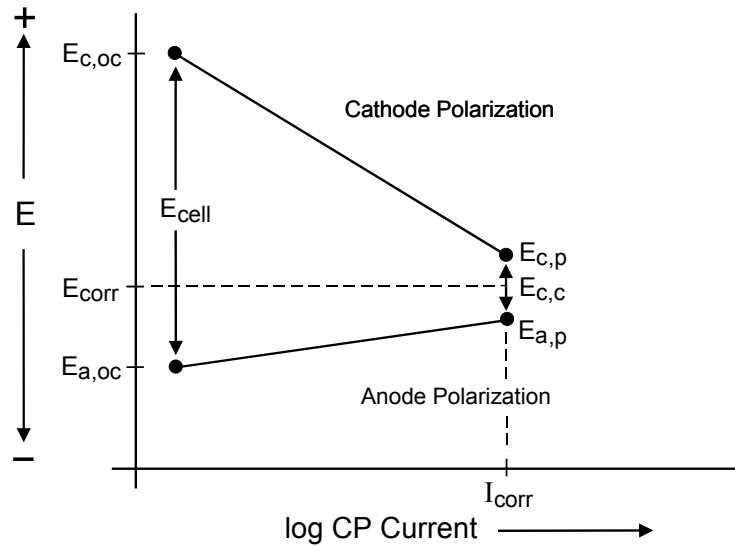
**Figure 2-8: Evans Diagram for Corrosion Cell**

At this point the new driving potential ($E_{cc}$) for corrosion current is the difference between the polarized potentials of the cathode and the anode ($E_{c,p} - E_{a,p}$). The magnitude of current between the anode and cathode ($I_{corr}$) reflects the overall reaction rates determined at this steady state condition. This is the corrosion current for the cell. At this steady state operating point, the potential of the corrosion cell measured relative to a stable reference electrode is the corrosion potential ($E_{corr}$). As previously indicated, this potential will be a weighted (geometrical and electrical) average somewhere between the final polarized potential of the anode and the final polarized potential of the cathode. The Evans diagram (E log I diagram), shown in Figure 2-8, shows the steady state operating condition of the corrosion cell.

When cathodic protection current is applied to the corrosion cell, the current collects at the cathodic site resulting in an increase in the cathodic reaction rate beyond the steady state rate previously achieved by the corrosion cell. This upset (perturbation) to the steady state condition causes changes in current magnitudes (reaction rates) and polarization levels. The charge transfer rate at the cathode increases resulting in a greater level of polarization. Since the driving voltage for corrosion current decreases, the anode reaction rate (corrosion current) must decrease. With time, the corrosion cell reaches a new steady state condition where the polarization levels of the cathode and the anode have changed. These changes result in a new operation point for the corrosion cell with a reduced corrosion rate (magnitude of anodic current, $I'_{corr}$) compared to the original cell. This new operating condition is shown in Figure 2-9.
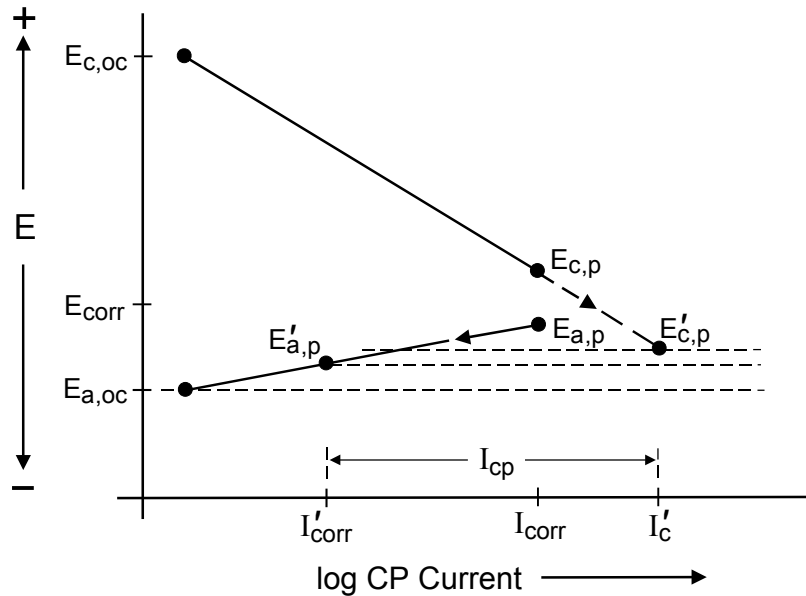
**Figure 2-9: Evans Diagram for Corrosion Cell with CP**

The extent of the reduction in corrosion current relates directly to the characteristics of the cathodic polarization curve for the structure and the open circuit potential of the most active anode. Since nothing has occurred to change the polarization characteristics of the structure, the polarization curves will not change. Therefore, the increased cathode polarization is shown by extending the cathodic polarization slope of the corrosion cell to the new operating point, and the decreased anodic polarization is indicated by sliding the anode operating point back down the anodic polarization curve. As previously suggested by Equation 2-3, the anodic current ($I'_{corr}$) is now the total cathodic current ($I'_c$) minus the cathodic protection current supplied ($I_{CP}$). From Figure 2-9, it is apparent that complete cathodic protection has not been achieved because a residual corrosion current ($I'_{corr}$) exists. Supplying additional cathodic protection current causes the polarized potential of the cathode to reach the open circuit potential of the anode. Evans diagrams show steady state conditions only. They do not show the transient changes that occur to reach the new operating point. The polarization curves shown on an Evans diagram represent the locus of operating points established at steady state conditions.

The objective of applying cathodic protection to a corrosion cell is to slow significantly or stop the oxidation reaction occurring at the anode. This oxidation reaction results in the loss of the metal through the familiar generalized reaction shown in Equation 2-6,

$$M^o \rightarrow M^{+n} + ne^- \qquad\qquad [2\text{-}6]$$

or Equation 2-7 in the case of a steel structure.

$$Fe^o \rightarrow Fe^{+2} + 2e- \qquad\qquad [2\text{-}7]$$

To accomplish this goal, the rate of the cathodic reactions must increase, as previously indicated. Although a number of different cathodic reactions are possible, the two most common reactions in soils and natural waters involve the reduction of oxygen or the evolution of hydrogen. For **neutral or alkaline conditions,** these cathodic reactions are as shown by Equations 2-8 and 2-9.

Oxygen reduction: $\qquad 2H_2O + O_2 + 4e^- \rightarrow 4OH^- \qquad [2\text{-}8]$

*or*

Electrolysis of water: $\qquad 2H_2O + 2e^- \rightarrow H_2 + 2OH^- \qquad [2\text{-}9]$
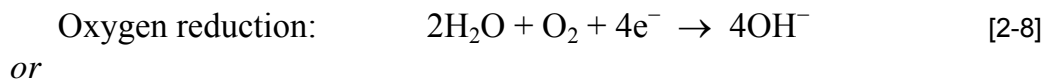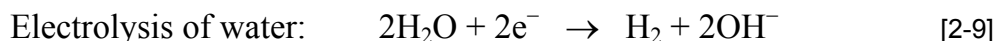
For **acid conditions**, the reactions are as provided in Equations 2-10 and 2-11.

Oxygen reduction: $\qquad 4H^+ + O_2 + 4e^- \rightarrow 2H_2O \qquad [2\text{-}10]$

*or*

Hydrogen ion reduction: $\quad 2H^+ + 2e^- \rightarrow H_2 \qquad [2\text{-}11]$
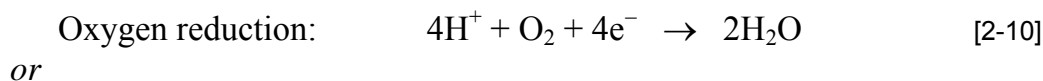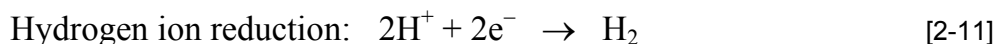
The specific cathodic reaction dominating will depend on the pH, equilibrium potentials of the reactions, concentration of possible reactants, and exchange current densities for the possible reactions. Since the equilibrium potential for oxygen reduction is always more positive than the equilibrium potential for hydrogen evolution, oxygen reduction is always the favored reaction thermodynamically. However, the exchange current density (kinetics) must be considered. For low pH conditions, the exchange current density for the evolution of hydrogen is much higher than the exchange current density for oxygen reduction. However, this situation changes as the pH increases. Therefore, the pH will determine the dominant reaction due to the kinetics involved. For a low pH (acid) aerated environment, the hydrogen evolution reaction dominates. However, for a higher pH (neutral or alkaline) aerated environment, oxygen reduction will be the dominant cathodic reaction up to its limiting current density.[60,61,62]

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[60] *John O'M. Bockris and Amulya K. N. Reddy, Modern Electrochemistry vol. 2 (New York, NY: Plenum Press, 1970), p. 1298-1300.*
[61] *E. E. Stansbury and R. A. Buchanan, Fundamentals of Electrochemical Corrosion, (Materials Park, OH: ASM International, 2000), p. 116-120 and 172-174.*

The air in the earth's atmosphere supplies the oxygen available for the reduction process (20%). Since the solubility of oxygen in water is relatively low and the dissolved oxygen must diffuse to the structure surface, the limiting current density for oxygen reduction can be reached at relatively low current densities.[60,61] However, with the increasingly negative potentials, the electrolysis of water producing hydrogen gas becomes possible.[62] This reaction is observed, at least in the laboratory, as the controlling reaction for a steel structure under cathodic protection and may explain the apparent limit to true polarization potential of around 1.15 $V_{CSE}$ observed in the field.[63]

## 2.3.2 *Activation and Concentration Polarization*

As increments of cathodic protection current are applied, the structure polarizes in the electronegative direction due to the increasing rate of the cathodic reactions on the structure. At a specific applied current density, the change in polarization potential and the shape of the polarization curve for the structure depends on the slowest step in the reaction process at that point. Two different mechanisms can account for these effects: activation polarization and concentration polarization.

*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 control. Equation (2-12) describes activation polarization.[64]

$$\eta_a = \pm \beta \log\left(\frac{i}{i_o}\right) \qquad\qquad [2\text{-}12]$$

*where:*  $\eta_a$ = activation polarization (V)
$\beta$ = polarization slope (V)
$i$ = current density (mA/cm$^2$)

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[62]*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.).*
[63]*T. J. Barlo and R. R. Fessler, "Interpretation of True Pipe-to-Soil Potentials on Coated Pipelines with Holidays," CORROSION/83, paper no. 292, (Houston, TX: NACE, 1983).*
[64]*Mars G. Fontana, Corrosion Engineering, Third ed. (New York, NY: McGraw-Hill, 1986), p. 19-21 and 454-462.*

$$i_o \;=\; \text{exchange current density (mA/cm}^2)$$

The activation polarization equation is also known as the *Tafel equation*. When plotted on an Evans (E log I) diagram, activation polarization appears as a straight line with the slope of the line equal to the Tafel constant, $\beta$. The polarization slope of a cathodic reaction is negative while the slope of an anodic reaction is positive. **The Tafel slope is a function of the specific reaction, the electrolyte chemistry, and the reacting surface.** The exchange current density, $i_0$, is the rate of the oxidation and reduction reactions at equilibrium and provides an indirect indication of the relative ease with which the reactions can take place.[64]

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 reaction process involves waiting for arrival of reactants or the removal of reaction products, the reaction is under concentration polarization control. Equation 2-13 describes concentration polarization.

$$\eta_c \;=\; \frac{2.3\,RT}{n\,F}\,\log\!\left(\frac{i_L - i}{i_L}\right) \tag{2-13}$$

*where:*
$\quad\eta_c \;=\;$ concentration polarization (V)
$\quad R \;=\;$ universal gas constant (8.3145 J/mol °K)
$\quad T \;=\;$ temperature (°K)
$\quad n \;=\;$ number or electrons transferred
$\quad F \;=\;$ Faraday's constant (96,500 coulombs/mol)
$\quad i_L \;=\;$ limiting current density (A/cm$^2$)
$\quad i \;=\;$ current density (A/cm$^2$)

A plot of the concentration polarization equation indicates very little change in polarization until the current density approaches the limiting current density. Since the limiting current density for a specific reaction cannot be exceeded, the polarization potential will become very large as this limit is approached. Concentration polarization is most commonly associated with cathodic reactions.[65]

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[65]*Mars G. Fontana, Corrosion Engineering, Third ed. (New York, NY: McGraw-Hill, 1986), p. 19-21 and 454-462.*

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.

As seen in Equation 2-14, **the limiting current density is a function of the concentration of reactants, the diffusion coefficient, and the thickness of the diffusion layer.** The thickness of the diffusion layer is a function of the system geometry, the shape of the reacting surface, and the solution agitation and must be determined experimentally for a specific case.[65]

$$ i_L \quad = \quad \frac{D\,n\,F\,C_B}{x} \qquad\qquad [2\text{-}14] $$

*where:*

$i_L$ = limiting current density (A/cm$^2$)
$D$ = diffusion coefficient (cm$^2$/s)
$n$ = number of electrons transferred
$F$ = Faraday's constant (96,500 coulombs/mol)
$C_B$ = reactant concentration in bulk soln. (mol/cm$^3$)
$x$ = thickness of diffusion layer (cm)

The total polarization of a structure will be the sum of the activation and concentration polarization, as indicated in Equation 2-15.

$$ \eta_{total} \quad = \quad \eta_a + \eta_c \qquad\qquad [2\text{-}15] $$

Consider what happens with the application of the first increments of cathodic protection current assuming a single cathodic reaction. At first, 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. Therefore, the cathodic reaction occurring on the structure is most likely under activation control. However, with increasing increments of cathodic protection current, the reaction rate continues to increase until the availability of reactants at the interface begins to decrease, and the reaction products begin to accumulate. At this point, concentration polarization is beginning to control, and the current approaches the limiting current density. As the current nears the limiting current density, the polarization 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.

However, if another cathodic reaction becomes possible, the current density can continue to increase with the availability of new reactants. This is the most likely scenario for steel under cathodic protection in a neutral, aerated soil environment where oxygen reduction occurs at first up to the limiting current density for this reaction, and then water electrolysis occurs as the potentials become more negative. This polarization response is shown by the 20% $O_2$ line in Figure 2-10.
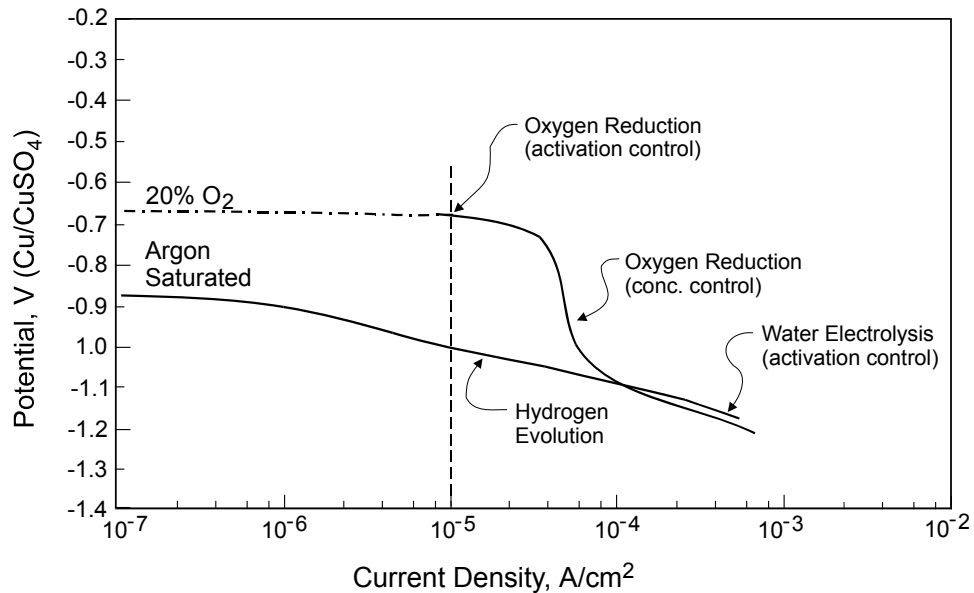


**Figure 2-10: Polarization Curves in Aerated and Deaerated Solutions of pH 7**

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.).

## 2.3.3   Factors Affecting Polarization

Many factors can affect the polarization characteristics of a structure. To evaluate the polarization response to a specific change, we must evaluate the change based on its effect on the **equilibrium potential, the exchange current density, the limiting current density, and the polarization slope,** since these factors control the level of polarization (See Table 2-3). If a change involves variations in chemical concentrations, we first need to determine whether the species involved are reactants or reaction products for the type of reaction of interest (anodic or cathodic).

<p align="center"><b>Table 2-3: Factors Controlling Polarization Response</b></p>

| Symbol | Units | Factor |
|--------|-------|--------|
| $E_{M/M+}$ / $E_{oc}$ | Volts | Equilibrium Potential |
| $i_0$ | mA/cm$^2$ | Exchange Current Density |
| $i_L$ | mA/cm$^2$ | Limiting Current Density |
| $\beta$ | Volts/decade | Tafel Slope |

The arrow in a chemical reaction formula points in the direction the reaction is proceeding. Standard form for a reaction is with the reaction arrow pointing from left to right. Reactants are the components required for the reaction to occur, and reaction products are the components produced by the reaction. Per standard form, reactants are all of the components on the left side of the reaction formula. If the reaction is a cathodic or reduction reaction, one of the necessary reactants is one or more electrons. The reaction products always appear on the right side of the reaction arrow, according to standard form. For an oxidation or anodic reaction, one of the necessary reaction products is one or more electrons.

As indicated in Chapter 1, the Nernst equation (Equation 1-10) determines the equilibrium potential for a specific reaction. The equilibrium potential varies with changes in the specific reaction occurring, the concentration ratios of the reactants and reaction products, and the temperature. The equilibrium potential shifts in the noble direction as the concentration of oxidized species (reaction product for anode/reactant for cathode) increases, as indicated in Table 2-4. It also shifts in the noble direction as the concentration of reduced species (reactant for anode/reaction product for cathode) decreases as indicated in Table 2-4.
.

**Table 2-4: Factors Controlling Equilibrium Potential, $E_{M/M+}$**

| Factor | Factor Change | Direction of Potential Change | |
| --- | --- | --- | --- |
| | | Anodic | Cathodic |
| Specific reaction | --- | --- | --- |
| Concentration of reactants | increase | active | noble |
| Concentration of reaction products | increase | noble | active |
| Temperature | increase | variable | variable |

The exchange current density is a function of the type of metal electrode, the specific reaction occurring, the ratio of oxidized and reduced species present (concentrations), temperature, surface roughness, and the presence of surface films, as indicated in Table 2-5. For a cathodic reaction, the exchange current density increases for increasing concentration of reactants, decreasing concentration of reaction products, increasing temperature, the absence of surface films and greater surface roughness.

**Table 2-5: Factors Controlling Exchange Current Density, $i_0$**

| Factor | Factor Change | Exchange Current Density Change | |
| --- | --- | --- | --- |
| | | Anodic | Cathodic |
| Type of metal | --- | --- | --- |
| Specific reaction | --- | --- | --- |
| Concentration of reactants | increase | increase | increase |
| Concentration of reaction products | decrease | increase | increase |
| Temperature | increase | increase | increase |
| Surface roughness | increase | increase | increase |
| Surface films | increase | decrease | decrease |

As indicated by Equation 2-14, the limiting current density increases with greater reactant concentration in the bulk electrolyte. It also increases as the diffusion layer thickness, x, decreases. The diffusion layer thickness is at its maximum value under stagnant conditions and decreases with relative movement between the reaction interface and the electrolyte. Because the diffusion coefficient increases and the diffusion layer thickness decreases with increasing temperature, the

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limiting current density increases with increasing temperature. The effect of these variables on the limiting current density is summarized in Table 2-6.

**Table 2-6: Factors Controlling Limiting Current Density, $i_L$**

| Factor | Factor Change | Limiting Current Density Change | |
|---|---|---|---|
| | | Anodic | Cathodic |
| Concentration of reactants | increase | increase | increase |
| Concentration of reaction products | increase | decrease | decrease |
| Diffusion coefficient | increase | increase | increase |
| Diffusion layer thickness | increase | decrease | decrease |
| Temperature | increase | increase | increase |
| Agitation | increase | increase | increase |

As previously indicated and summarized in Table 2-7, the polarization slope (Tafel slope, β) depends on the specific reaction occurring and the temperature. The polarization slope is not a function of the concentration of the reactants or reaction products. The polarization slope is normally greater in the presence of surface films.[66,67]

**Table 2-7: Factors Controlling Polarization Slope, β**

| Factor | Factor Change | Polarization Slope Change | |
|---|---|---|---|
| | | Anodic | Cathodic |
| Specific reaction | --- | --- | --- |
| Reacting surface | --- | --- | --- |
| Surface films | increase | increase | increase |
| Temperature | increase | decrease | decrease |

With the above thoughts in mind, we will investigate the effects various changes might have on the polarization response of a structure under cathodic protection. To better understand the results of a specific change, it is necessary to compare the

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[66]*John M. West, Basic Corrosion and Oxidation, Second ed. (Chichester, West Sussex, England: Ellis Horwood Ltd, 1986), p. 92-94.*

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

polarization response of the structure before and after the change. Since the important polarization response in the case of the application of cathodic protection is the cathodic polarization response of the structure, we will concentrate on this response. Because the structure surface area is constant in the following discussions, we can plot the polarization potential versus the log of the total current (E log I), rather than the current density.

## 2.3.3.1   Aeration (Oxygen)

Consider changes to the amount of oxygen present in the electrolyte. Oxygen is a cathodic reactant; therefore, increases in the quantity of oxygen present result in a noble shift in the equilibrium (open circuit) potential of the cathodic reaction on the structure. A larger exchange current density is also probable due to the oxygen increase. Because the solubility of oxygen in water is relatively low, as the reaction rate increases due to cathodic protection, concentration polarization will dominate. Figure 2-11 compares the operating conditions of a cathodically protected structure before and after the amount of oxygen in the electrolyte is increased. The primed values represent the new values with an increase in oxygen concentration. The increase in oxygen results in an increase in the corrosion current and the amount of cathodic protection current necessary. In fact, as shown in Figure 2-11, although the level of cathodic protection current has increased, the structure is no longer polarized sufficiently to meet the potential criterion.
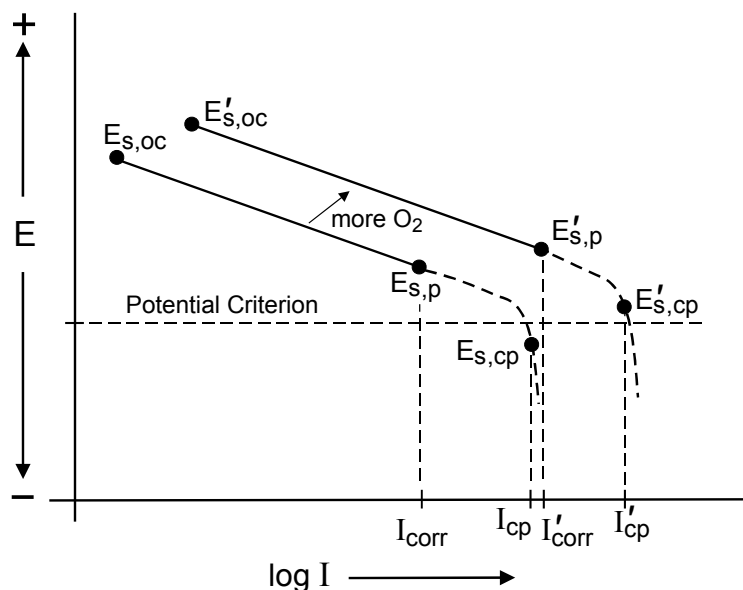


**Figure 2-11: Effect of Increasing Oxygen Concentration**

## 2.3.3.2  Agitation (Velocity)

As the level of agitation or movement at the metal/electrolyte interface increases, more reactants are swept to the reaction surface, and the reaction products are swept away. As a result, the effective diffusion layer thickness decreases, and the limiting current density increases. If the cathodic reaction is under concentration polarization control, the corrosion current will increase and the cathodic protection current will increase, but the overall protection level will decrease, as indicated in Figure 2-12.

Agitation level is not a direct function of velocity, however. As the velocity is gradually increased, laminar flow conditions prevail until the fluid reaches some critical velocity. Beyond this critical velocity, the flow changes from laminar to turbulent flow. Turbulent flow conditions result in a significant increase in the agitation level at the reaction surface. This becomes more apparent if we consider some unit volume of the electrolyte flowing past the reaction surface, Figure 2-13.

Under laminar flow conditions, the unit volume of electrolyte remains in contact with the reaction surface from one end of the flow stream to the other allowing time for depletion of the reactants within the unit volume. Under turbulent flow conditions, however, the unit volume would be swept up to the reaction surface momentarily, and then swept away only to be replaced by another unit volume. Under these conditions, the reactants near the reaction surface never have an opportunity to be depleted at all. Therefore, the agitation effect increases with increasing velocity up to the point of transition to turbulent flow conditions. At that point, the agitation effect increases significantly; however, beyond this point additional velocity has little effect.
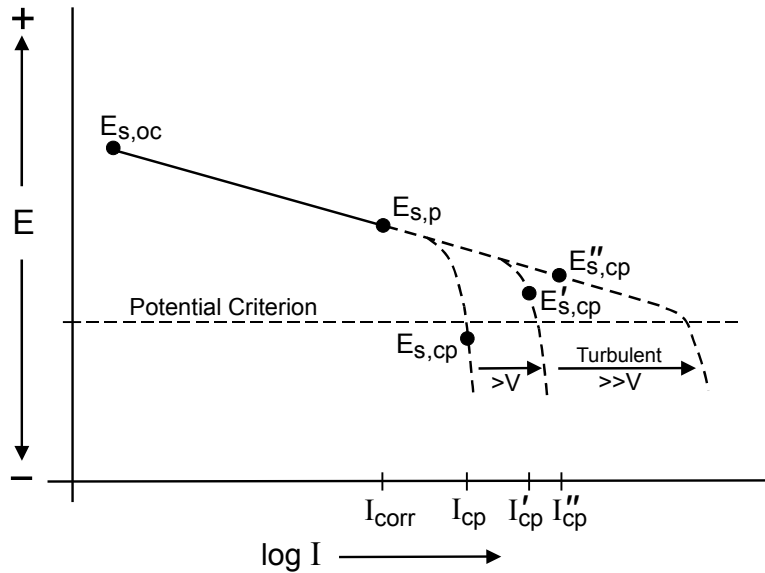
**Figure 2-12: Effect of Increasing Agitation**
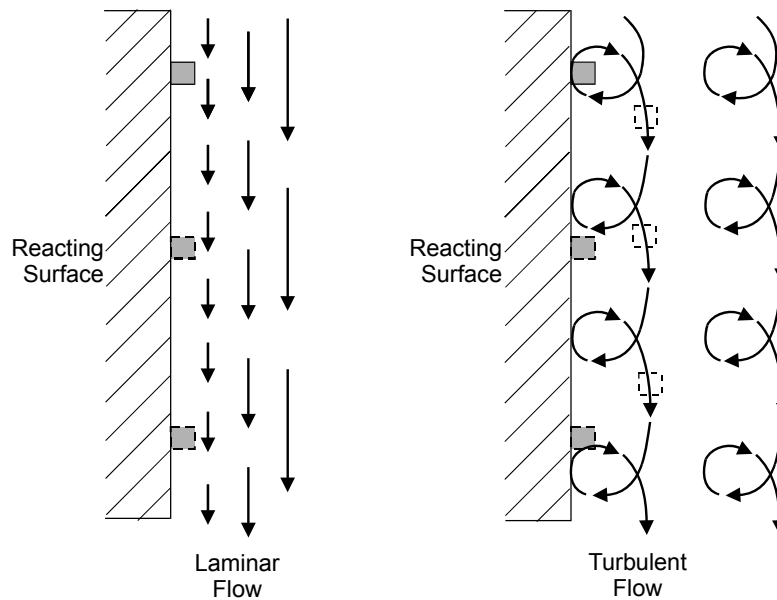


**Figure 2-13:  Laminar Flow Versus Turbulent Flow**

### 2.3.3.3   Temperature

Temperature changes can have a number of different effects on the polarization response of a structure.  Temperature effect on the equilibrium potential depends on the relative concentrations of the reactants/reaction products and the sign of the temperature coefficient of the equilibrium potential. Therefore, the change in the

equilibrium potential with temperature is variable; however, the exchange current density increases with increasing temperature. Because a temperature increase adds more energy to the system, the activation energy barrier, which must be overcome for the reactions to occur, is effectively lowered increasing the reaction rate for activation polarization control. In other words, the polarization slope decreases. Although the concentration polarization equation appears to indicate increasing polarization at higher temperatures, the temperature effect is more complicated. A temperature increase also results in a greater degree of ionization and increased mobility of the ions in the electrolyte causing an increase in the limiting current density for concentration polarization control. All of these factors result in a depolarization of the structure and an increase in the current requirement for adequate cathodic protection as indicated in Figure 2-14.
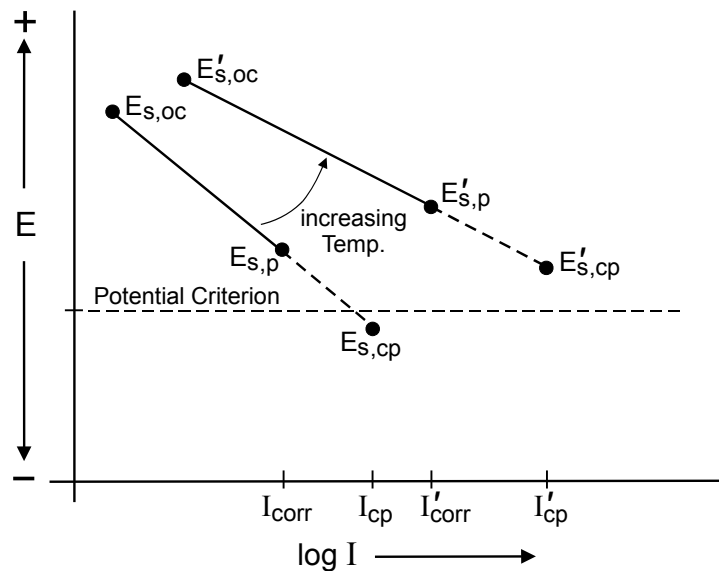


**Figure 2-14:  Effect of Increasing Temperature**

Increasing temperature can have the opposite results in some cases. As temperature increases, the solubility of oxygen in water decreases. Therefore, in cases where the concentration of oxygen in the bulk electrolyte is the controlling factor, increasing temperature can result in a decrease in the cathodic current requirement.

### 2.3.3.4   pH

As discussed in Chapter 1, one necessary condition for formation of a corrosion cell is the presence of an electrolyte. An *electrolyte* is a conductive medium (solution) where charge flow occurs by ion movement. Water is as an electrolyte;

however, pure water is not very conductive (resistivity of distilled water > 1,000,000 $\Omega$-cm). Since pure water does not contain contaminating ions, water must dissociate (ionize) to a degree or no ions would be present for conduction to occur. However, since pure water is not a very good conductor, it is apparent that water does not ionize significantly. The ionization of water is described as follows:

$$H_2O \leftrightarrow H^+ + OH^-$$
[2-16]

The ionization of water according to Equation 2-16 is a reversible reaction (reacts in both directions) that in time reaches a dynamic equilibrium where the rate of water dissociation is equal to the rate of ion recombination. Therefore, the law of chemical equilibrium, Equation 2-17, applies to this reaction. The law of chemical equilibrium states that at a constant temperature the ratio of the molar concentration of the reaction products to the molar concentration of the reactants, each raised to the power of the number of moles reacting, is a constant, $K_e$. Therefore, for water the equation for the equilibrium constant, $K_e$, is as follows with the number of moles reacting for each of the species equal to one, as indicated in Equation 2-17.

$$K_e = \frac{[H^+][OH^-]}{[H_2O]}$$
[2-17]

where:    $K_e$ = equilibrium constant
$[H^+]$ = hydrogen ion concentration (moles/liter)
$[OH^-]$ = hydroxyl ion concentration (moles/liter)
$[H_2O]$ = water molecule concentration (moles/liter)

However, since the number of water molecules that dissociate is relatively small, the concentration of water molecules remains relatively unchanged. Therefore, we will define a new constant, $K_i$, by Equation 2-18. This constant is called the ionization constant or ion-product constant.

$$K_i = K_e [H_2O] = [H^+][OH^-]$$
[2-18]

The value of the ionization constant for water at 25° C is $1 \times 10^{-14}$. At a temperature of 100° C, the ionization constant increases to $1 \times 10^{-12}$. This means that ten times the number of water molecules ionize at the higher temperature. Since for every water molecule that dissociates, one hydrogen ion and one hydroxyl ion are created, the concentration of hydrogen ions and hydroxyl ions

must be equal. From Equation 2-18, this means that at 25° C the concentration of hydrogen ions is equal to $1 \times 10^{-7}$.

pH is defined as the negative logarithm of the hydrogen ion concentration (or more correctly, activity), as indicated in Equation 2-19. Therefore, the pH for pure water at 25° C is 7. This is neutral pH where the number of hydrogen ions is exactly equal to the number of hydroxyl ions.

$$pH = -\log\left[H^+\right] = \log\left[\frac{1}{H^+}\right] \qquad\qquad [2\text{-}19]$$

The ionization (ion-product) constant of water at a given temperature always remains constant. Therefore, if we add hydrogen ions to water, the number of hydroxyl ions in the solution must decrease. The relationship between the concentration of hydrogen ions, hydroxyl ions, and pH is shown in Table 2-8. Remember, a pH change of one represents a concentration change of ten.

**Table 2-8: Relationship Between [H$^+$], [OH$^-$], and pH**

| pH | [H$^+$] | [OH$^-$] | |
|----|---------|----------|------------------|
| 0  | $10^{0}$ (1) | $10^{-14}$ | Strongly Acidic |
| 1  | $10^{-1}$ | $10^{-13}$ | |
| 2  | $10^{-2}$ | $10^{-12}$ | |
| 3  | $10^{-3}$ | $10^{-11}$ | |
| 4  | $10^{-4}$ | $10^{-10}$ | |
| 5  | $10^{-5}$ | $10^{-9}$ | |
| 6  | $10^{-6}$ | $10^{-8}$ | |
| 7  | $10^{-7}$ | $10^{-7}$ | Neutral |
| 8  | $10^{-8}$ | $10^{-6}$ | |
| 9  | $10^{-9}$ | $10^{-5}$ | |
| 10 | $10^{-10}$ | $10^{-4}$ | |
| 11 | $10^{-11}$ | $10^{-3}$ | |
| 12 | $10^{-12}$ | $10^{-2}$ | |
| 13 | $10^{-13}$ | $10^{-1}$ | |
| 14 | $10^{-14}$ | $10^{0}$ (1) | Strongly Basic |

Hydrogen ions are cathodic reactants. Therefore, lowering the pH will increase the exchange current density and result in a noble shift in the equilibrium potential for

the structure cathodes. Decreasing the pH increases the cathodic protection current requirement as shown in Figure 2-15.
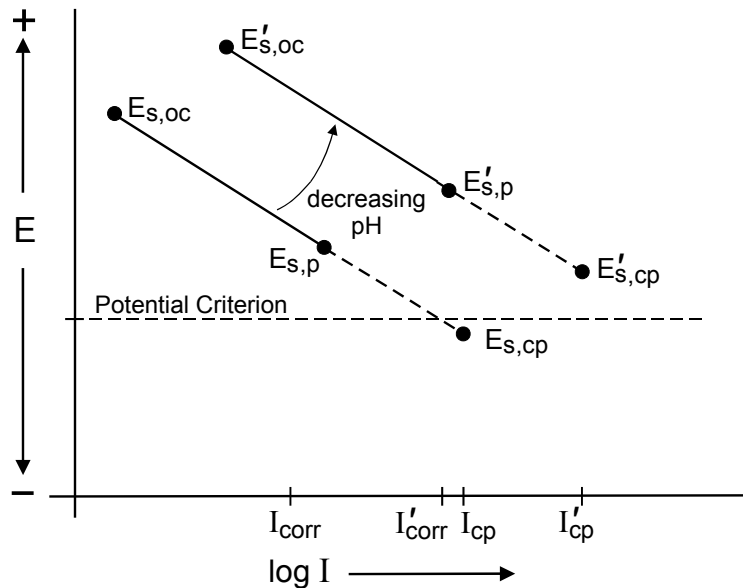


**Figure 2-15:  Effect of Decreasing pH**

### 2.3.3.5   Surface Area

For a given applied cathodic protection current, increasing the surface area of the structure has the effect of reducing the current density on the structure. For all of the changes considered up to this point we have assumed that the surface area is constant and plotted the polarization potentials versus the logarithm of the total current rather than the current density as required by the Tafel equation (Equation 2-12). To continue with our E log I plot analysis, we must consider how to show a change in surface area on this plot. Begin by replacing current density, i, with the total current, I/A, in Equation 2-12 for a cathodic polarization slope.

$$\eta_a \ = \ -\beta \log \left( \frac{\frac{I}{A}}{i_o} \right) \tag{2-20}$$

*where:*     A  =  surface area

Rearranging, we have

$$\eta_a \;=\; -\beta \log\!\left(\frac{I}{i_o\,A}\right) \qquad\qquad \text{[2-21]}$$

Taking the logarithm of the numerator and denominator separately and multiplying by β, we have

$$\eta_a \;=\; -\beta \log(I) + \beta \log(i_o\,A) \qquad\qquad \text{[2-22]}$$

Now, since everything in the last term on the right is a constant for a specific case,

$$\eta_a \;=\; -\beta \log(I) + k \qquad\qquad \text{[2-23]}$$

*where:* $\qquad\qquad k \;=\; \beta \log(i_o\,A) \qquad\qquad$ [2-24]

From the above analysis, it is apparent that if the area remains constant, the E log I polarization plot will be exactly the same as a plot of Equation 2-12 in terms of current density with the curve shifted in the noble direction by the value of the constant k. However, if the surface area is increased, the constant k will also increase; therefore, the E log I plot must shift upward. Because nothing has changed in this analysis except the surface area, the specific polarization slope, β, and exchange current density, $i_0$, remain unchanged. However, since the exchange current density is constant, but the surface area has increased, the total exchange current, $I_o$, must also increase. (Since the plot is in terms of current, not current density, we must also plot the total exchange current, $I_0$, not the exchange current density, $i_0$.) Therefore, as the surface area changes, the E log I plot must shift upward and to the right by a constant amount as seen in Figure 2-16. As seen from the figure, an increase in surface area results in a greater current requirement for cathodic protection.
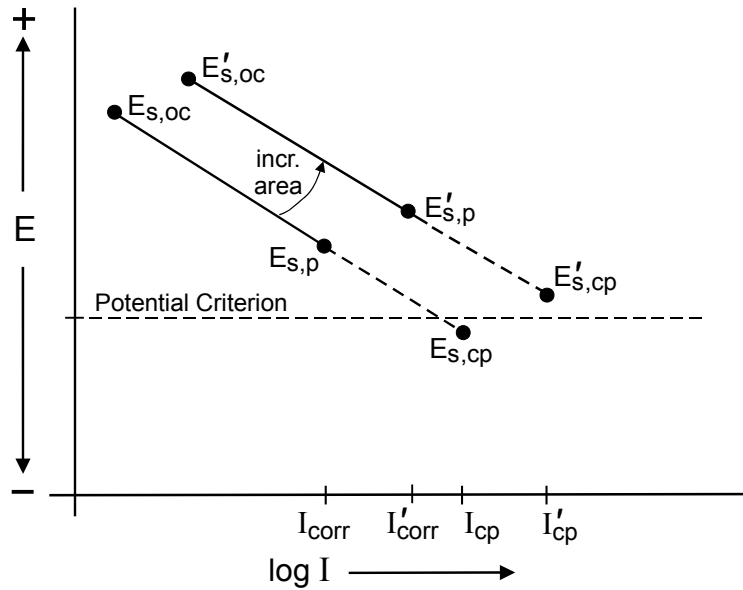
**Figure 2-16: Effect of Increasing Surface Area**

Consider the polarization curve plotted versus current density and the effect of increasing the surface area. As seen in Figure 2-17, the effect of increasing the surface area is to slide the operating point back up the same polarization curve. Whether considering Figure 2-16 or Figure 2-17, the results are the same. Increasing the surface area results in decreased overall polarization and a higher cathodic protection current requirement.
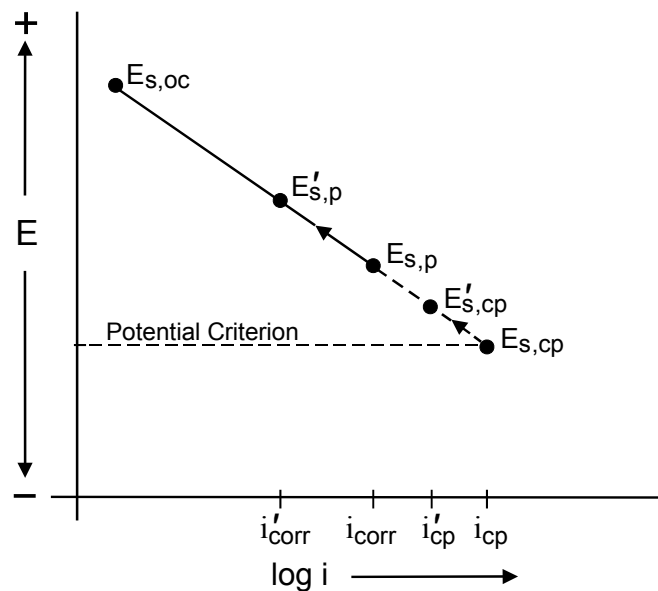


**Figure 2-17: Effect of Increasing Surface Area (Current Density)**

## 2.3.3.6    Effect of Time

Polarization is an interface phenomenon driven by charge flow (current). Since the charge flow occurring within the electrolyte is ion movement and ions are massive particles, time is required for the mass movement to occur. Polarization requires time. Activation polarization requires time for charge separation at the interface (capacitance charging). Concentration polarization requires time for concentrations to adjust. In fact, a concentration gradient will establish itself from the reaction interface into the bulk solution. Therefore, whenever we switch a current on or change the level of current, the polarization level at the interface must change over time to a new steady state value.

In addition to the corrosion rate reduction associated with cathodic activation polarization of the interface, a number of environmental changes (concentration polarization) occur near the reaction surface also reducing the corrosion rate. First, the most common cathodic reactions result in a pH increase at the structure surface due to hydroxyl ion production. The pH at the metal/electrolyte interface can be increased substantially over the pH of the bulk electrolyte because of cathodic reactions. With time, the cathodic reactions establish a pH gradient (concentration gradient) from the metal surface into the bulk electrolyte. The distance from the metal surface into the bulk electrolyte involved in the pH gradient depends on the diffusion coefficient, pH, and buffering capacity of the bulk electrolyte and on the thickness of the diffusion layer. Kobayashi reported a very steep pH gradient at the interface of a steel surface cathodically polarized at 38 $\mu A/cm^2$ (35 mA/ft$^2$) in an open water (3% NaCl solution) test. Figure 2-18 indicates the pH gradient in his test for five different solutions with various levels of bulk pH. It is interesting to note the magnitude of pH attained at the interface and the rate of gradient dissipation (within 1 mm of the steel surface) in this open container test.[68]

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[68]*Toyoji Kobayashi, "Effect of Environmental Factors on the Protective Potential of Steel," Proceedings of the 5$^{th}$ International Congress on Metallic Corrosion, (Houston, TX: NACE, 1974), p. 627-630.*

Figure 2-18: Variation of pH with Distance

Source:  Toyoji Kobayashi, "Effect of Environmental Factors on the Protective Potential of Steel," Proceedings of the 5th International Congress on Metallic Corrosion, (Houston, TX: NACE, 1974), p. 627-630.

Investigators have shown that pH values can reach values of 10 and higher even in low pH soils.[69] In fact, some investigators have reported pH values as high as 14.[70] An increase in pH at a steel interface increases the tendency for the steel surface to form passive films. The high pH values and associated passivation can significantly affect the anodic polarization behavior of the steel surface.[71,72]

[69]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.).

[70]Komei Kasahara, Taisaku Sato, and Haruhiko Adachi, "Results of Polarization Potential and Current Density Surveys on Existing Buried Pipelines," MP, 19, 9 (1980): p. 49-51.

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

In addition to the beneficial pH changes that occur at the structure interface, the reduction reactions consume oxygen and water. Since oxygen is a primary oxidizer and moisture is a necessary component for electrochemical corrosion, the environment becomes less corrosive as these components decrease. The reduction in moisture content, especially in the case of a nonsaturated soil environment, can significantly affect the structure polarization behavior. Also, due to the electric field direction, chloride ions and other potentially harmful anions are forced away from the structure surface.[72]

All of these changes occur over a significant time period until the environment near the structure reaches a new steady state condition. Because, unlike aqueous solutions, ionic movements in soils are more restricted soil environments tend to be stagnant with reaction products maintained near the structure surface. Due to the restricted, stagnant environment, the chemistry near the structure surface can be significantly different from the bulk electrolyte. As a result of the restricted movement, the final steady state chemical gradient can require weeks or even months to stabilize.[72]

Another time-related, environmental change sometimes observed involves the deposition of calcareous films on steel surfaces. Although these calcareous deposits are commonly found in seawater environments, bicarbonates of calcium and magnesium may form deposits on steel surfaces in soil environments when cathodic protection increases the pH. Calcareous deposits increase oxygen concentration polarization by restricting oxygen access to the steel surface. The restriction of oxygen access is primarily due to a decrease in the diffusion coefficient, D, (See Equation 2-14) through the calcareous deposits. This reduces the limiting current density resulting in a significant reduction in the current required to maintain adequate polarization. In fact, designs of cathodic protection systems for seawater environments usually rely on the formation of these calcareous deposits to reduce the maintenance current requirement significantly. The primary constituents of the calcareous deposits found in seawater are calcium carbonate and magnesium hydroxide ($CaCO_3$ and $Mg(OH)_2$).[73,74,75,76]

[72]Neil G. Thompson, Kurt M. Lawson, and John A. Beavers, "Exploring the Complexity of the Mechanism of Cathodic Protection," CORROSION/94, paper no. 580, (Houston, TX: NACE, 1994).

[73]John Morgan, Cathodic Protection, 2nd Ed. (Houston, TX: NACE, 1987), p. 37, 152-175, 205, and 254-258.

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

[75]Francis L. LaQue, Marine Corrosion: Causes and Prevention, (New York, NY: John Wiley & Sons, 1975), p. 104-109.

Carbon dioxide dissolves in seawater to produce carbonic acid, which dissociates into bicarbonate and carbonate ions in a two-step process. Equations 2-25 through 2-27 show these equilibrium reactions.

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \qquad \text{(carbonic acid)} \qquad [2\text{-}25]$$

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^- \qquad \text{(bicarbonate ion)} \qquad [2\text{-}26]$$

$$HCO_3^- \leftrightarrow H^+ + CO_3^{-2} \qquad \text{(carbonate ion)} \qquad [2\text{-}27]$$
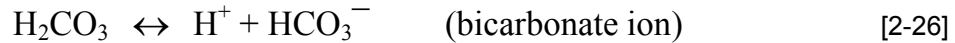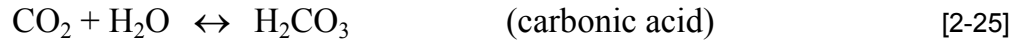
This carbon dioxide system acts as a natural buffering system against pH changes in seawater. As cathodic reactions add hydroxyl ions to the system, equilibrium reactions (2-26) and (2-27) are shifted to the right opposing any pH change. The addition of hydroxyl ions results in the precipitation of calcium carbonate and magnesium hydroxyl according to Equations 2-28 through 2-30. A number of factors can influence the precipitation of calcareous deposits including temperature. Increased temperature increases the rate of precipitation. Therefore, calcareous deposits more readily form in warmer waters.[76]

$$OH^- + HCO_3^- \rightarrow H_2O + CO_3^{-2} \qquad \text{(carbonate ion)} \qquad [2\text{-}28]$$

$$CO_3^{-2} + Ca^{+2} \rightarrow CaCO_3 \downarrow \qquad \text{(calcium carbonate)} \qquad [2\text{-}29]$$

$$Mg^{+2} + OH^- \rightarrow Mg(OH)_2 \downarrow \qquad \text{(magnesium hydroxide)} \qquad [2\text{-}30]$$
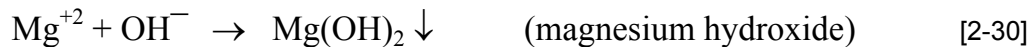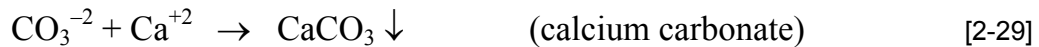
## 2.4  Types of Cathodic Protection Systems

We can use either galvanic (sacrificial) anodes or semi-inert anodes plus a power supply to provide cathodic protection current to a structure. For galvanic anodes to supply current, the electrochemical potential of the galvanic anode must be more electronegative than the structure to be protected. In fact, sufficient potential difference must exist between the galvanic anode and the structure to overcome the circuit resistance and supply adequate current to achieve polarization of the structure. Since galvanic anodes provide protective current through the process of electrochemical corrosion, practical galvanic anodes must also be low cost and

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[76]*William H. Hartt, Charles H. Culberson, and Samuel W. Smith, "Calcareous Deposits on Metal Surfaces in Seawater – A Critical Review,"* Corrosion*, 40, 11 (1984): p. 609-618.*

have sufficient current capacity to be cost effective. For the protection of steel, the three galvanic anodes commonly used are aluminum, magnesium, and zinc.

Impressed current systems use semi-inert (semisoluble) anodes to supply protective current. Since these anodes are relatively inert, they exhibit relatively noble electrochemical potentials. To produce charge flow in the direction to cathodically polarize a steel structure, it is necessary to connect an external power supply in series between the semi-inert anode and steel structure. The power supply must overcome the galvanic potential difference between the noble anode and steel structure before it can supply the first increments of protective current to the structure. The potential the power supply must first overcome is sometimes called "backvoltage."

## 2.4.1  Galvanic Anodes

### 2.4.1.1  Aluminum Anodes

Pure aluminum cannot function as a galvanic anode because the formation of stable oxide films causes the electrochemical potential to shift to a very noble potential (passivation). However, adding activators to the alloy to disrupt the oxide film formation can maintain an active electrochemical potential for the aluminum alloy. Therefore, by proper alloying we can use aluminum anodes to supply cathodic protection current. The aluminum alloy consists of a combination of zinc plus cadmium, indium, mercury, or tin to keep the anode active. The zinc initially activates the anode with the cadmium, indium, mercury, or tin maintaining long-term activation. With the addition of these activators, the aluminum alloy experiences self-corrosion. Some formulations add manganese, silicon, or titanium to the alloy to optimize the balance between activation and self-corrosion. Both iron and copper can have detrimental effects on the current capacity and the driving potential of the anode. Small additions (up to 0.11%) of silicon can overcome some of the detrimental effects of iron. Table 2-9 provides information about two common aluminum anode alloys.[77,78,79,80,81]

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[77] *W. von Baechmann and W. Schwenk, Handbook of Cathodic Protection, (Surrey, England: Portcullis Press Ltd., 1975), p. 37-38, 58-59, 153-173, 185-198, and 208-217.*

[78] *CP 4–Cathodic Protection Specialist Course Manual, (Houston, TX: NACE, 2002), p. 1:25-1:27, 3:4-3:14, 3:18-3:33, and 8:34-8:35.*

[79] *Ed Lemieux, William H. Hartt, and Keith E. Lucas, "A Critical Review of Aluminum Anode Activation, Dissolution Mechanisms, and Performance," CORROSION/2001, paper no. 1509, (Houston, TX: NACE, 2001).*

[80] *R. F. Crundwell, "Sacrificial Anodes – What is in Them and Why," CORROSION/82, paper no. 166, (Houston, TX: NACE, 1982).*

Table 2-9: Aluminum Anode Alloys

| Element | Alloy I | Alloy III |
|---|---|---|
| Zn | 0.35 - 0.50% | 2.8 - 3.5% |
| Si | 0.14 - 0.21% max | 0.08 - 0.2% max |
| Hg | 0.035 - 0.048% | --- |
| In | --- | 0.01 - 0.02% |
| Cu | <0.01% | <0.01% |
| Fe | <0.12% | <0.12% |
| Al | remainder | remainder |
| Use | open seawater | seawater/mud |
| Nominal Potential | -1.05 $V_{SSC/sea}$ | -1.10 $V_{SSC/sea}$ |
| Efficiency | 95% | 85% |
| Capacity - sea | 2830 A-h/kg (1280 A-h/lb) | 2530 A-h/kg (1150 A-h/lb) |
| Consumption – sea rate | 3.10 kg/A-y (6.83 lb/A-y) | 3.46 kg/A-y (7.63 lb/A-y) |
| Capacity - mud | --- | 2180 A-h/kg (990 A-h/lb) |
| Consumption – mud rate | --- | 4.02 kg/A-y (8.87 lb/A-y) |

Aluminum anodes generally require chloride ions in the electrolyte to function properly. As the quantity of chloride ions decreases below normal seawater concentrations (3.5% or 35,000 ppm), the current capacity of the anode decreases, and the anode potential becomes more noble. According to Schrieber and Murray, the type III aluminum alloy (indium activated) can function with a chloride concentration of only 1800-2000 ppm or about 5% of seawater concentration. However, the corrosion potential of the anode becomes more noble at chloride concentrations below about 33% of seawater, and at 12% seawater concentrations the potential reaches the minimally acceptable potential of −1.0 $V_{SSC/sea}$. The capacity of the anode remains relatively constant down to the 12% seawater strength but deteriorates significantly below this level. Most investigators agree that the current capacity of aluminum anodes decreases with decreased current

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[81] *DNV RP B401 Appendix A, "Recommended Practice for Accelerated Laboratory Testing of Sacrificial Anode Materials with the Objective of Quality Control," Det Norske Veritas Industri Norge AS (1993), p.40-44.*

density. Figure 2-19 shows a plot of current capacity versus current density for aluminum anodes in seawater and saline mud.[82]
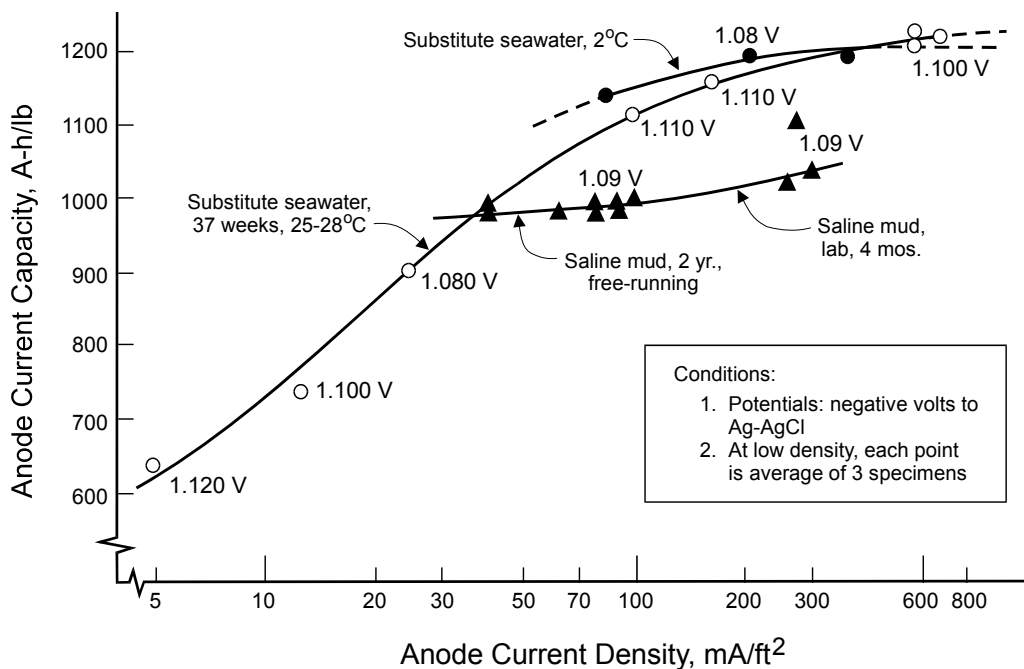


**Figure 2-19: Current Capacity Versus Current Density for Aluminum**

Source:  C. F. Schrieber and Reece W. Murray, "Effect of Hostile Marine Environments on the Al-Zn-In-Si Sacrificial Anode," CORROSION/88, paper no. 32, (Houston, TX: NACE, 1988).

The potentials and current capacities in Table 2-9 are based on ambient temperatures of approximately 25ºC. As the temperature increases, the current capacity increases up to temperatures of approximately 70ºC. The current capacity begins to deteriorate rapidly beyond 70ºC. Meanwhile, the corrosion potential of aluminum anodes become less negative as the temperature increases from 25ºC to 100ºC.[81]

Due to the requirement for chloride ions to prevent passivation, aluminum anodes are used primarily in seawater applications. Because of their relatively high current capacity and light weight, aluminum anodes have virtually replaced zinc in seawater applications. Common applications for aluminum anodes include bracelet anodes for offshore pipelines, standoff anodes for platforms, eyebolt and threaded

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stud anodes for pier, piling, and heater-treater applications, and flush-mount anodes for hulls and special applications.

## 2.4.1.2 Magnesium Anodes

Pure magnesium exhibits a very electronegative potential, but the self-corrosion rate of unalloyed magnesium is excessive. The addition of about 6% aluminum and 3% zinc results in a more electropositive corrosion potential but the self-corrosion rate is significantly improved. Zinc promotes a more uniform corrosion and reduces the sensitivity of the anode to other impurities. However, small concentrations of copper, nickel, silicon, and iron can cause significant reductions in both the current capacity and the electronegative potential of magnesium anodes. Nickel concentrations must be kept below 0.001% due to the rapid loss in capacity above this concentration. Copper concentrations should be held below about 0.05% for the same reason. The addition of about 0.3 % manganese can reduce the negative effects of iron by sequestering the iron within the alloy. With the sequestering benefit of manganese, iron concentrations up to about 0.01% can be tolerated.[83,84,85]

The two most common alloys are the high-potential magnesium alloy (M1) and the AZ-63 (H1) alloy as seen in Table 2-10. The high-potential alloy takes advantage of the very electronegative corrosion potential of pure magnesium by adding only a small percentage (about 1%) of manganese to improve the efficiency. The AZ-63 (H1) alloy employs aluminum and zinc as primary alloying agents to improve the efficiency. Even after taking advantage of alloying improvements, the efficiency of magnesium is nominally around 50% under the best of environmental conditions. However, efficiencies have been reported of about 10 to 60% using standard test procedures.[83,84,86,87,88]

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[83] *W. von Baechmann and W. Schwenk, Handbook of Cathodic Protection, (Surrey, England: Portcullis Press Ltd., 1975), p. 37-38, 58-59, 153-173, 185-198, and 208-217.*

[84] *R. F. Crundwell, "Sacrificial Anodes – What is in Them and Why," CORROSION/82, paper no. 166, (Houston, TX: NACE, 1982).*

[85] *R. A. Gummow, "Performance Efficiency of High Potential Magnesium Anodes for Cathodically Protection Iron Watermains," Proceedings of Northern Area Eastern Conference, CD-ROM (Houston, TX: NACE, September 15-17, 2003).*

[86] *W. von Baechmann and W. Schwenk, Handbook of Cathodic Protection, (Surrey, England: Portcullis Press Ltd., 1975), p. 37-38, 58-59, 153-173, 185-198, and 208-217.*

[87] *CP 4–Cathodic Protection Specialist Course Manual, (Houston, TX: NACE, 2002), p. 1:25-1:27, 3:4-3:14, 3:18-3:33, and 8:34-8:35.*

[88] *ASTM G 97-97 (Reapproved 2002), "Standard Test Method for Laboratory Evaluation of Magnesium Sacrificial Anode Test Specimens for Underground Applications," (West Conshohocken, PA: ASTM, 1997), p. 1-4.*

**Table 2-10:  Magnesium Anode Alloys**

| Element | High-potential | AZ-63 or H1 Alloy | | |
|---|---|---|---|---|
| | | Grade A | Grade B | Grade C |
| Al | 0.010% max | 5.3 - 6.7% | 5.3 - 6.7% | 5.0 - 7.0% |
| Mn | 0.50 - 1.30% | 0.15% min | 0.15% min | 0.15% min |
| Zn | --- | 2.5 - 3.5% | 2.5 - 3.5% | 2.0 - 4.0% |
| Si | 0.05% max | 0.10% max | 0.30% max | 0.30% max |
| Cu | 0.02% max | 0.02% max | 0.05% max | 0.10% max |
| Ni | 0.001% max | 0.002% max | 0.003% max | 0.003% max |
| Fe | 0.03% max | 0.003% max | 0.003% max | 0.003% max |
| Other (total) | 0.30% max | 0.30% max | 0.30% max | 0.30% max |
| Mg | remainder | remainder | remainder | remainder |
| Use | soil/fresh water | | | |
| Nominal potential | -1.75 $V_{CSE}$ | -1.55 $V_{CSE}$ | | |
| Efficiency | 50% | | | |
| Capacity | 1100 A-h/kg  (500 A-h/lb) | | | |
| Consumption Rate | 7.97 kg/A-y  (17.5 lb/A-y) | | | |

Not only does the alloy composition affect the efficiency of magnesium but also the composition of the surrounding environment. The efficiency (current capacity) rapidly decreases as the pH of the environment decreases to the point that below a pH of about 5 using magnesium as an anode is no longer practical. In addition, increasing concentrations of chloride ions can have a detrimental affect on magnesium anode efficiency. On the other hand, the presence of the sulfate ion can increase the efficiency. Finally, as with all galvanic anodes, the efficiency of the anode is a function of the current density. Increasing the current density causes an increase in efficiency, as seen in Figure 2-20 for the AZ-63 alloy.[89,90,91]

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[89] *W. von Baechmann and W. Schwenk, Handbook of Cathodic Protection (Surrey, England: Portcullis Press Ltd., 1975), p. 37-38, 58-59, 153-173, 185-198, and 208-217.*

[90] *R. F. Crundwell, "Sacrificial Anodes – What is in Them and Why," CORROSION/82, paper no. 166, (Houston, TX: NACE, 1982).*

[91] *R. A. Gummow, "Performance Efficiency of High Potential Magnesium Anodes for Cathodically Protection Iron Watermains," Proceedings of Northern Area Eastern Conference, CD-ROM (Houston, TX: NACE, September 15-17, 2003).*
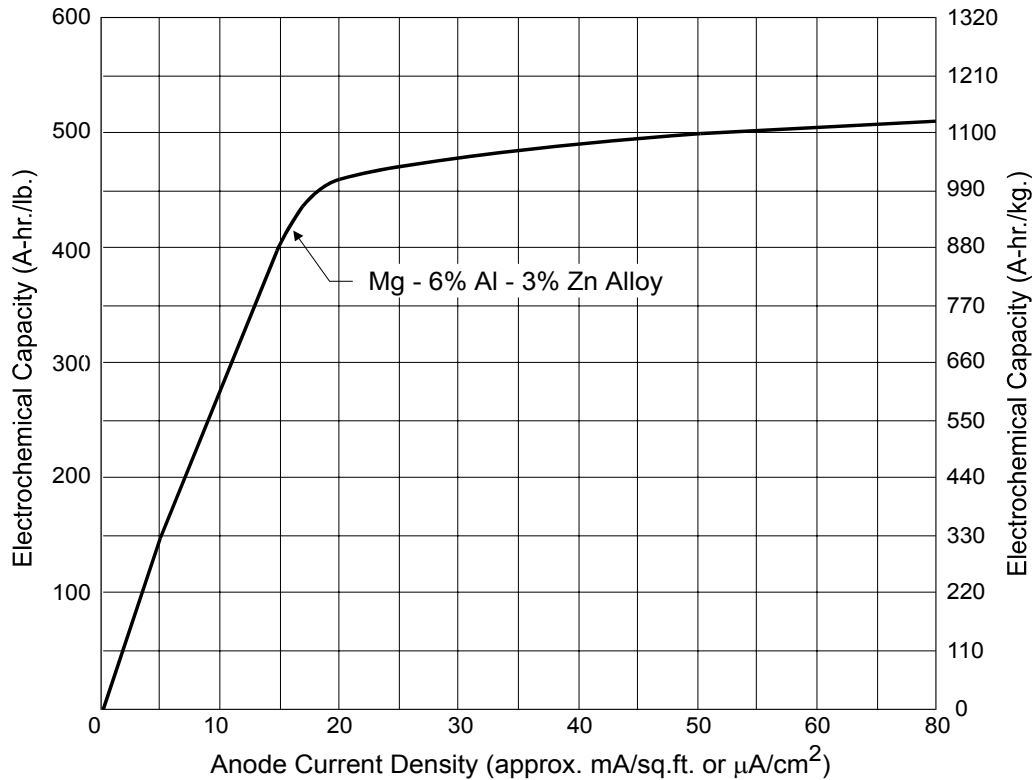
**Figure 2-20: Current Capacity of AZ63 Magnesium Alloy vs. Current Density**

Source:  R. A. Gummow, "Performance Efficiency of High Potential Magnesium Anodes for Cathodically
Protection Iron Watermains," Proceedings of Northern Area Eastern Conference, CD-ROM
(Houston, TX: NACE, Sept. 15-17, 2003).

Due to the very electronegative corrosion potential of magnesium, it is normally the galvanic anode of choice for higher resistivity environments such as soils and fresh water. For higher resistivity soil applications, we normally use long, cylindrical magnesium anodes because the increased length lowers the resistance-to-earth of the anode. In fact, using very long extruded magnesium ribbons or rods we can obtain minimum resistance. However, magnesium anodes are available in spheres or blocks for use in vessels. Magnesium anodes are also available in flush-mount designs.

## 2.4.1.3   Zinc Anodes

Zinc is one of the oldest galvanic anode materials, first used around 1824 by Sir Humphrey Davy. Early failures of zinc anodes were due to passivation of the zinc because of trace iron impurity. Researchers discovered that to prevent passivation in high-purity zinc anodes, they had to hold the iron content below 0.0014%. Alloys were subsequently developed containing about 0.5% aluminum

and up to 0.15% cadmium. This addition allowed zinc anodes to tolerate iron impurities up to 0.005%. The most common formulations of the two primary zinc alloys (high-purity and Al/Cd alloy) are listed in Table 2-11. Recent revisions to ASTM B-418 lowered the allowable cadmium content and raised the allowable lead content.[92,93,94,95,96,97]

**Table 2-11:  Zinc Anode Alloys**

| Element | High Current | Mil Spec A-18001K | ASTM B-418-01 Type I | ASTM B-418-01 Type II | High-Purity |
|---------|--------------|-------------------|----------------------|-----------------------|-------------|
| Al | 0.1 - 0.4% | 0.10 - 0.50% | 0.10 - 0.50% | 0.005% max | --- |
| Cd | 0.025 - 0.06% | 0.025 - 0.07% | 0.025 -0.07% | 0.003% max | 0.003% max |
| Fe | 0.005% max | 0.005% max | 0.005% max | 0.0014%max | 0.0014% max |
| Pb | 0.006% max | 0.006% max | 0.006% max | 0.003% max | 0.003% max |
| Cu | --- | 0.005% max | 0.005% max | 0.002% max | --- |
| Si | --- | 0.125% max | --- | --- | --- |
| Zn | remainder | remainder | remainder | remainder | remainder |
| Use | seawater & brackish water (T<50ºC) [120°F] | | | soil & fresh water | |
| Nominal potential | $-1.10$ V$_{CSE}$ | | | | |
| Efficiency | 90% | | | | |
| Capacity | 738 A-h/kg  (335 A-h/lb) | | | | |
| Consumption Rate | 11.9 kg/A-y  (26.2 lb/A-y) | | | | |

The addition of aluminum and cadmium to zinc resulted in an alloy with a smaller grain structure improving the uniformity of the corrosion pattern on the zinc anode. However, with the addition of the aluminum the zinc alloy was susceptible to intergranular corrosion with increasing temperature. The addition of cadmium

[92] W. von Baechmann and W. Schwenk, Handbook of Cathodic Protection (Surrey, England: Portcullis Press Ltd., 1975), p. 37-38, 58-59, 153-173, 185-198, and 208-217.

[93] CP 4–Cathodic Protection Specialist Course Manual (Houston, TX: NACE, 2002), p. 1:25-1:27, 3:4-3:14, 3:18-3:33, and 8:34-8:35.

[94] R. F. Crundwell, "Sacrificial Anodes – What is in Them and Why," CORROSION/82, paper no. 166, (Houston, TX: NACE, 1982).

[95] George W. Kurr, "Zinc Anodes – Underground Uses for Cathodic Protection and Grounding," MP, 18, 4 (1979): p. 34-41.

[96] ASTM Standard B 418-01, "Standard Specification for Cast and Wrought Galvanic Zinc Anodes," (West Conshokocken, PA: ASTM, 2002).

[97] MIL-A-18001K, "Military Specification Anodes, Sacrificial Zinc Alloy," Department of Defense, December 16, 1991, p. 4.

further aggravated the susceptibility to intergranular corrosion and resulted in a significantly decreased the anode efficiency. Use of the Al/Cd alloy is generally restricted to environmental temperatures below about 50ºC (120ºF).[98,99,100,101]

Although zinc has a low current capacity compared with the other galvanic anodes, the capacity is relatively independent of current density. Even at a current density as low as 50 mA/m$^2$ (5 mA/ft$^2$) an efficiency of 90% or greater is anticipated. There is a slight decrease in current capacity at higher temperatures.[98,102,103]

The environment can adversely affect the corrosion potential of zinc. A noble shift in the corrosion potential of zinc occurs with increasing temperature. Also, in environments where carbonates, bicarbonates, or nitrates dominate, the potential of zinc can become very noble due to the presence of passivating surface films. Although passivation and the accompanying noble shift in potential can occur at room temperature in these environments, higher temperatures accelerate the passivation. Passivation of zinc does not occur when sulfates or chlorides predominate in the environment regardless of the temperature. In fact, it has been shown that zinc with passive potentials as noble as –0.50 $V_{CSE}$ established at room temperature in a bicarbonate-rich environment can be rapidly restored to the nominal corrosion potential (–1.1 $V_{CSE}$) by adding sulfates in the form of gypsum.[98,100]

We use high-purity zinc anodes in soil and fresh water environments in the form of ribbons and rods primarily. Grounding cells or structure grounding applications also commonly use high-purity zinc anodes. Applications requiring AC mitigation or safety grounding mats at test stations may use zinc ribbons. Zinc grounding cells employ two or four zinc rods spaced very close together, but insulated from physical contact, and placed in a special chemical backfill. The Al/Cd zinc alloy is

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[98]*W. von Baechmann and W. Schwenk, Handbook of Cathodic Protection, (Surrey, England: Portcullis Press Ltd., 1975), p. 37-38, 58-59, 153-173, 185-198, and 208-217.*

[99]*R. F. Crundwell, "Sacrificial Anodes – What is in Them and Why," CORROSION/82, paper no. 166, (Houston, TX: NACE, 1982).*

[100]*George W. Kurr, "Zinc Anodes – Underground Uses for Cathodic Protection and Grounding," MP, vol. 18, no. 4 (1979): p. 34-41.*

[101]*ASTM Standard B 418-01, "Standard Specification for Cast and Wrought Galvanic Zinc Anodes," (West Conshokocken, PA: ASTM, 2002).*

[102]*C. F. Schrieber and Reece W. Murray, "Effect of Hostile Marine Environments on the Al-Zn-In-Si Sacrificial Anode," CORROSION/88, paper no. 32, (Houston, TX: NACE, 1988).*

[103] *DNV RP B401 Appendix A, "Recommended Practice for Accelerated Laboratory Testing of Sacrificial Anode Materials with the Objective of Quality Control," Det Norske Veritas Industri Norge AS (1993), p.40-44.*

used in seawater or chloride environments normally in the form of bracelets or flush-mounted shapes.

## 2.4.1.4   Polarization Diagram

When discussing polarization diagram for a cathodic protection system, we must take care not to confuse the anodes and cathodes of the corrosion cells on the structure and the cathodic protection anode with the macroscopic anodes and cathodes of the cathodic protection system. Therefore, there are three sets of corrosion cells each with their respective anodes and cathodes to be considered. The polarization diagram for a galvanic cathodic protection system in Figure 2-21 illustrates this point.
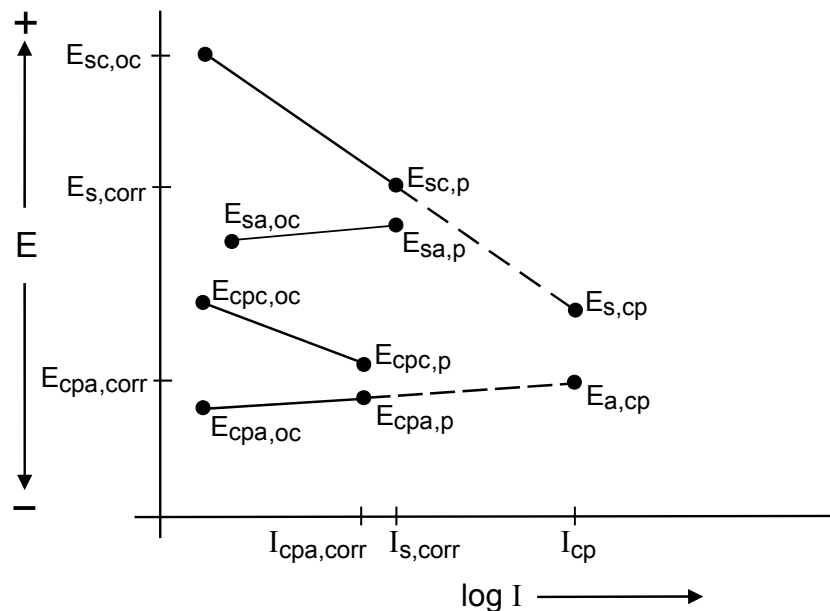


**Figure 2-21: Polarization Diagram for Galvanic Anode System**

In Figure 2-21, each of the three separate corrosion cells has an associated operating point described by a corrosion current and a corrosion potential. Often when our primary concern is the cathodic protection cell, we ignore the corrosion cells existing on the structure and the cathodic protection anode and show only the corrosion cell representing the cathodic protection system. Figure 2-22 illustrates the cathodic protection system.
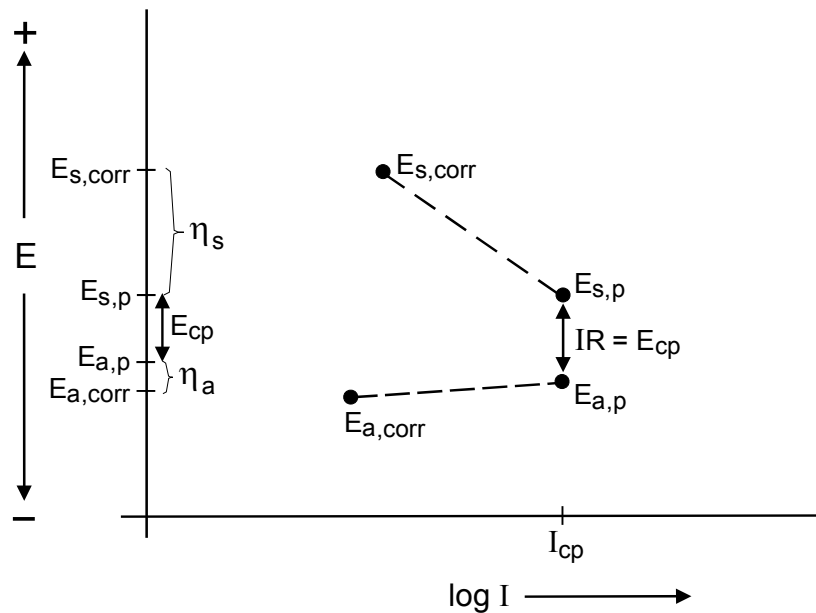
**Figure 2-22: Polarization of Structure and CP Anode**

From Figure 2-22, we see that the difference between the corrosion potential for the structure, $E_{s,corr}$, and the polarized potential, $E_{s,p}$, for the structure is equal to the polarization of the structure, $\eta_S$. The difference between the corrosion potential for the cathodic protection anode, $E_{a,corr}$, and the polarized potential of the cathodic protection anode, $E_{a,p}$, is equal to the polarization of the cathodic protection anode, $\eta_A$. The difference between the polarized potential of the structure, $E_{s,p}$, and the polarized potential of the cathodic protection anode, $E_{a,p}$, is the driving potential for cathodic protection current, $E_{CP}$. Since the IR drop within the cathodic protection circuit exactly balances the driving potential for cathodic protection current, the difference between the polarized potential of the structure and the polarized potential of the cathodic protection anode is also equal to the total IR drop in the cathodic protection circuit.

### 2.4.1.5  Backfill

A special chemical backfill is often used to surround galvanic anodes placed in a soil environment. To take advantage of the chemical energy stored in a galvanic anode, the electrochemical reaction producing cathodic protection current must occur on the surface of the galvanic anode. This reaction, oxidation, results in the conversion of the galvanic metal to metallic ions according to the generalized corrosion reaction shown in Equation 2-6. Therefore, one chemical backfill

characteristic required for galvanic anodes is that it must be ionically, not electronically, conductive. The primary purposes of the chemical backfill are to provide 1) a homogeneous, favorable environment to minimize self-corrosion of the anode, 2) a low resistivity fill to minimize earth contact resistance for the anode, 3) a chemical environment that will minimize anode polarization, and 4) a backfill that will absorb and retain the moisture necessary for ionic conduction. Table 2-12 provides the most common chemical backfills for magnesium and zinc.

**Table 2-12: Galvanic Anode Backfills**

| MAGNESIUM ANODE BACKFILL | | |
|---|---|---|
| 75% | Ground hydrated gypsum | $CaSO_4$ |
| 20% | Powdered bentonite | clay |
| 5% | Anhydrous sodium sulfate | $Na_2SO_4$ |
| ZINC ANODE BACKFILL | | |
| 50% | Ground hydrated gypsum | $CaSO_4$ |
| 50% | Powdered bentonite | clay |

The primary purpose of the gypsum (calcium sulfate) is to supply an abundance of sulfate ions. When the galvanic anode corrodes to produce cathodic protection current, the metal ions (cations) release into the electrolyte adjacent to the anode surface. However, these cations will further react with anions available in the electrolyte to form stable compounds. If the primary anions available are carbonates, bicarbonates, or phosphates, relatively insoluble compounds form, which deposit on the anode surface causing polarization of the anode. However, if sulfate ions are available in abundance, relatively soluble magnesium sulfate and zinc sulfate compounds form. Because these compounds are relatively soluble, they can harmlessly migrate away from the anode surface in the electrolyte.

The bentonite is present in the backfill to retain moisture at the anode surface and to provide a source of conductive ions. Bentonite, sodium montmorillonite, is a form of clay, which readily absorbs and retains moisture. Sodium and other cations adsorb and loosely bind to the surface of the clay particles; therefore, when moisture is present, the cations can readily move providing the means for ionic conduction.

Finally, the sodium sulfate will readily ionize providing a source of conductive ions. Sodium sulfate lowers the resistivity of the backfill and, therefore, lowers the earth contact resistance of the anode. Sodium sulfate is not generally added to the

zinc anode backfill because zinc anodes are primarily used in soils with low resistivity.

### 2.4.1.6   Typical Uses

Since galvanic anodes have relatively small, fixed driving potentials and metal consumption is a necessary result of CP current discharge, a designer typically considers galvanic anodes as the first choice in designs where the environment resistivity is low and/or the current output is small. The higher the environment resistivity for a particular situation, the larger (longer) the galvanic anode must be to obtain useable current outputs. Also, the larger the current requirement for a specific structure, the greater the galvanic anode weight must be.

Typical situations where galvanic anodes may be the best choice include:

- Small isolated, coated structures
- Small, isolated fittings such as valves, risers, or couplings
- Structures where electrical continuity presents a problem
- Internal surfaces of small vessels
- Structures in seawater environments
- Structures where geometry presents a current distribution problem
- Environments where explosion hazards limit the use of power sources
- Mitigation of AC and DC interference

### 2.4.2   Impressed Current Anodes

Since impressed current anodes are relatively inert, the anode material itself corrodes but at a very low rate. The metallic oxidation reaction shown in Equation 2-6 represents corrosion of the anode. If we surround the impressed current anode with electronically conductive carbon backfill, the outer surface of the carbon backfill serves as the primary reaction surface. In this case, the anode functions simply as an electrical contact to the carbon backfill. The primary reactions occurring at the periphery of the carbon backfill are oxidation of the carbon or oxidation of species within the electrolyte. Other than metallic oxidation, Equations 2-31 to 2-34 are the most common oxidation reactions.

*Electrolysis of water:*     $2H_2O \rightarrow 4H^+ + O_2 \uparrow + 4e^-$            [2-31]

*Oxidation of chloride ion:*   $2Cl^- \rightarrow Cl_2 \uparrow + 2e^-$            [2-32]

*Oxidation of carbon:*        $C + 2H_2O \rightarrow 4H^+ + CO_2 \uparrow + 4e^-$        [2-33]

or

$C + H_2O \rightarrow 2H^+ + CO \uparrow + 2e^-$        [2-34]
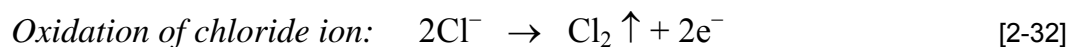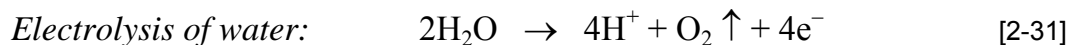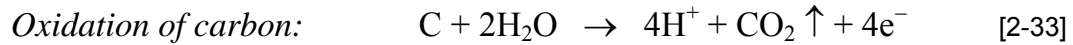
Notice from the above common impressed current oxidation reactions that in all cases gases are produced at the reaction surface. The only exception where gases are not produced involves the metallic consumption reaction. Also, the pH at the reaction surface decreases as hydrogen ions are produced. This is obvious from all of the anodic reactions except the reactions involving metallic consumption of the anode and oxidation of chloride ions. However, the pH also decreases in these two cases due to secondary reactions. In the case of metallic consumption of the anode, the metal cation reacts with water to produce a metallic hydroxide and hydrogen ions as seen in reaction Equation 2-35. In the case of the chloride ion oxidation, the chlorine gas reacts with water to produce hydrochloric and hypochlorous acids as seen in reaction Equation 2-36.

$$M^{+n} + nH_2O \rightarrow M(OH)_n + nH^+$$        [2-35]

$$Cl_2 \uparrow + H_2O \rightarrow HCl + HOCl$$        [2-36]

Therefore, impressed current anode components and associated wiring must be resistant to oxidizing gases and acids for successful long-term operation.

Impressed current anodes can be classified in two major groups based on corrosion behavior: massive anodes and dimensionally stable anodes (DSA). Massive anodes are large anodes such as graphite and high-silicon iron anodes that become shorter and smaller in diameter as they corrode. Dimensionally stable anodes such as mixed metal oxide, platinum, and polymer anodes do not change physical dimensions as they deteriorate. In fact, loss of the anode material is usually not obvious by visual inspection of DSAs.

## 2.4.2.1   Massive (Large) Anodes

The two primary types of massive (large) anodes are soluble and semisoluble. One of the first materials used as an impressed current anode, iron, is a soluble anode. This material consumes at a rate of approximately 9.1 kg/A-y (20 lb/A-y). Therefore, a relatively large quantity of material is necessary for a reasonable output capacity. Aluminum is another soluble anode material sometimes used as an impressed current anode in potable water tanks.

Although soluble type anodes are not as commonly used today as in the past due to the need for large masses of material, one significant advantage to this type of anode can make it useful. Soluble anodes produce current through metal consumption reactions, not gas evolution reactions as with semisoluble anodes. This major difference can be useful in applications involving confined or restricted spacing. If the anode is very near the cathode, products of the anodic reaction, oxygen and hydrogen ions, can interfere with the polarization of the cathode (cathodic depolarizers). Using a soluble anode would minimize the production of these depolarizers.

Although several other massive type impressed current anodes are used, by far the two most common semi-soluble anodes in this classification are graphite and high-silicon cast iron (HISI). Both anodes have a long history of use in the cathodic protection industry with graphite anodes first used in the 1940s and HISI anodes first introduced in 1954. Both anodes are generally available in long cylindrical shapes; HISI anodes are also commonly available in hollow, tubular forms. Diameters from 5 - 10 cm (2 - 4 in.) and lengths from 152 – 213 cm (60 - 84 in.) are the most common sizes for soil applications. Other sizes are available for special applications.[104,105]

Graphite anodes perform well in environments where either oxygen or chlorine evolution occurs. However, the graphite consumption rate is higher when oxygen is evolved (fresh water and soil) due to the chemical reaction with oxygen producing carbon dioxide. In the case of chlorine evolution (sea or brackish water), hypochlorous acid is produced, which chemically reacts with graphite to produce carbon dioxide and hydrochloric acid. However, in this case the quantity of hypochlorous acid is generally small and easily moved away from the graphite surface without reacting.[106,107]

When high-silicon iron anodes are alloyed with a minimum of 14.5% silicon, the anode forms a protective oxide film on its surface when anodically polarized. This oxide film lowers the consumption rate of the anode. The protective film consists of hydrated, silicon dioxide. Although silicon dioxide is normally very high in

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

[105]*NACE Publication 10A196, "Impressed Current Anodes for Underground Cathodic Protection Systems," (Houston, TX: NACE International, May 1996).*

[106]*W. von Baechmann and W. Schwenk, Handbook of Cathodic Protection, (Surrey, England: Portcullis Press Ltd., 1975), p. 37-38, 58-59, 153-173, 185-198, and 208-217.*

[107]*David H. Kroon and Charles F. Schrieber, "Performance of Impressed Current Anodes for Cathodic Protection Underground," CORROSION/84, paper no. 44, (Houston, TX: NACE, 1984).*

resistivity, when anodically formed under wet conditions the film becomes conductive. However, if the film is formed with insufficient moisture present, the film becomes high in resistivity and contact resistance of the anode-to-earth is high.[108,109,110]

In 1959, chromium was added to the high-silicon iron alloy. The addition of 3 to 5% chromium reduced pitting attack of high-silicon iron anodes in chloride environments, thus reducing the overall corrosion rate.[106]

Table 2-13 provides a summary of helpful application information for massive type impressed current anodes. Current density and consumption rate information for these anodes varies considerably from source to source, due in part to lack of consideration of variations in different environments. In the case of HISI anodes, some of the variation is due to differences in alloy composition. The information provided in Table 2-13 represents an integration of the recommendations from a number of sources with extreme values eliminated. The current densities provided represent nominal recommended values, not maximum values.[105,106,107,111,112,113]

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[108]*CP 4–Cathodic Protection Specialist Course Manual, (Houston, TX: NACE, 2002) p. 1:25-1:27, 3:4-3:14, 3:18-3:33, and 8:34-8:35.*

[109]*NACE Publication 10A196, "Impressed Current Anodes for Underground Cathodic Protection Systems," (Houston, TX: NACE International, May 1996).*

[110]*Ibid. 104.*

[111]*W. von Baechmann and W. Schwenk, Handbook of Cathodic Protection, (Surrey, England: Portcullis Press Ltd., 1975), p. 37-38, 58-59, 153-173, 185-198, and 208-217.*

[112]*John Morgan, Cathodic Protection, 2nd Ed. (Houston, TX: NACE, 1987), p. 37, 152-175, 205, and 254-258.*

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

**Table 2-13:  Massive Type Impressed Current Anodes**

| | Graphite | HISI |
|---|---|---|
| **Nominal Current Density:** | | |
| **Soil/fresh water, A/m$^2$** | **2 – 10** | **2 – 5** |
| (A/ft$^2$) | (0.2 – 1) | (0.2 – 0.5) |
| **Carbon backfill, A/m$^2$** | **5 – 10** | **5 – 10** |
| (A/ft$^2$) | (0.5 – 1) | (0.5 – 1) |
| **Seawater A/m$^2$** | **5 – 10** | **10 – 50** |
| (A/ft$^2$) | (0.5 – 1) | (1 – 5) |
| **Consumption Rate:** | | |
| **Soil/fresh water, kg/A-y** | **0.5 – 0.9** | **0.1 – 0.5** |
| (lb/A-y) | (1 – 2) | (0.2 – 1.2) |
| **Carbon backfill, kg/A-y** | **0.1 – 0.2** | **0.05 – 0.3** |
| (lb/A-y) | (0.2 – 0.5) | (0.1 – 0.7) |
| **Seawater, kg/A-y** | **0.1 – 0.3** | **0.3 – 0.5** |
| (lb/A-y) | (0.2 – 0.7) | (0.7 – 1) |
| **Comments / Limitations:** | **Avoid:** Low pH, High sulfate, Temp. > 50° C **Consider:** End effect, Treatment, Brittle | **Avoid:** Dry soils, High pH, High sulfate **Consider:** End effect, Brittle, Chrome alloy - halides |

One major consideration in the application of impressed current anodes, especially massive type anodes, is end effect. End effect manifests itself as accelerated corrosion at the ends of long, cylindrical anodes often described as "penciling" of the anode. This accelerated corrosion is due to the increased current density discharged from the ends of long, cylindrically shaped anodes. The most significant result of end effect is the premature loss of electrical connection to the anode since the electrical connection is most often within about 15 cm (6 in.) of the end of the anode. One cost-effective solution is to place the electrical connection at the center of the anode. This step is recommended to increase the operational life of deep and horizontally buried anodes. Center connection is unnecessary if the top of the anode is located near the surface of the earth since the current density from the top of the anode is reduced due to the nonconducting plane (air) near the anode end.[114,115,116]

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[114]*BP 4–Cathodic Protection Specialist Course Manual, (Houston, TX: NACE, 2002) p. 1:25-1:27, 3:4-3:14, 3:18-3:33, and 8:34-8:35.*

## 2.4.2.2    Dimensionally Stable Anodes

Platinum, mixed metal oxide, and polymer anodes represent some common DSA options. Platinum-coated anodes were first introduced to the cathodic protection field in the early 1960s for offshore applications. Mixed metal oxide anodes, on the other hand, arrived on the cathodic protection scene in Europe in the early 1980s. Both of these have active anode surfaces covering an inactive substrate metal such as titanium or niobium. These substrate metals, known as "valve metals," form thin, adherent, protective, self-healing, high-resistance oxide films when anodically polarized. These high-resistance surface films will not permit the passage of anodic current until a voltage sufficiently high to destroy the film is applied directly across the oxide interface. The magnitude of the breakdown voltage depends on the environment. In fresh waters, where chloride concentrations are low, the breakdown voltage of titanium is greater than 60 volts. However, in high-chloride environments the breakdown voltage is in the range of 8 to 10 volts. It is reduced even further in the presence of bromides or iodides, at higher temperatures, and with impurities present in the titanium, especially iron. The breakdown voltage for niobium, however, exceeds 100 volts even in the presence of high chloride concentrations. When the protective film is destroyed, the substrate metal corrodes and the anode surface is undercut.[117,118,119]

### 2.4.2.2(a)  Platinum Anodes

Platinum anodes are available with a very thin layer of platinum electroplated or clad onto the substrate metal. Common platinum thicknesses range from about 1.2 to 7.5 microns (50 to 300 micro-inches). Platinum anodes are available in many different sizes and shapes, but wires, rods, and strips are the most common. The consumption rate for platinum in seawater, which is relatively constant at current densities from 540 to 5400 A/m$^2$ (50 to 500 A/ft$^2$), is in the range of 2.4 to 12 mg/A-y with 8 mg/A-y most often quoted. In fresh water, the consumption rate is approximately two to five times higher, and in brackish water is even higher. At

[115]T. H. Lewis, Jr., *Deep Anode Systems: Design, Installation, and Operation, (Houston, TX: NACE International, 2000), p. 28-32.*

[116]Thomas H. Lewis, Jr., *"End Effect Phenomena," CORROSION/78, paper no. 163, (Houston, TX: NACE, 1978).*

[117]NACE Publication 10A196, *"Impressed Current Anodes for Underground Cathodic Protection Systems," (Houston, TX: NACE International, May 1996).*

[118]David H. Kroon and Charles F. Schrieber, *"Performance of Impressed Current Anodes for Cathodic Protection Underground," CORROSION/84, paper no. 44, (Houston, TX: NACE, 1984).*

[119]M. A. Warne, *"Precious Metal Anodes – The Options for Cathodic Protection," CORROSION/78, paper no. 142, (Houston, TX: NACE, 1978).*

chloride concentrations of approximately 25% of seawater, the consumption rate increases dramatically reaching values of ten times or more the consumption rate in undiluted seawater.[114,115,120,121,122]

Some considerations and concerns when using platinum anodes are silting and deposits, abrasion damage, and attenuation problems. Platinum anodes do not perform well in environments where silting or deposits can cover the anode surface. Under these conditions, the anode life can be shortened to only 10% of the anticipated life in open seawater. The significantly increased platinum consumption rate and corrosion of the substrate occur because of the low pH environment created by the restricted mass flow. Abrasion can damage the active platinum surface; therefore, the installer must exercise care during installation and operation of these anodes. Attenuation of current along the length of the long, small diameter platinum wire anodes can prevent effective use of the entire anode surface. In these cases, copper-cored platinum anodes are often used to reduce attenuation effects.[123,124,125]

Use of platinum anodes in soil environments has had mixed results. Even at relatively low current densities, platinum anodes have failed prematurely in both shallow and deep groundbed applications. The failures have primarily manifested as loss of the electrical connection due to corrosion of the titanium substrate, perhaps due to low pH. However, there are examples of good long-term performance of platinum when installed in a clean, conductive carbon backfill within a uniform, homogeneous soil stratum and operated at low current densities of 55 to 75 A/m$^2$ (5 to 7 A/ft$^2$).[120,122,126]

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[120]*Cathodic Protection – Theory and Data Interpretation Course Manual, (Houston, TX: NACE, 1998), p. 6:25-6:28.*

[121]*M. A. Warne and P. C. S. Hayfield, "Platinized Titanium  Anodes for Use in Cathodic Protection," MP, vol. 15, no. 3 (1976): p. 39-42.*

[122]*A. C. Toncre and P. C. S. Hayfield, "Consumption Rates and Operating Limits for Platinized Anodes in Brackish Waters," CORROSION/83, paper no. 148, (Houston, TX: NACE, 1983).*

[123]*Ibid. 115*

[124]*M. A. Warne and P. C. S. Hayfield, "Platinized Titanium  Anodes for Use in Cathodic Protection," MP, 15, 3 (1976): p. 39-42.*

[125]*P. C. S. Hayfield and M. A. Warne, "Variables Affecting Platinized Anodes in Cathodic Protection Systems," CORROSION/82, paper no. 38, (Houston, TX: NACE, 1982).*

[126]*NACE Publication 10A196, "Impressed Current Anodes for Underground Cathodic Protection Systems," (Houston, TX: NACE International, May 1996).*

## 2.4.2.2(b)  Mixed Metal Oxide Anodes

The active surface of mixed metal oxide anodes consists of a solid state solution of rare metal oxides (Group IV and Group VIII metals in the periodic table) with other nonprecious metal oxides. Some of the oxides often found in this application include iridium, ruthenium, tantalum, and titanium oxides. Since the active surface is preoxidized, the consumption rate of the surface coating is very low. In fact, anode failure is not attributed to consumption of the mixed metal oxide, but rather to the formation of a high-resistance, passive oxide film between the active surface coating and the titanium substrate blocking current between them. Formation of this nonconductive oxide film and, therefore, anode life are a function of the anode current density.[123,127]

Because major characteristics of the oxide film, such as specific oxide formulation, application technique, and film thickness, may vary for a specific anode or manufacturer, it is important to use design information (recommended environment, current density, and anticipated life) supplied for a specific anode by the manufacturer. However, Table 2-14 provides general guidelines for current density ratings in various environments along with the specific design life based on information from several manufacturers. Mixed metal oxide anodes designed specifically for installation in carbon backfill generally have reduced film thickness to make the anode more economical. Consequently, the recommended current density for a specific design life is also reduced for this particular anode.[128,129,130]

**Table 2-14: Mixed Metal Oxide Anodes**

| | Carbon Backfill | | Fresh Water | Brackish Water | Seawater | Mud Saline |
|---|---|---|---|---|---|---|
| | High Current | Special | | | | |
| **Current Density**, $A/m^2$ ($A/ft^2$) | 83-140 (7.7-13) | 35-40 (3.3-3.8) | 83-170 (7.7-16) | 83-260 (7.7-24) | 480-610 (45-57) | 83-240 (7.7-22) |
| **Life, yrs** | 20 | 20 | 20 | 15 | 15 | 15 |
| **Comments:** | Above ratings do not apply to expanded mesh anodes. Current densities must be dearated at temperatures below 5-10° C. Electrolyte impurities can affect ratings. Mixed metal oxide surface is susceptible to abrasion damage. Attenuation should be considered in long, thin wires & rods. | | | | | |

[127]*Richard A. Kus, "Advances in Coating Technology," World Pipelines (November/December, 2002).*
[128]*Ibid. 123*
[129]*CerAnode Technologies International, Product Catalog, August, 1999.*
[130]*Eltech Systems Corporation, Lida Products Catalogue,*
  *http.//www.lidaproducts.com/catalogue/catframe.htm (November 10, 2003).*

Mixed metal oxide anodes are available in a number of different sizes and shapes including tubes, wires, rods, meshes, and strips. Wires and rods may also include copper cores to improve conductivity, thus reducing attenuation. However, as for any long, small diameter anode, the designer should evaluate attenuation for each specific case and carefully evaluate the effects of differing soil resistivities in soil applications. Significant variation in environmental resistivities can cause excessive discharge within the low resistivity areas resulting in premature anode failure.[125]

### 2.4.2.2(c)  Polymer Anodes

Polymer anodes, introduced in the early 1980s, are manufactured by extruding a semiconductive polymer coating over a copper wire. The active anode material consists of a polymer matrix loaded with conductive carbon. This anode is designed for use in carbon backfill where the backfill surface provides the primary oxidation reaction site. The polymer anode primarily serves as an electrical contact to the carbon backfill.[131]

Currently only one size polymer anode is commercially available. This anode has an outside diameter of 13 mm (0.5 in.) and contains a #6 AWG stranded, copper conductor. When used with a high quality carbon backfill, the anode is rated for a 20-year life at a current output of 52 mA/m (16 mA/ft) of length.[128,132]

The primary design concerns with long, polymer anodes are attenuation and variations in current discharge along the anode due to soil resistivity variations. In addition, abrasion or penetration by sharp surfaces can damage the anode. Polymer anodes are available either bare or prepackaged with carbon backfill.[128] When packaged in carbon backfill, the anode must be centered in the backfill to prevent premature failure.

## *2.4.3   Polarization Diagram*

In constructing a polarization curve for an impressed current system, note that the corrosion potential (open CP circuit) of the anode is more noble than the corrosion potential for the cathode (structure). Of course, the anode potential must become even more electropositive as the anode polarizes (positive polarization slope);

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[131]*NACE Publication 10A196, "Impressed Current Anodes for Underground Cathodic Protection Systems,"*
   *(Houston, TX: NACE International, May 1996).*

[132]*Tyco Adhesives, Reychem AnodeFlex 500, http://tycoadhesives.com/site/pdf/DCANODEFLEX_500.pdf*
   *(November 10, 2003).*

therefore, the entire polarization curve for the anode must be more electropositive than the cathode curve. Ignoring the corrosion cells on the cathodic protection anode and structure, Figure 2-23 is the polarization graph for an impressed current system.

It is apparent from the polarization plot that the rectifier output voltage must be equal to the sum of the galvanic potential difference between the CP anode and the structure ($E_{gal}$), the polarization of the anode ($\eta_{cpa}$), the IR drop at the anode ($IR_{cpa}$), the polarization of the structure ($\eta_s$), and the IR drop at the structure ($IR_s$) as indicated in Equation 2-37. The polarization curves for both the anode and cathode are straight lines on the E log I plot due the logarithmic relationship between the current and polarization potential (Tafel equation). Since the IR drop associated with each electrode has a linear relationship with the current, this plot must be curvilinear on a logarithmic scale as seen in Figure 2-23.
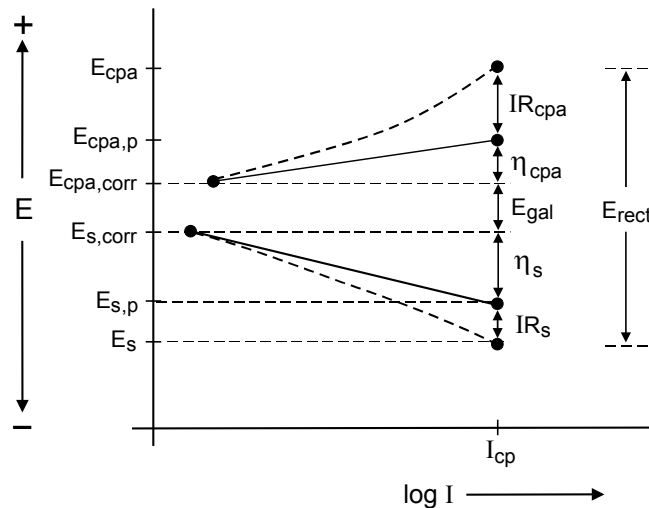


**Figure 2-23: Polarization Diagram for Impressed Current CP System**

$$E_{RECT} = E_{gal} + \eta_S + IR_S + \eta_{cpa} + IR_{cpa} \qquad [2\text{-}37]$$

## 2.4.4  Carbon Backfill

The previous section on impressed current anodes indicated that the oxidation reactions would occur on the periphery of the carbon backfill rather than at the anode surface. Further exploring the contact interface between the primary cathodic protection anode and the carbon backfill, we realize that this view is too simplistic since there are two possible conduction paths present at the anode interface. First, there is the electronic path from the anode surface through the

particles of carbon backfill; however, there is also an ionic conduction path from the anode surface into the pore water between the carbon particles, as indicated in Figure 2-24.
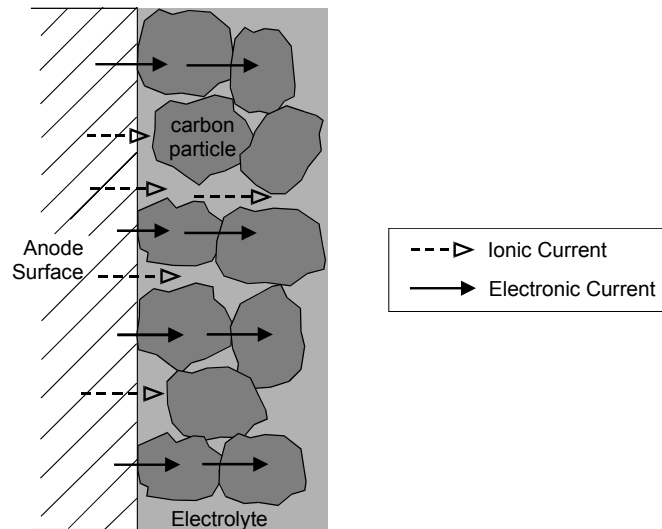


**Figure 2-24:  Current Discharge Paths from Anode Surface**

If current transfers from the anode surface through the carbon particles, no electrochemical reaction will occur at the anode surface. However, if current leaves the anode surface through the pore water, an electrochemical reaction must occur to allow the charge transportation to change from electronic to ionic. In the case of electronic transfer of current through the carbon, the periphery of the carbon backfill becomes the reaction surface . In the case of ionic transfer into the pore water, the reaction surface is the anode surface itself. Since the carbon backfill surface is much larger than the anode surface, the current density at this surface must necessarily be much smaller than at the anode surface. Therefore, the opportunity for polarization is reduced significantly.

Since the two paths for current discharge from the anode surface are in parallel, some charge must flow through each path. If the ionic discharge is minimized, the anode life is increased, and the electrochemical reactions occur primarily at the periphery of the backfill reducing the possibility of anode operational problems. Therefore, the ratio of the resistances of each path, one through the pore water and one through the carbon backfill, is the determining factor in improving anode life and long-term system operation. The resistivities of the water and the carbon backfill control the resistance through each path. Since the water resistivity is generally outside of our control, minimizing the carbon backfill resistivity

becomes the critical control factor. The in-situ bulk resistivity of the carbon is the important factor.

The resistivity of the carbon backfill is a function of the specific resistivity of the carbon particles, particle size, and the contact resistances between individual particles. Contaminants within the unprocessed carbon (green coke) and the carbon heat treatment determine the specific resistivity of the carbon. Selection of a very pure carbon (coke) and optimal calcination (heat treatment) of the carbon with electrical conduction as the desired characteristic minimize the specific resistivity of the final product.

Carbon backfill for impressed current anodes begins as a form of hydrocarbon. The two primary raw hydrocarbons used to produce carbon backfill are coal, used to produce metallurgical coke, and petroleum (oil), used to produce petroleum coke. Metallurgical coke is produced by heating coal in the absence of oxygen in large coking ovens. This process drives gases and liquids out of the coal leaving a porous, solid carbon residue (coke). Due to the variability of the naturally produced coal and the lack of temperature controls with the coking ovens, the final product varies considerably. Petroleum cokes produced for their electrical characteristics begin with the selection of heavy crude oils carefully chosen for specific properties and heat-treated to exacting standards.

Since coke has many different end uses, it is important to select cokes produced specifically for electrical conduction properties. The single largest use for coke is as a boiler fuel where BTU content is the important characteristic. Another major application of coke is chemical carbon raising for steel production. Unlike impressed current carbons, the electrical properties of the coke are not important in either of these major applications.

The output of the coker for petroleum coke production is called "green" or "raw coke" and is not electrically conductive. The raw coke must be calcined to become conductive. As the raw petroleum coke is heated, the remaining hydrocarbon chains are broken burning off the gaseous hydrogen, increasing the density of the particles, reducing the resistivity of the particles, and beginning the carbon crystallization process (graphitization). At the optimal point of calcination, the carbon particles have minimal specific resistivity while maintaining a high density. At this stage, the carbon is a semi-graphitized, surface-activated coke.

Since the bulk, in-situ resistivity is the major concern, the particle-to-particle contact resistance must also be minimized. This contact resistance is a function of applied pressure and the carbon surface properties. The pressure pushing the

carbon particles together is due to the weight of the particles within the carbon column after settling underwater. Therefore, to maximize this pressure we must enhance the weight of the particles underwater. By maximizing the specific gravity (weight of carbon particle relative to water) and releasing tiny air pockets trapped on the particle surface by treating with surface tension reducers (surfactants), the pressure forcing the particles together increases. The final reduction in in-situ resistivity is achieved through surface treatment of the carbon particles.[133]

Sizing of the carbon particles is also important. The average size of the carbon particles must be small when compared to the diameter of the anode to ensure maximum contact points per unit surface area of the anode. This will maximize the contact surface area to the anode and promote electronic current transfer from the anode surface. However, there is a limit to how small the carbon particles should be since particles less than about 75 microns become high in ash content, higher in resistivity, and dusty.

Finally, in the application of carbon backfills it is important to ensure that the carbon surrounding the anode surface is as clean as possible. Any soil or mud contaminating the anode surface or carbon particles will hinder electronic current transfer. In addition, the installer should completely surround the anode with carbon on all sides to minimize the possibility of ionic current transfer from the anode surface. This is especially true for polymer-type anodes. If current transfers directly into the soil waters from a polymer anode, the polymer will become brittle and crack. This will result in attack of the internal copper conductor resulting in loss of anode continuity.

## 2.4.5  Typical Uses

Since the output current and voltage available from an impressed current system are limited only by the power supply and groundbed design ratings, designers typically select impressed current systems for high current requirements and/or high resistivity environments. Because of the requirement for an external power supply, impressed current systems lend themselves to electronic monitoring and control. Within the limits of the specific design, output current and voltage can be adjusted as necessary to accommodate changes in the protection requirements of the structure.

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[133] *T. H. Lewis, Jr., Deep Anode Systems: Design, Installation, and Operation, (Houston, TX: NACE International, 2000), p. 28-32.*

Impressed current systems have the disadvantage of increased maintenance and power costs due to the required external power supply. Designers must carefully evaluate safety matters related to electrochemical oxidation products at the anode and any step and/or touch potentials associated with the groundbed or power supply. Also, because higher currents are normally associated with impressed current systems, electrical interference with other metallic structures becomes more important.

## 2.4.6   *Impressed Current Power Supplies*

### 2.4.6.1(a)  Standard Transformer/Rectifiers

The most common type of power supply used for impressed current cathodic protection is a transformer/rectifier, commonly referred to simply as a *rectifier*. The rectifier input is an AC voltage from the commercial electrical power grid. 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.

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 2-25. Three-phase rectifiers are available in wye (3 diodes) or full-wave (6 diodes) bridges with full-wave bridges (shown in Figure 2-26) 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.[134]

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[134] *R. L. Bianchetti, ed., Control of Pipeline Corrosion, Second ed. (Houston, TX: NACE, 2001), p. 90, 166-173, 308-310, and 315-317.*
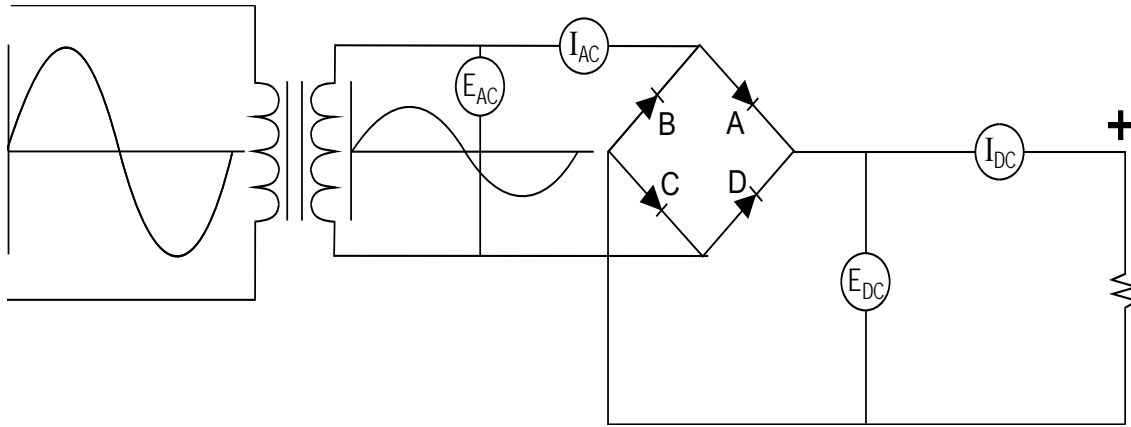
**Figure 2-25: Single-Phase Bridge Rectifier Circuit**

Source:  CP 2–Cathodic Protection Technician Course Manual,, (Houston, TX:  NACE, 2002), pp. 2:18 and 2:20.
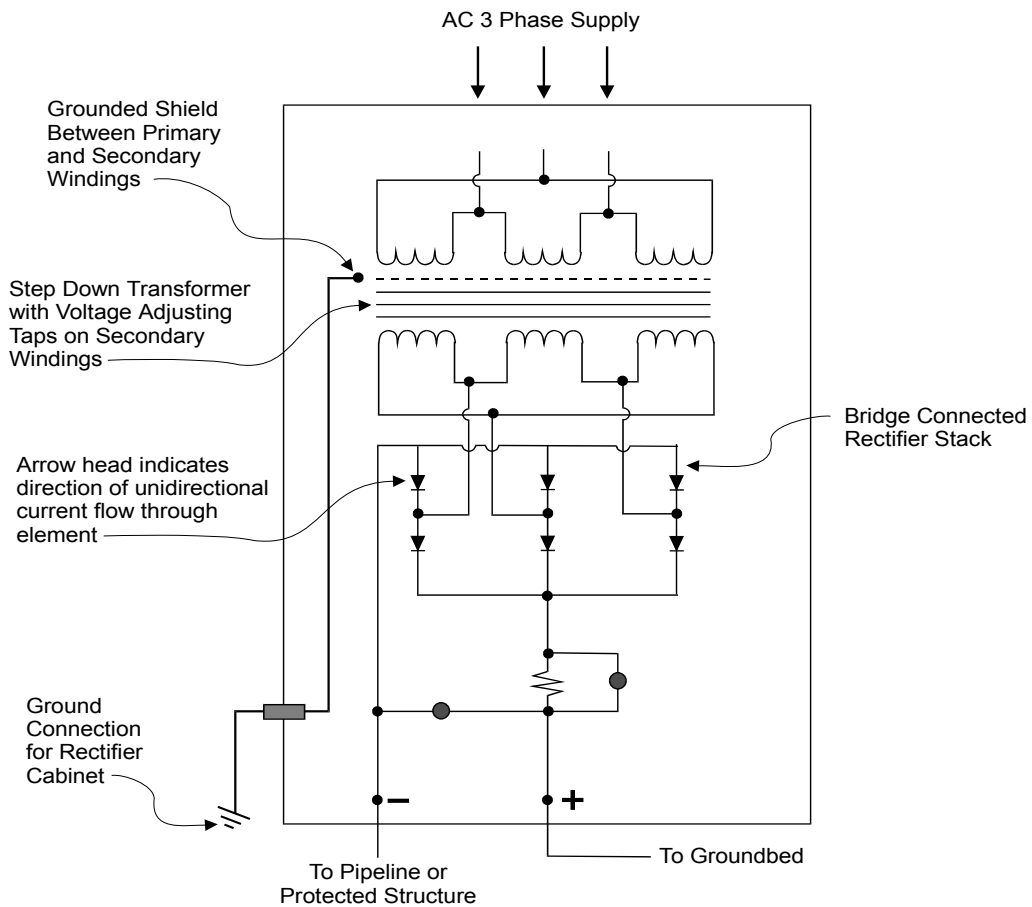


**Figure 2-26: Three-Phase Bridge Rectifier Circuit**
Source:  CP 2–Cathodic Protection Technician Course Manual,
(Houston, TX:  NACE, 2002), p. 2:18 and 2:20.

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 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.[135]

We can illustrate the rectification process by considering the bridge circuit shown in Figure 2-27. 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 2-28 shows the input signal between terminals I1 and I2, and the bottom portion of Figure 2-28 shows the resulting output signal between terminals O1 and O2.

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[135] *R. L. Bianchetti, ed., Control of Pipeline Corrosion, Second ed. (Houston, TX: NACE, 2001), p. 90, 166-173, 308-310, and 315-317.*
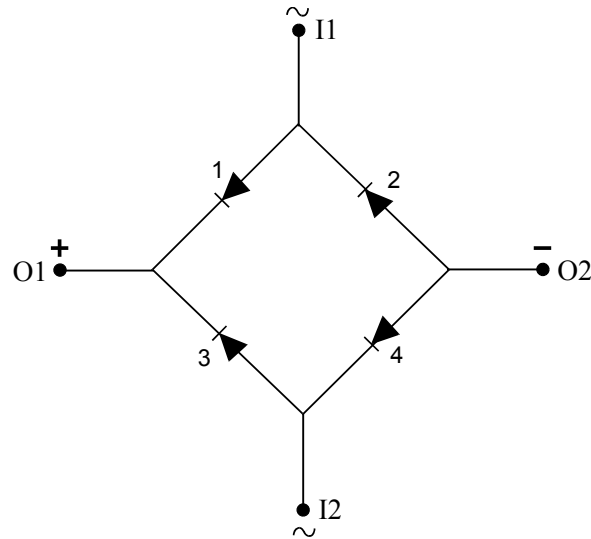
**Figure 2-27: Single-Phase Diode Bridge**
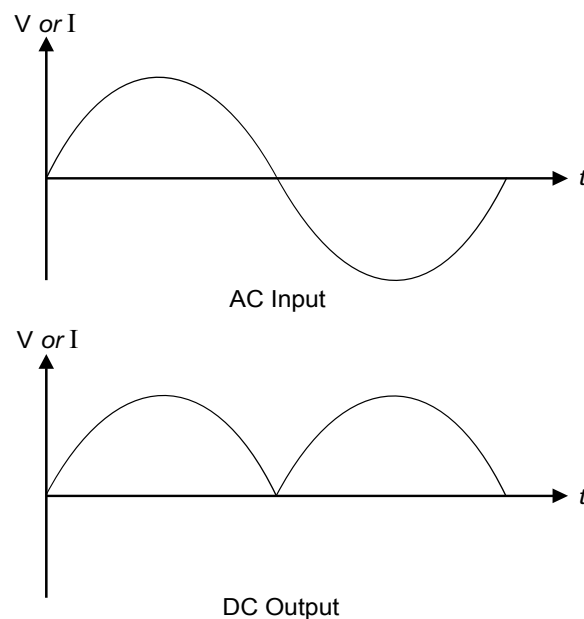


**Figure 2-28: Input and Output Signals from Single-Phase Diode Bridge**

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. Also, other alternative power supplies are available when the AC power grid is unavailable. The more common alternate power supplies include solar panels,

wind driven generators, batteries, thermoelectric generators, and more recently, fuel cells.

## 2.4.6.1(b)  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 2-29. 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 2-29. 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.
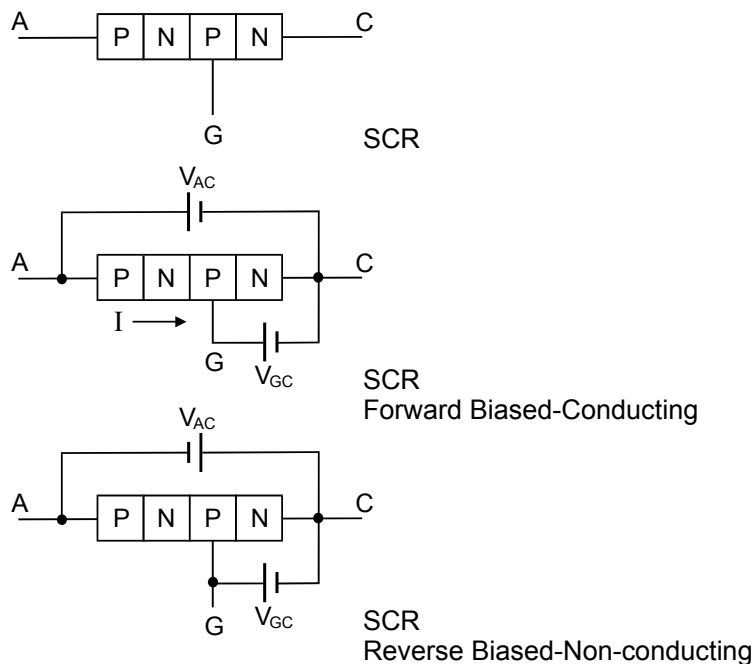


**Figure 2-29:  Silicon Controlled Rectifier (SCR)**

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°).
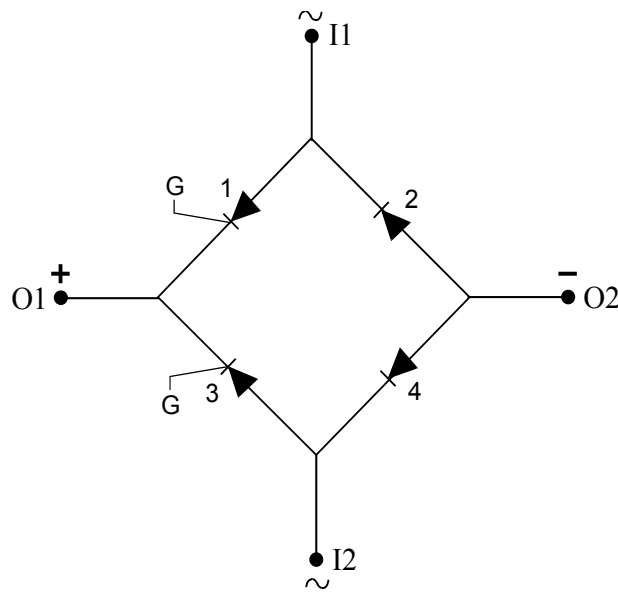


**Figure 2-30: Single-Phase SCR Controlled Bridge**

If we construct a full-wave bridge by replacing diodes 1 and 3 with SCRs as shown in Figure 2-30, 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 2-31. 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.

$V_{IN}$

Input Voltage

$V_O$

Conduction Angle = 180°

$V_O$

Conduction Angle = 120°

$V_O$

Conduction Angle = 90°
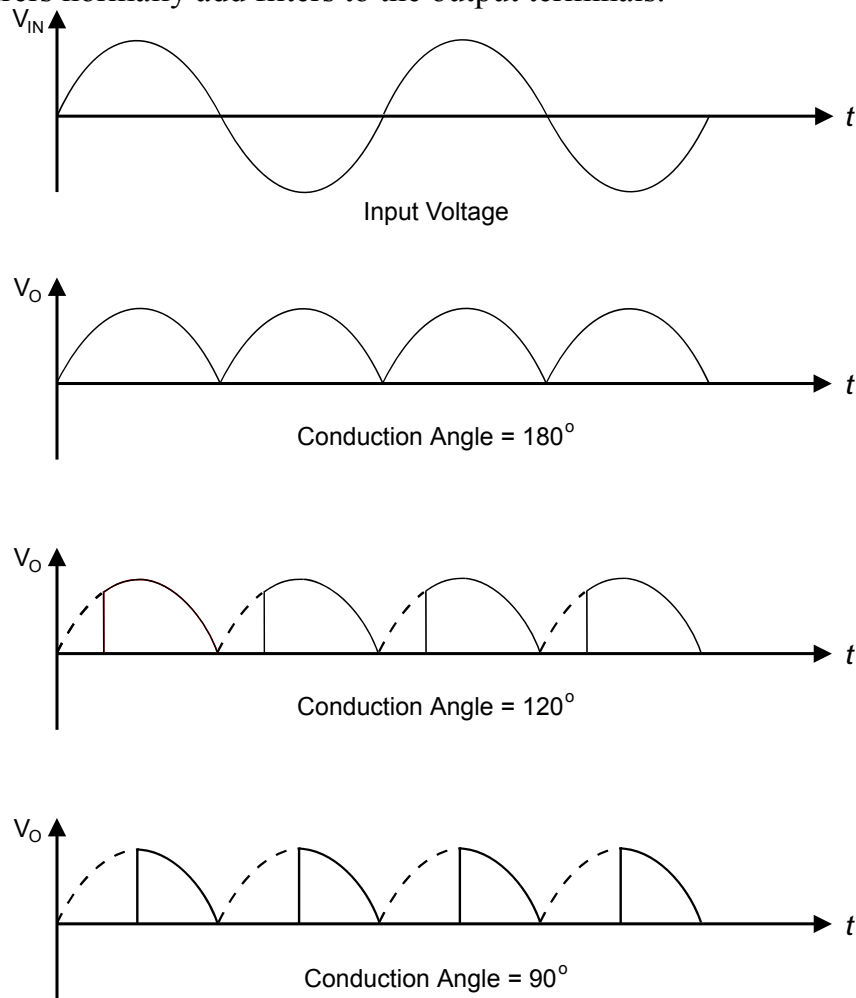
**Figure 2-31:  Full-Wave SCR Bridge Output Waveforms**

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 across the output terminals, the SCRs can again turn off normally at the end of each half-cycle.

## 2.4.6.1(c)  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 500k Hz) 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 2-32. This diagram can be compared to the block diagram for a standard transformer/rectifier shown in the top of Figure 2-32.
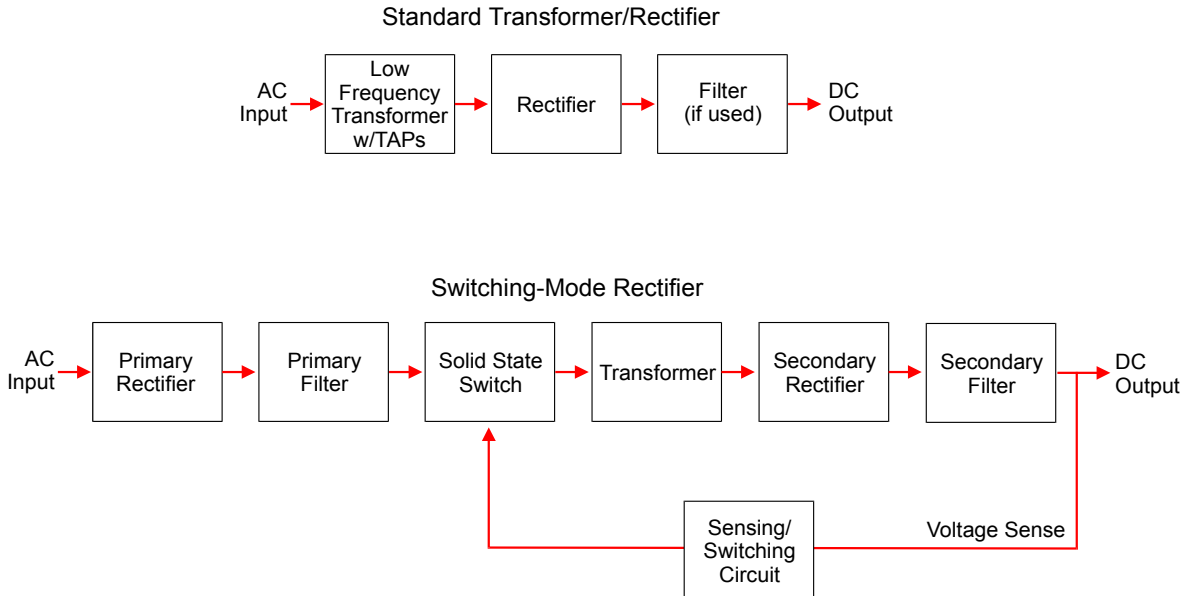


**Figure 2-32:  Block Diagrams for Switching-Mode and Standard Rectifiers**

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

As indicated in Figure 2-32, 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 pluses 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.[136]

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 significant source of high frequency noise (EMI/RFI)
- Reliability less due to number of components
- Prone to higher ripple (more filtering required)
- Repair of individual modules not practical[133]

## 2.4.6.2   Solar Power Supplies

Figure 2-33 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 productions costs significantly in the future. Research is currently under way combining the

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

amorphous silicon with CIS producing a double layer, thin film photovoltaic cell with a conversion efficiency of 15.6%.[137,138,139]

A single photovoltaic cell produces a very small voltage and current. By connecting a number of cells in series, the output voltage available increases. 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 volts with power outputs ranging from 5 to 160 watts. Designers can also connect solar panels in series or parallel, as necessary, to produce an even larger output current or voltage.[140]

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.

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[137]*Shell Solar, Solar Panels, http://www.shell.com (November11, 2003).*

[138]*Siemens, Solar Panels, http://siemenssolar.co.uk (November 11, 2003).*

[139]*Go Solar Company, Solar Panels, http://www.solarexpert.com (November 11, 2003).*

[140]*Go Solar Company, Solar Panels, http://www.solarexpert.com (November 11, 2003).*
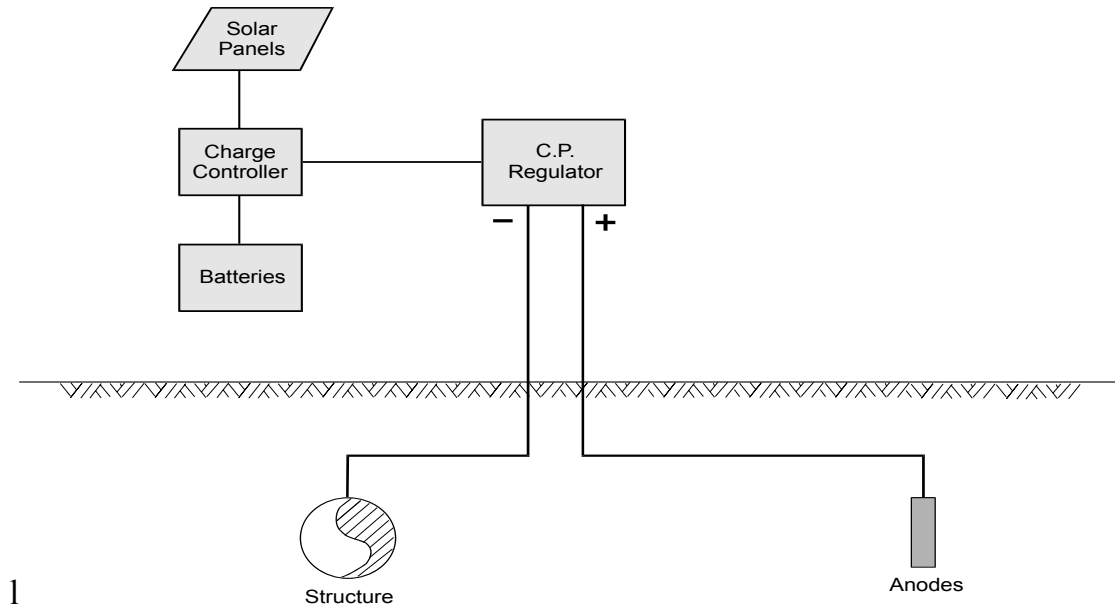
**Figure 2-33: Solar Power Supply System**

## 2.4.6.3   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 about 16 km/h (10 mph) with maximum output achieved at speeds of 40-55 km/h (25-35 mi/h). 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.

Due to the high maintenance requirements of wind-driven generators, these power sources are now used less frequently especially with the continuing development of other more cost competitive alternate power sources. Wind-driven generators are available in 400 to 3000 watt sizes with voltage outputs ranging from 12 to 240 volts.[141]

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

### 2.4.6.4  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 amps a battery can supply for a specific time interval, hours. Temperature can have a significant effect on output capacity of batteries, especially lead-acid batteries. At a temperature of 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.[142]

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.

### 2.4.6.5  Thermoelectric Generators (TEG)

Another alternative energy power supply available for cathodic protection applications is the thermoelectric generator (TEG). 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.[143]

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

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[142]*Go Solar Company, Solar Panels, http://www.solarexpert.com (November 11, 2003).*

[143]*Donald 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.*

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.[144,145]

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 volts and power ratings of over 500 watts. 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 ohm). 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.[146]

### 2.4.6.6  Fuel Cells

One of the newer and currently emerging alternative energy power supplies available is the fuel cell. Although NASA originally developed this technology for the space program, 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.[153,147]

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[144]*CP 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.*

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

[146]*Global Thermoelectric, 8550 Thermoelectric Generator Operating Manual (Calgary, Alberta, Canada: Global Thermoelectric, 2002).*

[147]*Online Fuel Cell Information Center, Fuel Cells, http://www.fuelcells.org (November 11, 2003).*

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.[154,155]

## 2.4.6.7   Modes of Operation

The power supply for a cathodic protection system can operate in any one of three possible modes: constant voltage, constant current, or constant potential. Constant voltage is the most common mode of operation since a standard rectifier is basically a constant voltage output device. For a standard rectifier the variation in output voltage with a change in the load resistance is relatively minor and caused by changes in IR voltage drops within the unit. If the external load resistance increases, the current output must decrease. The voltage output only changes when the transformer tap adjustment is manually changed.

In the constant current mode of operation, the output voltage from the power supply automatically adjusts with changes in the external load resistance to supply a constant current output. This change in voltage to maintain constant current can only occur within the design limits of the unit. Either a saturable reactor, a silicon controlled rectifier, or a switch-mode design can achieve the constant current output. A designer normally selects a constant current mode for applications where the current requirement is not expected to change but the anode or structure resistance will vary. An example of this application is a dock structure where the chloride ion concentration varies enough to affect the dock and anode resistances, but the current requirement is relatively constant.

The constant potential mode is really a constant structure potential mode of operation. In this mode of operation, the rectifier maintains the potential of the cathodically protected structure within specific limits. The power supply control circuit monitors the potential of the structure using a permanent reference cell. The control circuit compares this potential with internal set potential limits. When the structure potential is outside the set potential limits, the control circuit adjusts the rectifier output voltage until it is within the set limits. Either a silicon control rectifier or a switch-mode rectifier accomplishes the automatic output voltage adjustment necessary. An example of an application using this mode of operation is a coated, potable water storage tank. As the water level within the tank changes, the current requirement changes resulting in an automatic adjustment to the output voltage.

## *Experiment 2-1*
# Demonstrate the Use of a Galvanic Anode to Mitigate Corrosion in a Local-Action Cell
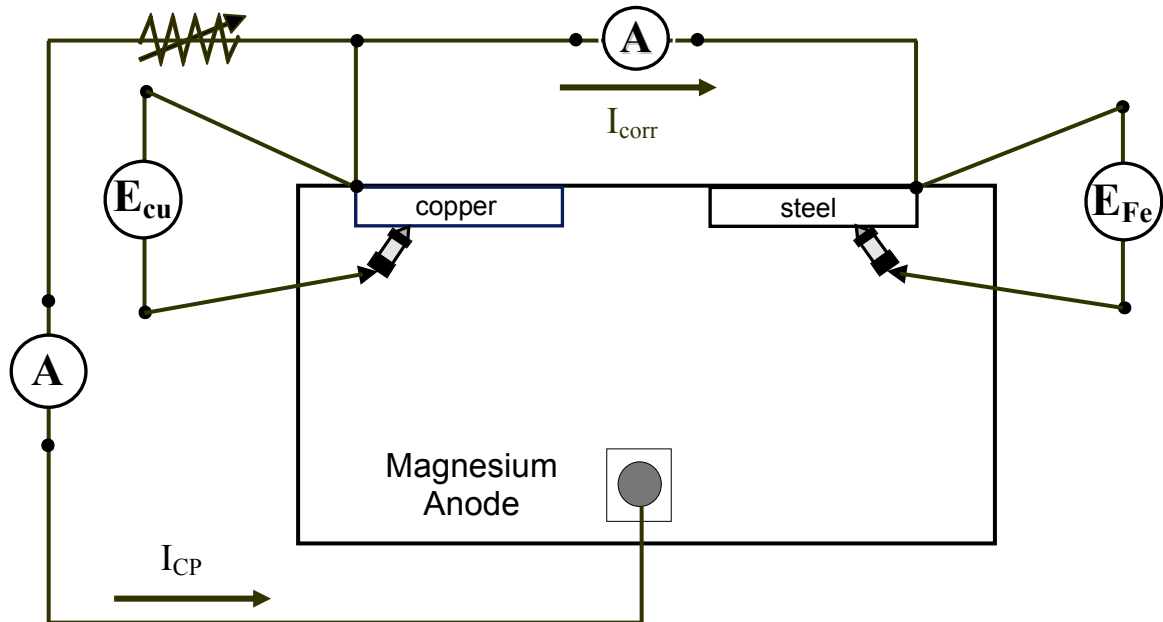


**Figure 2-34: Experiment to Demonstrate Corrosion Mitigation of Local-Action Cells by Galvanic Anode Cathodic Protection**

## PROCEDURE

**Part A**

1. This experiment is a continuation of Experiment 1-1 from Chapter 1. The copper and steel sheets should have been connected directly together through an ammeter at the conclusion of Experiment 1-1.

2. Using the data from Experiment 1-1, record the previously measured static potentials of the copper and steel in the following Results Table.

3. Record the polarized potential of the copper and steel and the corrosion current.

## Part B

1. Place the magnesium anode in the tray on the opposite side from the steel and copper sheets. Connect the magnesium anode to the copper sheet through an ammeter and a 10,000-ohm resistor.
2. After stabilization of current (approx. 1-2 min.). Measure the corrosion current ($I_{corr}$).
3. Measure the cathodic protection current ($I_{c,p}$).
4. Measure the polarized potentials of steel and copper with the reference cell in the same location as before.

## Part C

1. Repeat Part B using resistors listed in Results Table.

## Part D

1. Connect the magnesium anode directly through the ammeter to the copper sheet (zero resistance in series).
2. Allow the CP current to polarize the corrosion cell overnight.

## PART E

1. Measure the CP current first thing in the morning.
2. Measure pH at steel and copper surfaces (directly on surface) with CP current on.
3. Measure the polarized potentials of the steel and copper with the reference cell in the same location as before with CP current on.
4. Disconnect the magnesium anode and record the potentials over time as the steel and copper depolarize.
5. Note the condition of the steel and copper surfaces.

## RESULTS

| Circuit Conditions | $E_{steel}$ | $E_{copper}$ | Corrosion Current $I_{corr}$ (mA) | CP Current $I_{CP}$ (mA) |
|---|---|---|---|---|
| Static (OC) | | | | |
| Polarized | | | | |
| 10,000 ohms | | | | |
| 1,000 ohms | | | | |
| 800 ohms | | | | |
| 600 ohms | | | | |
| 400 ohms | | | | |

| | | | | |
|---|---|---|---|---|
| 200 ohms | | | | |
| 100 ohms | | | | |
| 10 ohms | | | | |
| 0 ohms | | | | |

**NEXT MORNING:** _____Hours with CP current on

| Circuit Conditions | $E_{steel}$ | $E_{copper}$ | CP Current $I_{CP}$ (mA) |
|---|---|---|---|
| Polarized Condition | | | |
| **After Disconnecting Magnesium Anode** | | | |
| **Time** | **$E_{steel}$** | **$E_{copper}$** | X |
| Instant Off | | | X |
| 15 seconds | | | X |
| 30 seconds | | | X |
| 1 minute | | | X |
| 5 minutes | | | X |
| 10 minutes | | | X |

## CONCLUSIONS

1. Corrosion current decreases as cathodic protection current increases.

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

3. Polarized potential of the structure shifts electronegatively with time.

4. Cathodic protection current decreases with time.

5. pH at the cathode increases with the application of CP and increasing time.

## 3.1 Introduction

In cathodic protection, the term *interference* refers to electrical interference as opposed to physical or chemical interference. Hence interference can be defined as any detectable electrical disturbance on a structure caused by a stray current. *Stray current* is defined as a current in an unintended path.

Many electrical systems rely on the earth as a conducting medium, either for the main transmission of electrical energy as with cathodic protection systems or as an electrical ground. Still other systems such as electrified transit systems may not be adequately isolated from ground. Regardless, any electrical system in contact with the earth is a possible source of stray currents. As illustrated in Figure 3-1, a current entering the earth at point A has many parallel paths available to point B.
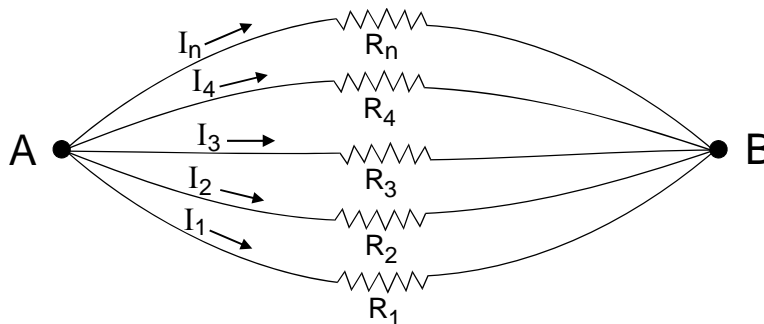


**Figure 3-1:  Parallel Current Paths in the Earth**

The amount of current in each path is inversely proportional to the resistance of each path. It can be argued therefore that current will take all available paths. If point A is considered an impressed current groundbed connected to the positive terminal of a transformer-rectifier and point B is a pipeline connected to the negative terminal, then the parallel current paths may all be similar in resistance in which case all the currents are the same. This is only possible in homogeneous soil where points A and B are far apart and the pipe has no lineal resistance.

However if the soil resistivity varies or the pipe has lineal resistance, then the current paths will have unequal resistances as illustrated in Figure 3-2.
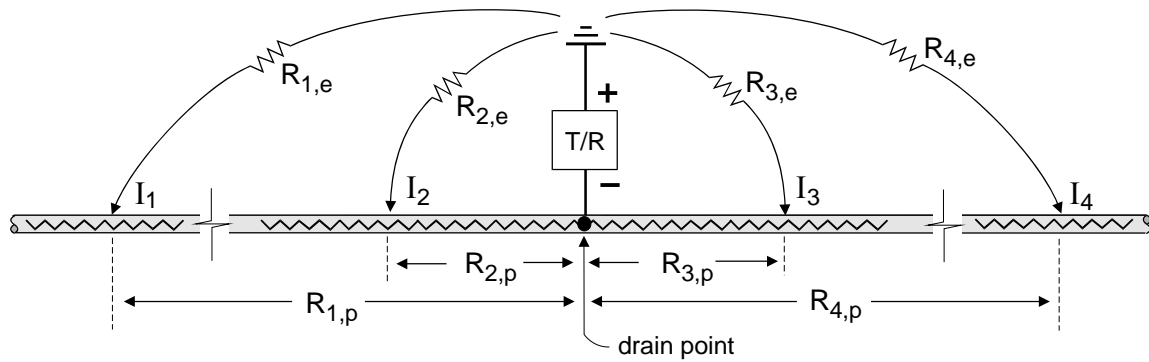
**Figure 3-2: Parallel Current Paths in a Pipeline Cathodic Protection System**

It is apparent that each current path is composed of resistance through the earth ($R_e$) plus a resistance through the pipe ($R_p$) from the point of current pick-up back to the drain point. Therefore the total resistance ($R_{t,i}$) of each parallel path is different and given by Equation 3-1.

$$R_i = R_{i,e} + R_{i,p}$$ [3-1]

Because the length of each current path is different, both in the earth and in the pipe in any direction away from the drain point, the total resistance of each current path will increase with distance from the drain point. The amount of current in each path is given by Equation 3-2

$$I_i = \frac{R_{t,n}}{R_i} I_t$$ [3-2]

*where:*

$$\frac{1}{R_{t,n}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \cdots \frac{1}{R_n}$$

*and:*

$$I_t = I_1 + I_2 + I_3 + I_4 \ldots I_n$$

In stratified soil conditions where the soil resistivity or cross-sectional area of each stratum is different, even current paths of equal length will not have equal resistances as illustrated in Figures 3-3 and 3-4.
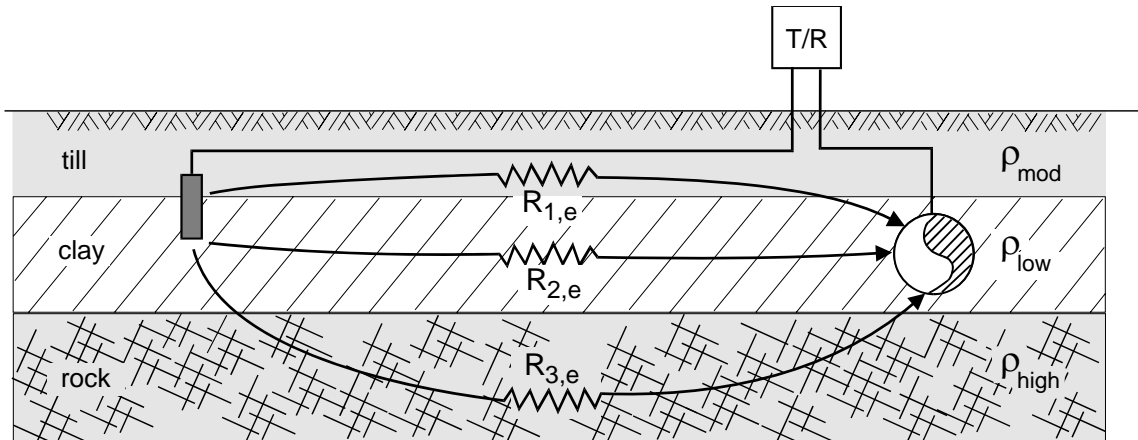
**Figure 3-3: Parallel Current Paths in Vertically Stratified Soil Conditions**
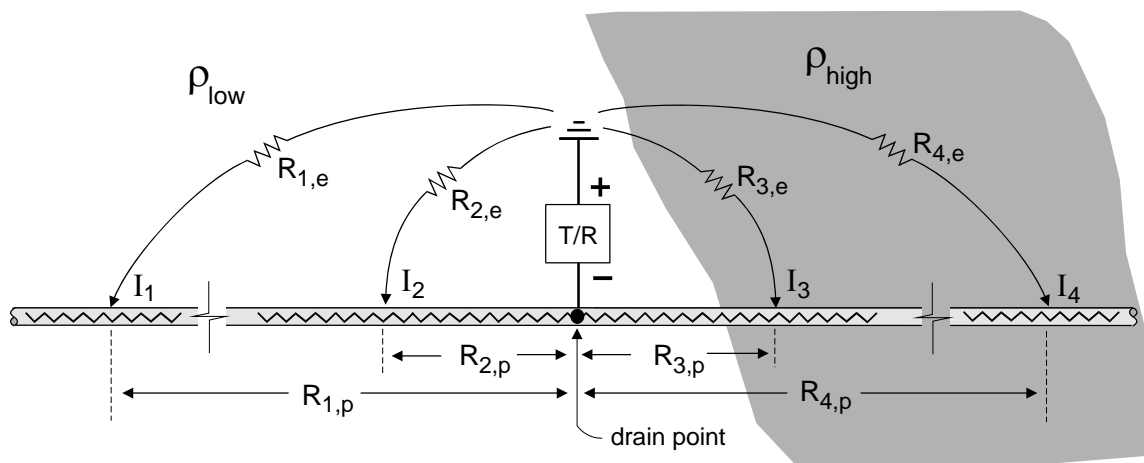


**Figure 3-4: Parallel Current Paths in Horizontally Stratified Soil Conditions**

It is more common than not for soil geology to be stratified both vertically and horizontally and for the current in the low resistivity soils to be proportionately greater than in the high or moderate resistivity soils. The stratification need not be caused by different soils but can be due to similar soils with different moisture content.

In the vertically stratified soils, the resistance of the current paths is not only a function of the soil resistivity but is also dependent on the cross-sectional area of the current path as in Equation 3-3.

$$R_{i,e} = \rho_s \frac{L}{A_{x,s}}$$                                       [3-3]

*where:*

$$R_{i,e} = \text{resistance of the current path (ohm)}$$
$$\rho_s = \text{resistivity of the soil}$$
$$L = \text{length of current path}$$
$$A_{x,s} = \text{cross-sectional area of soil path}$$

From a point source electrode like a cathodic protection groundbed, the cross-sectional area of the soil increases exponentially with distance from the electrode, and therefore the resistance of each current path is not linear with distance from the source.

Soil resistivities ($\rho_s$) are typically in the range of $10^3$ to $10^6$ $\Omega$-cm, whereas metal resistivities ($\rho_m$) are in the range of $10^{-5}$ to $10^{-6}$ $\Omega$-cm. Hence the ratio of metal/soil resistivity can range from:

$$\frac{\rho_m}{\rho_s} = \frac{10^{-5}}{10^3} \text{ to } \frac{10^{-6}}{10^6}$$

$$\frac{\rho_m}{\rho_s} = 10^{-8} \text{ to } 10^{-12}$$

Put in perspective, for high soil resistivity (e.g., $10^6$ ohm-cm) a metal object in the earth having a cross-sectional area of 100 cm$^2$ or $10^{-2}$ m$^2$ is equivalent in resistance to a cross section of soil given by Equation 3-4.

$$\frac{\rho_m}{\rho_s} = \frac{A_{x,m}}{A_{x,s}} \qquad\qquad [3\text{-}4]$$

*substituting:*
$$\frac{\rho_m}{\rho_s} = 10^{-12}$$

*then:*
$$A_{x,s} = \frac{A_{x,m}}{10^{-12}}$$

$$A_{x,s} = \frac{10^{-2}}{10^{-12}} = 10^{10} \text{ m}^2$$

That is, a metal conductor having a 0.01 m$^2$ cross-sectional area is equal to a soil cross-sectional area of $10^{10}$ m$^2$ if the soil resistivity is $10^6$ $\Omega$-cm. This means that

when a metallic structure is present in the earth, it can be a very attractive current path thus resulting in a stray current ($I_s$) in the metallic structure as illustrated in Figure 3-5.
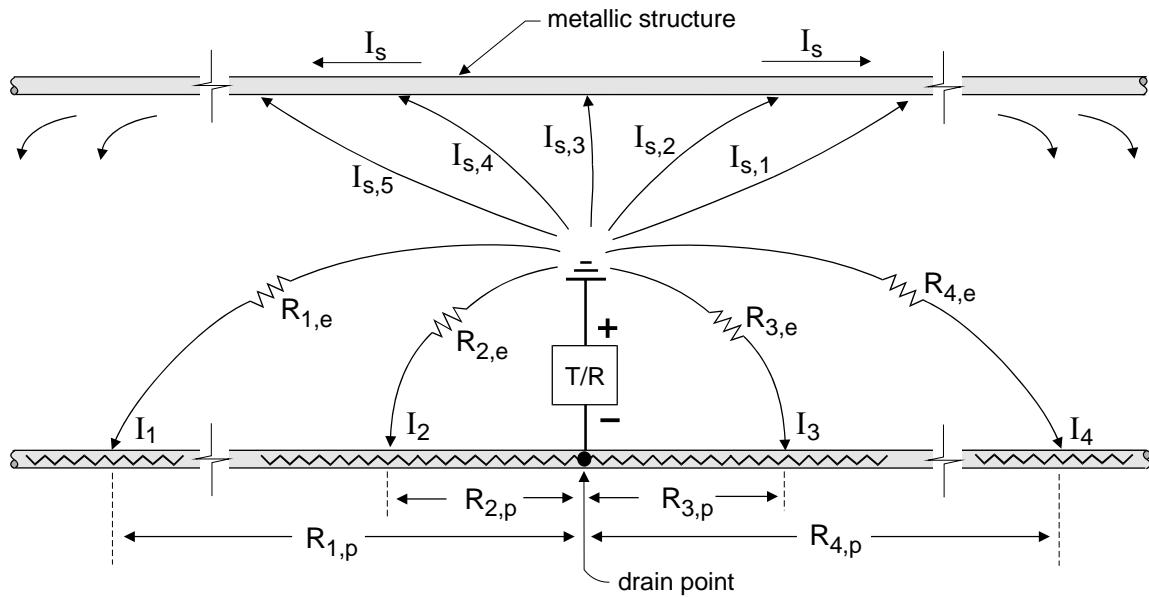


**Figure 3-5:  Stray Current in a Metallic Structure Parallel to a Cathodically Protected Structure**

The stray current is picked up on the foreign metallic structure where it is being impacted by the groundbed anodic voltage gradient. If there is no direct electronic path between the foreign structure and the pipeline, the current will discharge from the metallic structure remote from the pick-up area.

The amount of stray current in the metallic structure is a function of the resistance of the stray current paths and the driving voltage left at the location where the foreign metallic structure intersects the anodic voltage gradient.

Currents from a single electrode, placed vertically in the earth, produce a voltage drop in the soil near the electrode forming equipotential surfaces perpendicular to the current paths as illustrated in Figure 3-6.
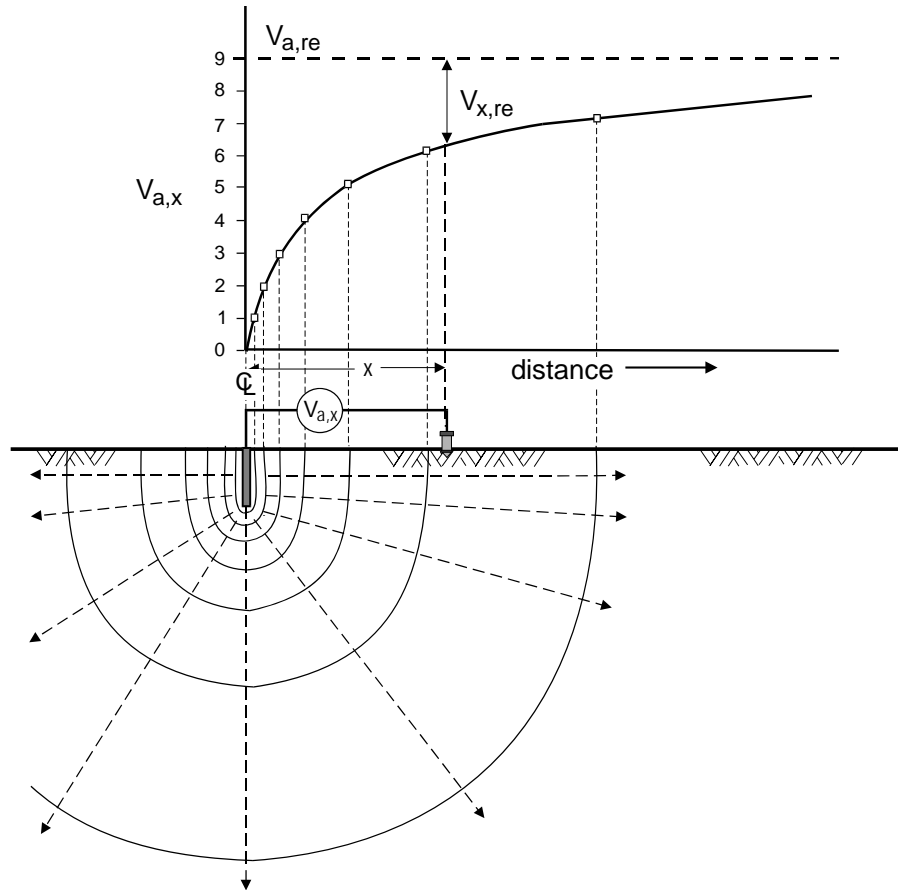
**Figure 3-6:  Voltage vs. Distance from a Vertically Oriented Anode**

An equipotential surface has the same voltage difference between the anode and any place on its surface. Projection of each equipotential surface at grade and denoting its voltage and distance produces the voltage drop ($V_{a,x}$) profile in the earth with distance from the anode, as illustrated.

The voltage rise ($V_{x,re}$) in the earth with respect to remote earth can be calculated using Equation 3-5.

$$V_{x,re} \;=\; \frac{I\rho_s}{2\pi L}\left[\ln\left(\frac{L + \sqrt{L^2 + x^2}}{x}\right)\right] \qquad\qquad [3\text{-}5]$$

*where:*

$V_{x,re}$ = voltage rise in earth with respect to remote earth at a distance (x) from the anode

I = anode current output (A)

$\rho_s$ = soil resistivity

L  =  length of anode

For example, for a 10 m long anode in 3000 Ω-cm soil having an output of 10A, the voltage rise at 100 m is:

$$V_{x,re} = \frac{10\,A \times 30\ \Omega\text{-}m}{2\pi 10\,m}\left[\ln\left(\frac{10\ m + \sqrt{(10\,m)^2 + (100\,m)^2}}{100\,m}\right)\right]$$

$$= 4.77\left[\ln\left(\frac{10\,m + 100.5\,m}{100\,m}\right)\right]$$

$$= 4.77\,[\ln 1.105]$$
$$V_{x,re} = 4.77\,[0.1]$$
$$= 0.48\ V$$

If a metallic structure was present 100 m from this anode, it would be subjected to about 0.5 V between that point and remote earth. This is the driving voltage that would produce a stray current in the structure.

A similar voltage drop occurs in the earth around a bare pipeline as indicated in Figure 3-7.
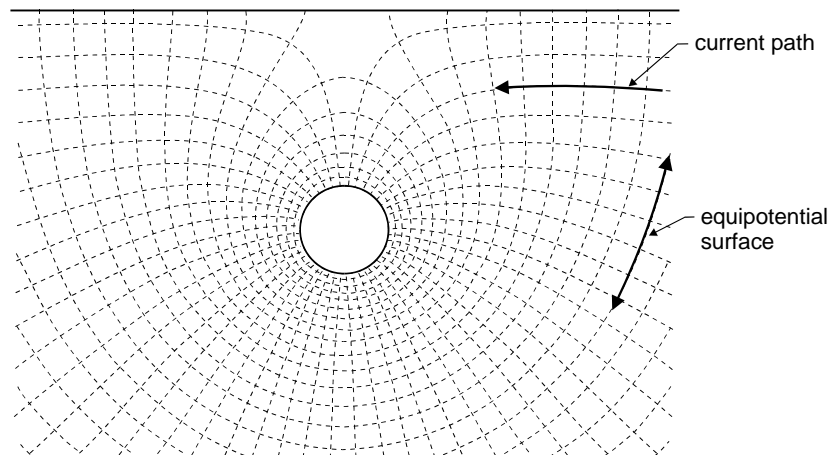


**Figure 3-7:  Voltage Gradient in the Earth around a Cathodically Protected Bare Pipeline**

The typical cathodic protection circuit can then be modeled as a series circuit shown in Figure 3-8.
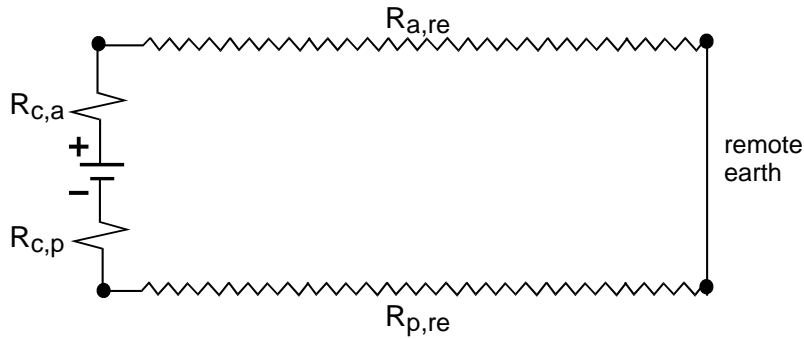


*where:*

$R_{c,a}$ & $R_{c,p}$ = cable resistances

$R_{a,re}$ = anode resistance to remote earth

$R_{p,re}$ = pipe resistance to remote earth

**Figure 3-8:  Cathodic Protection Circuit Model**

If a metallic structure is located in the earth as shown in Figure 3-5, it will intercept the anode voltage gradient such that there will be a parallel path inserted into the model as illustrated in Figure 3-9.
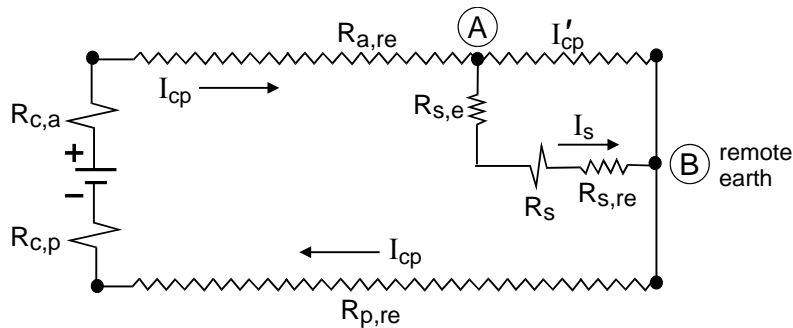


*where:*

$R_{c,a}$ & $R_{c,p}$ = cable resistances

$R_{a,re}$ = anode resistance to remote earth

$R_{p,re}$ = pipe resistance to remote earth

$R_{s,e}$ = resistance of foreign pipe to earth in a stray current pick-up area

$R_{s,re}$ = foreign structure resistance to remote earth

$R_s$ = longitudinal resistance of foreign structure between pick-up and discharge sites

**Figure 3-9:  Cathodic Protection Circuit Model with Foreign Structure Intercepting the Anode Gradient**

The presence of the foreign structure has introduced a parallel circuit into the model where the voltage drop between point A and remote earth is applied to the foreign structure. This will lower the overall resistance of the anode to remote earth and diminish the cathodic protection current beyond point A to $I'_{cp}$ by the amount of $I_s$.

If the foreign structure also crosses the pipeline, as shown in Figure 3-10, then the foreign structure resistance to the pipeline will be lowered because of the close proximity of the two pipelines at the crossing. This would result in a larger stray current because the driving voltage between A and B will be greater (per Figure 3-11).
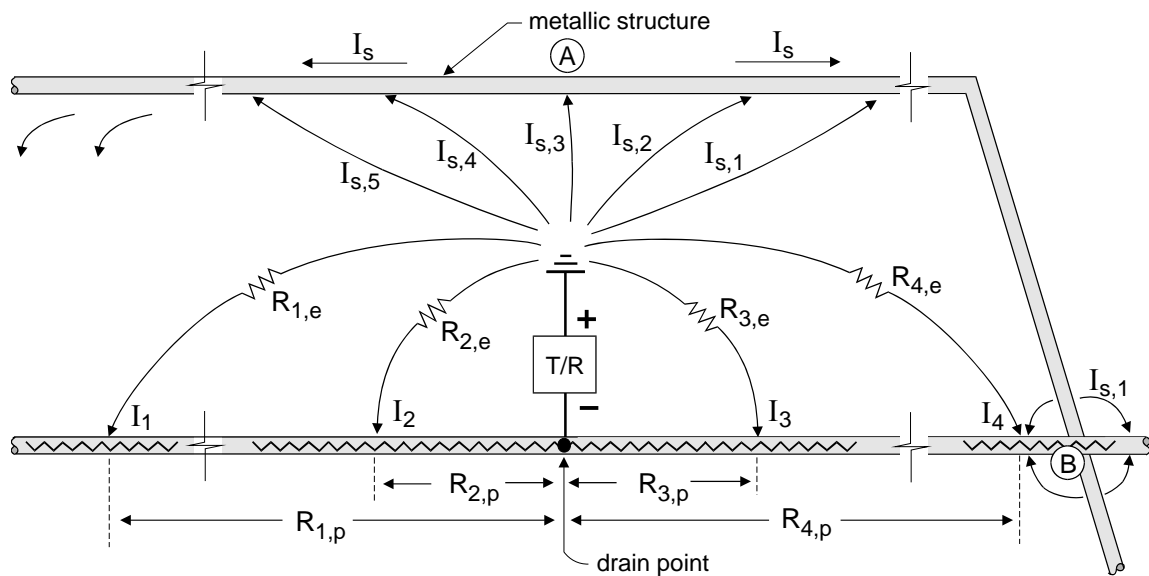


**Figure 3-10:  Stray Current in a Foreign Metallic Structure that Intercepts
both the Anodic and Cathodic Voltage Gradient**

*where:*

$R_{c,a}$ & $R_{c,p}$ = cable resistances

$R_{a,re}$ = anode resistance to remote earth

$R_{p,re}$ = pipe resistance to remote earth

$R_{s,e}$ = resistance of foreign pipe to earth in a stray current pick-up area
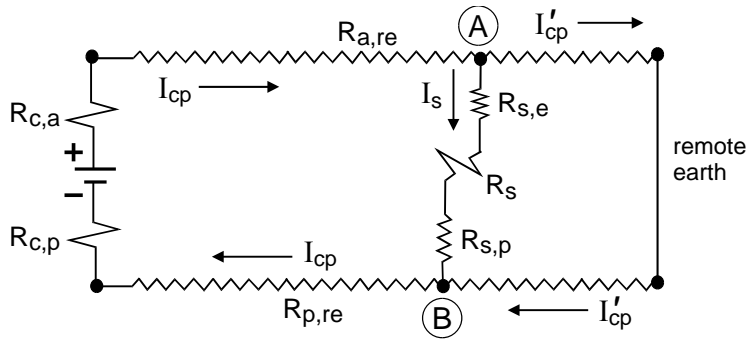
$R_{s,p}$ = resistance of foreign pipe to cathodically protected pipe at discharge area

$R_s$ = longitudinal resistance of foreign structure between pick-up and discharge sites

**Figure 3-11: Cathodic Protection Circuit Model with Foreign Structure Intercepting both Anodic and Cathodic Voltage Gradient**

A metallic foreign structure can also be subject to a stray current even if it only intersects the cathodic voltage gradient as illustrated in Figures 3-12 and 3-13.
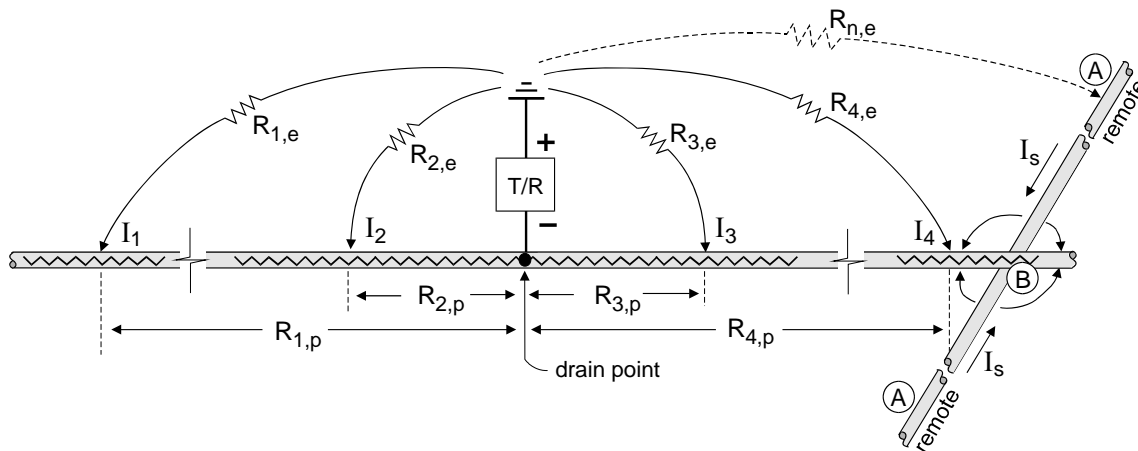


**Figure 3-12: Stray Current in a Foreign Metallic Structure that Intercepts the Cathodic Protection Gradient**

In this situation the affected pipeline picks up stray current at remote earth A and transports it to the crossing where it discharges back to the interfering structure. This means that any pipeline protected by impressed current systems can cause interference on crossing metallic structures that are otherwise remote from the impressed current groundbeds. Also, the stray current discharge need not be to the

interfering structure but rather to a third party structure acting as an intermediate current path.
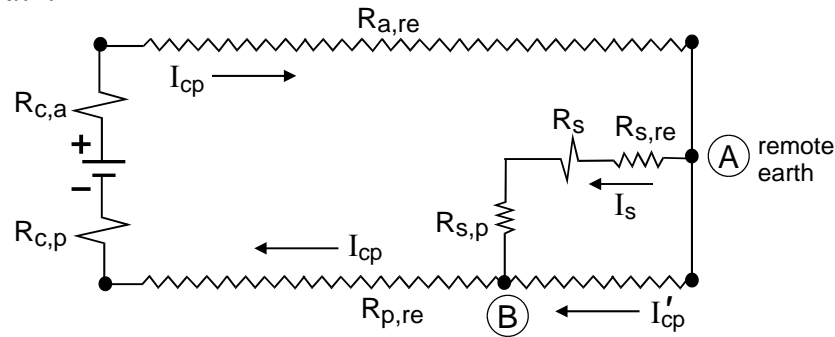


*where:*

$R_{c,a}$ & $R_{c,p}$ = cable resistances

$R_{a,re}$ = anode resistance to remote earth

$R_{p,re}$ = pipe resistance to remote earth

$R_{s,re}$ = foreign structure resistance to remote earth

$R_{s,p}$ = foreign structure resistance to cathodically protected structure at stray current discharge location

$R_s$ = longitudinal resistance of foreign pipe between remote earth and discharge location

**Figure 3-13: Cathodic Protection Circuit Model for Foreign Structure Intercepting the Cathodic Voltage Gradient**

As demonstrated, a stray current can occur in a foreign metallic structure if it is impacted by either the anodic or cathodic voltage gradient produced by a pipeline impressed current system. The magnitude of the stray current is directly proportional to the voltage between the current pick-up and discharge location and inversely proportional to the resistance of the interference current path.

## 3.2  Detecting Stray Current

There will be potential and current changes on and near a metallic structure due to any stray current. These electrical disturbances are as follows:

- structure-to-soil potential changes at both stray current pick-up and discharge locations
- current changes in the structure between the current pick-up and discharge locations
- current changes in the earth near the structure at the current pick-up and discharge locations.

If the output of the transformer-rectifier shown in Figure 3-10 is cyclically interrupted and a close interval potential survey is conducted over the foreign structure from left to right, the potential profile as illustrated in Figure 3-14 would be typical.
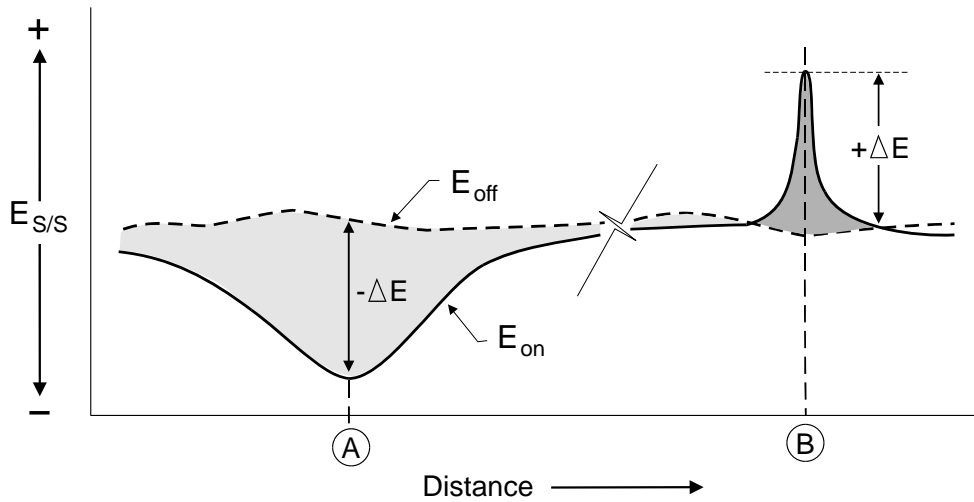


**Figure 3-14: Typical Potential Profile on an Interfered-with Structure that Intersects both Anodic and Cathodic Voltage Gradient with the Current Source Interrupted**

Point A is the location on the structure immediately opposite the groundbed location and point B is at the pipeline crossing. When the current source is on there is a negative shift at the pick-up region (point A) and a positive shift at the discharge location (point B).

Detection of current magnitude changes involved in the stray current situation in Figures 3-5, 3-10, and 3-12 are illustrated in Figure 3-15.



$$\textit{where:} \quad \Delta V_e = I_s R_e$$
$$\Delta V_{st} = I_s R_{s,1}$$
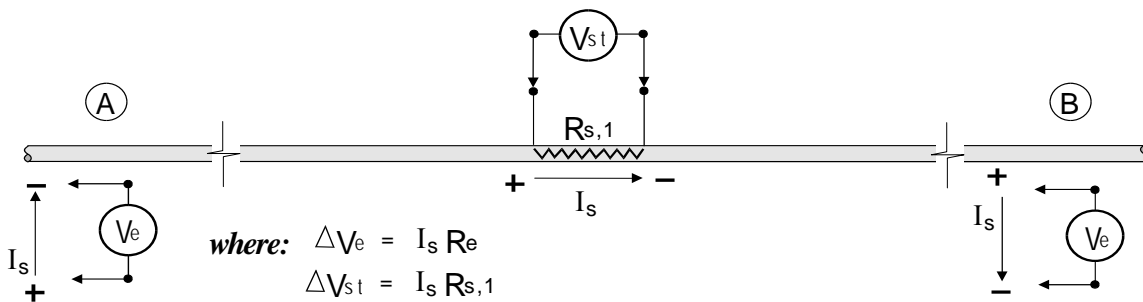
**Figure 3-15: Current Changes In and Near an Interfered-with Structure**

Current changes are detected by measuring the voltage drop in the earth adjacent to the interfered-with structure and over a length of the structure with the stray current source cyclically interrupted. Therefore there is a change in the earth

voltage drop ($V_{e,g}$) at both A and B due to the stray current $I_s$. At A $\Delta V_{e,g}$ will be positive since the stray current is toward the structure, and at B it will be negative indicating a current away from the structure. The change in structure voltage drop will be in the positive direction for the meter polarity shown.

## *3.2.1  Effects of Stray Current on Metallic Structures*

The effects of stray current on metallic structures as illustrated in Figure 3-10 can be harmful, beneficial, or innocuous depending on the magnitude of the current density, type of structure, and location of current pick-up and discharge areas.

### 3.2.1(a)  At Area of Current Pick-Up

At the area of current pick-up, a negative shift will result in cathodic polarization, and if the foreign structure is mild steel then there is a beneficial effect as the structure is receiving some measure of cathodic protection. If the structure is coated and has its own cathodic protection system, the additional polarization from the stray current pick-up may result in cathodic blistering of the coating.

If the foreign structure is not mild steel but is made of an amphoteric metal such as aluminum, lead, or zinc, then the high pH developed at the structure/earth interface due to the reduction reaction can cause "cathodic" corrosion. Amphoteric metals are susceptible to corrosion at both high and low pH as shown in Figure 3-16 for aluminum and zinc.
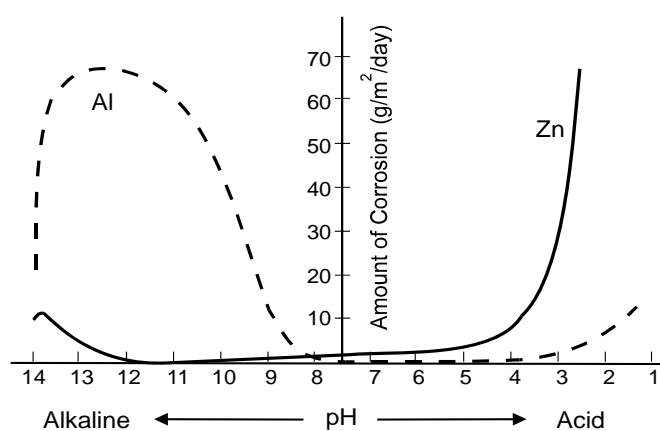


**Figure 3-16:  Comparison of Zn and Al  for Corrosion Resistance as Functions of pH**

Aluminum is particularly sensitive to high pH attack. It is often used underground for water irrigation systems, gas distribution piping in rural areas, AC secondary

distribution conductors, and the sheathing on communication cables. Lead sheathing was commonly used on below ground AC power cables.

Prestressed concrete cylinder pipe (PCCP) used for both water and sewage transmission is composed of a mild steel inner cylinder over which a highly stressed steel wire is wound to give the concrete/steel cylinder strength. Typical cross sections of the two types of PCCP pipe are shown in Figures 3-17a and 3-17b.
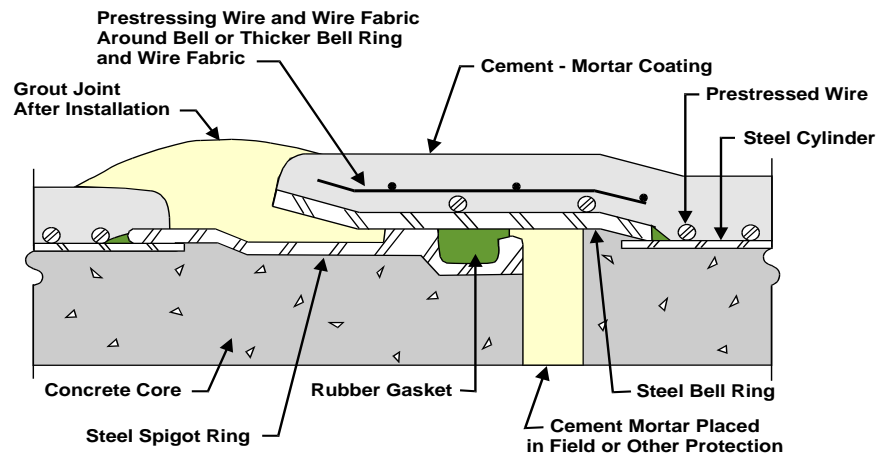
**a. Lined Cylinder Pipe**
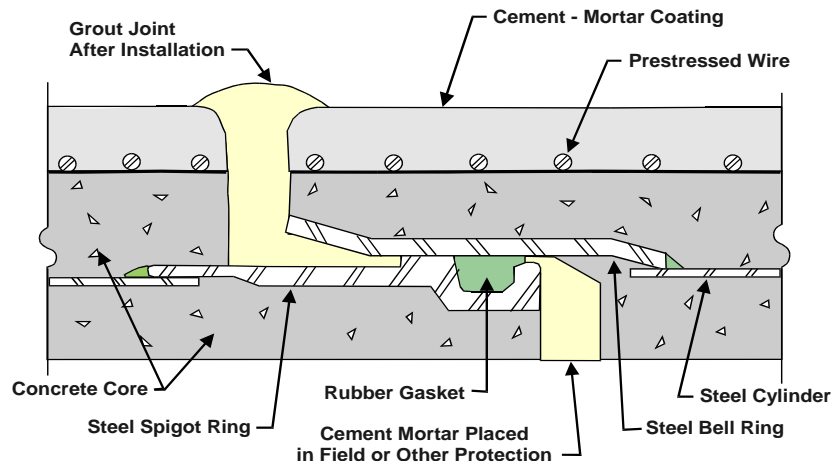
**b. Embedded Cylinder Pipe**

**Figure 3-17:  Typical Section through a Joint in Two Types of PCCP Pipe**
Source: Prestressed Concrete Pressure Pipe-Steel Cylinder Type for Water and Other Liquids, AWWA Standard C301, American Water Works Association, Denver, CO

The prestressing wire in these pipes is normally cold drawn steel with a yield strength in the order of 200 ksi. The cold-worked hardened surface of the wire

makes it susceptible to hydrogen embrittlement. It is recommended that the polarized potential be limited to –970 mV$_{cse}$ or less negative to minimize the production of atomic hydrogen. If a stray current causes excessive cathodic polarization, a catastrophic failure could occur.

If the foreign structure is coated at the stray current pick-up site, then coating blistering or disbondment can occur. Coating blistering is caused by the pressure buildup beneath the coating due to the electro-osmotic movement of water through the coating (Figure 3-18). The high pH produced by the reduction reaction at the metal surface can attack the coating adhesion bonds or a surface oxide layer resulting in coating disbondment.
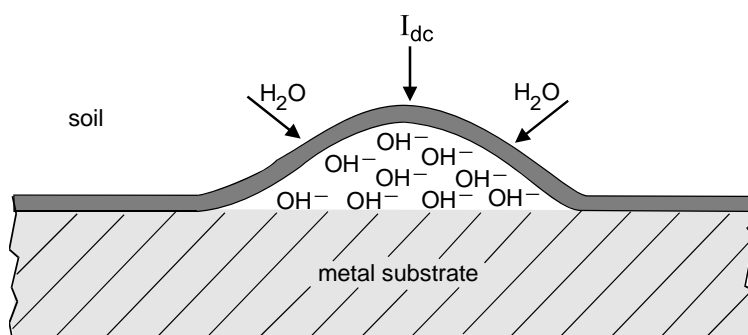


**Figure 3-18:  Cathodic Blistering/Disbondment of Protective Coating**

## 3.2.1(b)  Along the Structure

Stray current in a metallic structure does not usually cause damage between the stray current pick-up and discharge locations unless the current is very large or the structure is not electrically continuous. If the structure is electrically discontinuous, such as is often the case with cast iron water distribution piping or PCCP transmission piping, the structure resistance ($R_s$) is greater than if it were electrically continuous. This reduces the magnitude of $I_s$, but creates a current discharge/current pick-up pattern at each electrical discontinuity as illustrated in Figure 3-19a and 3-19b.

In many of these structures not every joint is discontinuous, but localized corrosion will occur on the discharge side of the discontinuous joints. On water and sewer piping, there is not only a soil path for the stray current but also an internal path through the aqueous medium as illustrated in Figure 3-19b.
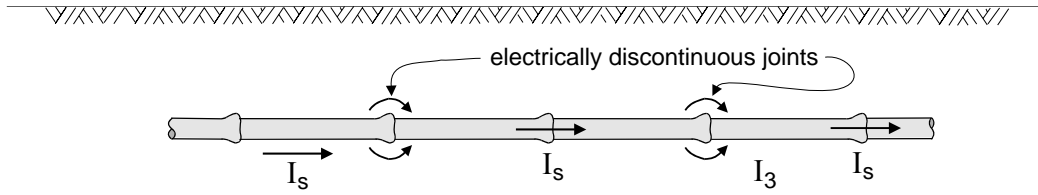
**Figure 3-19a: Stray Current Discharge and Pick-Up Around an Electrically Discontinuous Joint Through the Earth**
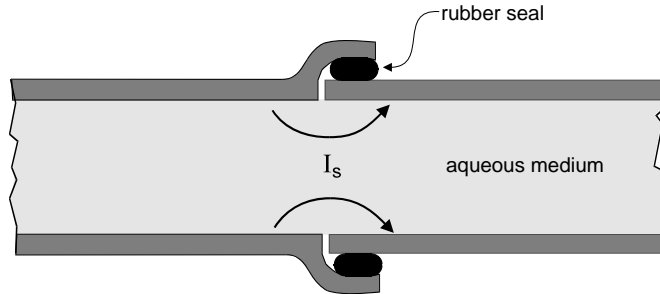


**Figure 3-19b: Stray Current Discharge and Pick-Up Through the Internal Aqueous Medium Around an Electrically Discontinuous Bell and Spigot Joint on Cast Iron Piping**

Current in an AC distribution system can also affect the transformation characteristics in distribution transformers. At the AC distribution transformer which supplies the AC service for an impressed current transformer-rectifier, a ground cable is normally run from the AC neutral to a ground rod at the base of the service pole. The ground rod, being relatively close to the groundbed, will pick up stray current which will be carried by the distribution neutral and the AC phase conductor to ground at remote transformers since DC does not see a high resistance through the primary winding. This circuit is illustrated schematically in Figure 3-20.
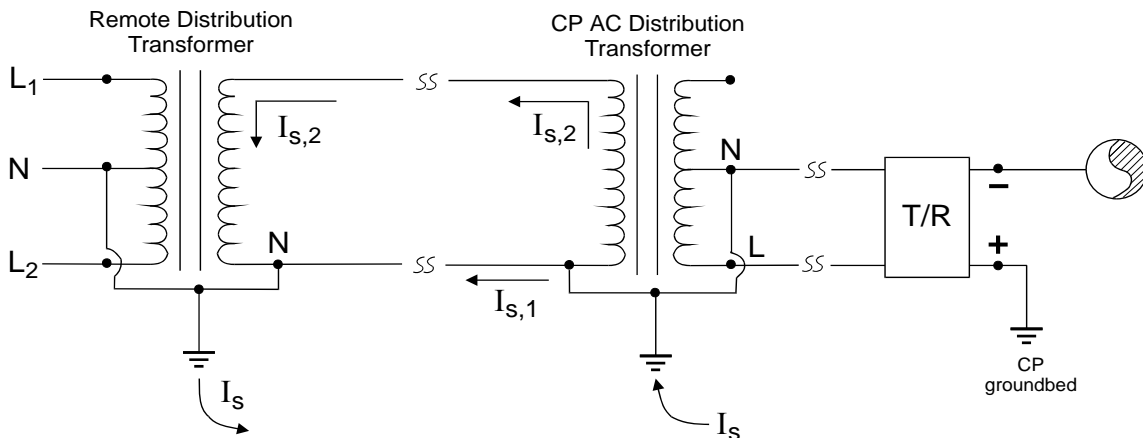


**Figure 3-20: Stray Current Circuit in an AC Electrical Distribution System**

A DC current in the primary or secondary windings of a transformer will produce a magnetic flux in the transformer core that will tend to saturate the core and thus spoil its voltage transformation properties. This is a harmful effect in addition to the corrosion damage that results from the stray current discharging off the ground rod at the remote distribution transformer.

## 3.2.1(c)  Effects at the Stray Current Discharge Location

Considerable attention is given to identifying the site of current discharge in stray current investigations because this is where corrosion damage is most likely to occur on all metallic structures. When a current transfers from a metallic structure to earth, as depicted in Figure 3-21, it must do so via an oxidation reaction which converts electronic current to ionic current.
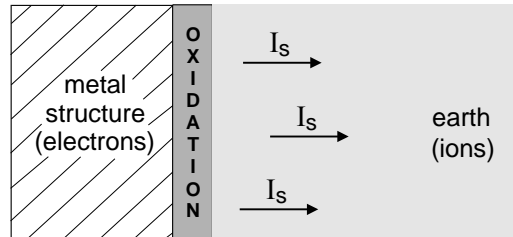


**Figure 3-21:  Current Discharge from a Metal Structure to Earth via an Oxidation Reaction**

The generic oxidation reaction is the corrosion of the metal as in Equation 3-6.

$$M^o \ \rightarrow \ M^{n+} + \ ne^- \qquad\qquad \text{[3-6]}$$

For steel, the oxidation reaction is

$$Fe^o \ \rightarrow \ Fe^{++} + \ 2e^- \qquad\qquad \text{[3-7]}$$

Stray current discharge from a metallic structure may not cause corrosion attack if the structure is receiving cathodic protection as in Figure 3-22.
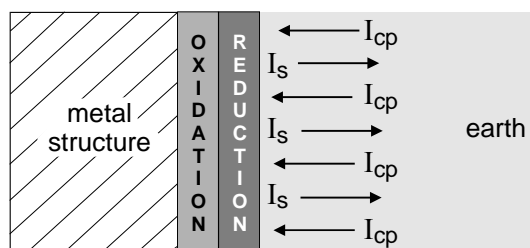
**Figure 3-22:  Current Discharge from a Cathodically Protected Metal Structure to
Earth via an Oxidation Reaction**

Cathodic protection current transfers across the metal/earth interface via a reduction reaction that produces hydroxyl ions in either of the two following reactions:

$$O_2 + 2H_2O + 4e^- \;\rightarrow\; 4OH^- \tag{3-8}$$

$$2H_2O + 4e^- \;\rightarrow\; H_2\!\uparrow + 2OH^- \tag{3-9}$$

In the presence of a high concentration of hydroxyl ions a possible oxidation reaction is given in Equation 3-10 involving the oxidation of hydroxyl ions to oxygen and water.

$$4OH^- \;\rightarrow\; O_2 + 2H_2O + 4e^- \tag{3-10}$$
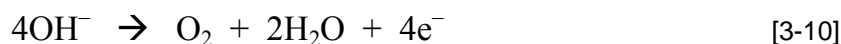
This latter reaction does not consume metal atoms and therefore there is no corrosion damage. Hence as long as the polarized potential at the structure/electrolyte interface is not driven more electropositive than the cathodic protection criterion (e.g., $-850$ mV$_{cse}$), then corrosion would not be expected.

If the metal has a surface passive film or is a relatively inert material, as are some of the impressed current anode materials, not all the stray current need transfer through a corrosion reaction. If the stray current polarizes the metal surface electropositively to the oxygen line on the Pourbaix diagram, hydrolysis[1] of water molecules by the reaction in Equation 3-11 is likely.

$$2H_2O \;\rightarrow\; 4H^+ + O_2\!\uparrow + 4e^- \tag{3-11}$$

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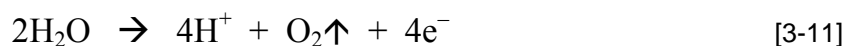
[1] Hydrolysis *is defined as a double decomposition reaction involving the splitting of water into its ions and the formation of a weak acid or base or both.  CRC Handbook of Chemistry and Physics, CRC Press, 53$^{rd}$ Edition, 1972-1973, PF-83.*

This oxidation reaction does not result in the consumption of the metal surface, but it does produce an acidic pH because of the generation of hydrogen ions.


### 3.2.2    Mitigation of Interference Effects from Impressed Current Cathodic Protection Systems

A number of methods can be used to lessen the harmful effects of cathodic protection system stray currents, as listed below:

- Remove the source or reduce its output.
- Install electrical isolating fittings in the interfered-with structure.
- Bury a metallic shield parallel to the interfered-with structure at the stray current pick-up zone.
- Install additional cathodic protection at current discharge locations on the interfered-with structure.
- Install a bond between the interfered-with and interfering structure.
- Apply a coating to the interfered-with structure in the area of stray current pick-up or to the interfering structure where it picks up the returning stray current.

Before any mitigation activity can begin, conduct mutual interference tests where the output of the suspected source is cyclically interrupted and field measurements are taken in the presence of representatives of the interfering and interfered-with companies involved. Interference cases are often reported through local electrolysis committees, especially where there may be more than one interfered-with party.

Presuming a need for mitigation is determined, the mutually acceptable mitigation technique(s) depend on the location and severity of the interference, on the cathodic protection operational preferences of each party, and on the relative capital and maintenance costs of the mitigation options.


### 3.2.2(a)   Source Removal or Output Reduction

It is a difficult proposition to have a source removed if the interfering system was present before the interfered-with structure was installed. However, in the opposite situation, where the interfering source is newly installed, this method has greater appeal.

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If the interference is caused primarily by the proximity of the interfered-with structure to the interfering groundbed, it may not be necessary to remove the transformer-rectifier but simply relocate the groundbed or reduce the current output.

Equation 3-5 or similar equations[2] can be used to estimate how remote a particular groundbed needs to be from a foreign structure to minimize the interference effects.

It should be noted however that the voltage rise at any point distance $x$ from the groundbed is a percentage of the total voltage drop to remote earth ($V_{x,re}/V_{gb,re} \times 100$). It is a function only of the geometry of the groundbed (i.e., its length, L) since the groundbed current output and soil resistivity would not change. Therefore, only the length parameter in the equation significantly affects the percentage.

Reducing the current output of the source is also a viable option as long as there are safeguards to prevent the output from being raised inadvertently.

### 3.2.2(b)   Installation of Isolating Fittings

Installation of isolating fittings as a stray current mitigation measure is an attempt to increase the path resistance ($R_s$) of the interfered-with structure thus decreasing the stray current ($I_s$). This is seldom adequate as a standalone method.

The stray current will certainly be reduced but the lesser amount of stray current will bypass each isolating fitting in the soil path thus creating several points of interference as previously shown in Figure 3-19a. Consequently, additional cathodic protection may be needed at each isolating joint to compensate for the residual stray current.

The installation of isolating fittings to electrically sectionalize piping systems as illustrated in Figure 3-23 is a common practice.

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[2] *Von Baekmann, Schwenk, and Prinz, Cathodic Corrosion Protection, 3rd Edition Gulf Publishing, 1997, p.538-539.*
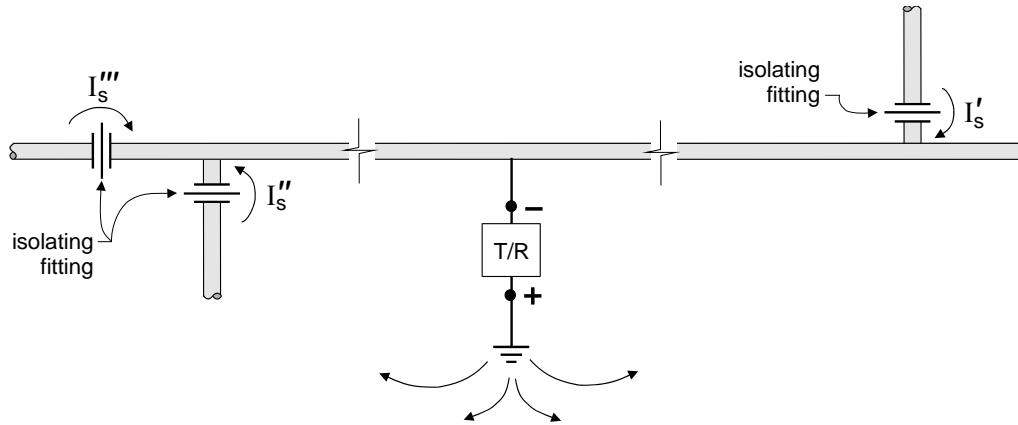
**Figure 3-23: Stray Current Arising from Installation of Isolating Fittings**

Unfortunately, inserting electrical isolation often produces a stray current condition at the isolating fitting. Therefore, on piping networks protected with impressed current systems, electrical isolation should be used sparingly and, when used, facilities to mitigate the expected interference should be provided at each point of electrical isolation.

## 3.2.2(c)   Burying a Metallic Shield Next to the Affected Structure

The intent of a buried metallic conductor is to intercept the stray current and thus provide an alternative low resistance path for the stray current compared to the metallic structure path. Connecting the metallic shield, which could be a bare cable or pipe, directly to the negative terminal of the offending transformer-rectifier, as shown in Figure 3-24 and modeled in Figure 3-25, would be more effective than connecting it to the interfered-with structure.
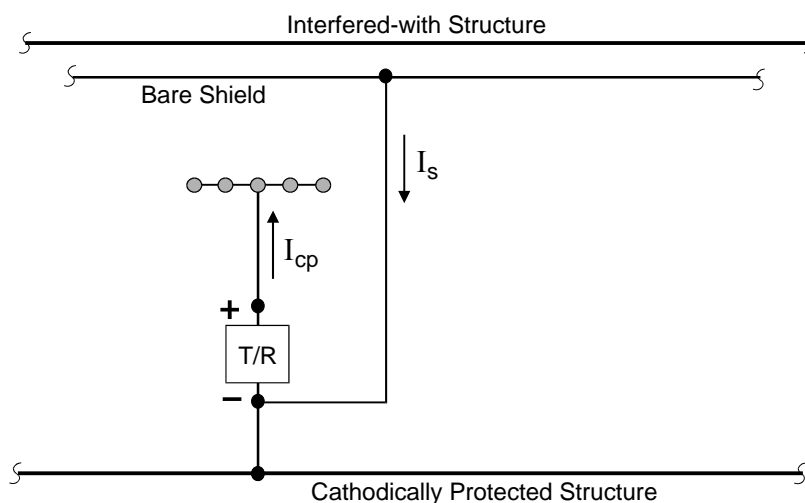


**Figure 3-24: Using a Buried Metallic Cable or Pipe as a Shield to Reduce Stray Current Interference**
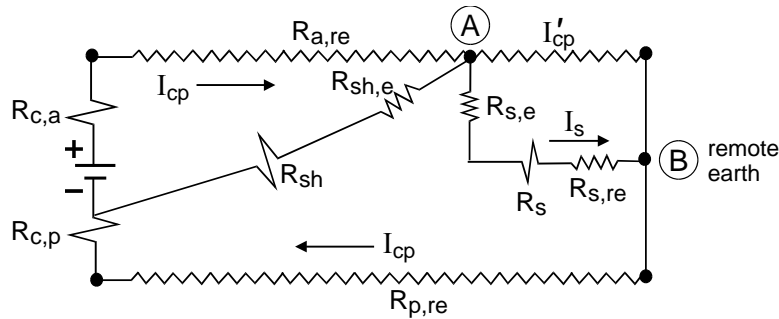
*where:*

$R_{c,a}$ & $R_{c,p}$ = cable resistances

$R_{sh,e}$ = shield resistance to earth

$R_{sh}$ = shield cable longitudinal resistance

**Figure 3-25:  Cathodic Protection Current Model for a Buried Metallic Shield Connected to the Negative Terminal of the Transformer-Rectifier**

The alternative approach, which would be to connect the buried metallic shield to the interfered-with structure, would increase the stray current discharge at point B.

This buried metallic shield method has the most merit where the interfered-with structure is either made of an amphoteric material or where there is a concern about coating blistering or cathodic disbondment.

This technique puts the interfering system at a considerable disadvantage. It can seriously disrupt the current distribution pattern to the cathodically protected structure, perhaps even necessitating the installation of additional cathodic protection units to make up for the poorer current distribution.

### 3.2.2(d)  Installation of Galvanic Anodes on the Interfered-with Structure at Point of Stray Current Discharge

When the area of stray current discharge is very localized, such as at a crossing with the interfering structure and where the total stray current ($I_s$) is typically less than an ampere, the installation of galvanic anodes as depicted in Figure 3-26 has considerable benefit.

With the anodes placed alongside the interfering structure, the resistance through the anodes (Rp,g) is minimized and hence the stray current(Is') in this path is maximized. Unfortunately, the galvanic anodes may also more closely couple the interfering structure's cathodic potential gradient, thus increasing the magnitude of the interference current. The anodes can also be arranged parallel with the

interfered-with structure which minimizes the anode circuit resistance and therefore maximizes the cathodic protection current (Icp.g) Less coupling between the anodes and interfering structure also results with this arrangement.
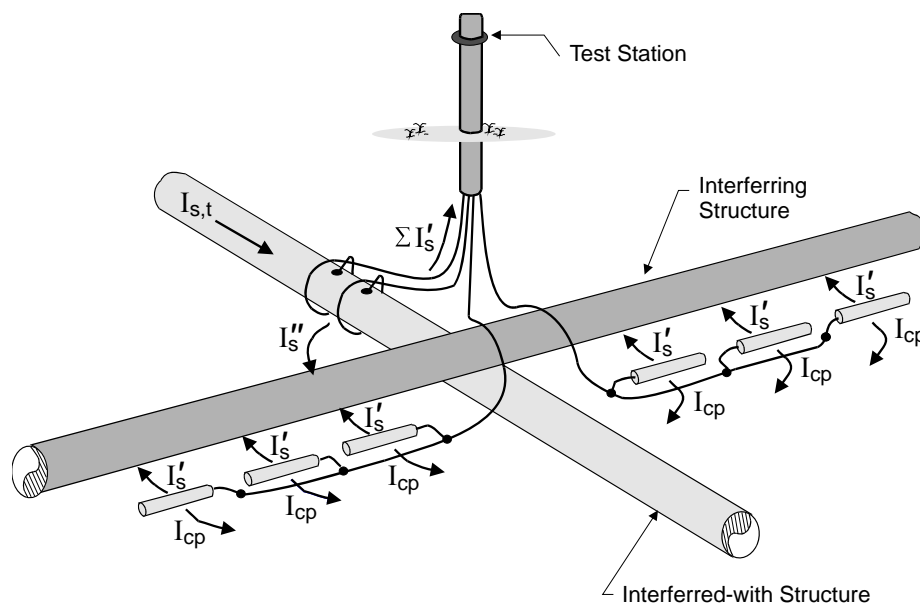


**Figure 3-26:  Interference Mitigation using Galvanic Anodes at Stray Current Discharge Location**

If the interfered-with structure is coated at the crossing, the path resistance ($R_{a,p}$) through the galvanic anodes will be substantially less than the interfered-with structure resistance ($R_{s1,p}$) (depicted in the electrical circuit model in Figure 3-27). Although there can still be a residual stray current ($I_s''$), the total cathodic protection current ($\Sigma I_{cp}$) is expected to be greater, thus assuring total remediation of the interference.
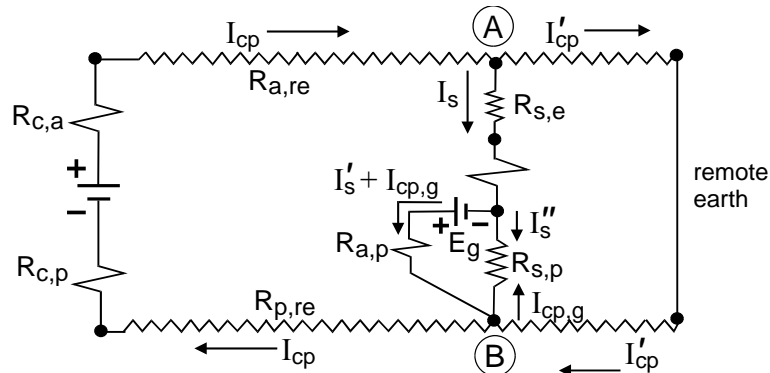
**Figure 3-27: Electrical Circuit Model for Mitigating Stray Current Interference at a Stray Current Discharge Site Using Galvanic Anodes**

Ideally, the galvanic anodes are distributed alongside the interfering structure to minimize the path resistance ($R_{a,p}$) so the stray current ($I'_s$) is a large percentage of the total stray current ($I_{s,t}$). The design life of the galvanic anodes must take into account the additional consumption by the stray current ($I'_s$) component of its total output.

There are several advantages of this method as follows:

- The interfered-with structure can maintain cathodic protection independence.
- The galvanic anode cathodic protection current output boosts the level of protection at the crossing as an added buffer should the interference current ($I_{s,t}$) increase.
- Maintenance requirements are low compared to a direct bond.

The disadvantages are that it is relatively expensive compared to a direct bond, and the interference current mitigation capacity is somewhat limited. To mitigate large interference currents an impressed current system can be used with the drain point at the crossing but the groundbed remote from both piping systems.

### 3.2.2(e)   Installation of an Impressed Current Distribution System on the Affected Structure at Point of Stray Current Discharge

The stray current situation depicted in Figure 3-5 results in a typical potential profile along the interfered-with structure where the stray current discharge ($+\Delta E$) occurs in an end-wise fashion as illustrated in Figure 3-28.
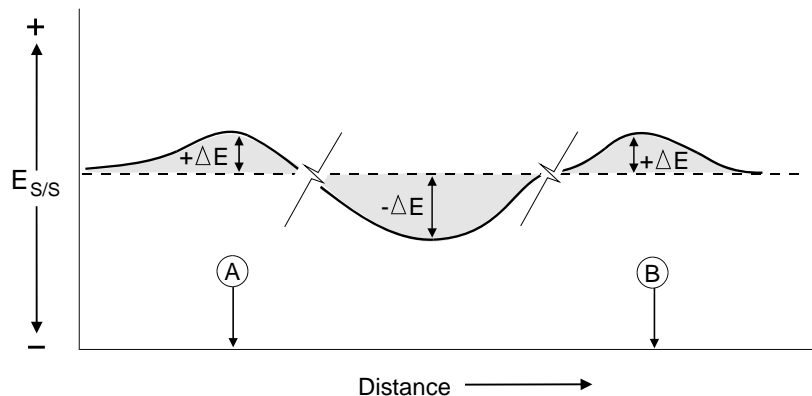


**Figure 3-28:  Potential Profile Changes on a Pipeline Where Stray Current is Discharging in an End-Wise Pattern**

Although the positive potential shift may be modest, the length of the discharge can be extensive. Under these conditions the installation of an impressed current system at the discharge locations (A and B) can be an effective means of compensating for the stray current interference. Care must be taken to ensure that the impressed current systems do not create interference on the original interfering structure.

### 3.2.2(f)   Installing a Bond Between the Interfered-with and Interfering Structures

Perhaps the most common stray current mitigation method is installation of a bond, usually having some resistance between the two structures and usually at the point of maximum stray current discharge such as at a crossing as shown in Figure 3-29.
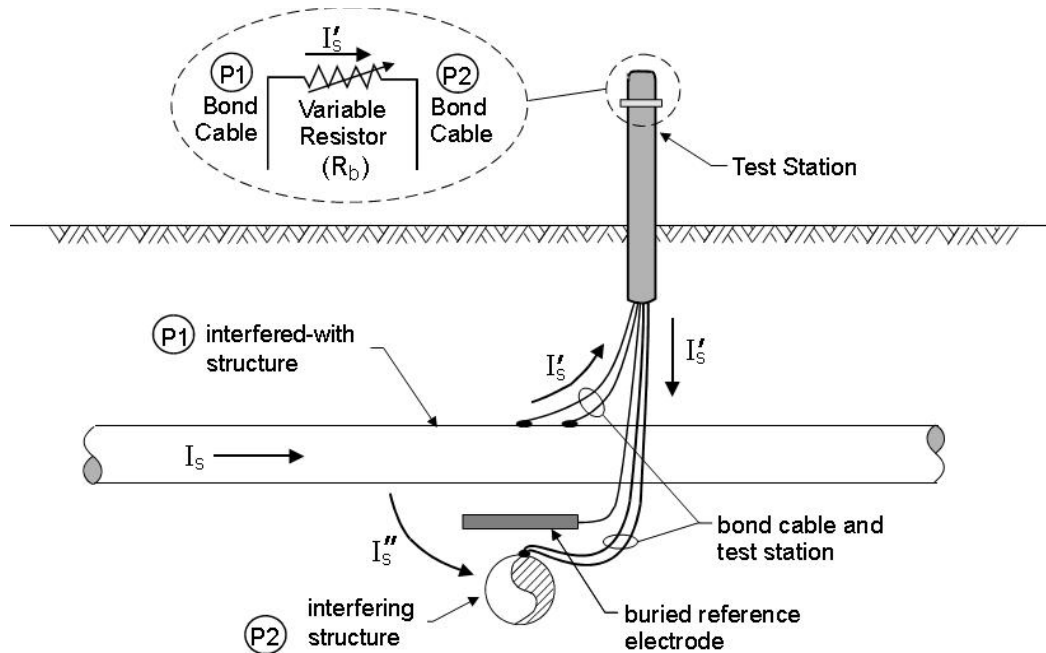
**Figure 3-29:  Interference Mitigation Using a Resistance Bond**

The electrical circuit model is similar to Figure 3-27 except with the bond resistance ($R_b$) replacing the galvanic anode resistance ($R_{a,p}$) in the circuit. Typically, the bond resistance is determined by monitoring the potential of the interfered-with structure while adjusting the resistance until the interfered-with structure is returned to its cathodic protection criterion or native potential on a structure having no cathodic protection. A zinc reference installed between the two structures at the crossing is an optional but worthwhile feature.

A resistance bond will not eliminate all the current discharge at the crossing as there will still be a residual stray current discharge ($I_s''$) that must be countered by the interfered-with structure's cathodic protection system.

The major advantages of resistance bonds over other mitigation methods are:

- relatively inexpensive installation
- easy to adjust if stray current magnitude changes
- high current capacity

Disadvantages of resistance bonds include:

- resistance bonds are vulnerable to AC fault current transients that can burn out the resistor unless protected with fault current devices
- connecting two structures through a resistance bond means that cathodic protection changes on either structure will affect protection levels on the other structure
- surveys to measure true polarized potentials on either structure may require the synchronous interruption of the bond or impressed current systems on both structures
- resistance bonds are considered critical components and by regulation require frequent inspection.

### 3.2.2(g)   Using Coatings to Mitigate Interference Effects

Applying a coating is an attempt to increase the resistance of the stray current path thus decreasing the stray current magnitude. As a standalone method, coating should only be applied at current pick-up locations. If the discharge area of a structure is coated, there is a risk of corrosion failure due to a high discharge current density at a holiday in the coating.

There are two current pick-up regions—one on the interfered-with structure and one on the interfering structure in the vicinity of the stray current discharge as shown in Figure 3-30.
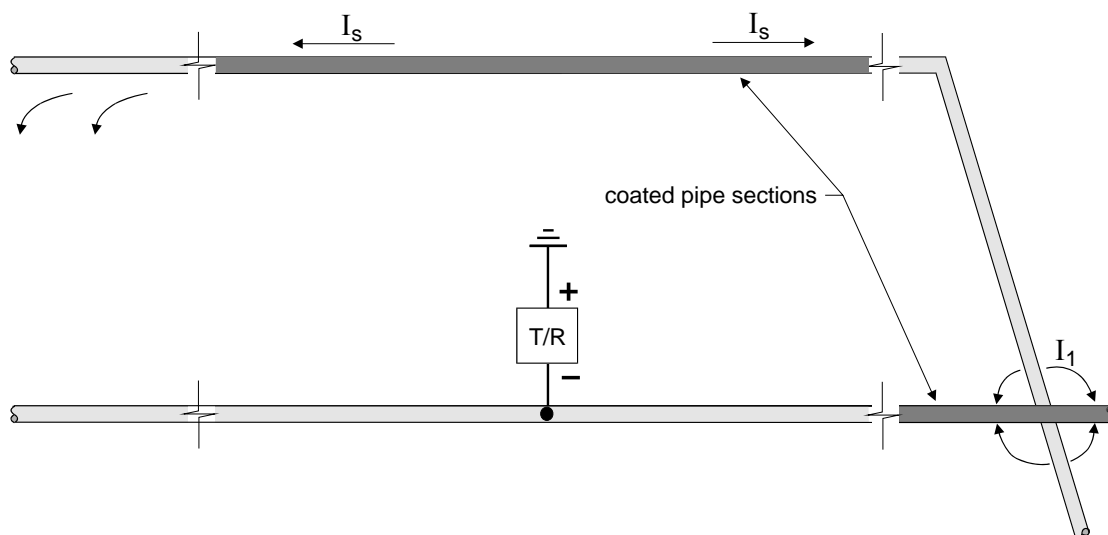


**Figure 3-30:  Use of a Dielectric Coating to Mitigate Interference**

This technique is easy to implement on a new structure where a higher quality coating can be used in areas where stray current pick-up is anticipated, but it may be impractical for existing facilities.

## 3.2.3   Other Sources of DC Stray Current

Besides impressed current cathodic protection systems, other sources of DC stray current are as follows:

- DC transit systems
- DC welding equipment
- high voltage DC transmission systems (HVDC)
- DC rail systems in mines

Due to the variable loading nature of these sources, the resulting stray current activity is dynamic (i.e., effects vary in magnitude and often location with time). Another source of dynamic stray current, telluric currents, is discussed in Section 3.4.

### 3.2.3(a)   DC Transit Systems

The electrification of transit systems in the late 1800s throughout North America resulted in considerable interference corrosion on gray cast iron water mains. Much of the early attempts to mitigate this interference led eventually to the development of cathodic protection technology.[3]

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[3] *Kuhn, R.J., Cathodic Protection of Underground Pipelines from Soil Corrosion, API Proceedings, Nov. 1933, Vol. 14, p.164.*
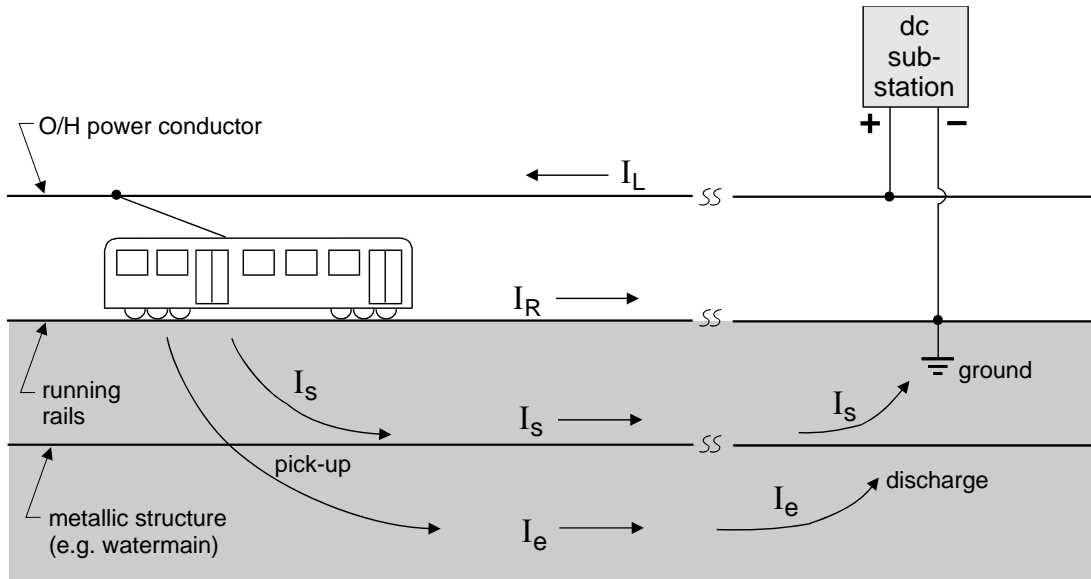
**Figure 3-31:  Typical Stray Current Paths Around a DC Transit System**

The load current ($I_L$), after passing through the trolley motor, divides into a number of current paths depending on the resistance of each path.

*therefore:* $$I_L = I_R + I_s + I_e$$

Despite the rails being a relatively low resistance path, the current leakage off the rails can be 5-10% of the load current. While this seems a small percentage, the stray currents can be substantial since the start-up load current can be several hundred amperes for a single trolley and several thousand amperes for a subway train.

Not only will the magnitude of the stray current vary with time of day and whether or not the vehicle is accelerating or decelerating, but the location of stray current pick-up on the metallic structure will change as the trolley moves along the rail. Thus, a structure-to-soil potential recording will have a dynamic appearance as shown in Figure 3-32.
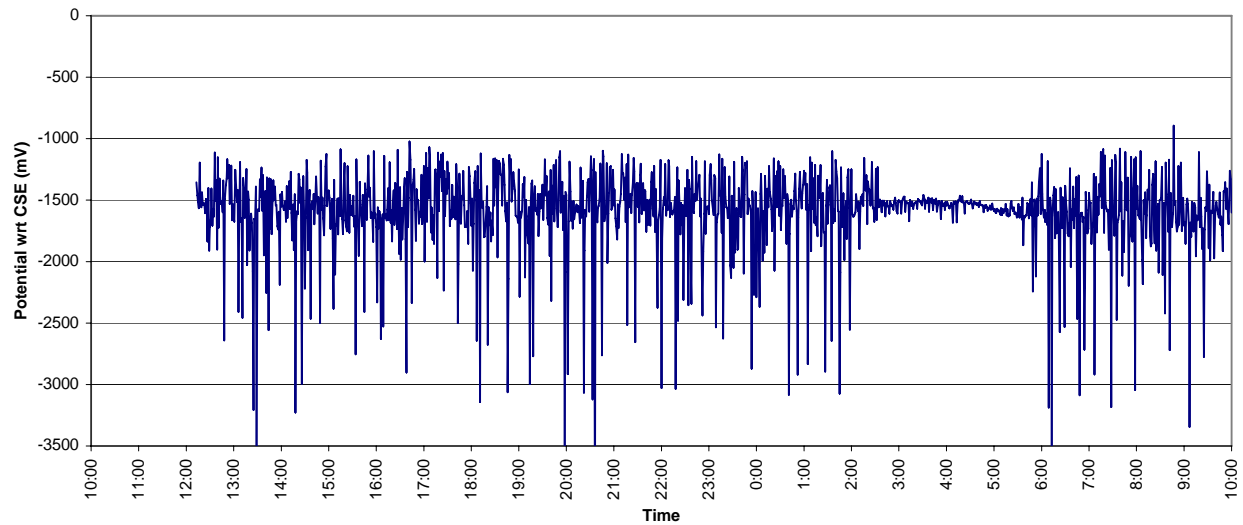
**Figure 3-32:  Typical Structure-to-Soil Potential Recording with Time Caused by
Interference from a DC Transit System**

The potential-time recording of stray current effects from a DC transit system has a distinctive pattern. There are considerable potential fluctuations during the morning and evening rush-hour periods, light activity in the middle of the day and late evening, and virtually no changes during the early morning hours.

Although the stray current pick-up locations change with time, the discharge sites are usually close to the substation ground. In urban areas, localized stray current can discharge from water piping around electrically discontinuous joints and from crossings with other utilities remote from the substation ground.

Determining the impact of transit-caused stray current on metallic facilities in urban areas requires considerable potential and current recording, starting in the vicinity of the substation grounds and along the transit system route.

A comprehensive method of analyzing dynamic stray current activity involves the construction of "beta" curves from current and potential measurements. This technique is not covered in this course but is discussed extensively in the NACE CP Interference Course.

## 3.2.3(a)(i)    Mitigation of Transit System Stray Currents

Mitigation methods for minimizing the harmful effects of DC transit system stray currents are similar to those used for mitigating cathodic protection stray currents and include:

- electrical isolation of rails and substation
- electrical bonds
- reverse current switches
- forced drainage bonds
- cathodic protection

On existing transit systems, stray current has been reduced significantly by improving the isolation between the rail and ballast. This is accomplished by installing insulating pads between the rail and ties, between the hold-down plates and the rail, and ensuring that the ballast is well drained. These measures coupled with disconnecting the negative rails from electrical grounds have proved relatively successful in many instances. Disconnecting the DC substation from electrical ground allows the rails and transit vehicles to electrically float. This then requires switching devices be installed connecting the rails to earth if a specific rail voltage-to-ground potential is exceeded. The effectiveness of substation isolation in minimizing stray current activity is therefore lost when switches are activated.

For new transit systems, it has become commonplace to electrically isolate the entire rail pocket if the rail is embedded in the road surface (Figure 3-33a) or to isolate the rail from ties (Figure 3-33b).



**Figure 3-33b:  Typical Direct-Fixation Isolating Fastener**

Source: Fitzgerald J.H. and Lauber, M.D., Stray Current Control for the St. Louis Metrolink Rail System, MP, 34, 1, (1995): p.22.

**Figure 3-33a:  Typical Embedded Track Installation**
Source:  Sidoriak, W., Rail Isolation on the Baltimore Central Light Rail Line, MP, 32, 7, (1993): p.36.

Some transit systems use a separate isolated rail (or "fourth rail") as a current return path which negates the need to isolate the running rails.

The earliest attempts to mitigate the corrosive effects of transit stray currents simply involved running bonds from the utilities to the negative bus at each substation. This provided an electronic path for the stray current to return thus reducing the amount of stray current in the electrolytic path as shown in Figure 3-34.
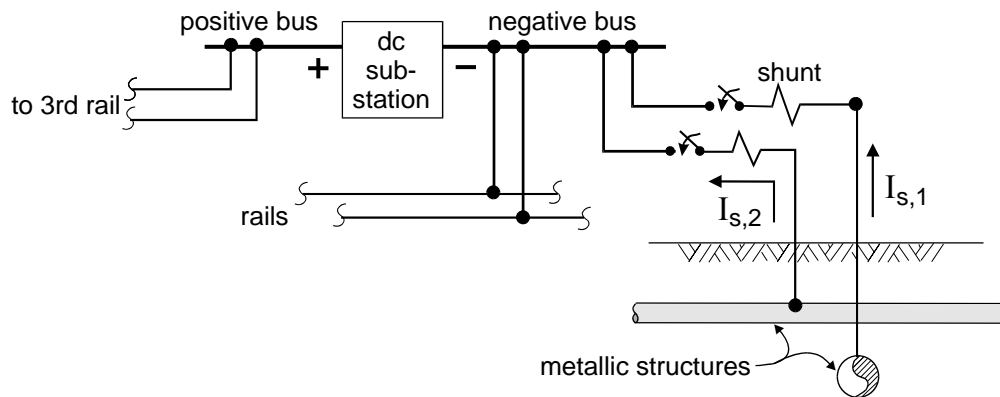


**Figure 3-34:  Typical Utilities Drainage System at a Transit Substation**

Facilities such as lead sheathed power cables, steel gas piping, telephone grounds, and iron water piping would be connected in series with a switch and a shunt to the negative bus. The shunt provides a means of recording the stray current magnitude and direction.

One weakness of this drainage arrangement is that providing a direct low resistance path for the stray current results in the underground structures picking up more current than they would otherwise. For structures with electrical discontinuities, such as iron water mains, this can result in more severe corrosion at the isolating joints.

A second disadvantage of the direct bond drainage system is that where there are multiple substations and many trains, the utilities represent an alternative path to the rails between substations and the stray currents can actually reverse. This situation is depicted in Figure 3-35.
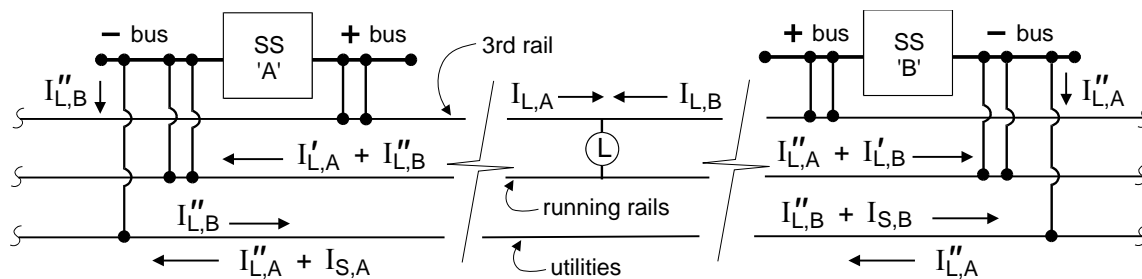
**Figure 3-35:  Schematic Showing Circulating Current between Transit Substations Through Direct Bonds to Utilities**

With the transit load located between substation A and B, it will draw some of the load current from each station. Each substation's load current has an alternative path through the utility bonds back to its respective source.

To prevent circulating currents, reverse current switches can be installed in each bond. These devices present a high resistance in one direction (the reverse direction) and a low resistance in the other (direction of intended drainage). There are several types of reverse current switches,[4] as listed in Table 3-1, each with differing operational characteristics.

**Table 3-1:  Types of Reverse Current Switches**

| Type | Characteristics |
|---|---|
| Electromagnetic (relay) | Requires AC power to operate the relay, relay must conduct all current, may be slow to open |
| Diodes (germanium, silicon) | Requires a minimum of 0.4V to conduct, have resistance, subject to surge failures and reverse voltage breakdown |
| Hybrid (relay in parallel with diodes) | Smaller relay required since diodes carry most current and are subject to reverse voltage breakdown. |
| Potential Controlled Rectifier (Figure 3-36) | Can drain all the stray current but are relatively expensive. |

Although cathodic protection is beneficial in mitigating transit system stray current, the stray currents are often so large that it precludes mitigation with galvanic anodes. Moreover, large capacity impressed current systems in an urban area are likely to

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4 *Munro, J. I., Comparison and Optimization of Reverse Current Switches, CORROSION/80, paper no. 142, (Houston, TX: NACE, 1980).*

create interference on other facilities. Hence, cathodic protection has limited effectiveness.

One the most successful measures is the use of a forced drainage bond. As shown in Figure 3-36, a forced drainage bond is a bond with a potential controlled rectifier connected in series with the bond.
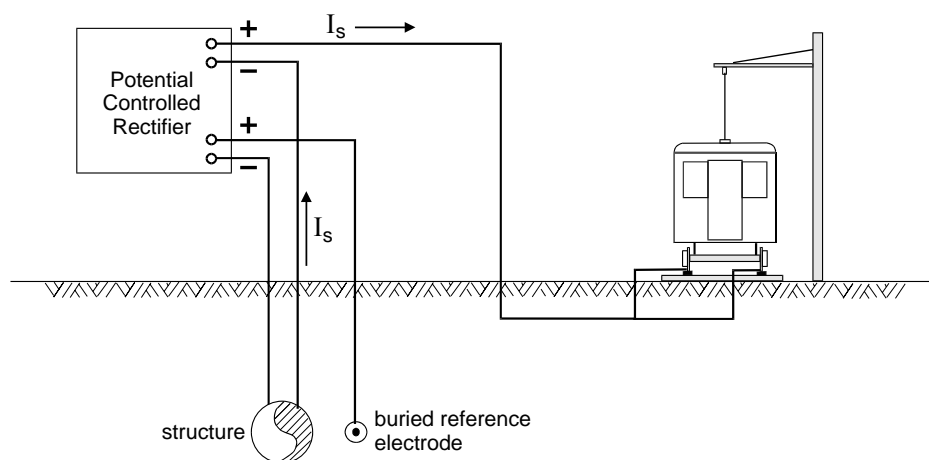


**Figure 3-36:  Forced Drainage Bond Using a Potential Controlled Rectifier**

The voltage output of the auto-potential rectifier varies depending on the potential measured between the structure and a buried reference electrode. If the measured potential is more positive than the potential set on the controller, the rectifier output voltage increases to force more current through the bond. With a DC voltage source in series with the bond, the bond resistance is negative ensuring that all the stray current is drained from the structure and there is no residual stray current in the soil path. But the controller must be adjusted so there is no bond current during periods of no stray current activity, otherwise the transit system rails and grounding system will be corroded.

To be completely effective, the forced drainage bond must be located at the point of maximum discharge. Just as with a resistance bond, if the structure is not electrically continuous a forced drainage system will aggravate corrosion at any isolating joints.

## 3.2.3(b)  High Voltage Direct Current (HVDC) Electrical Transmission Systems

HVDC systems for transmitting large blocks of electrical power over long distances have operating cost advantages over high voltage alternating current (HVAC) transmission. Unlike HVAC systems, there are no inductive or capacitive losses on HVDC, and for lengths greater than about 800 km, the power savings easily justify the extra capital costs to build the AC/DC converter stations and their extensive electrical grounding systems.

HVDC systems are built to operate in bipolar mode; that is, there is both a positive and negative circuit with large grounding electrodes at each terminus as illustrated in Figure 3-37.
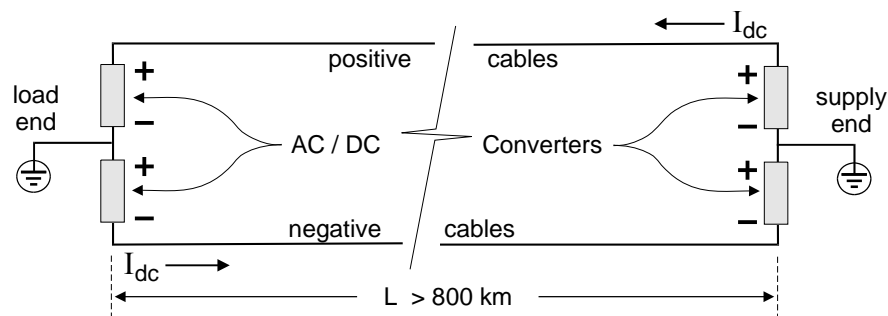


**Figure 3-37:  Electrical Schematic for a HVDC System**

The DC line currents are typically in the 1000 A range and imbalance currents, under normal operating conditions, are varying and about 1-2% of the line currents. Such small currents do not pose a significant stray current risk on underground metallic structures since the electrodes are intentionally located remote from other utilities.

During emergency operating conditions where either the positive or negative cable networks are faulted or de-energized for maintenance, the line current passes through the earth via the grounding electrodes. Under these circumstances the system is operating in monopolar mode.

HVDC grounding electrodes are large compared to impressed current groundbeds, although cathodic protection anode materials such as high silicon iron and coke are often used. The electrode is typically in the shape of a ring with about 100 m diameter and a depth of 1-2 m. Despite the large size and relative remoteness, the voltage gradient around the electrode can be appreciable even a

long distance away when the electrode is passing hundreds of amperes. For example, the voltage rise in earth at some distance *x* from such an electrode can be estimated using Equation 3-12.

$$V_{g,x} = \frac{I_e \, \rho_s}{2\pi x} \qquad \text{[3-12]}$$

*where:*

$V_{g,x}$ = voltage rise with respect to remote earth at a distance x from the electrode

$I_e$ = electrode current

$\rho_s$ = soil resistivity

x = distance from the electrode

*given:*  $I_e$ = 500 A

$\rho_s$ = 50 Ω-m

x = 1000 m

*then:*  $V_{g,x\,@\,1km} = \dfrac{500\,A \times 50\,\Omega\text{-}m}{6.28 \times 1000\,m} \approx 4V$

Hence a metallic structure located 1 km from the electrode would be exposed to 4V during monopolar operation under these conditions. It is claimed that the HVDC system will operate in monopolar mode a small percentage of time. Nevertheless the rather large voltage gradients can present a serious corrosion risk on some structures on a cumulative basis.

Also, the effect can be either a positive or negative potential shift on the structure as shown in Figure 3-38 depending on which of the power circuits has the outage.
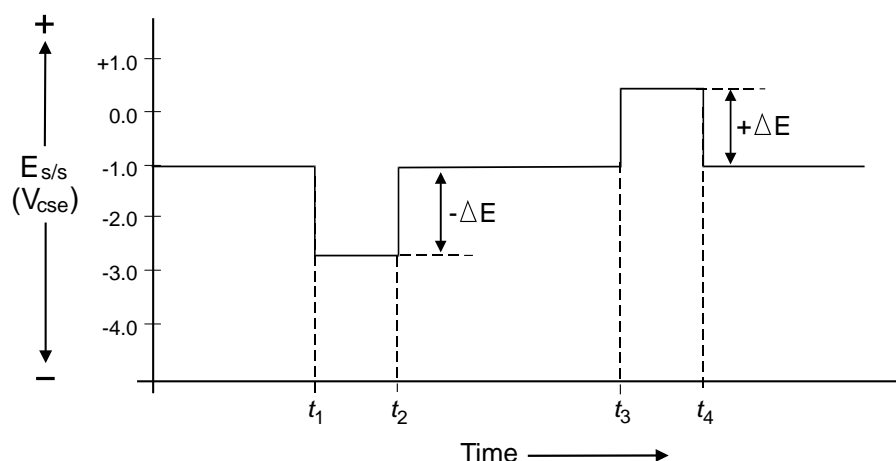
**Figure 3-38:  Potential-Time Plot for a Metallic Structure being Interfered-with by a HVDC System**

Assume that the potential plot in this figure was from a structure located near the supply end groundbed. Then the negative shift from $t_1 \rightarrow t_2$ would result from a failure on the positive circuit and the positive shift from $t_3 \rightarrow t_4$ would result from a failure on the negative circuit. Note that the potential shifts are not necessarily equal, even if the stray current is the same, since the cathodic and anodic polarization characteristic can be different.

Most structures would not extend the full 800 km nor be close enough to the electrode to make it economical to install a bond. Because of the large voltage shifts, galvanic anodes many not adequately compensate. The most practical mitigation method is to use an impressed current system powered by a potential controlled rectifier. Not only would the cathodic protection power supply be able to counteract the large positive potential shifts, but during the negative shift periods it would shut down, thus minimizing the stress on the coating if the structure was a coated steel pipeline.

### 3.2.3(c)  DC Welding Operations

Welding operations on ships and barges have been known to create stray current interference, sometimes so severe that it has resulted in the sinking of the vessel. Interference arises where the negative of the welding generator is connected to electrical ground on the dock and there is no electrical bond between the dock and the vessel. Under these circumstances, the welding current, which can be hundreds of amperes, discharges from the vessel to the dock as illustrated in Figure 3-39.

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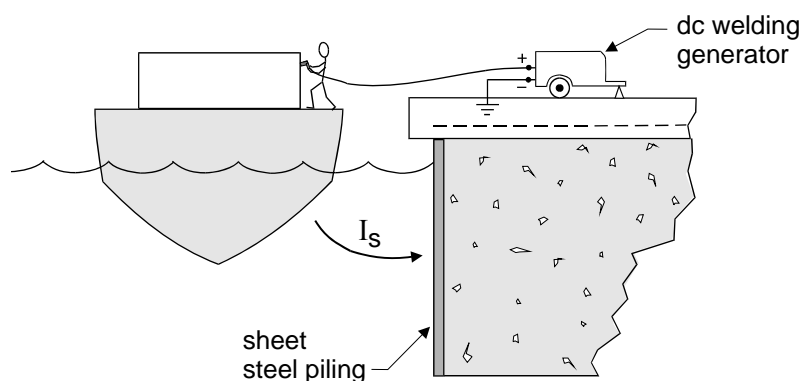
**Figure 3-39:  Stray Current Caused by DC Welding Operations**

The interference is mitigated by bonding the vessel to the dock or by attaching the negative of the welding generator directly to the vessel.

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**Experiment 3-1:**
    To Demonstrate DC Interference and Its Mitigation

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# 3.3  AC Interference

## 3.3.1  Introduction

Electrical energy from an overhead power line can be transferred to a pipeline by three possible mechanisms—conductive coupling (during fault conditions), electrostatic or capacitive coupling, and electromagnetic or inductive coupling. How each of these affect a pipeline and how these effects can be predicted and mitigated is discussed in this chapter.

It should be noted that predicting AC interference effects is a complex matter requiring fairly sophisticated mathematics. This course discusses methods of estimating the effects for a few very simple cases, but most problems can only be solved using either complicated analytical techniques[5] or specialized software.[6]

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[5] *"Power Line-Induced AC Potentials on Natural Gas Pipelines for Complex Rights-of-Way Configurations," Electric Power Research Institute, EPRI Report N° EL-3106.*
[6] *"AC Predictive and Mitigation Techniques," Pipeline Research Council International, Inc., PRCI Report N° PR-200-9414, May 1999.*

A pipeline can experience AC interference as a result of being near any AC power line. However, the vast majority of interference problems are created by three-phase power transmission systems, since these involve both high currents (steady-state and fault conditions) and high voltages and are more likely to parallel pipelines for long distances than are low voltage distribution systems, for instance.

A three-phase (3ϕ) power transmission system consists of three power lines, each having the same voltage to ground and each carrying approximately the same amount of current. One or two additional conductors, known as shield wires, may also be present, running between the tops of the power line support structures (Figure 3-40). Although their purpose is to protect the power line from lightning strikes rather than to transmit power, shield wires (as well as any other paralleling conductors) nevertheless affect how electrical energy is transferred to a pipeline.

In a three-phase circuit, the AC waveforms for each of the three phases are 120 degrees apart from one another (Figure 3-41). Waveforms that have the same frequency but start and end at different times are said to be "out of phase with one another." The point at which a waveform begins along the x-axis (in degrees) is known as the waveform's *phase angle*. When AC waveforms are discussed, phasor notation is used to indicate both the magnitude and the phase angle of the waveform. For instance, in Figure 3-41, the three voltage waveforms would be represented as 0.7∠0°, 0.7 ∠120°, and 0.7 ∠240° in phasor notation.[7]



**Figure 3-40:  Typical Three-Phase AC Power Line
(Horizontal Configuration with Two Shield Wires)**

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[7]*Note that the peak voltage shown in Figure 3-41 is 1.0 V, but the voltage magnitude shown in phasor notation is 0.7V.  This is because, when discussing the magnitudes of AC waveforms, "rms" (root mean square) values rather than peak values are generally used.  For a sinusoidal waveform, the rms value of a voltage or current is $1/\sqrt{2}$ (approximately 0.7) times its peak value.*

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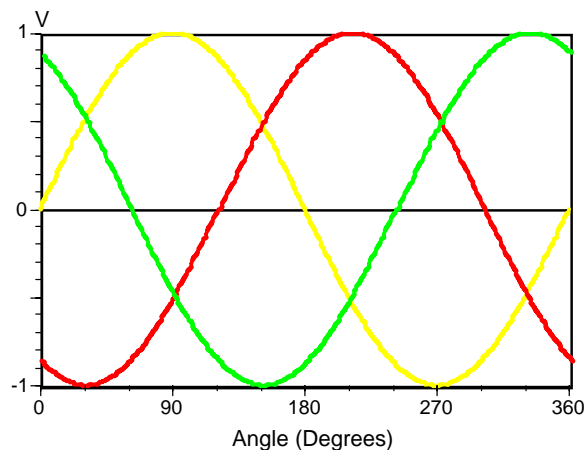
**Figure 3-41:  AC Voltage Waveforms in a Three-Phase Circuit**

## 3.3.2   Conductive Coupling Due to Faults

### 3.3.2(a)  Description

Conductive coupling can occur when there is a line-to-ground short circuit or fault on the power line. On high-voltage power lines, faults are most likely to occur as the result of lightning, which can ionize the air in the vicinity of an insulator. Typically, a high-voltage transmission line experiences less than one lightning related fault per 100 km per year. Faults can also occur as the result of high winds, failure of the power line structures or insulators, or accidental contacts between the power line and other structures, such as cranes and other construction equipment.

Under fault conditions, the current leaving the power line will return to its source using all paths available to it, including power line shield wires, the earth, and metallic structures in the earth such as pipelines. The amount of current transferred to a pipeline is dependant on the relative impedances of all parallel paths available to the fault current. It is also a function of the separation distance between the faulted structure and the pipeline, the available fault current, the impedance of the faulted structure to ground, and the impedance of the pipeline to ground.

Fault current is conducted to the pipeline through its coating. The better the coating quality (i.e., the fewer the holidays) and the higher the coating's dielectric strength (i.e., breakdown voltage), the lower the current transfer to the pipeline.
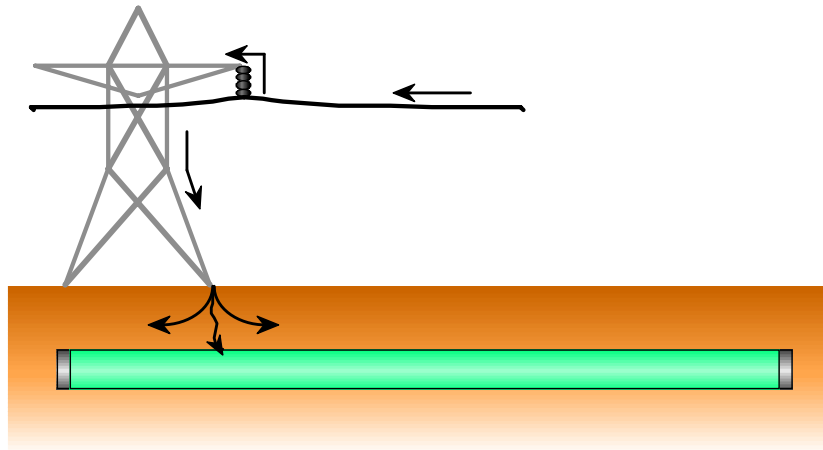
**Figure 3-42: Conductive Coupling During Line-to-Ground Fault Conditions**

## 3.3.2(b)  Deleterious Effects

Fault currents (a transient condition) are much greater in magnitude than steady-state power line currents, so conductive coupling can result in very high pipeline voltages; however, the length of time these voltages are present on the pipeline is limited to a fraction of a second (typically 0.1 second) due to power system protection devices. Even over such a short time period, large amounts of energy can be transferred to the pipeline, resulting in coating damage or even pipeline failure due to melting or cracking of the pipe wall.

The high pipeline voltages resulting from conductive coupling represent a safety hazard to pipeline personnel and perhaps the general public in cases where test leads and pipeline appurtenances are accessible. While electric shocks can be painful and can result in the loss of muscular control at body currents of less than 50 mA, the primary concern for short duration (transient) shocks resulting from fault currents is ventricular fibrillation, which may occur at body currents of greater than 50 mA and certainly occurs at body currents of greater than 100 mA. Ventricular fibrillation results in the total loss of coordination of the heart due to the disruption of its electrical signals and will result in death without defibrillation (i.e., a strong electrical pulse to restore the heart to its normal beating pattern). The maximum current that can be tolerated before the onset of ventricular fibrillation is a function of body weight and duration of current flow, as indicated by Equation 3-14.

An electric shock can occur when a person touches an energized structure or even when a person is simply standing in the vicinity of an energized structure in

contact with the earth. As an example, the structure in Figure 3-43 is energized to a voltage of 10 kV. The fault current $I_F$ passes from the structure to the earth, creating a voltage gradient. A person touching the structure will be exposed to 2 kV, since this is the potential difference between the structure and the point on the earth where the person is standing. A second person, who is not touching the structure, is exposed to 1 kV, since this is the potential difference between the two points on the earth where the person is standing. In general, "touch voltage" is defined as the potential difference between a grounded metallic structure and a point on the earth's surface separated by a distance equal to the normal maximum horizontal reach (approximately 1 m). "Step voltage" is the potential difference between two points on the earth's surface separated by a distance of one pace (approximately 1 m) in the direction of maximum potential gradient.
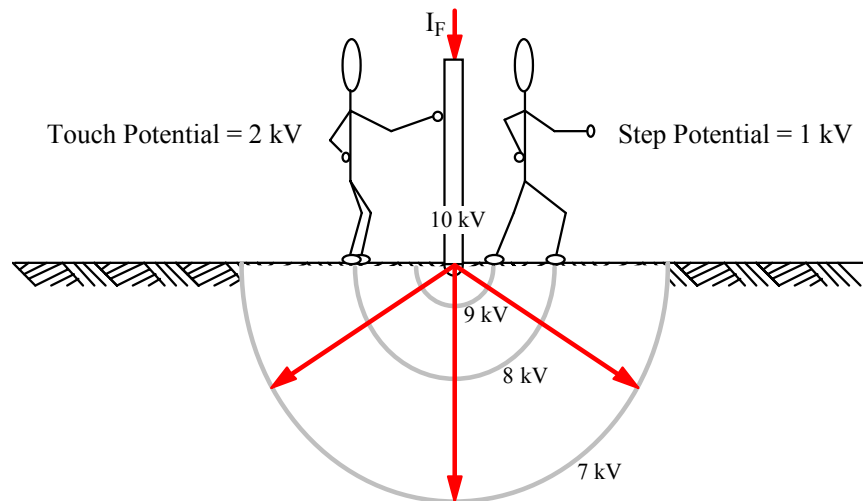


**Figure 3-43:  Example of Touch and Step Voltages at an Energized Grounded Structure**

## 3.3.2(c)  Prediction and Mitigation

The greatest concern regarding the transfer of fault current between a faulted power line structure and a pipeline is whether or not there is enough energy available to create an electric arc through the soil. If this should occur, the current path through the soil to the pipeline becomes ionized resulting in much higher currents and current densities than would be the case during normal conditions of soil conduction leading to a greater risk of pipeline damage.

The most effective means of preventing arcs during fault conditions is to maintain a safe separation distance between the power line structures and the pipeline.

Minimum separation distances are usually specified by both the power company and the pipeline company; however, safe separation distances specifically to prevent arcing must either be calculated or determined from research reports. One such calculation is provided by Sunde,[8] who provided the following equations for the distance $r$ (m) over which an arc could occur, based on soil resistivity $\rho$ ($\Omega$-m) and fault current magnitude $I_f$ (kA).

$$r = 0.08\sqrt{I_f \cdot \rho} \quad (\rho \leq 100\,\Omega\text{-}m); \quad r = 0.047\sqrt{I_f \cdot \rho} \quad (\rho \geq 1000\,\Omega\text{-}m) \qquad [3\text{-}13]$$

If safe separation distances are unattainable, then screening electrodes can be used to intercept the fault current. These would typically consist of either lengths of zinc ribbon or banks of packaged sacrificial anodes connected directly to the pipeline, installed between the pipeline and the power line structure. While screening electrodes may prevent damage to the pipe at the location of fault current pick-up, they lower the resistance between the pipeline and the power line structure, thereby encouraging fault current to use the pipeline as a current path. Since this could possibly increase the risk of pipeline damage at locations of fault current discharge, screening electrodes should be used with caution.

It is not possible to know when, where, or how a fault will occur, so it is difficult to predict the effects of a fault and the mitigation required to protect both the pipeline and personnel. When the probability of a fault is much higher than normal (e.g., electrical storms, ice storms, high winds), it is common sense to avoid activities involving pipe contact (e.g., CP surveys, CP installations, pipeline maintenance) to minimize the chance of an electrical shock. Pipeline companies should also take extra precautions with pipelines located in power line corridors to ensure that the public does not have access to pipeline appurtenances and cathodic protection test leads where hazardous voltages could possibly be contacted. The use of lockable test stations (Figure 3-44) and test stations with dead-front construction (Figure 3-45) should be considered.

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[8] *Sunde, E.M., "Earth Conduction Effects," Dover Publications, 1968, p.296-298.*

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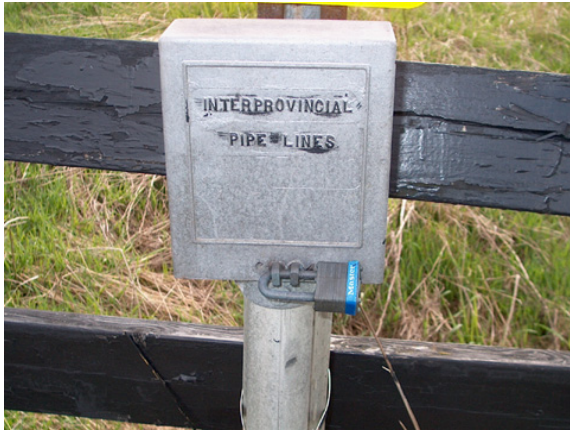
**Figure 3-44:  Lockable Test Station**          **Figure 3-45:  "Dead-Front" Test Station**

Should a transient electrical shock hazard occur, the goal of a mitigation system is to limit the current through a person's body to a value that can be tolerated (i.e., a value that will not result in ventricular fibrillation). This can be done by either minimizing the voltage to which a person might be exposed or by raising the person's body resistance.

The maximum transient (short term) current $I_B$ a human body can tolerate depends on shock duration $t_S$ (seconds) and body weight and is calculated as follows:[9]

$$I_B = \frac{0.157}{\sqrt{t_S}} \quad (\text{for a 70 kg body}) \qquad I_B = \frac{0.116}{\sqrt{t_S}} \quad (\text{for a 50 kg body}) \qquad [3\text{-}14]$$

(The above equations have been developed and tested for a transient shock hazard within the time interval of from 0.03 to 3 seconds in duration.)

Considering the resistance of a human body and the contact resistance between the feet and the earth (which depends on soil resistivity $\rho$ in $\Omega$-m), equations have been developed for the electrical power industry to predict the maximum voltages that can be tolerated from hand to feet (touch voltage) or from foot to foot (step voltage) for various body weights as follows:[10]

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[9] *"IEEE Guide for Safety in AC Substation Grounding," Institute of Electrical and Electronics Engineers, ANSI/IEEE Std. 80-1996.*
[10] *"IEEE Guide for Safety in AC Substation Grounding," Institute of Electrical and Electronics Engineers, ANSI/IEEE Std. 80-1996.*

$$V_{step_{70}} = (1000 + 6\rho)\frac{0.157}{\sqrt{t_s}} \qquad\qquad V_{step_{50}} = (1000 + 6\rho)\frac{0.116}{\sqrt{t_s}}$$

[3-15]

$$V_{touch_{70}} = (1000 + 1.5\rho)\frac{0.157}{\sqrt{t_s}} \qquad\qquad V_{touch_{50}} = (1000 + 1.5\rho)\frac{0.116}{\sqrt{t_s}}$$

[3-16]

These voltage limit equations are derived from Ohm's Law by multiplying the total resistance of the shock current flow path times the magnitude of the tolerable shock current. The resistance estimated for the feet in contact with the earth is a function of the soil resistivity, as seen in the above equations, and assumes homogeneous soil resistivity. Addition of a thin layer of high resistivity surface material, such as crushed stone (3000 $\Omega$-m), can significantly increase this contact resistance. According to IEEE standard 80, with the addition of a high resistivity surface layer the foot contact resistance is first calculated assuming the resistivity of the high resistivity surface layer and then multiplied by a derating factor to account for the lower resistivity soil underneath. The derating factor can be estimated using Equation 3-17 below.[10]

$$C_s = 1 - \frac{0.09\left(1 - \dfrac{\rho}{\rho_s}\right)}{2\,h_s + 0.09}$$

[3-17]

Where:
$C_s$ = surface layer derating factor
$\rho$ = underlying soil resistivity, $\Omega$-m
$\rho_s$ = surface layer resistivity, $\Omega$-m
$h_s$ = thickness of surface layer, m

*Example:*
A pipeline running parallel to a power line may exhibit a maximum voltage to earth of 500 V for a duration of 1/2 second during a line-to-ground fault. Calculate the tolerable touch potential for a 50 kg person who is touching a pipeline appurtenance at the time of a fault while standing on 50 $\Omega$-m soil, and determine an appropriate mitigative measure.

$$V_{touch_{50}} = (1000 + 1.5\rho)\frac{0.116}{\sqrt{t_s}}$$

$$V_{touch_{50}} = (1000 + 1.5 \times 50)\frac{0.116}{\sqrt{0.5}} = 176\,V$$

The maximum touch potential the person could withstand is 176 V. To raise the tolerable touch voltage, a 150 mm thick layer of crushed stone having a resistivity of 3000 Ω–m is placed around the appurtenance. The tolerable touch potential becomes

$$V_{touch_{50}} = (1000 + 1.5\,\rho_s\,C_s)\frac{0.116}{\sqrt{t_s}}$$

Where:

$$C_s = 1 - \frac{0.09\left(1 - \dfrac{50}{3000}\right)}{2(0.150) + 0.09} = 0.77$$

$$V_{touch_{50}} = (1000 + 1.5 \times 3000 \times 0.77)\frac{0.116}{\sqrt{0.5}} = 732\,V$$

which exceeds the maximum pipe to earth voltage rise; and therefore, the pipeline is safe.

The touch voltage to which a person is exposed during a fault can also be minimized by installing a gradient control loop around the pipeline appurtenance and connecting it to the pipe. This loop is generally installed at a depth of between 300 and 500 mm and extends approximately 1,000 mm beyond the perimeter of the appurtenance. The loop raises the voltage of the earth during a fault and minimizes the voltage difference between a hand touching the pipeline and the feet. The loop is generally constructed of zinc ribbon, since copper wire, if directly connected to the piping, can be detrimental to the cathodic protection system.

The measures described above are illustrated in Figure 3-46.

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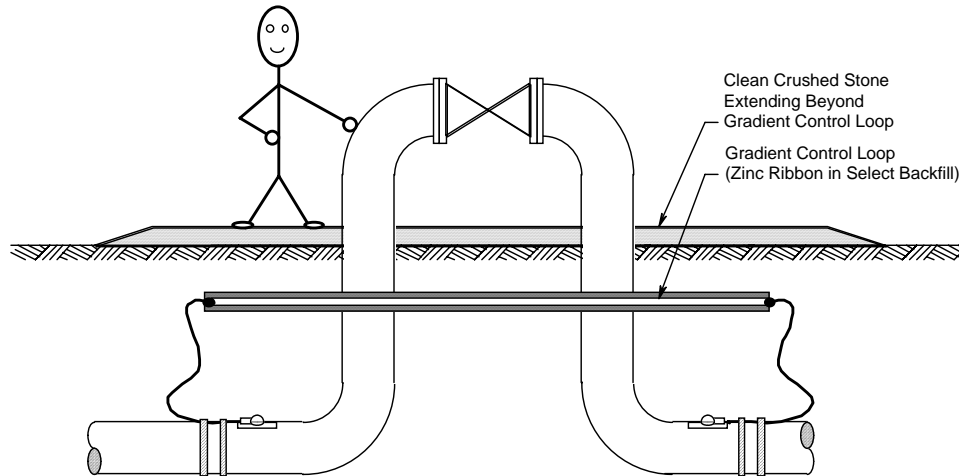
**Figure 3:46: Mitigation of Hazardous Touch Potentials at Aboveground Appurtenance**

Clean Crushed Stone
Extending Beyond
Gradient Control Loop

Gradient Control Loop
(Zinc Ribbon in Select Backfill)


## *3.3.3   Electrostatic (Capacitive) Coupling*

### 3.3.3(a)  Description

With electrostatic coupling, energy is transferred through the electrical capacitance that exists between the power line and the pipeline. Any two conductors separated by a dielectric material can be considered a *capacitor*. *Capacitance* is a measure of the ability to store electrical charge between two conductors relative to the voltage between the conductors. Capacitance is proportional to the area of the conductors but is inversely proportional to the separation between the conductors (Figure 3-47).

Consider the case in Figure 3-48 where a pipeline is under construction. Lengths of pipe have been strung out along the pipeline route and placed on wooden skids in preparation for welding. Although this may not look like a capacitor as previously discussed, the elements necessary for the construction of a capacitor are present—two conductive plates separated by a dielectric material. In this case, the power line is one conductive plate, the pipe is another, and these are separated by air that serves as a dielectric. Similarly, a second capacitor is formed between the pipe and the earth, since the earth (although nonmetallic) is also a conductive plate. A section of pipe sitting on skids beneath an AC power line can therefore be represented as an electrical circuit consisting of two capacitors in series with an AC source, which forms a capacitive voltage divider.
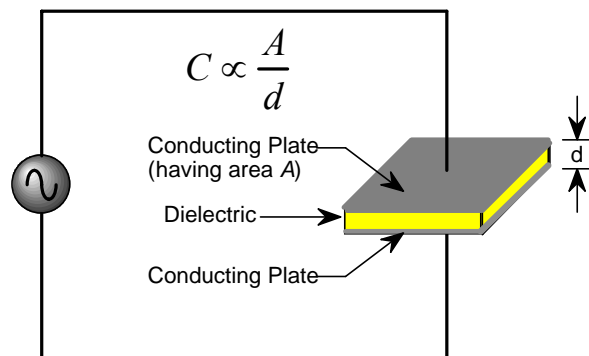
**Figure 3-47:  Elements of a Capacitor**
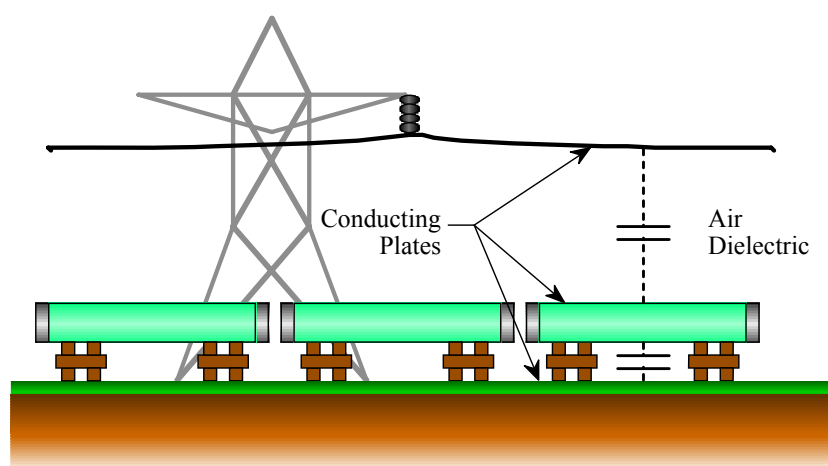


**Figure 3-48:  Pipeline During Construction Represented as a Capacitive Voltage Divider**

Recalling Kirchhoff's laws, the sum of the voltage drops across the resistors in a series circuit (Figure 3-49) will be equal to the sum of the voltage sources. Furthermore, these voltage drops are in direct proportion to the resistances that create them. Similarly, the voltage drops across the capacitors in an AC series circuit (Figure 3-50) will be in direct proportion to the respective capacitive reactances, and their sum will be equal to the sum of the voltage sources. Therefore, in the pipeline construction case of Figure 3-48, the line-to-ground voltage of the power line is divided between the two capacitors in inverse proportion to their capacitances.
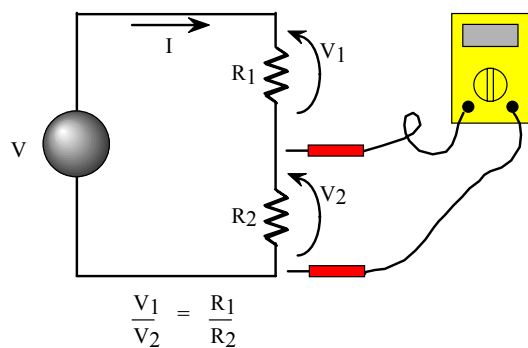
**Figure 3-49:  Resistive Voltage Divider**          **Figure 3-50:  Capacitive Voltage Divider**
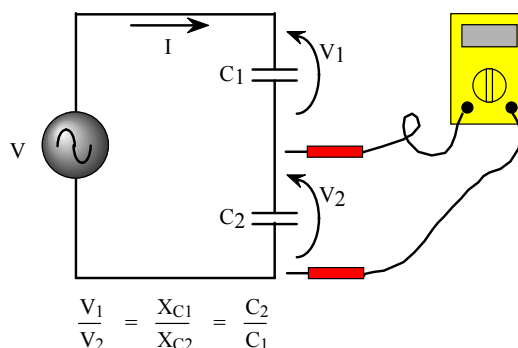
$$\frac{V_1}{V_2} = \frac{R_1}{R_2}$$

$$\frac{V_1}{V_2} = \frac{X_{C1}}{X_{C2}} = \frac{C_2}{C_1}$$

### 3.3.3(b)  Deleterious Effects and Mitigation

Depending on the relative capacitance values and the power line voltage, very large voltages (on the order of thousands of volts) can be electrostatically generated on a single pipe joint, assuming it is well insulated from earth. However, because the capacitance between the power lines and the pipe is very small, typically in the picofarad range ($10^{-12}$ farads), the capacitive reactance between them is very large, typically in the gigaohm range ($10^9$ Ω), so very little energy is transferred to the pipe by this mechanism.

Although electrostatic coupling cannot generally produce enough body current to create an electrical shock hazard, it can result in nuisance voltages that produce a sensation similar to a shock from static electricity. This could conceivably create a secondary safety hazard if, for instance, someone quickly overreacted to the sensation of a voltage while working on a pipeline project.

While the pipeline is up on skids and well insulated from ground, electrostatic voltages can be easily mitigated by connecting the pipeline to earth, even through a very high resistance ground connection, as long as the ground connection has a much lower resistance than the pipe-to-earth capacitive reactance. As pipe sections are welded together, the surface area of the pipeline increases and the capacitive reactances associated with the pipeline decrease allowing more electrical energy to be transferred electrostatically. However, at this stage of pipeline construction, the pipe is also being taken off of the skids and lowered into the trench. By decreasing the separation between the pipeline steel and the earth, the capacitive reactance between the pipeline and earth decreases significantly.

For example, if the pipeline is 500 mm above the earth when it is on skids but is separated from the earth by only 1 mm of coating when it is in the trench, the capacitive reactance of the pipe to ground decreases by a factor of 500 as does the electrostatically generated voltage that appears on the pipe. Furthermore, the pipe-to-earth capacitance is now paralleled by a pipe-to-earth resistance due to contact between the coated pipe and the soil. This resistance is generally so low relative to the power line-to-pipeline capacitive reactance that no significant electrostatic voltage will remain once the pipeline comes into contact with the earth.

## 3.3.4   Electromagnetic (Inductive) Coupling

### 3.3.4(a)   Description

Voltages and currents are electromagnetically induced onto a pipeline in the same manner that an inductive pipe locator induces an audio signal onto a pipeline or the primary winding of a transformer induces current to flow through the secondary winding.

First consider the flow of electric current in a simple conductor, as shown in Figure 3-51. The flow of current creates an electromagnetic field around the conductor, indicated by the lines of magnetic flux $\Phi$. The intensity of the magnetic field is directly proportional to the current magnitude and is inversely proportional to the distance from the conductor. Using a convention known as the right-hand rule, if a person were to place his right hand around the wire, with the thumb pointing in the direction of current flow, the fingers would indicate the direction of the magnetic flux.

Electromagnetic induction occurs whenever there is a relative motion between an electrical conductor and a magnetic field. This motion may either result from the physical movement of a conductor through a stationary magnetic field or the movement of a magnetic field through a stationary conductor. The most obvious example of the first case is an electrical generator in which a rotating coil of wire passes through a stationary magnetic field to generate electric current. A less obvious example discussed later in this chapter deals with telluric current interference where the tidal movement of seawater (a conductor) passing through the earth's magnetic field creates geomagnetic earth currents. In the second case, where both the source of the magnetic field and the conductor are stationary, the magnetic field itself must be in motion to induce current in the conductor. This is done by using AC current to create a time-varying magnetic field that expands

and collapses around the conductor, thereby creating a relative motion. The best example of this is an electrical transformer as shown in Figure 3-52.
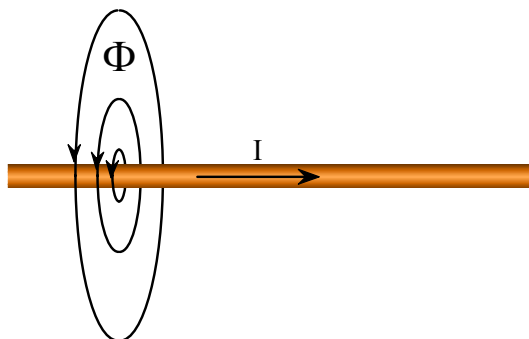


**Figure 3-51: Electromagnetic Field Created by Current Flow in a Wire**
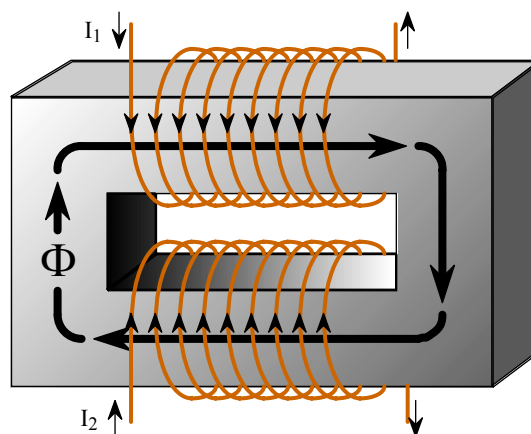
**Figure 3-52:  Electromagnetic Induction in a Multi-Turn, Iron Core Transformer**

An AC current ($I_1$) flows through the primary winding of the transformer. This creates a magnetic field around each turn of the winding, and these fields link together to create one large magnetic field. The magnetic field around this coil would normally tend to stray well outside the vicinity of the coil, but by introducing a transformer core made of iron or some other magnetic material, the magnetic field becomes primarily confined to the core. A secondary winding is also wound onto the iron core, and the magnetic field created by the primary winding is now expanding and collapsing around the turns of the secondary winding, which consequently induces a secondary current flow $I_2$.

To make transformers energy efficient, the windings and cores are designed to transfer as much energy as possible from the primary winding to the secondary winding. A transformer can be formed, however, simply by placing a conductor within a time-varying magnetic field around another conductor (Figure 3-53), although such a transformer would be highly inefficient. Note that in Figure 3-53 the induced current is indicated to flow in the opposite direction of the primary current; however, this is not strictly true. Lenz' law states that the induced current flows in a direction that creates a secondary magnetic field that tends to oppose any change in the primary magnetic field. Therefore it is more accurate to say that the induced current is out of phase with the primary current, which is what the arrows are intended to show.

The case of the single-turn, air-core transformer in Figure 3-53 is representative of the electromagnetic coupling that occurs when a pipeline runs parallel to a power line as shown in Figure 3-54. While the voltages generated electrostatically are proportional to power line voltage, the voltages and currents that are electromagnetically induced are proportional to power line current. As the length of parallelism between the pipeline and power line increases, the electromagnetic coupling between them improves, just as increasing the number of turns on the primary and secondary windings of a transformer improves the efficiency of the transformer. As was the case with conductive coupling, electromagnetic coupling can produce voltages and currents that affect both the integrity of the pipeline and the safety of personnel.
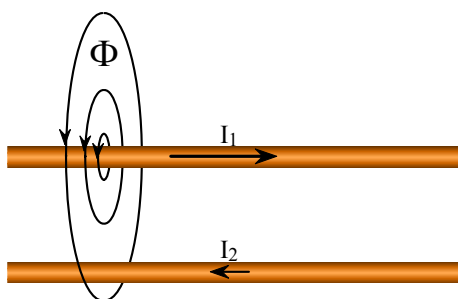


Figure 3-53:  Electromagnetic Induction in a
Single-Turn, Air-Core Transformer
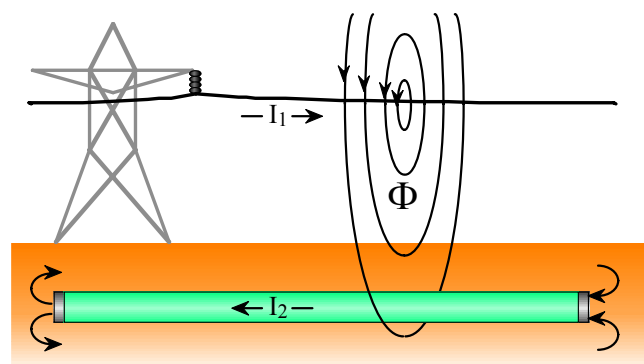
Figure 3-54:  Electromagnetic Induction in a
Pipeline due to an AC Power Line

## 3.3.4(b)  AC Corrosion[11]

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 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:

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[11] *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).*

$$i_{ac} < 20 \text{ A/m}^2 \dots\dots\dots\dots\dots\dots\dots\text{No Corrosion}$$
$$20 \text{ A/m}^2 < i_{ac} < 100 \text{ A/m}^2 \dots\dots\dots \text{ Corrosion Unpredictable}$$
$$i_{ac} > 100 \text{ A/m}^2 \dots\dots\dots\dots\dots\dots\text{Corrosion Expected}$$

The AC current density at a circular holiday is a function of the induced AC voltage on the pipeline ($V_{ac}$), the soil resistivity ($\rho$ [$\Omega$–cm]), and the holiday diameter ($d$ [cm]), and can be calculated as follows:

$$i_{ac} = \frac{8V_{ac}}{\rho\pi d} \qquad\qquad [3\text{-}18]$$

$i_{ac}$ – AC current density (A/m$^2$)
$V_{ac}$ – AC Volts (V)
$\rho$ – Soil resistivity ($\Omega$–m)
d- holiday diameter (m)

The AC voltage required to produce a 100 A/m$^2$ current density has been plotted against holiday area in Figure 3-55 for a variety of soil resistivities. As an example, for a holiday area of 1.5 cm$^2$, an induced AC voltage of 5.4 volts would produce an AC current density of 100 A/m$^2$ in 1000 $\Omega$-cm soil.
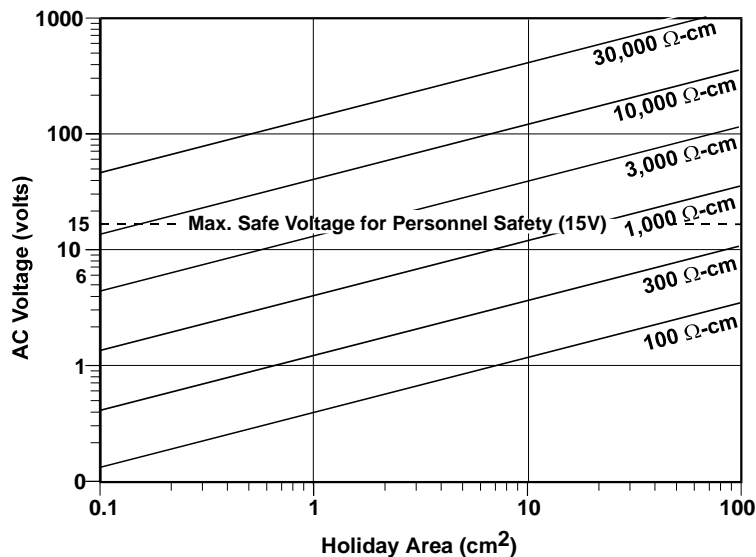


**Figure 3-55: AC Voltage Required to Produce 100 A/m$^2$ Current Density for a Variety of Holiday Sizes and Soil Resistivities**

Equation 3-18 indicates that AC current density increases as holiday diameter decreases, which suggests that AC corrosion is most likely to occur at pinholes rather than at large defects. It has indeed been found that corrosion rates increase

with decreasing holiday size; however, once the holiday becomes smaller than approximately 1 cm$^2$ in area, AC corrosion is generally not found to be a problem. Figure 3-56 shows an anomaly that occurred at a holiday on a cathodically protected pipeline.[12] The site of the anomaly exhibited a polarized potential of $-1170$ mV$_{CSE}$ and a pH of greater than 12. When the site was cleaned, a corrosion pit was discovered, even though the site was apparently well protected (Figure 3-57). Based on the diameter of the holiday (0.01 m), the soil resistivity (16 $\Omega$-m), and the pipeline voltage (50 V), the AC current density was calculated to be 800 A/m$^2$, and so the corrosion was concluded to be AC induced.



**Figure 3-56:  Pipeline Anomaly Due to AC Corrosion (Before Cleaning)**



**Figure 3-57:  Pipeline Anomaly Due to AC Corrosion (After Cleaning)**

## 3.3.4(c)  Electrical Shock Hazards[13]

Electromagnetic coupling results in steady-state induced pipeline voltages, so the duration of a shock is not necessarily short as it is in conductive coupling. The tolerable voltage limits for exposure to steady state voltages are therefore much lower than for fault voltages.

Various documents and standards have set the maximum allowable induced AC voltage to which a person should be exposed as 15 V.[14,15]  This is based on the

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[12] *Wakelin, R.G., Sheldon, C., "Investigation and Mitigation of AC Corrosion on a 300 mm Diameter Natural Gas Pipeline," CORROSION/2004, paper no. 4205 (Houston, TX: NACE, 2004).*

[13] *"IEEE Guide for Safety in AC Substation Grounding," Institute of Electrical and Electronics Engineers, ANSI/IEEE Std. 80-1996.*

[14] *"Principles and Practices of Electrical Coordination Between Pipelines and Electrical Supply Lines," National Standard of Canada (CAN/CSA-C22.3 N°.6 - M91).*

assumptions that the average resistance of a human body is 1,000 ohms, and that an average person can withstand a maximum current of 15 mA for a prolonged period of time. Such a current may be painful and may in fact cause muscular contractions that would prevent a person from letting go of an energized structure but isn't expected to result in breathing difficulties.

The 15 V exposure limit is conservative since it ignores the hand and foot contact resistances present in the actual shock current circuit. The actual voltage maximum based on the "let-go" current limit can be calculated using Equations 3-15 and 3-16 by replacing the transient current limit, Equation 3-14, with the steady-state let-go current limit of 15 mA. This is illustrated by the following equations.

$$V_{step} = (1000 + 6\rho)0.015$$

[3-19]

$$V_{touch} = (1000 + 1.5\rho)0.015$$

[3-20]

### 3.3.4(d)  Prediction

A pipeline can be modeled for cathodic protection purposes as a network of series resistances representing the per unit longitudinal resistance of the pipe ($R_L$) and parallel resistances representing the pipe's per unit shunt resistance to earth ($R_S$). When determining the pipe's response to AC interference, two other factors must be considered—the pipe's longitudinal inductance ($L_L$) and its shunt capacitance ($C_S$) as shown in Figure 3-58. Because of these two additional factors, an AC current traveling along a pipeline sees a greater longitudinal pipeline impedance than does a DC current and also a lower shunt impedance to earth, which means that an AC signal attenuates more rapidly along a pipeline than a DC signal. For simplicity, the longitudinal resistance and the inductive reactance can be combined to form a longitudinal impedance ($Z_L$). Similarly, the shunt resistance and capacitive reactance can be combined to form a shunt impedance ($Z_S$). These simplifications are shown in Figure 3-59, but for reasons of symmetry, the shunt impedance ($Z_S$) has been split into two shunt impedances of $2Z_S$ in parallel.

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[15]*NACE Standard SP0177 (latest version), "Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems,"(Houston, TX: NACE).*
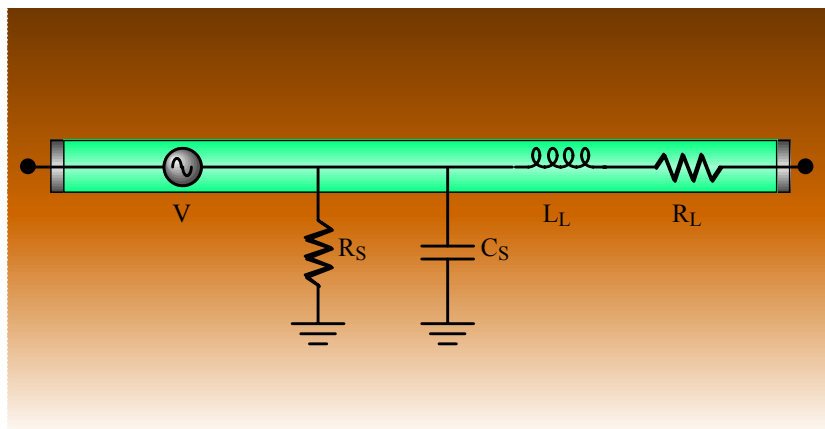
**Figure 3-58:  AC Model of Pipe Section**
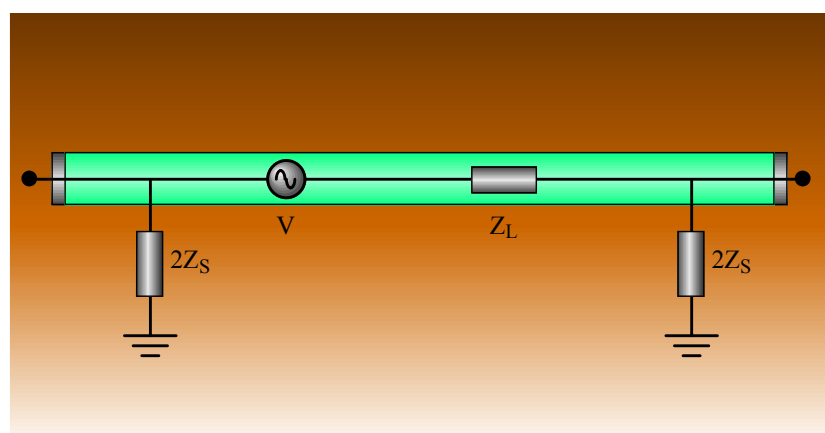


**Figure 3-59:  Simplified AC Model of Pipe Section**

To determine how voltages behave on a long pipeline, pipe sections as shown in Figure 3-58 can be joined and the voltages and currents can be determined using electrical network analysis techniques. As a simple example, consider the pipeline model in Figure 3-60 consisting of only two pipe sections. Assuming the electromagnetic field to which the pipeline is exposed is uniform along the length of the pipeline, then $V_1 = V_2$. Furthermore, it can be shown using Kirchhoff's laws that $I_1 = I_2$, but this should also be apparent from the symmetry of this simple case. The network in Figure 3-60 can therefore be simplified to the one shown in Figure 3-61.
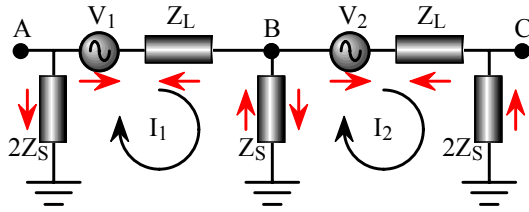
**Figure 3-60: Network Analysis of Two-Section Pipe Model**
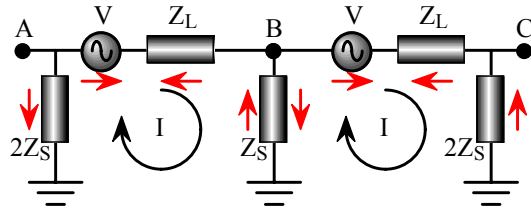
**Figure 3-61: Network Analysis of Simplified Two-Section Pipe Model**

The voltages at each end of the pipeline and at the midpoint can now be calculated.

$$V_A = 0 - 2Z_S I = -2Z_S I \qquad V_B = 0 + Z_S I - Z_S I = 0 \qquad V_C = 0 + 2Z_S I = 2Z_S I$$

Plotting these voltages gives the AC voltage profile shown in Figure 3-62. Note that AC voltages do not really exhibit polarity as shown in the plot. What polarity indicates in this case is that the AC waveform at one end of the pipeline is 180º out of phase with the waveform at the other end of the pipeline. If an AC voltmeter was used to measure voltages to earth at points A, B, and C, the profile in Figure 3-63 would be observed, but keeping in mind the voltage at point A is 180° out of phase with the voltage at point C, then the voltage between these two points would be twice the voltage at either point to ground.
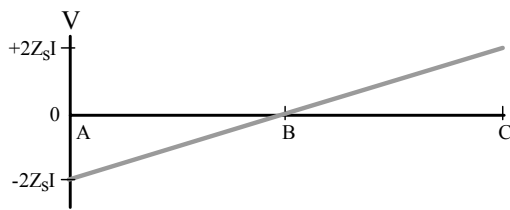


**Figure 3-62: AC Voltage Profile Along Pipeline with 'Polarity" Indicated**
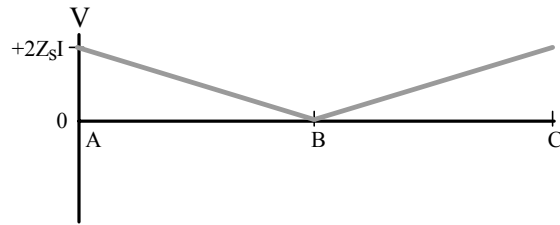
**Figure 3-63: AC Voltage Profile Along Pipeline as Measured Using AC Voltmeter**

Figure 3-63 indicates the actual voltage profile that would be seen along a well coated pipeline where the electrical characteristics of the pipe ($Z_L$, $Z_S$), the soil resistivity, and the electromagnetic field strength are all uniform along the length of the pipeline. A key assumption here is that the pipeline is well coated. When a pipeline is well coated, the series combination of all of the longitudinal impedances is insignificant compared to the parallel combination of all of the shunt impedances. In other words, for a pipeline consisting of N identical sections, $N \cdot Z_L \ll Z_S/N$. When this condition holds true, an AC signal entering the pipeline at one end will disperse to ground uniformly along the length of the

pipeline, since there would be no significant voltage drop along the pipeline; that is, the AC signal attenuates linearly. In this case, we say that the pipeline is "electrically short" (i.e., it behaves like a short piece of well coated pipe) rather than simply saying it is well coated.

On the other hand, when a pipeline is either poorly coated or is well coated but so long that the series combination of longitudinal impedances can no longer be ignored, we say that the pipeline is either "lossy" or it is electrically long. In this case, if an AC signal is injected into one end of a pipeline, more current will discharge to earth at the injection end than at the far end due to the longitudinal impedance of the pipe. On an electrically long pipe, the AC signal would attenuate exponentially rather than linearly. This exponential signal attenuation is similar to what we see with cathodic protection currents, except that the AC attenuation constant that determines the shape of the attenuation curve is different from the DC attenuation constant, since it is a function of pipeline inductance and shunt capacitance and not just the longitudinal and shunt resistances.

The effect of electrical length on the AC voltage profile is shown in Figure 3-64. Note that electrically long pipelines subjected to electromagnetic coupling can exhibit zero voltages over much of their length provided the electromagnetic field and the electrical characteristics of the pipeline and the soil are uniform along this length.
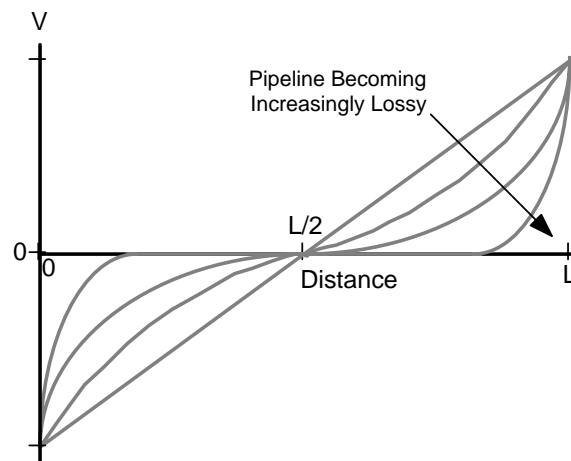


**Figure 3-64:  Effect of Electrical Length of Pipeline on AC Voltage Profile**

The electromagnetic field responsible for inducing voltages and currents onto the pipeline is usually referred to as the longitudinal electric field (LEF), which has the units of volts per meter (V/m). The LEF is represented by the symbol E and is a complex number, meaning it has a magnitude and a phase angle. Calculating the

LEF the pipeline is exposed to is a complicated mathematical task. In general the LEF is proportional to power line current and inversely proportional to pipeline-to-power line separation. The LEF is also a function of how the power lines are arranged on the tower. A set of curves is available that provides the LEFs for standard power line configurations from which induced AC pipeline voltages can be calculated.[16]

Alternatively, a procedure used for very simple pipeline-power line geometries can be used to estimate pipeline voltages. For the case shown in Figure 3-65, where a pipeline runs parallel to a power line at a fixed distance (d) and both ends of the pipeline are terminated with insulators, the LEF experienced by the pipeline can be estimated in the field using the procedure shown in Figure 3-66. An insulated conductor is laid out along the ground at a distance (d) from the centerline of the power line. If it is an existing pipeline, the wire should be placed on the opposite side of the power line from the pipeline so any fields created by the pipeline do not interfere with those of the power line. One end of the conductor is grounded, and the AC voltage at the other end of the wire is measured to earth. The induced voltage measured in the wire, divided by the length of the wire, is approximately equal to the magnitude of the LEF as seen by the pipeline.
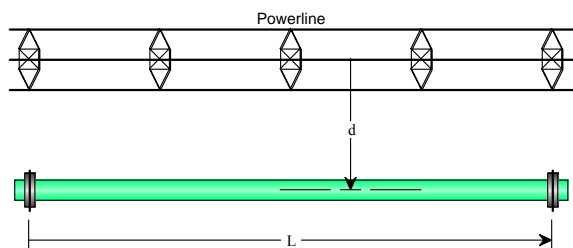


Figure 3-65: Simple Pipeline-Power Line Corridor (Plan View)

$$|E| \approx \frac{V}{x}$$
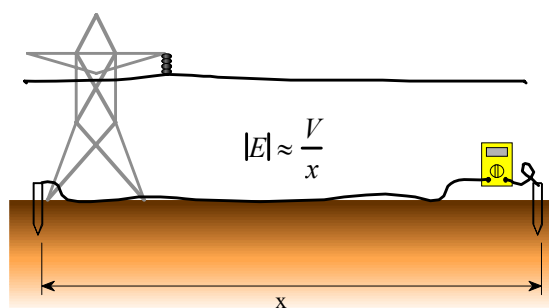
Figure 3-66:  Field Estimation of LEF

Current loading of the power lines can change significantly from hour to hour, from day to day, or seasonally. The time and date at which the LEF is measured should be recorded and, if possible, it should be correlated with the actual power line loading (available from the power company). For instance, if the power line was operating at 50% maximum load at the time of the measurement, it could be

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[16] *"Power Line-Induced AC Potentials on Natural Gas Pipelines for Complex Rights-of-Way Configurations,"* Electric Power Research Institute, EPRI Report No. EL-3106.

assumed that the LEF would be double the measured value during periods of maximum loading.

Once the magnitude of E has been measured, the voltage peaks on the pipeline can be calculated. As was shown in Figure 3-63, the voltage peaks for the simple pipeline-power line geometry shown in Figure 3-65 will always be at the insulators, with a zero voltage occurring at the midpoint. In the case of an electrically short pipeline, the voltages at the insulators can be calculated using Equation 3-21. The voltage profile for this ideal case is shown in Figure 3-67.

$$V_{O,L} = \pm \frac{|E| \bullet L}{2}$$
[3-21]

E – Longitudinal Electric Field [LEF] (V/m)
L – Length (m)

If the electrical characteristics of the pipeline are not symmetrical, the voltage peak at one end of the pipeline may be higher than that predicted by Equation 3-21, and the peak at the other end would be lower, as shown in Figure 3-68. The most extreme case occurs if one end of the pipeline is perfectly grounded (to a zero ohm ground) and the other end is insulated. In this case, the pipe voltage at the grounded end would be zero, but since the voltage induced from one end of the pipe to the other remains unchanged, the voltage at the opposite end will rise to twice what it was in the case of uniform conditions, as shown in Figure 3-69. It is important to remember that when mitigating induced voltages, the indiscriminate use of grounding electrodes may actually increase voltages.

If grounds are applied to both ends of the pipeline or if grounds are uniformly distributed along the pipeline, then all voltages can be mitigated to less than those predicted by Equation 3-21, as shown in Figure 3-70.
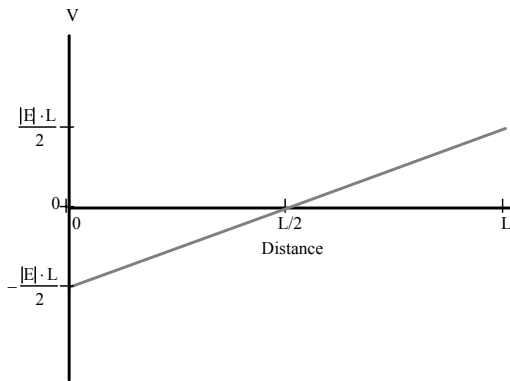
**Figure 3-67: AC Voltage Profile Along
an Electrically Short Pipeline
(Uniform Conditions - No Grounding)**
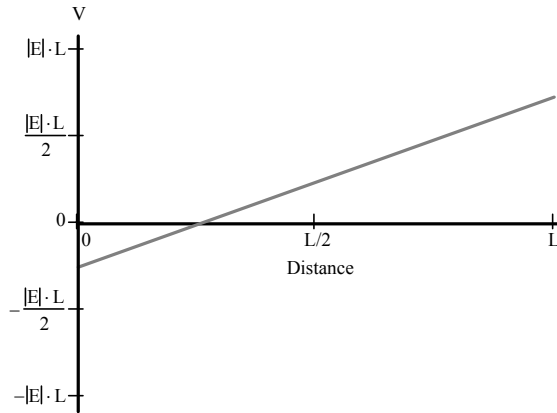
**Figure 3-68: AC Voltage Profile Along
an Electrically Short Pipeline
(Non-Zero Resistance Ground at Distance = 0)**
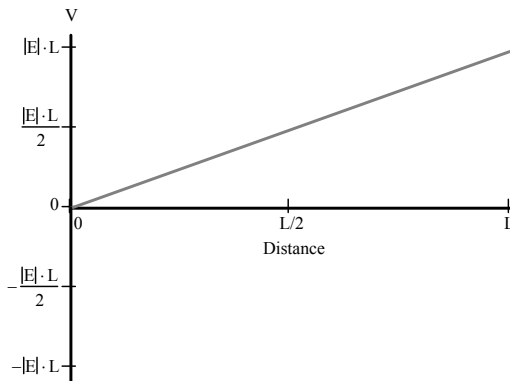
**Figure 3-69: AC Voltage Profile Along
an Electrically Short Pipeline
(Zero Resistance Ground at Distance = 0)**
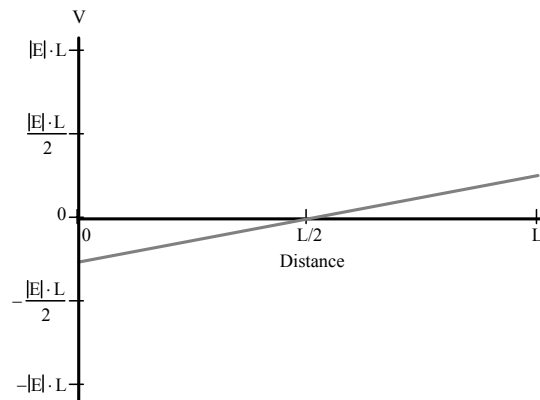
**Figure 3-70: AC Voltage Profile Along
an Electrically Short Pipeline
(Grounds Evenly Distributed or at Both Ends)**

It is important to note that the value $|E| \cdot L$ represents an absolute limit of the maximum induced voltage that can appear on a pipeline, regardless of whether the pipeline is electrically long or short or where the grounds and insulators are installed. For example, if the field strength along the pipeline is 10 V/km under maximum loading conditions, and the pipeline parallels the power line for 5 km, then the maximum voltage that can appear on the pipeline is 50 V. However it is more likely that this voltage would be more evenly distributed with approximately 25 V appearing at each end and 0 V appearing near the pipeline's midpoint.

As the pipeline increases in length, it becomes more lossy and instead of seeing a linear voltage profile as shown in Figures 3-67 through 3-70, we begin to see an exponential change in voltages, as was shown in Figure 3-64. Furthermore,

Equation 3-21 predicts that as pipeline length increases, pipeline voltages increase proportionately and without limit, which is not the case when the pipeline is lossy. To calculate voltages on an electrically long pipeline, the pipeline's length $\frac{L}{2}$ in Equation 3-21 is replaced by the pipeline's *electrical length*, $1/\Gamma$, resulting in Equation 3-22.

$$V_{O,L} = \frac{|E|}{\Gamma}$$  [3-22]

E – LEF (V/M)

$\Gamma$ – Propogation Constant $(\frac{1}{m})$

The parameter $\Gamma$ is known as the pipeline propagation constant. It is a constant related to the electrical characteristics of the pipeline and is closely connected to the pipeline's AC attenuation constant. The value of $\Gamma$ can be calculated, however it is a complicated function of pipe depth, soil resistivity, AC frequency, and coating resistance, as well as pipe diameter, wall thickness, and material. Alternatively, the value of $\Gamma$ can be obtained from tables or graphs.[17] Figure 3-71 shows the AC voltage profile along a pipeline for the simple pipeline-power line geometry shown in Figure 3-65, where the pipeline is electrically long or lossy. It was found in the case of an electrically short pipeline that grounding one end could actually increase voltages at the opposite end. In the case of an electrically long pipeline, however, grounding one end of the pipeline would have no effect on the other end, since the two points are electrically remote from one another (Figure 3-72).

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[17] *"Power Line-Induced AC Potentials on Natural Gas Pipelines for Complex Rights-of-Way Configurations,"* Electric Power Research Institute, EPRI Report No. EL-3106.
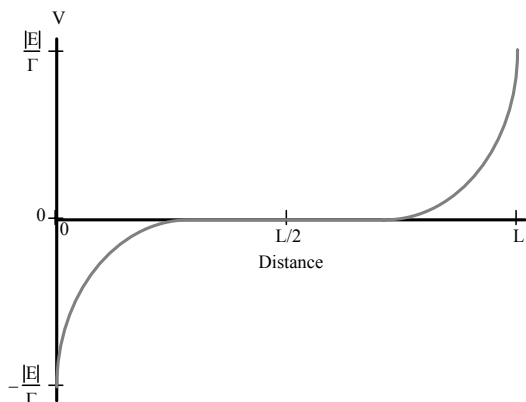
**Figure 3-71: AC Voltage Profile Along an Electrically Long or Lossy Pipeline (Uniform Conditions - No Grounding)**
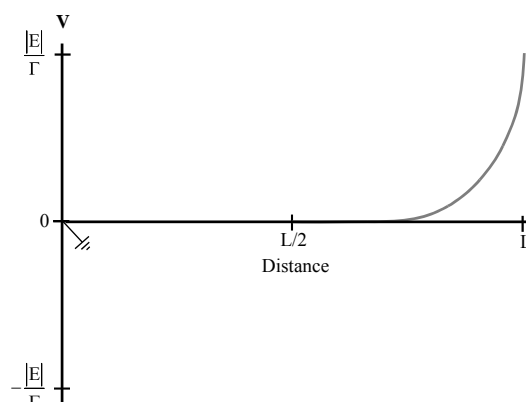
**Figure 3-72: AC Voltage Profile Along an Electrically Long or Lossy Pipeline (Zero Resistance Ground at Distance = 0)**

As previously mentioned, electrically long pipelines may exhibit zero voltages over much of their length provided the electromagnetic field and the electrical characteristics of the pipeline and the soil are uniform along this length. If any one of these parameters changed at some point along the pipeline (referred to as an *electrical discontinuity*), an additional voltage peak would be introduced at that point. Although the magnitude of this voltage peak would depend on the severity and nature of the discontinuity, it could possibly create an additional peak of $V = \frac{1}{2}E\frac{1}{2}G$. This is an important aspect of electrically long pipelines.

To better illustrate the difference between electrically long and electrically short pipelines, consider the case of a pipeline several hundred kilometers long running west across North America from the Atlantic coast. The pipeline is paralleled by a power line for the entire distance, and the electrical characteristics of the pipeline, power line, and the earth are uniform along the entire route. Because the pipeline is electrically long, voltage peaks would be created at each end of the pipeline having a voltage of $V = |E| / \Gamma$, whereas the majority of the pipeline would exhibit a zero voltage. Now consider what happens when the pipeline is extended to the Pacific coast, again assuming that all conditions remain uniform along the length of the pipeline. Even though the pipeline is now perhaps ten times longer, voltage peaks still exist only at the two ends of the pipeline, and the magnitude of these voltage peaks remains limited to $V = |E| / \Gamma$.

The installation of insulators will introduce additional voltage peaks on the pipeline. On an electrically short pipeline, the installation of an insulator essentially creates two electrically separate pipelines having smaller voltage peaks than the original pipeline, since the voltages are proportional to the physical lengths of each pipe section (Figure 3-73). On an electrically long

pipeline, however, the magnitudes of the voltage peaks are unaffected, as long as any new pipe sections created by the insulators may still be considered electrically long (Figure 3-74).
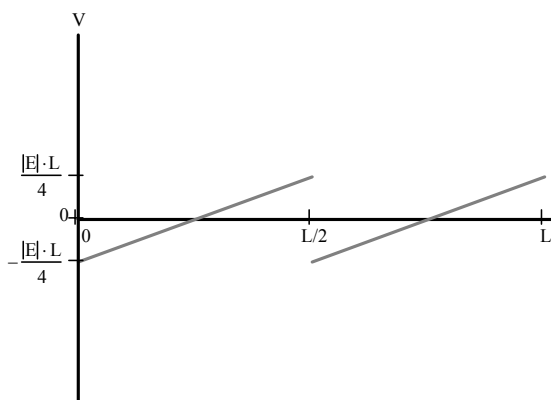


**Figure 3-73: AC Voltage Profile Along Electrically Short Pipeline with Insulator at Midpoint**
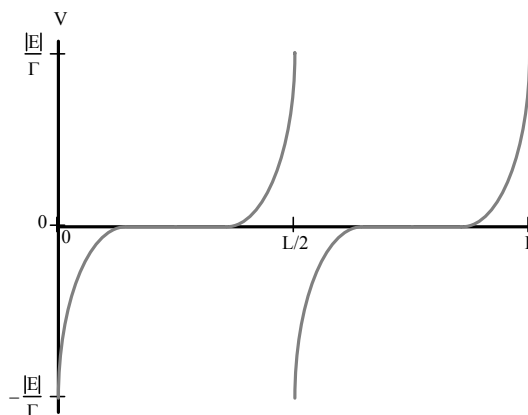
**Figure 3-74: AC Voltage Profile Along Electrically Long Pipeline with Insulator at Midpoint**

There is one other important aspect regarding the effects of electrical insulators on induced AC pipeline voltages. As shown in Figure 3-73, an insulator installed at the midpoint of an electrically short pipeline reduces peak voltages to one-half their previous values. However, the voltage that appears across this insulator is double the voltage that appears between the pipeline and earth. This is because the voltages on either side of the insulator, while equal in magnitude, are of opposite polarity or, more accurately, are 180 degrees out of phase with one another. In the case of an electrically long pipeline, voltage peaks are not reduced by the installation of an insulator, so the voltage that occurs across the insulator will be double the peak value or $\dfrac{2|E|}{\Gamma}$. Therefore, as was the case with electrical grounds, electrical insulators must not be used indiscriminately on a pipeline affected by induced AC interference, since this could introduce new voltage peaks and could create voltage differences twice as severe as what could exist between the pipeline and ground.

The prediction of induced AC voltages, as discussed above, requires knowing if the pipeline is electrically short or electrically long. If this is not known or if the pipeline falls somewhere in between these two cases, more complicated calculation procedures are required. Also, when there are changes in the power line circuit configuration or when the separation distance between the pipeline and power line changes significantly, the LEF will no longer be constant

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along the pipeline. Equations 3-21 and 3-22 cannot be used under these conditions and the additional voltage peaks created cannot be accounted for. Such problems can be very difficult to solve and require either laborious analytical treatments or the use of specialized software packages.

### 3.3.4(e)  Mitigation

To mitigate electromagnetically induced AC voltages to safe levels the pipeline must be grounded. Grounding the pipeline has the same effect as replacing a good coating with a poor coating; that is, by lowering the value of $Z_S$ in Figure 3-59 the voltages produced by the flow of AC current from the pipeline to earth are reduced.

Ground electrodes may consist of either packaged sacrificial anodes, sacrificial anode ribbons installed in special backfill, or conventional grounding materials such as ground rods and cables. Materials that are not anodic to the pipeline, such as copper cables, would seriously affect the effectiveness of the cathodic protection system if directly connected to the pipeline. Such materials should therefore only be used if they are *DC decoupled* from the pipeline using a suitable device, such as a polarization cell, or a solid state alternative to a polarization cell (Figure 3-75).



Ground electrodes may be evenly distributed along the pipeline, such as by installing packaged sacrificial anodes at regular intervals; however, it is often more effective to concentrate the ground electrodes at electrical discontinuities where the voltage peaks tend to occur. The effects that various mitigation systems have on induced AC voltages is difficult to predict without complex calculations or the use of specialized software and, as was shown previously, the indiscriminate use of ground electrodes may actually increase induced voltages at some points along a pipeline.

**Figure 3-75:  Solid State DC Decoupling Device**

Grounding is also used to minimize the risk of AC corrosion damage to the pipeline. By reducing induced AC voltages, the current densities at coating holidays as predicted by Equation 3-18 can be reduced. As a worst case, it is normally assumed that a coating holiday has a diameter of approximately 1 cm. Voltages are then mitigated to levels that would reduce AC current densities to less than 100 A/m$^2$ and preferably to levels less than 50 A/m$^2$.


## 3.4  Telluric Current Interference

Telluric currents are currents that are geomagnetically induced in the earth and in metallic structures on the earth, such as power lines and pipelines, as a result of the interaction of solar particles on the earth's magnetic field as shown in Figure 3-76.
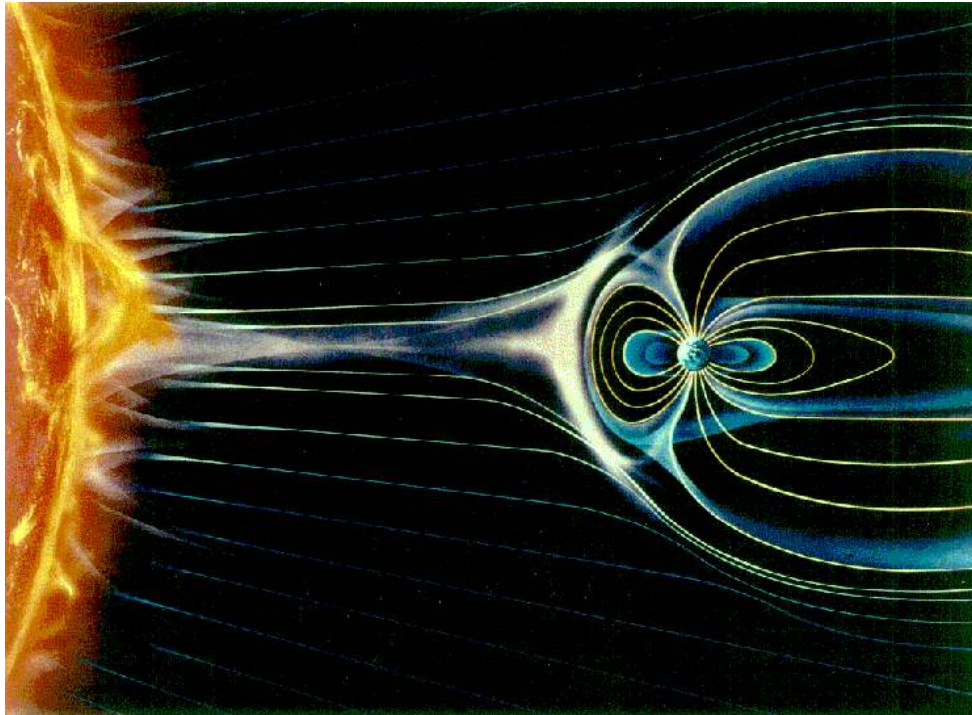


**Figure 3-76:  Interaction of Solar Particles with the Earth's Magnetic Field**

Charged solar particles entering the earth's atmosphere are deflected by the earth's magnetic field creating current rings in the ionosphere centered around the north and south poles. These current rings typically contain more charges than are generated by man on earth. Because of the amplitude variation and directional

changes in this electrojet current, a changing magnetic field is produced that induces an electric field in any metallic conductor on or near the earth's surface as depicted in Figure 3-77.
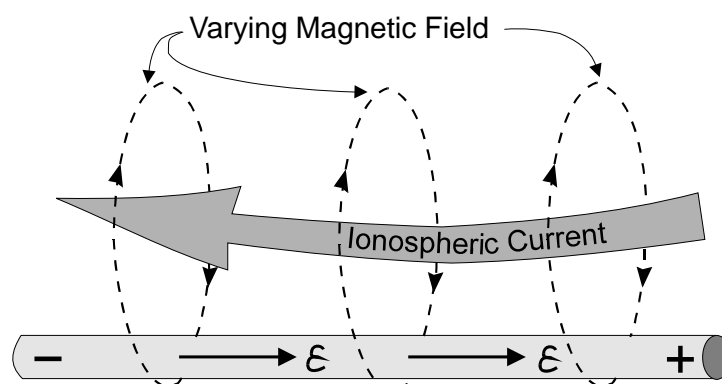


**Figure 3-77: Schematic of Geomagnetic Induction Directly into a Pipeline and the Resulting Change in Pipeline Potential Produced**

Source: Boteler, D.H., Gummow, R.A. and Rix, B.C., Evaluation of Telluric Current Effects on the Maritimes and Northeast Pipeline, NACE Northern Area Eastern Conference, Ottawa, October 1999, Paper No. 8A.3, p. 8

This induction process is similar to that caused by AC power lines, except the frequency and amplitude vary considerably due to many factors such as

- the solar cycle, which is a period of approximately 11 years between peaks of solar activity
- the sun's rotational frequency – 27 days
- the Earth's daily rotation – 24 hours (diurnal cycle)
- tidal fluctuations (~12.5 hours)
- direction of the magnetic field in the solar particle plasma

## *3.4.1   Interference Effects*

The magnetic variations show up as current and potential fluctuations on pipelines. An example of the latter is shown in Figure 3-78.
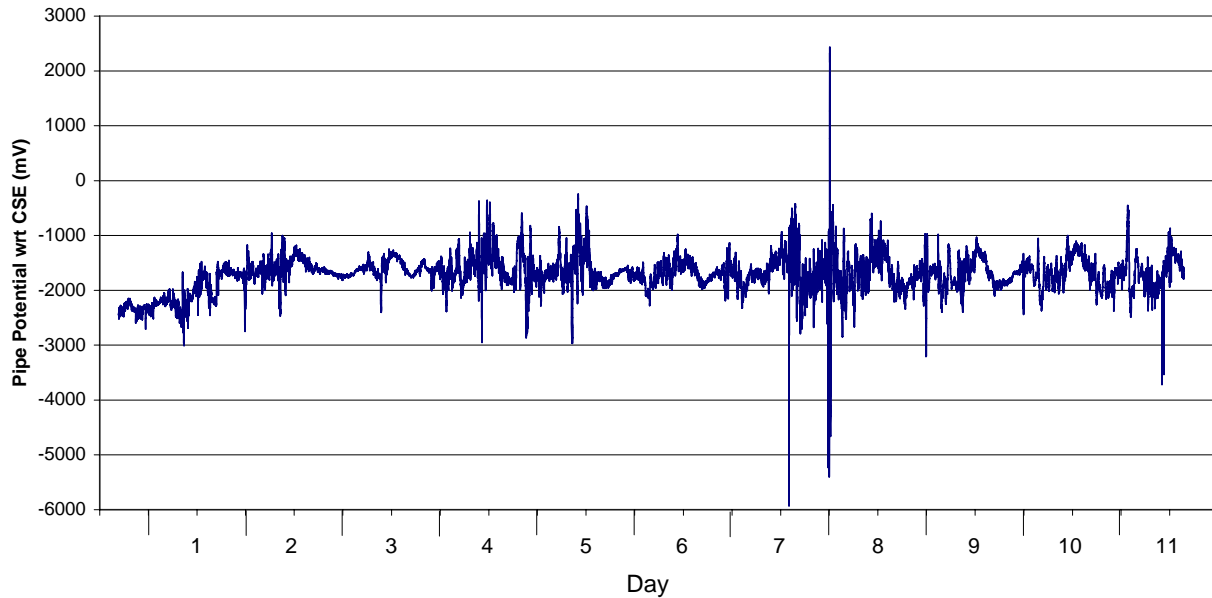
**Figure 3-78:  Example of Geomagnetically Induced Potential Fluctuations on a Pipeline**

This stray current pattern reflects tidal related fluctuations, general randomness of the telluric activity, and a more energetic magnetic storm (days 7 and 8).

Short-term positive excursions in potential do not represent a significant corrosion risk on a cathodically protected pipeline, but if the excursions occur daily, as with diurnal or tidal influences, serious corrosion can occur. The pipeline induced voltage versus distance profile is much the same as with AC induction. As illustrated in Figure 3-79, the longer the pipeline is and the better coated it is, the greater the induced voltage ($V_{p,g}$) will be.
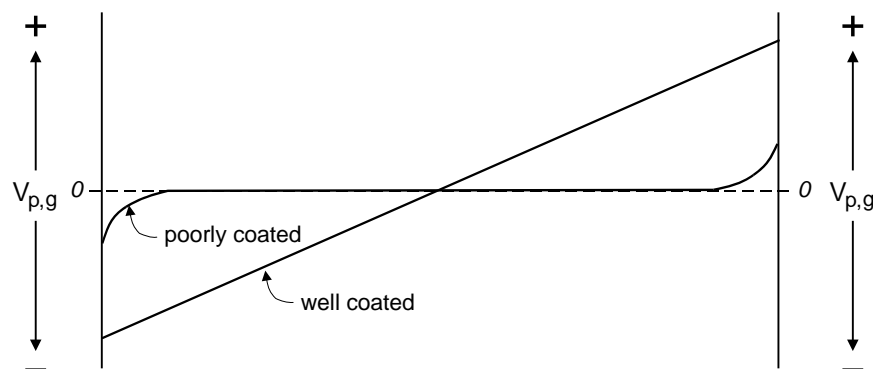


**Figure 3-79:  Typical Geomagnetically Induced Potential Profile on a Well Coated and Poorly Coated Pipeline**

This shows that a pipeline that is electrically lossy (i.e., leaks charges to earth) will have smaller amplitude fluctuations. Unfortunately, for cathodic protection purposes a very high resistance coating is desirable and improves cathodic protection current distribution.

Geomagnetically induced voltage peaks appear on a pipeline:

- at isolating joints
- at changes in direction
- as pipeline length increases
- as pipeline coating resistance increases
- as the pipeline location is closer to the earth's magnetic poles (but not at the poles)
- at or near a sea coast
- at or near sharp geological transitions or anomalies
- in high resistivity soil

Although one severe case of corrosion caused by telluric current has been reported,[18] the major effect of telluric currents on pipelines is in the ability to accurately measure the pipeline polarized potential ($E_p$). The telluric current activity produces an additional voltage drop in the earth ($V_t$) between the reference and the pipe holidays as illustrated in Figure 3-80.
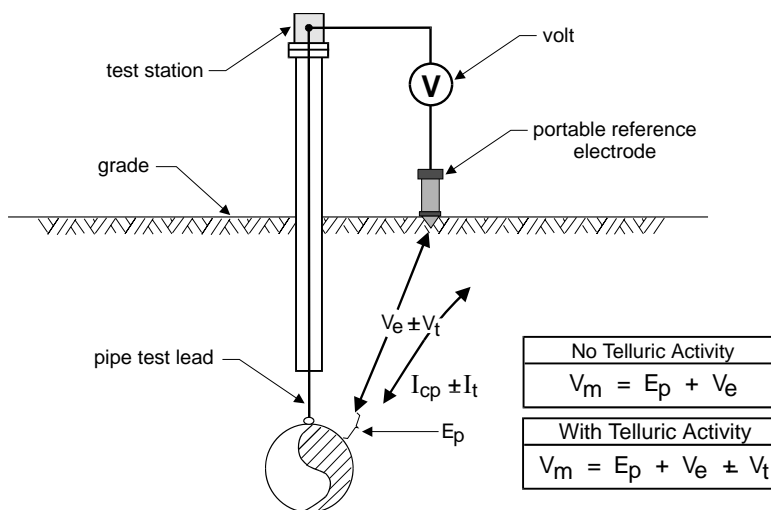


**Figure 3-80:  Typical Pipe-to-Soil Potential Measurement Situation Where Telluric Current Activity is Present**

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[18] *Brochu, B., NACE Northern Area Eastern Conference, Quebec City, August 2003.*

Whereas the voltage drop ($V_e$) in the earth due to cathodic protection current can often be interrupted, the telluric voltage drop ($V_t$) cannot. This can introduce a significant error in the potential measurement ($V_m$) as shown in Figure 3-81.
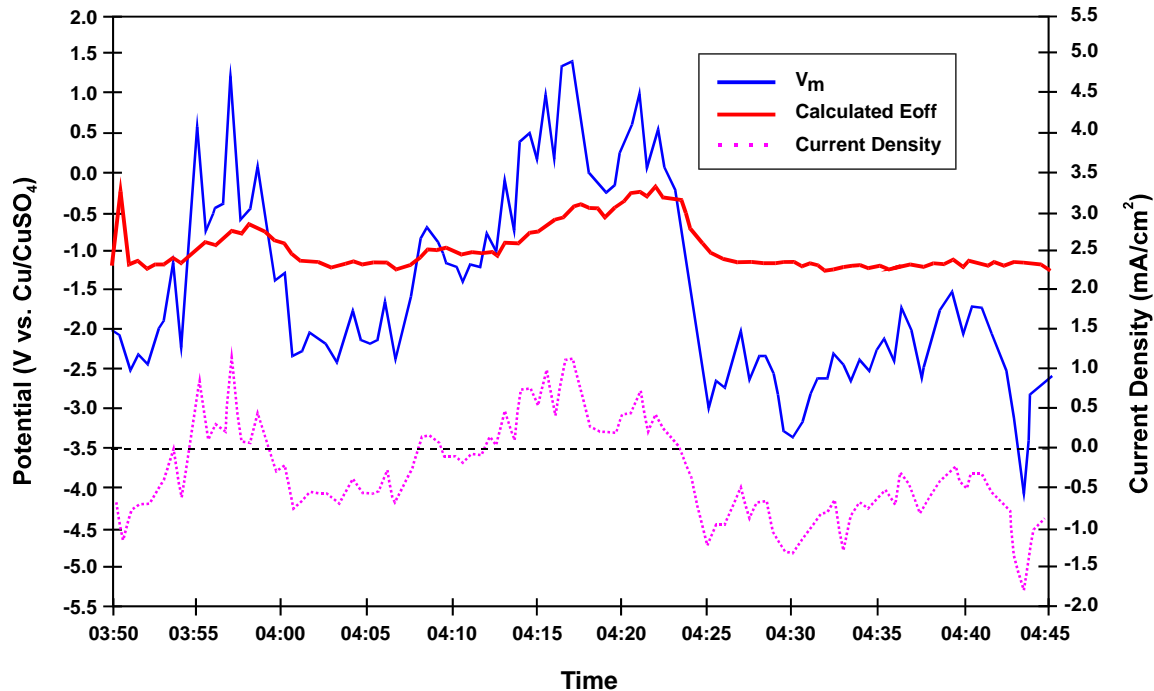


**Figure 3-81:  Current Flow and Calculated Off Potentials During a GIC Incident**

Source:  Redrawn from Hesjevik, S.M. and Birketveit, O., Telluric Current on Short Gas Pipelines in Norway – Risk of Corrosion on Buried Gas Pipelines, NACE Corrosion 2001, Houston, TX, Paper #313, p.6

With the calculated telluric voltage drop removed from the "On" potential measurement, during the positive potential excursions the calculated "Off" potential is not more positive than about –0.25$V_{cse}$, whereas the measured"On" potential goes more positive than zero on two occasions. The measured coupon current direction also reverses on these two occasions for a total of about 20 minutes during which one would expect corrosion to take place, although the corrosion rate is not as calculated by Faraday's law.

As with most dynamic stray current interference, an investigation of the effects requires considerable potential and current recordings. But measuring an accurate polarized potential in the presence of an uninterruptible stray current requires special procedures.

Coupons facilities that do not require disconnection of the coupon to measure a true potential can be used at test station locations, an example of which is shown in Figure 3-82.
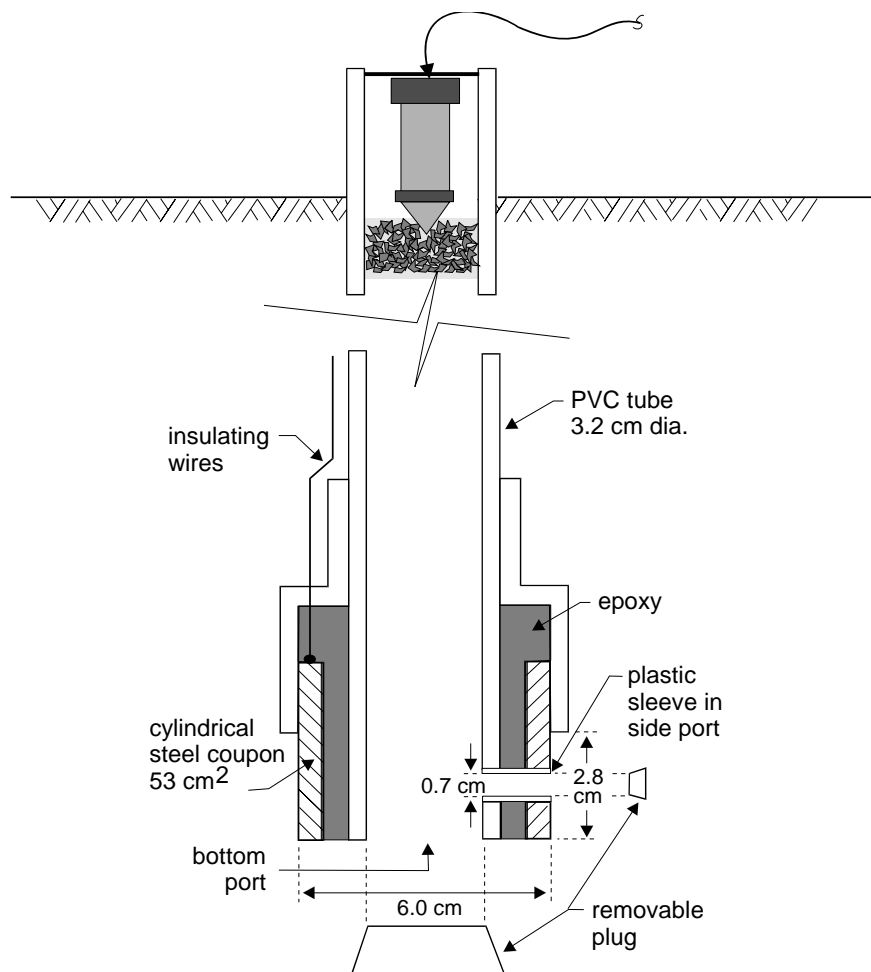


**Figure 3-82:  Example Test Station in Which Coupon Does Not Require Disconnection to Minimize IR Drop Error in the Potential Measurement**

Nekoksa, G. and Turnipseed, S., "Potential Measurements on Integrated Salt Bridge and Steel Coupons", CORROSION/'96, paper no. 206 p.9 (Houston, TX: NACE, 1996).

The benefit of such facilities is shown in Figure 3-83. In this case it would be difficult to evaluate the level of polarization based on the potential-time plot with respect to a copper-copper sulfate reference electrode placed on grade.
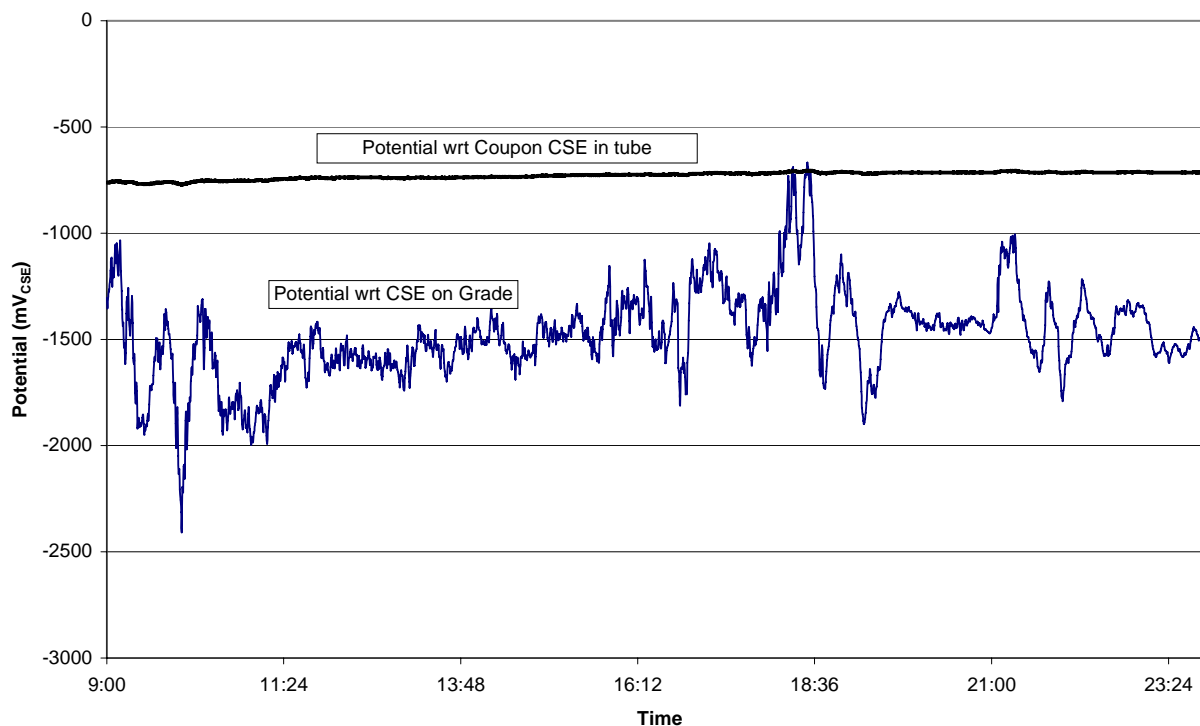


**Figure 3-83:  Example of Difference in Potential-Time Recording Between Reference Electrode at Grade and Inside a Soil Tube with a Coupon (e.g., Figure 3-82)**

Despite the large potential fluctuations recorded by a surface reference electrode, the polarized potential remained relatively steady.

Difficulty in minimizing the telluric current voltage drop is also a problem when conducting close interval surveys. One technique that has been used to account for the telluric IR drop error in the measurement, as shown in Figure 3-84, involves using two data loggers or a single data logger with two channels. Potentials are recorded with respect to a fixed reference electrode ($V_f$) and a moving reference electrode ($V_m$).
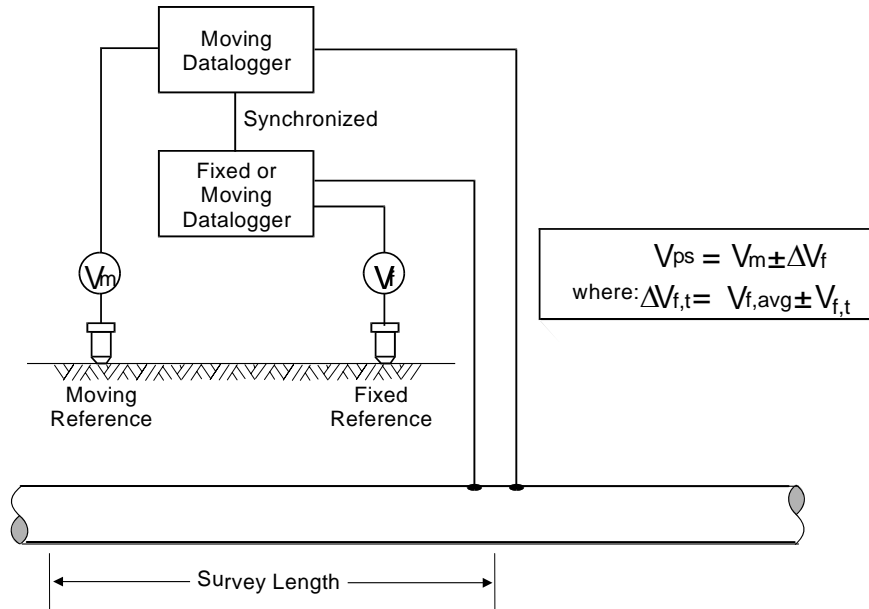
**Figure 3-84:  Pipe-to-Soil Potential Measurement Method to Compensate for Telluric Current Effects During a Close Interval CP Survey**

Before beginning the survey, potentials are recorded with respect to the fixed electrode to establish an average potential ($V_{f,avg}$) of the structure at the fixed electrode position. Then the potential recorded by the moving reference at any time (t) is corrected by the change in potential ($\Delta V_f$) that occurs at the fixed electrode at the same time. Hence for any time (t):

$$V_{p,t} \;=\; V_{m,t} \pm \Delta V_{f,t} \qquad\qquad [3\text{-}23]$$

*where:* $\qquad\qquad \Delta V_{f,t} \;=\; V_{f,avg} \pm V_{f,t} \qquad\qquad [3\text{-}24]$

the accuracy of this method diminishes as the distance between the moving reference and the fixed reference increases. Using a fixed reference at the start and finish of the close interval survey and extrapolating the changes in both fixed references ($\Delta V_{f,1}$ and $\Delta V_{f,2}$) linearly with distance between the moving electrode and fixed electrode improves the accuracy.

## 3.4.2   Mitigation of Telluric Current Effects

Mitigating telluric interference is similar to mitigating AC interference since both are induced currents. Providing safe low resistance leakage paths to earth without compromising the level of cathodic protection is the principal objective.

Galvanic anodes, distributed along the pipeline route, can be effective in minimizing telluric stray current corrosion effects provided the soil resistivity is low enough for the anode to produce a significant current. As depicted in Figure 3-85, some of the telluric current ($I'_t$) will leak to ground via the galvanic anode.



where:   $I_t = I'_t + I''_t + I'''_t$
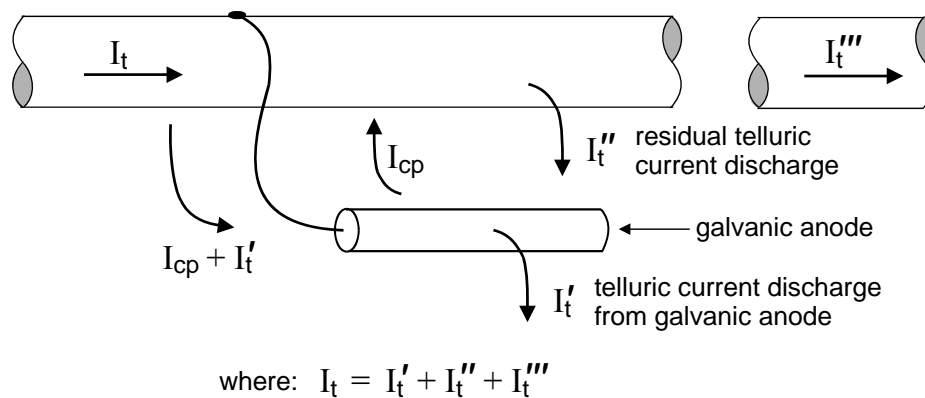
**Figure 3-85:  Mitigation of Telluric Current Discharge Effects Using Galvanic Anodes**

The effectiveness of this method relies on the anode cathodic protection current ($I_{cp}$) being greater than the residual telluric discharge current ($I''_t$). Typically distributed galvanic anodes can lower the pipe-to-earth resistance of a well coated pipeline by more than an order of magnitude.

If impressed current cathodic protection is preferred, potential controlled transformer-rectifiers should be used as schematically illustrated in Figure 3-86.
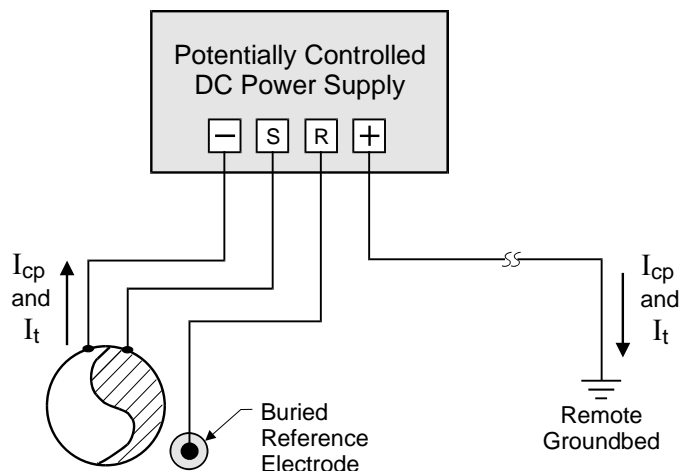
**Figure 3-86: Schematic of Potentially Controlled Cathodic Protection System Used
to Mitigate Telluric Current Effects**

When the buried reference electrode senses a positive shift in the pipe potential, the output voltage of the power supply is automatically increased, which makes the path through the rectifier to earth appear as a negative resistance to the telluric current. Thus, there should be no residual current discharge at this location during periods when the pipe tends to discharge the interference current unless the maximum current or voltage output of the power supply has been reached. The power supply and groundbed must be properly sized and rated to accommodate the anticipated telluric current activity.

When the pipeline is subjected to the negative telluric half-cycle (current pick-up period), the power supply will shut down since the pipeline will be receiving free cathodic protection. The typical operating characteristics of the impressed current mitigation system are shown in Figure 3-87.
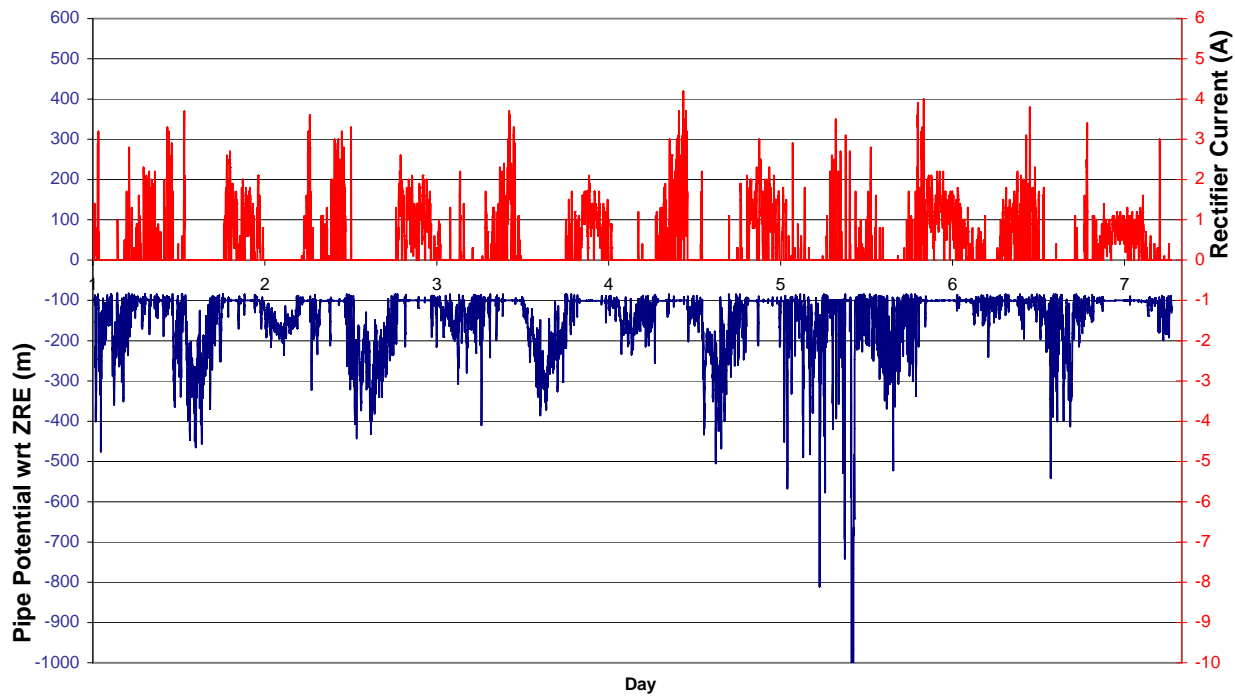
**Figure 3-87:  Pipe Potential and Rectifier Current Output vs. Time for an
Impressed Current System Operating in Potential Control**

This graph shows the current output and pipe potential with respect to a buried zinc reference electrode as a function of time. Note that when the potential attempts to shift more positive than $-100mV_{ZRE}$ the rectifier produces a current output, and when the potential is more negative than $-100mV_{ZRE}$ the rectifier output is zero. The autopotential control effectively clips the positive telluric excursions at the set point of $-100mV_{ZRE}$.

# *Experiment 3-1*
# To Demonstrate DC Interference and Its Mitigation
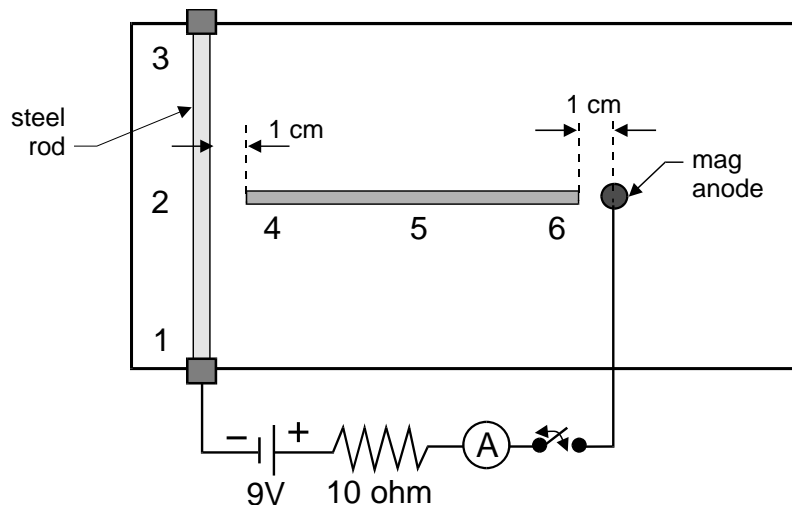


**Experiment Schematic No. 1**

## Procedure

**Step:**

A. Place bare steel rod along one end of the tub in 5 cm of water obtained from the cold water tap. Connect the 9V battery, 10 ohm resistor, ammeter, and switch in series between the steel rod and magnesium anode. Close the switch and allow the CP system to operate for a minimum of 5 minutes.

B. Measure and record the potential on the steel rod with the reference positioned at locations 1, 2, and 3. Record the current.

C. Open the switch and insert the second steel rod (foreign structure) perpendicular to the first steel rod at location 2.

D. Measure and record the foreign structure potential at reference locations 4, 5, and 6 with switch remaining open.

E. Close the switch and allow the CP system to operate for a minimum of 5 minutes.

F. Measure and record structure potentials at all reference locations on both structures and record the CP current.

G. Calculate the shift in potential at locations 4, 5, and 6 on the foreign structure and the change in CP current.

## *Discussion Break*

H. Mitigate interference using a resistance bond connected between the cathodically protected structure and the foreign structure as in Schematic No. 2. Adjust resistance bond until the foreign structure potential at location 4 is equal to or more negative than its native potential.
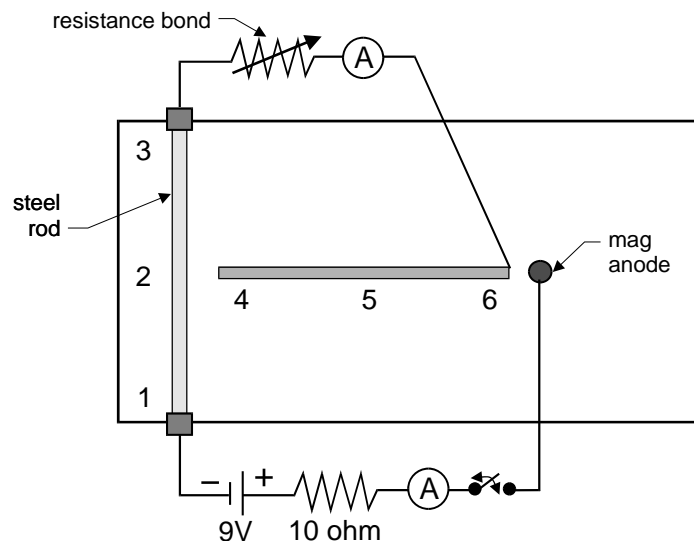


**Experiment Schematic No. 2**

I. Measure and record potentials on both structures. At all reference locations, measure CP and mitigation current and record bond resistance.

## *Discussion Break*

J. Disconnect the resistance bond and install a galvanic anode to mitigate the interference as shown in schematic No. 3.
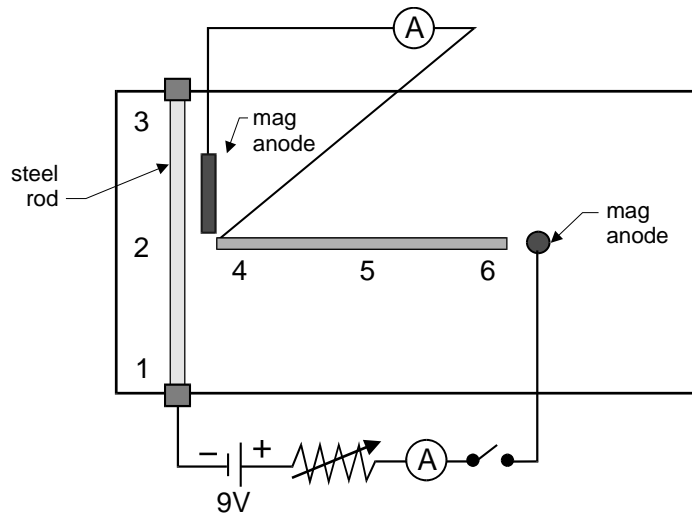
**Experiment Schematic No. 3**

K. Measure and record all structure potentials, CP current, and galvanic interference current ($I_{galv.}$).

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*Discussion Break*

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# Results

| | Structure Potentials (mV$_{CSE}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **STEP** | **CPed Structure** | | | **Foreign Structure** | | | **$I_{cp}$** | |
| | **1** | **2** | **3** | **4** | **5** | **6** | | |
| B | | | | X | X | X | | CPed structure only |
| D | X | X | X | | | | X | Foreign structure only |
| F | | | | | | | | Both structures |
| G | X | X | X | | | | | Shift calculations |
| | Mitigation | | | | | | | |
| I | | | | | | | | $I_b$ = _____  $R_b$ = _____ ohm |
| K | | | | | | | | $I_{galv.}$ _____ |

## Conclusions

1.  Foreign structure potential shifts electropositively at the stray current discharge location (#4).

2.  Foreign structure potential shifts electronegatively at the stray current pick-up location (#6).

3.  The cathodic protection current distribution on the CPed structure is affected by the presence of the foreign structure.

4.  The cathodic protection current increases when the foreign structure is present.

5.  The resistance bond mitigates the stray current interference on the foreign structure.

6.  The cathodic protection current increases with the resistance bond inserted but the CPed structure is less well protected.

7.  A galvanic anode mitigation system can mitigate the interference problem and maintain $E_{corr}$ on the foreign structure.

8.  The stray current magnitude is greater for the resistance bond than for the galvanic mitigation system.

## 4.1  Design Objectives

The principal cathodic protection design objectives are listed below:

- Provide sufficient current density continuously to all parts of the structure to polarize the structure to an acceptable criterion.

- Minimize interference effects to other metallic structures.

- Provide sufficient operational flexibility to accommodate expected changes in the environment, the coating, and the operation of the structure during the system service life.

- Ensure the safety of the public and operating personnel and adhere to all applicable codes and standards.

- Provide a system design life commensurate with the required life of the structure or system service life as stipulated by the owner or regulator.

- Provide testing facilities and monitoring equipment so performance of the cathodic protection system can be tested and monitored with respect to industry standards and regulations.

The cathodic protection design process for some structures can be very complex, requiring many iterations before arriving at an acceptable design. An example of a design procedure for a pipeline is outlined in the flow chart of Figure 4-1.
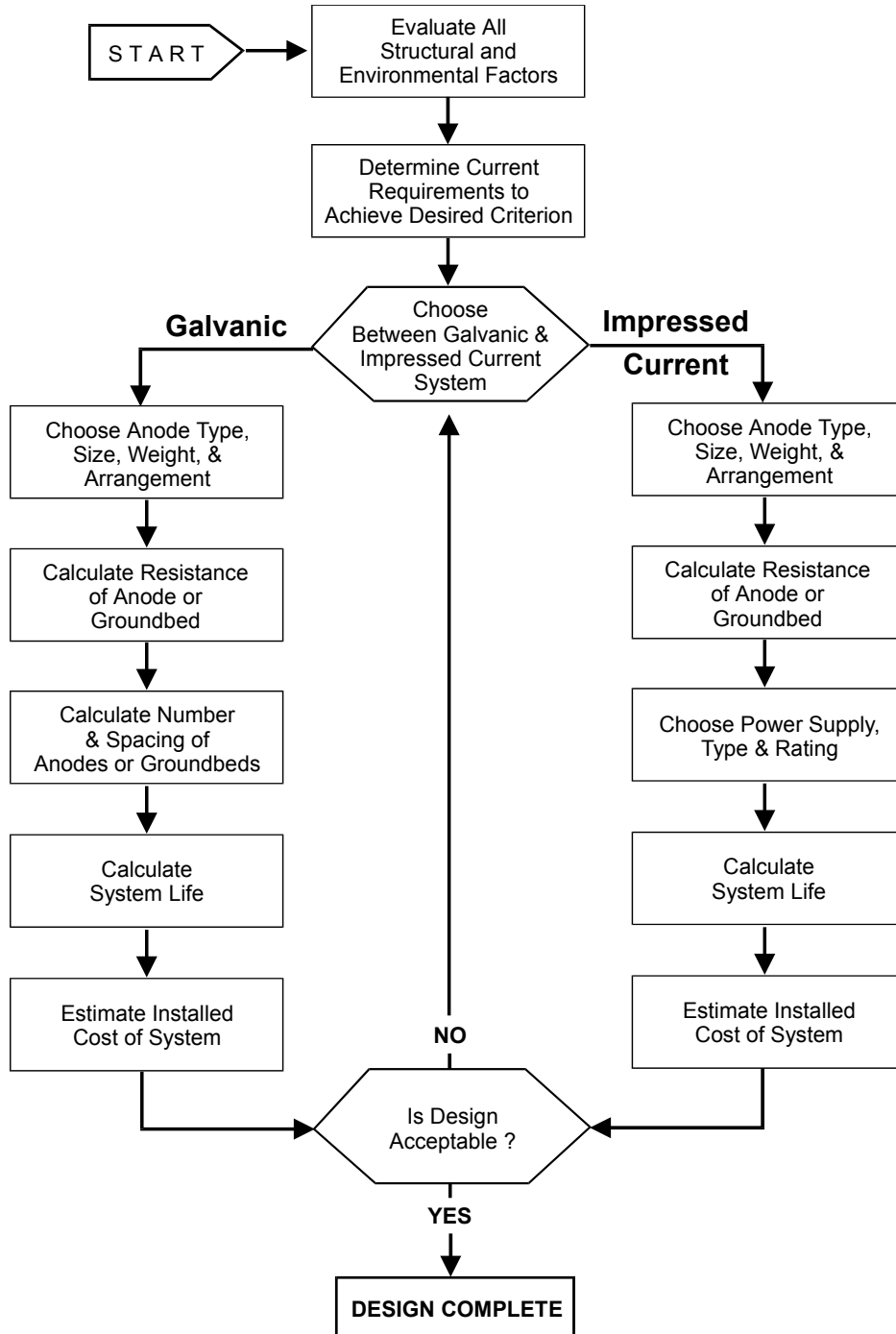
**Figure 4-1:  An Example of a Cathodic Protection Design Procedure**

The first step in the design process is to collect and evaluate pertinent data regarding the structure, its operational characteristics, and its environment. For a new pipeline cathodic protection project, the possible data set would include the following:

- **Pipeline Information**
    - construction specifications
    - pipe material, diameter, wall thickness, and pressure rating
    - pipe and joint coating type, thickness, and conductance
    - temperature, conductivity, and operating pressure ranges inside of medium inside pipeline
    - pipe route, number, and location of interconnections to related piping systems and feasibility of installing electrical isolation
    - electrical continuity of the pipeline
    - AC power availability and road access to possible CP facilities
    - number, length, and location of pipe casings
    - number, location, and operation of mainline valves and coating type
    - number, location, and extent of stations (e.g., compressor, pumping, metering, etc.)
    - number, length, and location of directionally drilled sections

- **Environmental Information**

    a) **Soil Conditions**
        - soil resistivity along the route at pipe depth
        - geotechnical information (soil types and depth)
        - moisture variability (seasonal)
        - temperature variability
        - pH variation

    b) **Electrical Interference Considerations**

        The presence, location, and operational characteristics of the following systems should be reviewed:

        - impressed current cathodic protection systems on foreign pipelines or other structures
        - electrical transit systems, high-voltage DC power lines, welding operations, and any other electrical system that uses the earth indirectly or directly as a current path
        - AC power transmission or distribution systems paralleling the pipeline or whose tower legs or electrical grounds are adjacent to the new pipeline

- foreign metallic structures and their susceptibility to interference damage
- susceptibility of the pipeline to telluric or ocean currents.

- **Other Information Required**
  - assess appropriate protection criteria
  - polarization characteristics to assess current requirement
  - structure attenuation characteristics
  - regulatory and permit requirements

- **Typical Field Surveys**
  - soil resistivity along pipeline route at pipeline depth and at a greater depth at prospective impressed current groundbed and galvanic anode locations
  - visual inspection of pipeline route for availability of electrical power for impressed current systems
  - induced AC test on an insulated wire along pipe route that parallels AC power lines
  - locating long-line corrosion "hot-spots" on bare piping.

## 4.2  Determining Current Requirements

### 4.2.1  Current Density

As shown in Figure 4-2, the polarized potential for steel varies widely over a current density range of 0.1 to 200 mA/ft$^2$ depending on soil conditions. Data in this figure were obtained by measuring the instant-off potential and current on bare steel coupons at 8 sites within the U.S. Note that the polarized potential at the Roswell site was less negative than –800 mV$_{cse}$ even at current densities approaching 100 µA/cm$^2$ (100 mA/ft$^2$), whereas a polarized potential of about –850 mV$_{cse}$ was obtained at the Greenup test location at current densities as low as 0.1 µA/cm$^2$ (0.1 mA/ft$^2$).
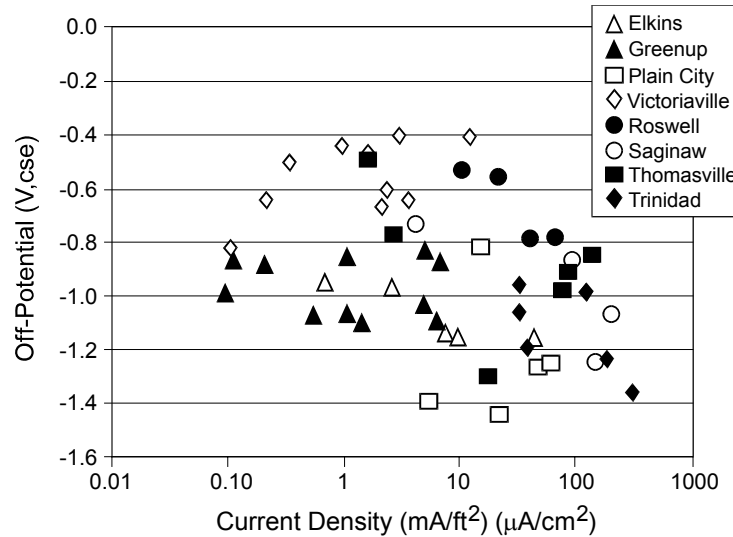
**Figure 4-2: Coupon Current Density as a Function of Off-Potential**

Source:  Thompson, N.G. and Lawson, K. M., Development of Coupons for Monitoring Cathodic Protection Systems, PRCI Contract PR-186-9220 (Catalog No. L51887), Dec. 2001, p.101, Fig. 93.

One of the major factors that produce such a wide range of current density involves the degree of dissolved oxygen available at the steel/earth interface. For instance, the difference in polarization characteristics of steel in clay (a typically unaerated environment) and sandy well drained soil (an aerated environment) is illustrated in Figure 4-3.
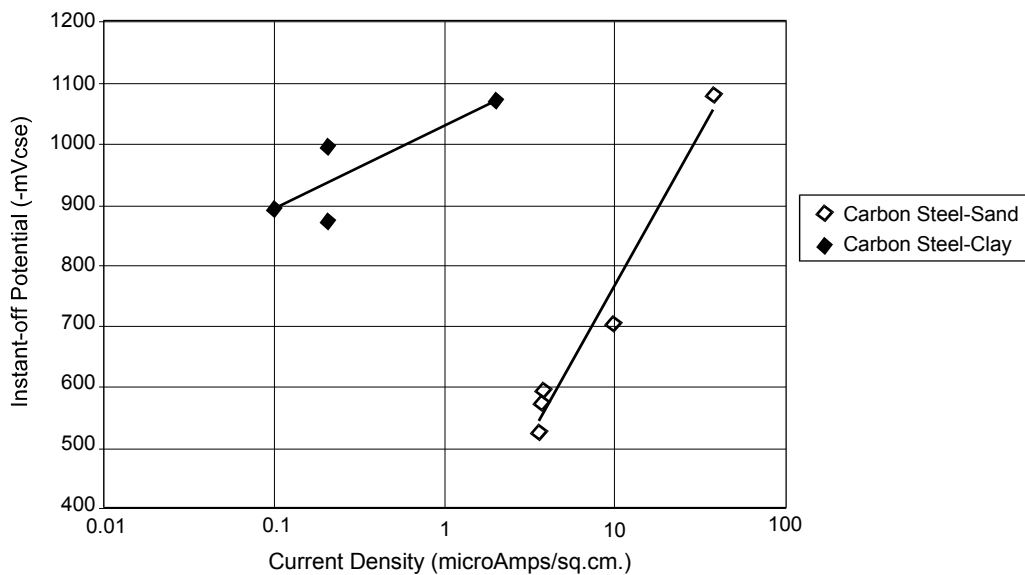


**Figure 4-3: Instant-off Potential vs. Current Density for Carbon Steel Electrode in Sand and Clay Soil from Long Term Polarization Test Results**

Source:  Gummow, R.A., Qian, S. and Baldock, B., AC Grounding Effects on Cathodic Protection Performance in Pipeline Stations, PRCI Contract PR-262-9913 (Catalog No. L51908), Dec. 2001, p.27, Fig. 2-24.

Part of the reason for the greater current density required in the aerated versus unaerated soils is that the corrosion potential for steel in high resistivity aerated sand is in the −300 to −400 $mV_{cse}$ range while in clay it is in the −700 to −800 $mV_{cse}$ range. Hence to polarize the steel to −850$mV_{cse}$ requires only a 50 to 150 mV polarized potential shift in clay versus a 450 to 550mV polarization shift in sand.

Dissolved oxygen however is a cathode depolarizer because it speeds up the transfer of charges across the steel/earth interface through the reduction reaction.

$$O_2 \text{ (dissolved)} + 2H_2O + 4e^- \rightarrow 4OH^- \qquad [4\text{-}1]$$
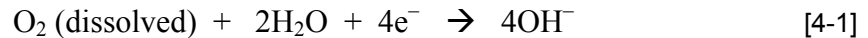
Thus, a higher current is needed to achieve a given amount of polarization as shown in Figure 4-4 that compares cathodic polarization for steel in saturated aerated and deaerated solutions.
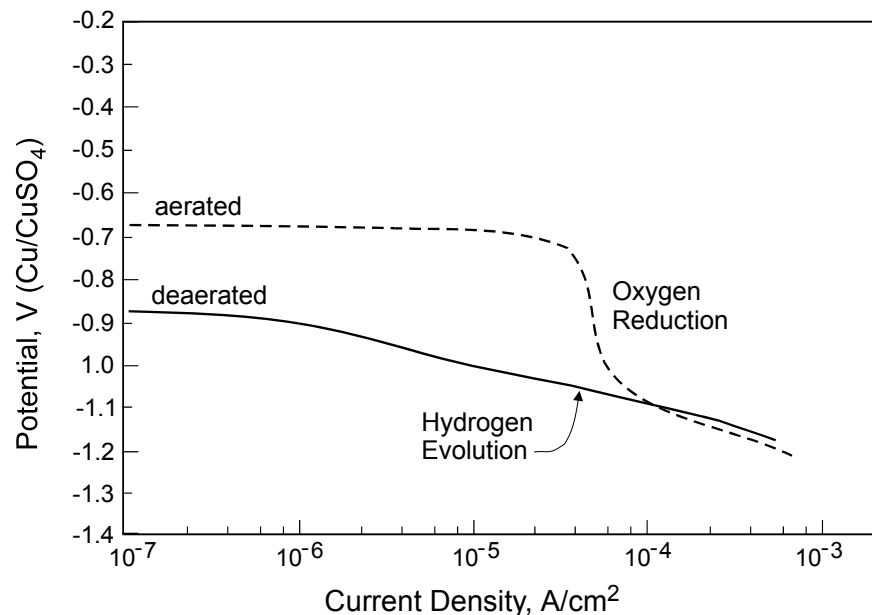


**Figure 4-4:  Polarization Curves in Aerated and Deaerated Solutions of pH7**

Source:  Fundamental Process of Cathodically Protecting Steel Pipelines, Thompson, N.G. and Barlo, T.J., 1983 International Gas Research Conference, p.278.

Finally, low pH and elevated temperature can also increase the current density requirements due to depolarization effects.

Because of the large variation in current density requirements, it is important to estimate the current density as accurately as possible. Once the current density requirements are determined, it is a simple matter of multiplying the required current density by the bare surface area to find the total current as follows:

$$I_{T,cp} \ = \ i_{cp,bare} \ \times \ A_{s,bare} \qquad\qquad [4\text{-}2]$$

Note that the total current calculated assumes the current can be distributed uniformly with no allowance for attenuation or non-uniform current density conditions. Also for well coated structures where the actual bare surface area may be quite small, Equation 4-2 may understate the actual current required because the conductance of the coating will let some current pass through it to the structure.

Therefore Equation 4-2 could be modified to include the current density through the coating as follows:

$$I_{T,cp} \ = \ i_{cp,bare} \ \times \ A_{s,bare} \ + \ i_{cp,coated} \ \times \ A_{s,coated} \qquad [4\text{-}3]$$

Sometimes on very well coated structures where the bare surface area is very small (i.e. $A_{s,bare}$ → 0) the current required for the bare surfaces is ignored and a conservative coated surface current density ($i_{cp,coated}$) is used.

For some structures that are exposed to markedly different polarization characteristics, current requirements may need to be considered on a zone basis. For instance, offshore drilling platforms are exposed to aerated and agitated water near the water surface, calmer and less agitated water with depth, and mud at the base of the platform. Thus for current requirement calculations the offshore platform is often divided into three zones as illustrated in Figure 4-5.
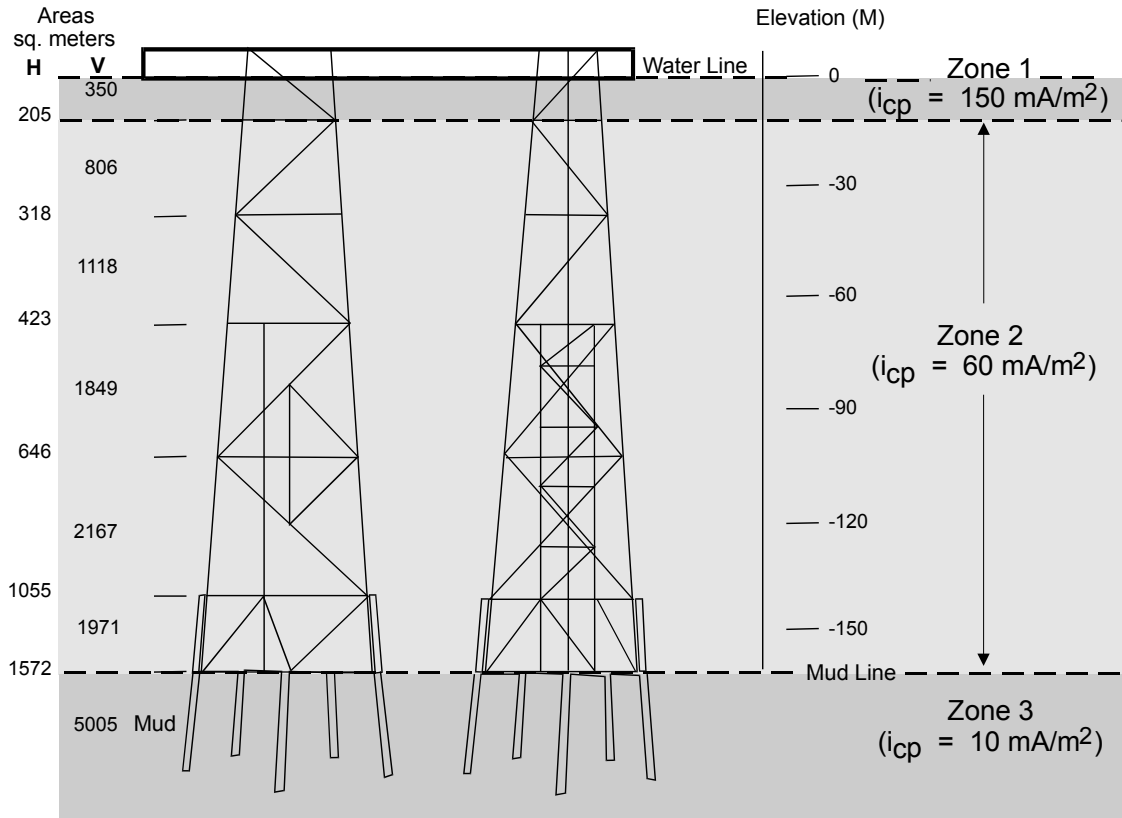
'H' column is surface area of horizontal structural members
'V' column is surface area of vertical structural members

**Figure 4-5:  Surface Areas and Current Densities for Different Zones
on an Uncoated Jacket Offshore Drilling Platform**

This zonal approach could also be used for poorly coated pipelines having
sections exposed to markedly different soil conditions or on coated pipelines with
distinctly different coating conductances.

# 4.3   Current Requirement Estimating Methods

Several methods of estimating the current required to achieve protection are in
common use.

## 4.3.1 Literature Sources

Tables of current density ranges for steel in the presence of different environments are available from the literature such as the following tables:

Table 4-1:  Approximate Current Requirements for Cathodic Protection of Steel

| Environmental Conditions | Current Density | |
|---|---|---|
| | mA/m$^2$ | mA/ft$^2$ |
| **Immersed in Seawater**[a] | | |
| Stationary | | |
|     Well coated | 1 to 2 | 0.1 to 0.2 |
|     Poor or old coating | 2 to 20 | 0.2 to 2 |
|     Uncoated | 20 to 30 | 2 to 3 |
| Low Velocity[b] | | |
|     Well coated | 2 to 5 | 0.2 to 0.5 |
|     Poor coating | 5 to 20 | 0.5 to 2 |
|     Uncoated | 50 to 150 | 5 to 15 |
| Medium Velocity[c] | | |
|     Well coated | 5 to 7 | 0.5 to 0.7 |
|     Poor coating | 10 to 30 | 1 to 3 |
|     Uncoated | 150 to 300 | 15 to 30 |
| High Velocity[d] | | |
|     Poor coating or uncoated | 250 to 1000 | 25 to 100 |
| **Buried Underground**[e] | | |
| Soil Resistivity | | |
|     0.5 to 5 Ω-m | 1 to 2 | 0.1 to 0.2 |
|     5 to 15 Ω-m | 0.5 to 1 | 0.05 to 0.1 |
|     15 to 40 Ω-m | 0.1 to 0.5 | 0.01 to 0.05 |

[a]Structures or vessels
[b]0.3 to 1 m/s (1 to 3 ft/s)
[c]1 to 2 m/s (3 to 7 ft/s)
[d]Turbulent flow
[e]Pipelines or structures, coated or wrapped

Source:  NACE Corrosion Engineers Reference Book, NACE International,
3rd Edition, Robert Baboian, Ed., 2002, p.162

The first section of this table lists current densities for bare and coated steel in seawater by water velocity with the current density increasing as the water velocity increases. These values could also be used for fresh waters since there is very little differences in polarization characteristics between fresh water and seawater.

The second section of the table lists the current density for well coated steel with respect to soil resistivity. The current density is shown to decrease with increasing soil resistivity. If the higher resistivity soil is also more aerated, a higher current density, not lower, would be required.

In both the seawater and soil environments, the current density for well coated steel is given as 1 to 2 mA/m$^2$ (0.1 to 0.2 mA/ft$^2$). Also the current density range for bare steel under stagnant seawater conditions is 20 to 30 mA/m$^2$ (2 to 3 mA/ft$^2$), which would also apply to soils and fresh water conditions.

Typical current density ranges are listed in Table 4-2 for bare steel in contact with different environments.

**Table 4-2: Typical Current Density Requirements for Cathodic Protection**[*]

| Environment | Current Density | |
|---|---|---|
| | mA/ft$^2$ | mA/m$^2$ |
| Neutral soil | 0.4 to 1.5 | 4.3 to 16.1 |
| Highly acidic soil | 3 to 15 | 32.3 to 161 |
| Heated soil | 3 to 25 | 32.3 to 269 |
| Moving fresh water | 3 to 6 | 32.3 to 64.6 |
| Fresh water, turbulent, with dissolved oxygen | 3 to 15 | 32.3 to 161.4 |
| Hot water | 3 to 15 | 32.3 to 161.4 |
| Seawater | 3 to 15 | 32.3 to 161.4 |
| Chemicals, acid or alkaline solution in process tanks | 3 to 15 | 32.3 to 161.4 |
| Wet concrete | 3 to 15 | 32.3 to 161.4 |

*Based on entire surface area of structure.*

Source: Shrier, L.L., Corrosion, Vol. 2, Newness-Butterworths, Boston, 1976, p11:65

Note that these values differ to some extent with those in Table 4-1, which illustrates the wide variation in the published literature. Certainly the current density range stated for steel in concrete is probably an order of magnitude greater than is being used in practice.

Current requirements for other metals, such as in electrical grounding systems, are similar in nonaerated, low resistivity clay soil as indicated in Table 4-3. For high resistivity, well aerated sandy soil, the current requirements vary considerably amongst the various types of grounding materials.

**Table 4-3: Typical Current Density Requirements to Cathodically Polarize Various Metals to –850 mV$_{cse}$** [1]

| Type of Grounding Electrode Material | Clay[(1)] $\mu$A/cm$^2$ | Sand [(2)] $\mu$A/cm$^2$ |
|---|---|---|
| Carbon steel | 0.1 | 20 |
| Copper | 0.1 | 100 |
| Tinned copper | 0.1 | 20 |
| High silicon iron | 0.1 | 20 |
| Stainless steel | 0.1 | 8 |

[(1)] nonaerated, low resistivity (1800 $\Omega$-cm)
[(2)] well drained, aerated, high resistivity (>50,000 $\Omega$-cm)

To improve the accuracy of estimates quoted in the literature, it is wise to seek current requirement information for applications that are as close to the intended application as possible.

## 4.3.2   Experience on Similar Structures in Similar Conditions

One of the most common methods of estimating current requirements is simply to use current density values that have proved successful in the past. This may take the form of a current requirement in terms of:

- current density per unit area of coating surface ($i_{cp,coated}$)
- current density per unit area ($i_{cp,bare}$) multiplied by an estimate of the amount of bare surface area, or
- current per unit area of an actual structure in similar environmental conditions.

The weakness of all these methods arises when the application conditions differ significantly from the circumstances from which the experience was gained.

## 4.3.3   Determining Current Requirements on a Coated Structure by Estimating the Percentage Bare

For a coated structure, it is common to estimate the percentage that is bare of the coating and then multiply by a current density appropriate to the environmental conditions. For example, if the structure is considered 1% bare (a common

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[1] *Gummow, R.A., AC Grounding Effects on Cathodic Protection Performance in Pipeline Stations, PRCI Contract #PR-262-9913, Final Report, Dec. 2001.*

assumption) and the bare area requires 20 mA/m² (2 mA/ft²), then the equivalent current density required ($i_{cp}$) for the entire coated surface is:

$$i_{cp} = \frac{\% \, bare}{100} \times i_{cp,bare} \qquad [4\text{-}4]$$

$$= 0.01 \times 20 \text{ mA/m}^2$$
$$= 0.2 \text{ mA/m}^2 \ (0.02 \text{ mA/ft}^2)$$

This method ignores the amount of current that passes through the coating, but the allowance for bare area is so overstated for a well coated structure that the calculated current requirement is usually more than adequate.

The percent of bare area on well coated pipelines (coating conductance < 100 µS/m²) is at least 2 orders of magnitude less than 1% bare as shown in Figure 4-6 for a fusion bonded epoxy coated steel.  However, if a percentage bare of 0.001% were used in Equation 4-4, the current required would be significantly understated. This is because on extremely well coated structures, most of the current passes through the coating since the coated surface is many orders of magnitude greater than the holiday surface areas (see Section 4.11.7).
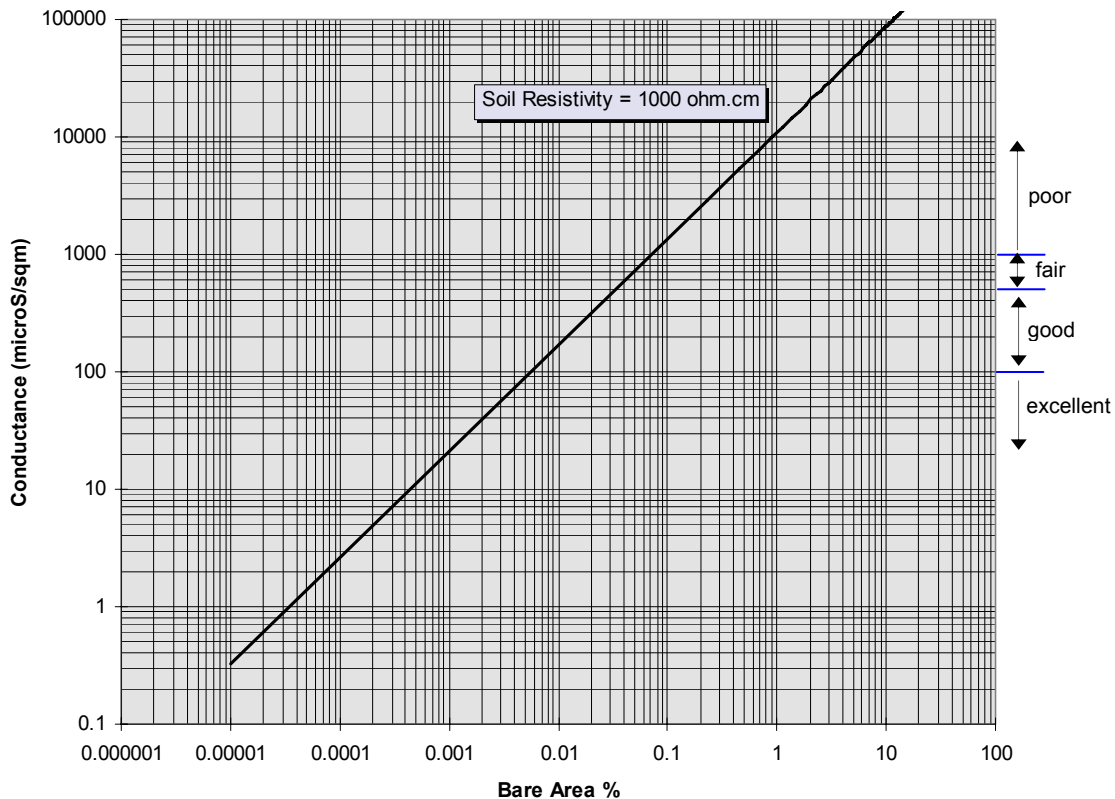
**Figure 4-6: FBE Coating Conductance versus Bare Area Normalized for a Soil Resistivity of 1000 Ω-cm as Related to General Coating Quality in Table 4-4**

Source: Gummow, R.A. and Segall, S.M., PRCI Contract PR-262-9738, In-Situ Evaluation of Directional Drill/Bore Coating Quality – Evaluation of Test Methods, Final Report, Oct. 1998, p.43

## *4.3.4  Minimum Voltage Drop Method*

Experience has shown that in mid-range soil resistivity conditions cathodic protection voltage of 300 mV applied between remote earth and a structure is sufficient for polarization to meet industry criteria. In fact, in the original NACE Standard SP0169, a minimum potential shift of 300 mV was one of the accepted criteria. Even after it was removed as a criterion, it is sometimes used as a start-up criterion when energizing rectifiers to determine initial current output settings. The 300 mV shift will overestimate the current required in low resistivity conditions (e.g., seawater, brackish water) and underestimate current requirements in high resistivity soils.

This method assumes that if a minimum voltage drop, such as 300 mV, is obtained between the structure and remote earth, the current required to do so is sufficient to provide adequate cathodic protection. This can be calculated using

the estimated coating conductance or the results from field tests as illustrated in Figure 4-7.

## 4.3.4(a)  Field Test to Determine Current Required on a Pipeline Based on Minimum Voltage Drop

A DC test current ($I_t$) is applied from a remote earth location through an ammeter and interruptible switch.
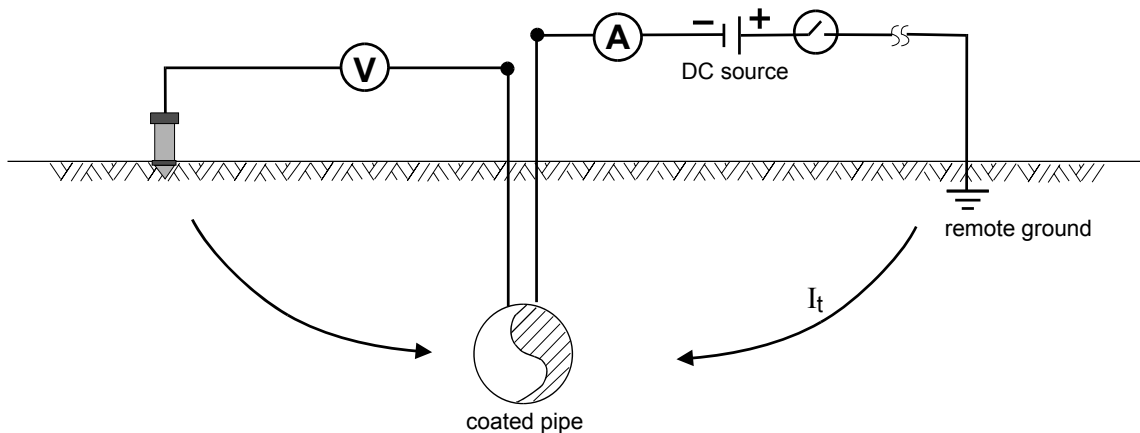


**Figure 4-7:  Voltage Drop Method of Determining Current Requirements**

The test current is switched on and off by an interrupter set so that the "on" cycle time is short compared to the "off" cycle time to avoid polarization effects. The pipe-to-soil potential with respect to a remote reference is measured when the current is on ($V_{on}$) and off ($V_{off}$). The change in potential ($\Delta V$) between $V_{on}$ and $V_{off}$ is expressed using the equation:

*e.g.,*
$$\Delta V = V_{on} - V_{off}$$
[4-5]

The current required is then calculated as the amount needed to shift the potential 300 mV.

$$I_{cp} = \frac{300\,mV}{\Delta V} \times I_t$$
[4-6]

For a long structure, it is usual to measure on/off pipe-to-soil potentials at a number of locations using the minimum shift location ($\Delta V_{min}$) to provide a conservative estimate of the required current. Also, where multiple cathodic protection current sources are anticipated, a lesser voltage drop criterion (e.g.,

150 mV) could be used at the intersection between two sources. It is assumed that each source would contribute a 150 mV of voltage drop thereby achieving a total of 300 mV. Although the 300 mV minimum potential shift is often used in current requirement calculations, it is not an industry standard criterion.

### 4.3.4(b)  Using Pipe-to-Earth Resistance to Determine Current Required by the Voltage Drop Method

If an isolated section of pipe is tested per the test arrangement in Figure 4-7, the average change in potential ($\Delta V_{ave}$) divided by the test current gives the average pipe resistance ($R_{p,re}$) to remote earth per Equation 4-7:

$$R_{p,re} \quad = \quad \frac{\Delta V_{ave}}{I_t} \qquad\qquad [4\text{-}7]$$

The current required by the test section to obtain a 300 mV shift would be:

$$I_{cp} \quad = \quad \frac{300\,mV}{R_{p,re}} \qquad\qquad [4\text{-}8]$$

The resistance of the pipe can also be calculated by other methods as will be covered later in this chapter.

The disadvantages of this method are that it does not determine the polarization characteristics of the structure and will vary considerably with the earth resistivity unless the coating is of very high quality. Thus in high resistivity soils this technique will result in a higher voltage drop than in a low resistivity soil and therefore a lesser calculated required current.

### *4.3.4(c)  Calculation of Current Required to Achieve a Minimum Voltage Drop on a Coated Structure Based on Coating Resistance*

Assuming that most of the voltage drop is across the coating rather than in the electrolyte when a cathodic current is applied to a structure, the specific coating resistance ($r'_c$) can be used to determine the current required for a unit area of surface with respect to a minimum voltage drop criterion (e.g., 300 mV) by Equation 4-9:

$$i_{cp} = \frac{300\,\text{mV}}{r'_c} \qquad [4\text{-}9]$$

*where:*    $r'_c$ is the specific coating resistance in $\Omega$-m$^2$ or $\Omega$-ft$^2$

The value of $r'_c$ can be obtained directly from Table 4-4 for typical pipe coating conductances of different quality coatings in 1000 $\Omega$-cm soil or indirectly from the specific coating conductance $(g')$ since

$$r'_c = \frac{1}{g'} \qquad [4\text{-}10]$$

**Table 4-4:  Typical Specific Pipe to Earth Leakage Conductance for**
**Dielectric Protective Coatings in 1000 $\Omega$-cm Soil**

| Long Pipelines with Few Fittings | Average Specific Coating Conductance g′ | | Average Specific Coating Resistance $r'_c$ | |
|---|---|---|---|---|
| Quality of Work | Siemens/ft$^2$ | Siemens/m$^2$ | $\Omega$-ft$^2$ | $\Omega$-m$^2$ |
| Excellent | <1 x 10$^{-5}$ | <1 x 10$^{-4}$ | >10$^5$ | >10$^4$ |
| Good | 1 x 10$^{-5}$ to 5 x 10$^{-5}$ | 1 x 10$^{-4}$ to 5 x 10$^{-4}$ | 2 x 10$^4$ to 10$^5$ | 2 x 10$^3$ to 10$^4$ |
| Fair | 5 x 10$^{-5}$ to 1 x 10$^{-4}$ | 5 x 10$^{-4}$ to 1 x 10$^{-3}$ | 10$^4$ to 2 x 10$^4$ | 10$^3$ to 2 x 10$^3$ |
| Poor | >1 x 10$^{-4}$ | >1 x 10$^{-3}$ | <10$^4$ | <10$^3$ |
| Bare Pipe (2 to 12 in.) (5 to 30cm) | 4 x 10$^{-3}$ to 2 x 10$^{-2}$ | 4 x 10$^{-2}$ to 2 x 10$^{-1}$ | 50 to 250 | 5 to 25 |

| Gas or Water Distribution with Many Fittings | Average Specific Coating Conductance g′ | | Average Specific Coating Resistance $r'_c$ | |
|---|---|---|---|---|
| Quality of Work | Siemens/ft$^2$ | Siemens/m$^2$ | $\Omega$-ft$^2$ | $\Omega$-m$^2$ |
| Excellent | <5 x 10$^{-5}$ | <5 x 10$^{-4}$ | >2 x 10$^4$ | >2 x 10$^3$ |
| Good | 5 x 10$^{-5}$ to 1 x 10$^{-4}$ | 5 x 10$^{-4}$ to 1 x 10$^{-3}$ | 10$^4$ to 2 x 10$^4$ | 10$^3$ to 2 x 10$^3$ |
| Fair | 1 x 10$^{-4}$ to 5 x 10$^{-4}$ | 1 x 10$^{-3}$ to 5 x 10$^{-3}$ | 2 x 10$^3$ to 10$^4$ | 2 x 10$^2$ to 10$^3$ |
| Poor | >5 x 10$^{-4}$ | >5 x 10$^{-3}$ | <2 x 10$^3$ | <2 x 10$^2$ |
| Bare Pipe (2 to 12 in.) (5 to 30 cm) | 4 x 10$^{-3}$ to 2 x 10$^{-2}$ | 4 x 10$^{-2}$ to 2 x 10$^{-1}$ | 50 to 250 | 5 to 25 |

For example, for 1 m$^2$ of excellent coating on a long pipeline in 1,000 $\Omega$-cm soil, the current density required to produce a 300 mV voltage drop would be

$$i_{cp\,@\,300\,mV} \quad = \quad \frac{0.3\,V}{10^4\,\Omega\text{-}m^2} \qquad\qquad [4\text{-}11]$$

$$= \quad 0.3 \times 10^{-4}\,A/m^2$$
$$= \quad 30\mu A/m^2 \;\; (\sim 3\mu A/ft^2)$$

If the soil resistivity is not 1,000 $\Omega$-cm, then it is usual to linearly extrapolate the specific resistance to the actual resistivity.

In the foregoing example for 10,000 $\Omega$-cm soil the specific resistance would be:

$$r'_{c\,@\,10,000\,ohm\text{-}cm} \quad = \quad r'_c \times \frac{10,000\,\Omega\text{-}cm}{1,000\,\Omega\text{-}cm} \qquad\qquad [4\text{-}12]$$

$$= \quad 10^4\,\Omega\text{-}m^2 \;\; x \;\; 10$$
$$= \quad 10^5\,\Omega\text{-}m^2\,(10^6\,\Omega\text{-}ft^2)$$

Therefore the current required by the voltage drop method would be:

$$i_{cp\,@\,300mV,\,10,000\,ohm\text{-}cm} \quad = \quad \frac{0.3\,V}{10^5\,\Omega\text{-}m^2} \qquad\qquad [4\text{-}13]$$

$$= \quad 3\,\mu A/m^2 \;\; (\sim 0.3\,\mu A/ft^2)$$

## 4.3.5   Polarization Test Method

The polarization test method is similar in setup to the voltage drop method except the test current is increased in small increments from a low value, the test current remains on for an extended period of time, and the interrupter is adjusted to interrupt the current for a very short off cycle. The reference electrode does not need to be placed at remote earth unless the structure is inaccessible as in the case of a well casing. The structure polarized potential ($E_{off}$) is then plotted on semi-log graph paper versus the applied test current as depicted in Figure 4-8.
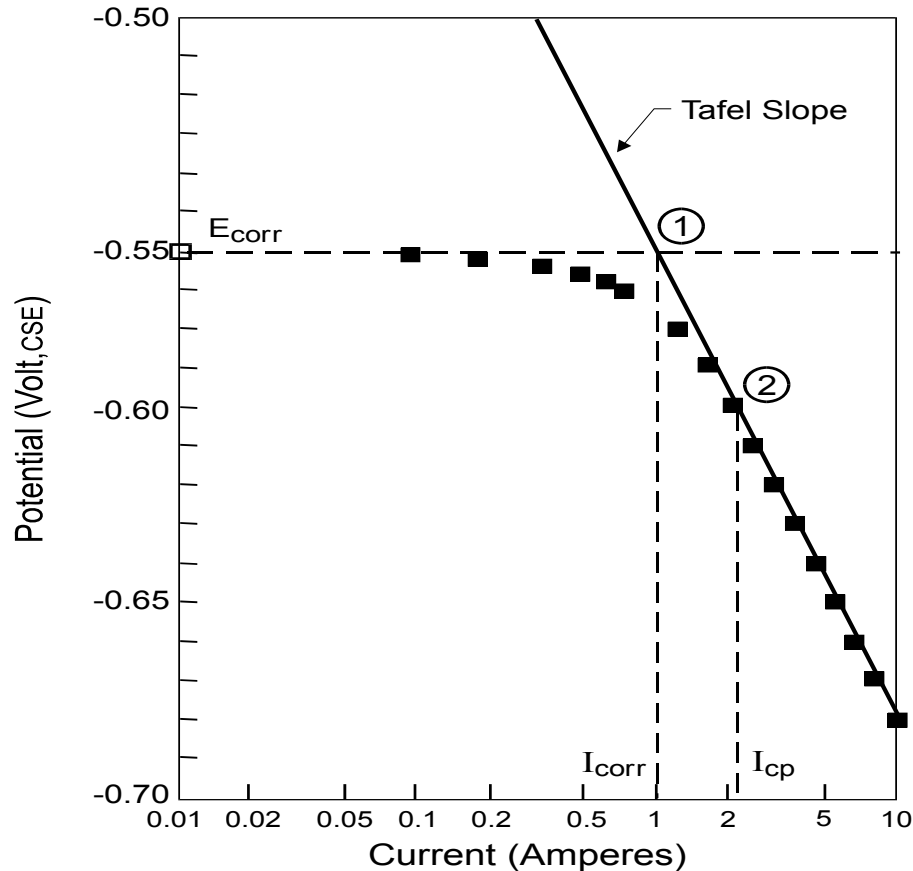
**Figure 4-8:  Cathodic Polarization Plot and Determination of
Cathodic Protection Current ($I_{cp}$) Required**

On the graph, the linear portion of the polarization curve is identified and a straight line is drawn to intersect with the original corrosion potential ($E_{corr}$) line. This line is called the *Tafel* line or slope if the data is collected in an oxygen free (anaerobic) environment. The point where this line intercepts the corrosion potential (pt.①) represents the magnitude of the corrosion current ($I_{corr}$). The point where the line departs from the plotted data (pt.②) identifies the required cathodic protection current.

In order to achieve Tafel behavior with short term polarization testing, the structure must be in an oxygen free (anaerobic) environment. If anaerobic conditions exist, the cathode reduction reaction will be hydrogen ion reduction under activation control; however, if aerobic conditions exist, oxygen reduction under concentration control is more likely. The polarization curve will not exhibit a Tafel straight line segment, but rather, will be curvilinear in a shape depicting concentration effects. In this case, short term polarization testing cannot provide

the current requirement adequate for cathodic protection. If Tafel behavior is observed, the current requirement for adequate cathodic protection is the current magnitude where the Tafel slope begins.

If the environment is aerobic, the polarization curve will change with time in a manner similar to Figure 4-9.
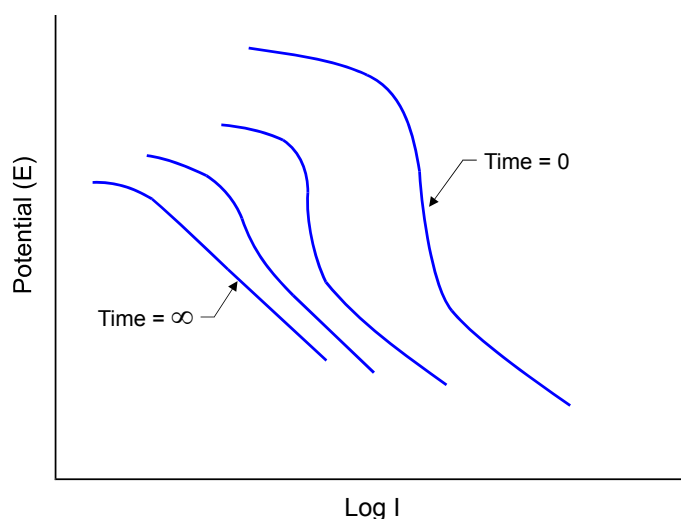


**Figure 4-9:  Effect of Time on the Shape of a Dynamic Cathodic Polarization Curve**

Source:  Nisancioglu, K., Gartland, per Olav, Dahl, T., and Sander, E., The Role of Surface Structure and Flow Rate on the Polarization of Cathodically Protected Steel in Sea Water, Corrosion /86, Paper No. 296

As the time interval increases, the current required to polarize steel to a specific potential decreases. The shape of the polarization curve changes from one exhibiting considerable oxygen concentration polarization (at time = 0) to a completely linear E log I relationship when $t \rightarrow \infty$. The latter behavior is probably due to the primary reduction reaction being the reduction of the hydrogen ion.

Clearly, the E log I current requirement criterion applied to these graphs would produce dramatically different current requirements with the shorter time duration curve producing the most inaccurate but most conservative result. Also, as the oxygen concentration polarization increases, the more difficult it is to draw a true straight line because the Tafel slope approaches tangency to the curve rather than intersecting a number of defined points on the curve.

Allowing long time intervals between incremental changes in the applied current imposes a time constraint as well as a cost penalty on this method as applied in the field. This technique has been used mainly for determining current

requirements on well casings, which because of their depth are generally exposed to unaerated soil conditions. Hence, the polarization characteristic is more linear and the polarized potential less time dependent.

Conducting cathodic polarization scans either galvanostatically (setting a current and measuring potential as per the previous example) or potentiostatically (setting a potential and measuring current) has considerable merit in determining the current requirements for steel in aqueous process streams. The tests can easily be conducted on coupons either in the laboratory or in the vessel on site using automated potentiostats.

## *4.3.6   Polarization Shift Method*

The polarization shift method involves applying a test current as illustrated in Figure 4-7 for a period of time until the change in polarized potential approaches zero $\left(\frac{\Delta E_p}{\Delta t} \to 0\right)$. The magnitude of the test current is selected to be a significant fraction of that obtained by a rough estimate of the current required.

When the "on" potential has stabilized, the interrupter is adjusted to interrupt with a short off-cycle so the polarized potential at the structure-to-earth measurement location can be recorded. The polarization potential shift at each location is determined by subtracting the corrosion potential ($E_{corr}$) from the instant-off (polarized) potential ($E_p$).

$$e.g., \qquad\qquad \Delta E_p \;=\; E_p \;-\; E_{corr} \qquad\qquad\qquad [4\text{-}14]$$

The required current is then computed by dividing the desired polarization shift for protection (e.g., 100 mV) by the test polarization shift multiplied by the test current.

$$e.g., \qquad\qquad I_{cp} \;=\; \frac{100\,\text{mV}}{\Delta E_p} \;\times\; I_t \qquad\qquad\qquad [4\text{-}15]$$

The advantage of this test over the E log I test is that less time is required on site and less test current capacity is needed. The disadvantage is that it assumes the relationship between polarized potential and applied current is linear, which it is not, as was illustrated in Figures 4-8 and 4-9. However, if the original estimate is close to the actual required current, this method gives good results.

Current density requirements per 100 mV of polarization, based on test results on fusion bonded epoxy coated pipe with artificial holidays, is plotted against % bare as shown in Figure 4-10.
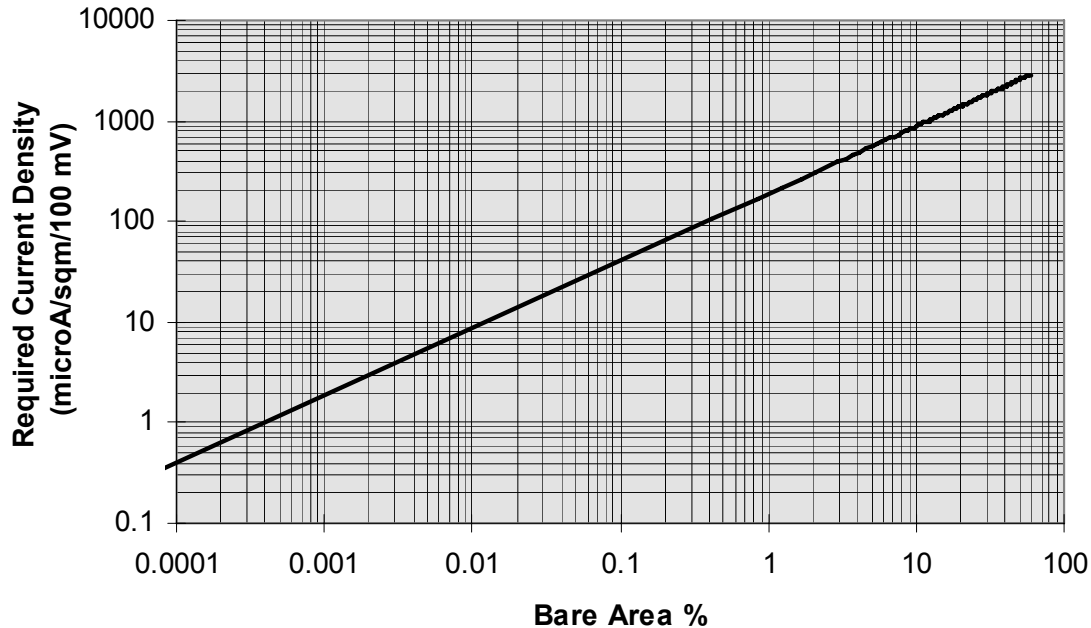


**Figure 4-10:  Current Density in Clay Soil for 100 mV Polarization Shift vs. % Bare on Coated Steel**

Source:  Gummow, R.A. and Segall, S.M., PRCI Contract PR-262-9738, In-Situ Evaluation of Directional Drill/Bore Coating Quality – Evaluation of Test Methods, Final Report, Oct. 1998, p.44

This curve considers only the situation where the pipe is buried in an unaerated environment.

For a well coated pipeline, the percentage bare should be 0.01% or less suggesting a current density requirement of 10 $\mu A/m^2$ per 100 mV of polarization.

# 4.4   Calculation of Cathodic Protection Circuit Resistances

After the cathodic protection current requirements are determined by one or more of the foregoing methods, galvanic or impressed current must be chosen as indicated in the flow chart in Figure 4-1. Many factors affect this design choice but the magnitude of the current required and the resistivity of the environment are the predominant factors that impact the cost of the system. Typically, as both

the current and resistivity increase, as shown in Figure 4-11, impressed current becomes the most economical option.
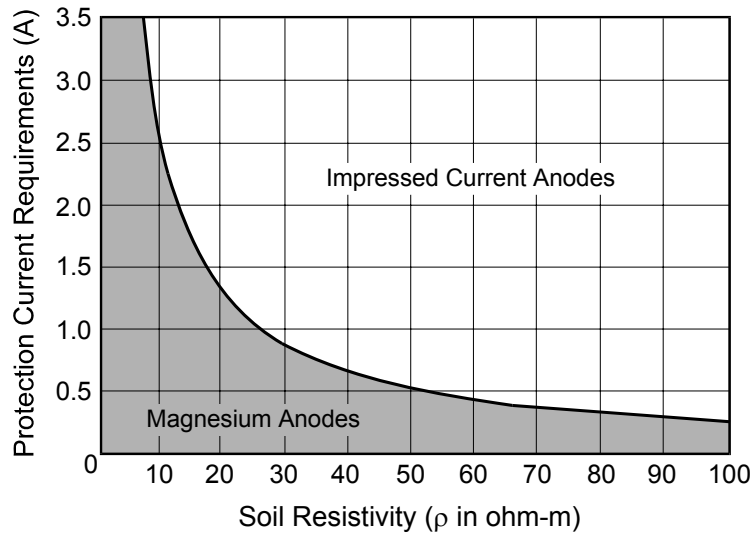


**Figure 4-11:  Relative Economic Range for Galvanic and Impressed Current Systems
as a Function of Current Required and Soil Resistivity**

Source:  von Baeckman, W., Schwenk, W., and Prinz, W., Handbook of Cathodic Corrosion Protection –
Theory and Practice of Electrochemical Protection Processes, Gulf Professional Publishing, 1997, p.495

The cathodic protection circuit for a galvanic system can be illustrated by the electrical schematic in Figure 4-12.



$E_{p,s}$ = polarized potential of structure (V)

$R_{s,re}$ = resistance of structure to remote earth (ohm)

$R_{a,re}$ = resistance of anode(s) to remote earth (ohm)

$E_{p,a}$ = polarized potential of anode(s) (V)

$R_c$ = cable resistance between anode & structure (ohm)
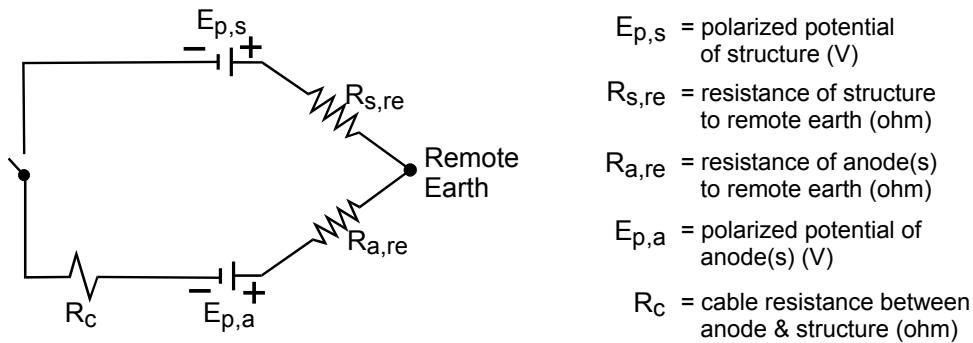
**Figure 4-12:  Electrical Schematic for an Operating Galvanic Cathodic Protection System**

The electrical schematic for an impressed current system illustrated in Figure 4-13 is similar to Figure 4-12.

$R_{c,s}$ = resistance of negative cable from the structure

$E_{p,s}$ = polarized potential of structure (V)

$R_{s,re}$ = resistance of structure to remote earth (ohm)

$R_{gb,re}$ = resistance of groundbed to remote earth (ohm)

$E_{p,a}$ = polarized potential of the groundbed (V)

$R_{c,a}$ = resistance of positive cable to groundbed
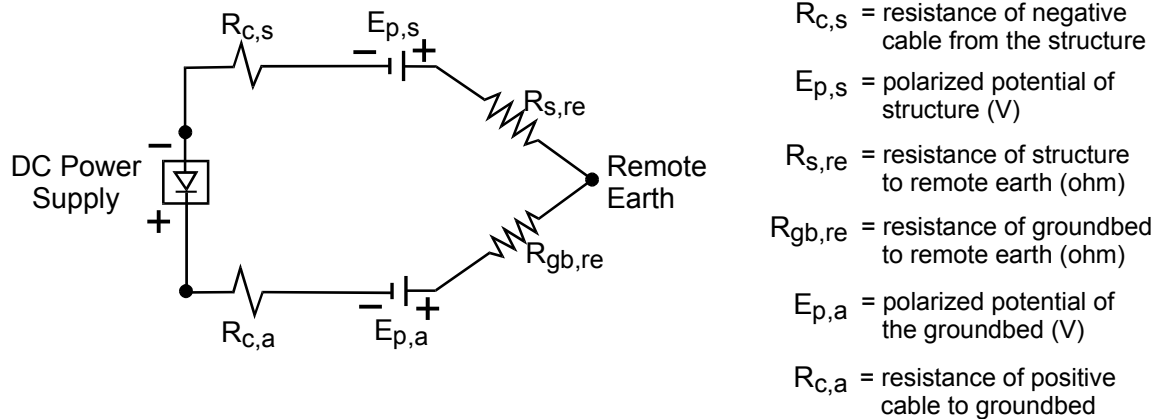
**Figure 4-13: Electrical Schematic for an Operating Impressed Current Cathodic Protection System**

After choosing the type of system, anode materials, and arrangement, the cathodic protection circuit resistance $R_{cp}$ needs to be calculated as follows:

*for an impressed current system*

$$R_{cp} = R_{c,a} + R_{c,s} + R_{s,re} + R_{gb,re} \qquad \text{[4-16]}$$

*for a simple galvanic system*

$$R_{cp} = R_c + R_{s,re} + R_{a,re} \qquad \text{[4-17]}$$

## 4.4.1 Resistance of a Single Rod Shaped Anode Positioned Vertically in the Earth

The resistance-to-remote earth ($R_{a,re}$) of a single anode positioned vertically in the earth with the top of the anode flush with grade as shown in Figures 4-14a and 4-14b can be calculated using Dwight's modified equation as follows.

$$R_{v,re} = \frac{\rho}{2\pi L}\left\{\left(\ln\frac{8L}{d}\right) - 1\right\} \qquad \text{[4-18]}$$

*where:*

$R_{v,re}$ = resistance of vertical anode to remote earth (ohms)
$\rho$ = resistivity of soil
$L$ = length of anode
$d$ = diameter of anode

(a) directly in earth contact          (b) in low resistivity backfill
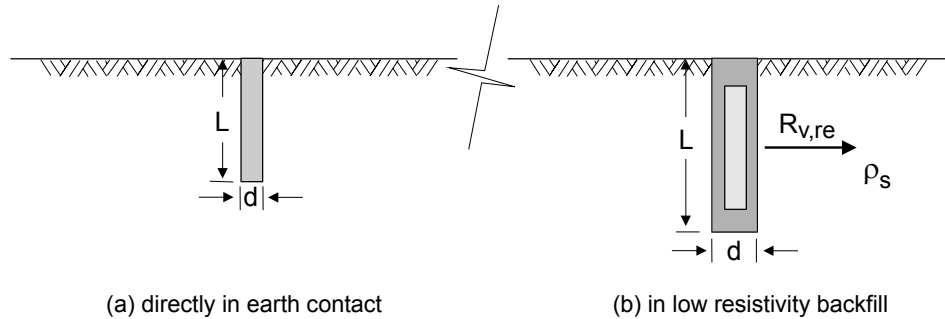
**Figure 4-14: Anode Placed Vertically in Earth at Grade**

This equation is applicable where L>>d, soil resistivity is homogeneous, and the anode is not located well below grade. For galvanic anodes surrounded by low resistivity sulfate-rich select backfill (typically $\rho_{backfill}$ < 100 Ω-cm) the outside dimensions of the packaged anode can be used in the calculation rather than the actual casting dimensions. This also applies to impressed current anodes that are surrounded by coke backfill material. The outside dimensions of the coke column can be used in Equation 4-18 without appreciably affecting its accuracy.

### *Example Calculation:*

Calculate using Dwight's equation the resistance of a 6 ft long by 2 in. diameter anode in 10,000 Ω-cm soil.

$\rho$  =  10,000 Ω-cm                               d  =  2 in. x 2.54 cm/in. = 5.1 cm
L  =  6 ft x 30.5 cm/ft  =  183 cm

$$R_v \; = \; \frac{10,000\,\Omega\text{-cm}}{2\,\pi\,183\,\text{cm}} \left\{ \left( \ln \frac{8 \times 183\,\text{cm}}{5.1\,\text{cm}} \right) - 1 \right\}$$

$$= \; 8.7\,\{(\ln 287) - 1\} \; = \; 8.7\,\{5.65 - 1\} \; = \; 40.5\,\Omega$$

For a deep well anode, where the depth (t) to the top of the anode or coke column is about the same order of magnitude as the length (L) of the anode or coke column, Equation 4-19 can be used.

$$R_{v,re} \; = \; \frac{\rho}{2\,\pi\,L} \left\{ \left( \ln \frac{4L}{d} \right) - 1 \right\} \qquad\qquad \text{[4-19]}$$

*where:*

$R_{v,re}$  =  resistance of vertical anode to remote earth (ohms)
$\rho$  =  resistivity of soil
L  =  length of anode
d  =  diameter of anode

### 4.4.2 Resistance of Multiple Vertical Anodes Connected to a Common Header Cable or Structure

When multiple anodes are connected in parallel to a common header cable, as illustrated in Figure 4-15, the resistance of the entire array of vertical anodes can be calculated as a simple parallel circuit if the anodes are sufficiently far apart (S>>L) and the header cable has negligible resistance.
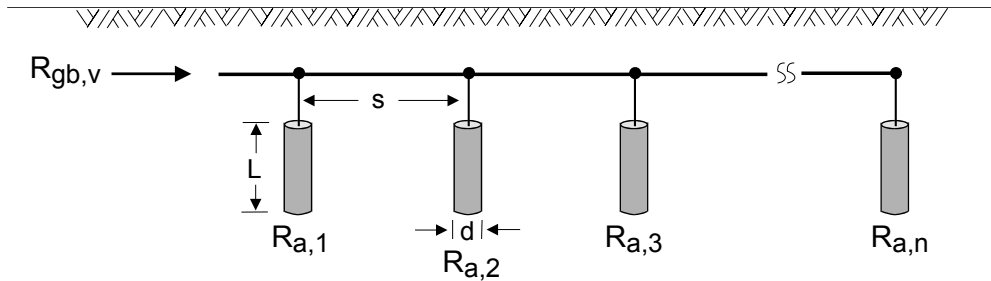


**Figure 4-15: Multiple Vertical Anodes Connected to a Common Header Cable**

That is, the parallel resistance of the groundbed ($R_{gb,v}$) is given by:

$$\frac{1}{R_n} = \frac{1}{R_{a,1}} + \frac{1}{R_{a,2}} + \frac{1}{R_{a,3}} \;\; .... \;\; \frac{1}{R_{a,n}}$$

[4-20]

$$\frac{1}{R_n} = N \times \frac{1}{R_a}$$

*therefore:* $\quad R_n = \dfrac{R_a}{N}$ $\qquad$ [4-21]

Thus the resistance of the multiple anode array, assuming that $R_{a,1} = R_{a,2} = R_{a,3}$, is simply the resistance of a single anode, calculated using Dwight's equation, divided by the number (N) of anodes. This also applies for galvanic anodes widely spaced and connected directly to the structure.

Since the anode spacing (S) is typically short (e.g., S < 10L), there is mutual interference (crowding effect due to the current from each anode competing for the same current path) causing the resistance to increase from that calculated in Equation 4-21.

The Sunde equation which follows includes a factor $\left[\dfrac{2L}{s} \ln (0.656N)\right]$

that calculates the added resistance due to the mutual interference.

$$R_v = \frac{\rho}{2\,\pi\,NL}\left\{\left(\ln\frac{8\,L}{d}\right) - 1 + \frac{2L}{s}\ln(0.656N)\right\}$$       [4-22]

*where:*

$R_v$ = resistance of multiple vertical anodes to remote earth, ohms
$\rho$ = soil resistivity
$L$ = length of anode
$d$ = diameter of anode
$s$ = anode spacing
$N$ = number of anodes

Note that this equation is just Dwight's equation divided by N with the "crowding" correction factor added.


### *Example Calculation:*

Calculate the resistance of 10 anodes (5.08 cm (2 in.) diameter by 182.9 cm (6 ft) long) connected to a header cable with a 152.4 cm (5 ft) spacing in 10,000 Ω-cm soil.

$$
\begin{aligned}
\text{diameter} &= \text{2 in. (5.08 cm)}\\
\text{length} &= \text{6 ft. (182.9 cm)}\\
\text{spacing} &= \text{5 ft. (152.4 cm)}\\
\text{resistivity} &= \text{10,000 Ω-cm soil}
\end{aligned}
$$

Using Equation 4-22:

$$R_v = \frac{10,000\ \Omega\text{-cm}}{2\,\pi\,10\ \text{anodes}\ \times 182.9\ \text{cm}}\left\{\left(\ln\frac{8\ \times\ 182.9\ \text{cm}}{5.08\ \text{cm}}\right) - 1 + \frac{2\ \times\ 182.9\ \text{cm}}{152.4\ \text{cm}}\ln(0.656\ \times\ 10\ \text{anodes})\right\}$$

*Therefore:*

$$
\begin{aligned}
R_v &= 0.87\ \{(5.66 - 1) + 2.41(1.88)\}\\
&= 0.87\ (4.66 + 4.51)\\
&= 0.87\ (9.17)\\
&= 7.98\ \Omega
\end{aligned}
$$

## 4.4.3   Resistance of a Single Rod Shaped Anode Positioned Horizontally in the Earth

As with all anodes the resistance is a function of the soil resistivity but also a function of the depth ($t$) as illustrated in Figure 4-16.



(a) directly in earth contact                              (b) in low resistivity backfill
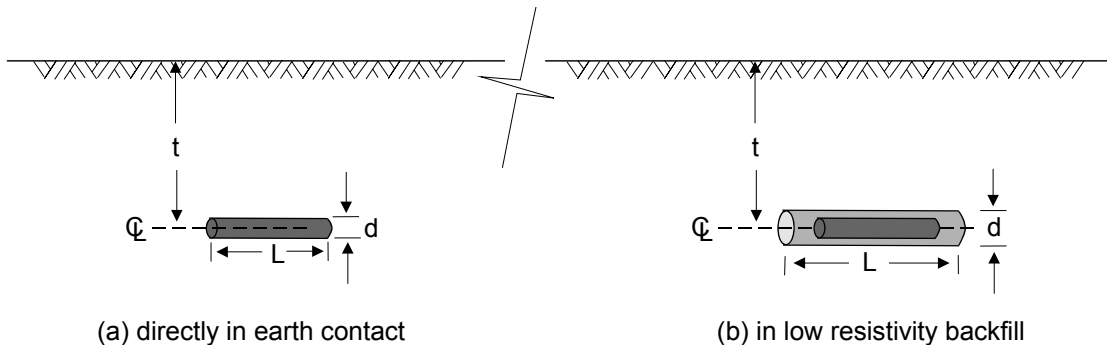
**Figure 4-16:  Anode Placed Horizontally Below Grade**

When the depth is shallow ($t \ll L$) and ($L \gg d$), Equation 4-23 applies:

$$R_{a,h} = \frac{\rho}{2\pi L} \ln\left(\frac{L^2}{td}\right) \qquad [4\text{-}23]$$

*where:*

$\rho$ = soil resistivity
L = length of anode
d = diameter of anode
$t$ = depth below grade

and when the depth is considerable ($t \gg L$), Equation 4-24 applies.

$$R_{a,h} = \frac{\rho}{2\pi L} \ln\left(\frac{2L}{d}\right) \qquad [4\text{-}24]$$

In both equations, it is assumed that the soil resistivity is uniform and the outside dimensions of packaged galvanic anodes and coke backfilled impressed current anodes can be used in the equations without introducing appreciable error.

Equation 4-24 can also be used to calculate the resistance of a single vertical rod where $t \gg L$.

Equation 4-23 can also be used to calculate the resistance of multiple horizontal anodes if they are placed relatively close together ($s < L_a$) and surrounded by continuous coke as illustrated in Figure 4-17a.
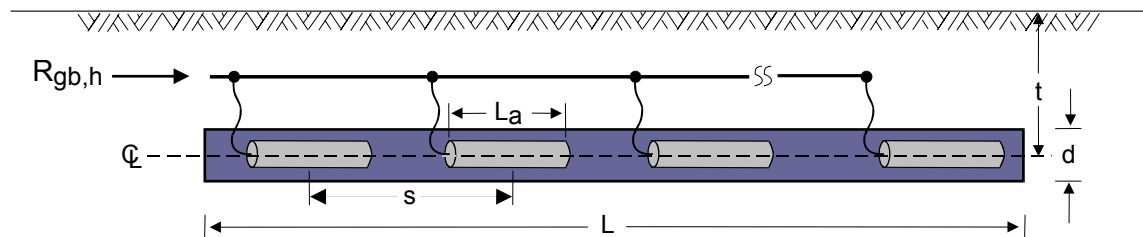


**Figure 4-17a: Multiple Horizontal Anodes in a Coke Trench Connected to a Common Header Cable**

---

**Class Group Exercise**

Calculate the resistance of the following anode positioned vertically and horizontally using Equations 4-18 and 4-23 respectively.

*where:*        $L = 2$ m            $t = 1$ m

                $D = 20$ cm         $\rho = 10$ Ω-m

---

### 4.4.4 Resistance of Multiple Horizontal Anodes Connected on a Common Header Cable

For multiple horizontal anodes connected to a common header cable having negligible resistance as in Figure 4-17b, the following equation, which includes a "crowding" factor F, can be used.
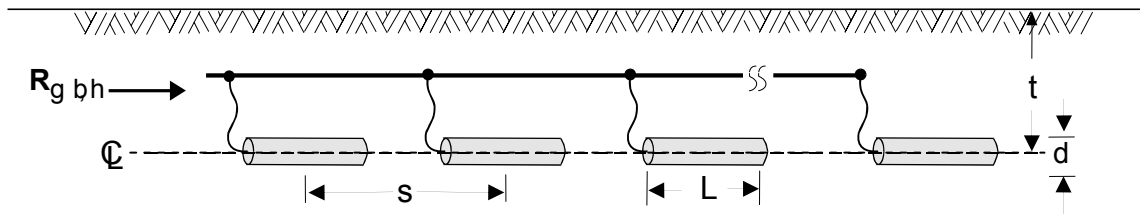


**Figure 4-17b: Multiple Horizontal Anodes Connected to a Common Header Cable**

$$R_{gb,h} = \frac{R_{a,h}}{N} \times F \qquad [4\text{-}25]$$

*where:*

$R_{gb,h}$ = resistance of N horizontal anodes
$R_{a,h}$ = resistance of a single anode
$N$ = number of anodes
$F$ = crowding factor

The crowding factor (F) can be calculated using Equation 4-26.

$$F = 1 + \frac{\rho}{\pi S R_{a,h}} \ln 0.656N \qquad [4\text{-}26]$$

*where:*

$F$ = multiple anode crowding factor
$\rho$ = soil resistivity
$S$ = center-to-center distance between anodes
$R_{a,h}$ = resistance of a single horizontal anode
$N$ = number of anodes connected in parallel

### *Example Calculation:*

Calculate the resistance of 10 – 2 in. diameter by 6 ft long horizontal anodes connected to a common header cable at 11 ft center-to-center spacing in 10,000 $\Omega$-cm soil using Equation 4-23.

$$
\begin{aligned}
\text{Length (L)} &= 6 \text{ ft.} \times 30.5 \text{ cm/ft} &= 183 \text{ cm.} \\
\text{Diameter (D)} &= 2 \text{ in.} \times 2.54 \text{ cm/in.} &= 5.1 \text{ cm} \\
\text{Spacing (S)} &= 11 \text{ ft.} \times 30.5 \text{cm/ft} &= 336 \text{ cm} \\
\text{Soil Resistivity } (\rho) &= 10,000 \ \Omega\text{-cm} \\
\text{Depth } (t) &= 3 \text{ ft.} \times 30.5 \text{ cm/ft} &= 91.5 \text{ cm}
\end{aligned}
$$

$$
R_{a,h} = \frac{\rho}{2\pi L} \ \ln\left(\frac{L^2}{td}\right)
$$

$$
= \frac{10,000 \ \Omega\text{-cm}}{6.28 \ \times \ 183 \text{ cm}} \ \ln\left(\frac{33489 \text{ cm}^2}{466.7 \text{ cm}^2}\right)
$$

$$
= 8.7 \ \ln 71.8
$$

$$
R_{a,h} = 8.7 \times 4.27 = 37 \ \Omega
$$

Substituting $R_{a,h}$ into Equation 4-26 to obtain the crowding factor (F).

$$
F = 1 + \frac{10,000 \ \Omega\text{-cm}}{\pi \times 336 \text{ cm} \times 37 \ \Omega} \ \ln(0.656 \times 10)
$$

$$
= 1 + 0.256 \times 1.88
$$

$$
F = 1.48
$$

Substituting F into Equation 4-25 yields:

$$
R_{g/b,h} = \frac{37 \ \Omega}{10} \times 1.48
$$

$$
= 5.5 \ \Omega
$$

This result compares favorably with the calculated resistance ($R_{gb,v}$) of 7.9 $\Omega$ or the vertical groundbed array having the same number of anodes, the same size anode, and the same spacing.

### *4.4.5  Calculating Pipe Resistance to Remote Earth*

There are several different methods of determining the resistance of a coated pipe to remote earth.  For any pipe, the potential shift ($\Delta V$) that occurs between the pipe and a reference placed at remote earth (as in Figure 4-7) with a test current interrupted can be used in Ohm's law to calculate the pipe resistance ($R_{p,re}$) as follows:

$$R_{p,re} \quad = \quad \frac{V_{ON} - V_{OFF}}{I_t} \ (\Omega)$$

[4-27]

$$R_{p,re} \quad = \quad \frac{\Delta V}{I_t} \ (\Omega)$$

To increase the reliability of the result, the change in voltage should be calculated at several points if the pipeline is extensive. For short sections of bare pipe, as illustrated in Figure 4-18, Equation 4-23 can be used to calculate pipe resistance. The section must be separated physically or electrically from adjoining or adjacent structures.
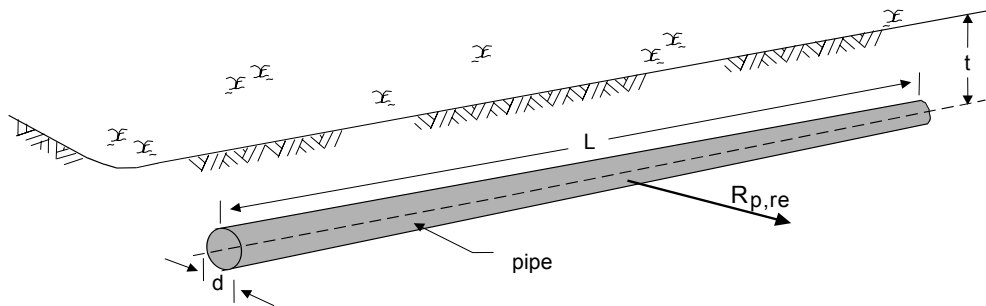


**Figure 4-18:  Resistance of a Horizontal Coated Pipe Section**

For a coated pipeline, most of the resistance to remote earth will be across the coating. Accordingly, if a specific coating resistance ($r'_c$) is assumed, the resistance of the pipe to remote earth ($R_{p,re}$) can be calculated from Equation 4-28.

$$R_{p,re} \quad = \quad \frac{r'_c}{A_s}$$

[4-28]

*where:*

$r'_c$ = specific coating resistance
$A_s$ = surface area of pipe

### *Example Calculation:*

Calculate the resistance of a 1,000 m long section of 21.9 cm diameter pipe in 5,000 $\Omega$-cm soil if the specific coating resistance ($r'_c$) in 1,000 $\Omega$-cm soil is $10^4\,\Omega$-m$^2$.

$$R_{p,re} = \frac{r'_c\ @\ 5,000\,\Omega\text{-cm}}{A_s}$$

*where:*

$$r'_c\ @\ 5,000\ \Omega\text{-cm} = r'_c\ @\ 1,000\ \Omega\text{-cm} \times \frac{5,000\ \Omega\text{-cm}}{1,000\ \Omega\text{-cm}}$$

$$= 1 \times 10^4 \times \frac{5,000\ \Omega\text{-cm}}{1,000\ \Omega\text{-cm}}$$

$$= 5 \times 10^4\ \Omega\text{-m}^2$$

*and:*

$$A_s = \pi dL$$
$$= 3.14 \times 0.219\ \text{m} \times 1,000\ \text{m} = 688\ \text{m}^2$$

*therefore:*

$$R_{p,re} = \frac{5 \times 10^4\ \Omega\text{-m}^2}{688\ \text{m}^2} = 72.7\ \Omega$$

## *4.4.6  Calculation of Cable and Pipe Lineal Resistances*

For solid copper cable the resistance of a conductor having a length (L) and a diameter (d) is given by the following equation:

$$R_c = \rho_{cu}\frac{L}{A_x} \tag{4-29}$$

*where:*

$L$ = length
$A_x$ = cross-sectional area
$\rho_{cu}$ = volume resistivity of copper (typically 1.72 $\mu\Omega$-cm)

But typical cable resistances can be obtained from published tables as in Table 4-5.

**Table 4-5: Concentric Stranded Copper Single Conductors Direct Burial Service Suitably Insulated**

| Size AWG | Overall Diameter not Including Insulation (inches) | Approx. Weight Not Including Insulation (lbs/1000 ft) | Maximum Breaking Strength (lbs) | Maximum DC Resistance @ 20°C (Ohms/1000 ft) | Max. Allowable DC Current Capacity (Amperes) |
|---|---|---|---|---|---|
| 14 | 0.0726 | 12.68 | 130 | 2.5800 | 15 |
| 12 | 0.0915 | 20.16 | 207 | 1.6200 | 20 |
| 10 | 0.1160 | 32.06 | 329 | 1.0200 | 30 |
| 8 | 0.1460 | 50.97 | 525 | 0.6400 | 45 |
| 6 | 0.1840 | 81.05 | 832 | 0.4030 | 65 |
| 4 | 0.2320 | 128.90 | 1320 | 0.2540 | 85 |
| 3 | 0.2600 | 162.50 | 1670 | 0.2010 | 100 |
| 2 | 0.2920 | 204.90 | 2110 | 0.1590 | 115 |
| 1 | 0.3320 | 258.40 | 2660 | 0.1260 | 130 |
| 1/0 | 0.3730 | 325.80 | 3350 | 0.1000 | 150 |
| 2/0 | 0.4190 | 410.90 | 4230 | 0.0795 | 175 |
| 3/0 | 0.4700 | 518.10 | 5320 | 0.0631 | 200 |
| 4/0 | 0.5280 | 653.30 | 6453 | 0.0500 | 230 |
| 250 MCM | 0.5750 | 771.90 | 7930 | 0.0423 | 255 |

Note that the stated resistances are for direct current not alternating current, since the resistance for alternating current is greater due to skin effects.

The longitudinal resistance ($R_p$) of a section of steel pipe having a length (L) and a resistivity ($\rho_{steel}$) is inversely dependent on the cross-sectional area ($A_x$) of the pipe wall. Hence from Equation 4-29.

$$R_p = \rho_{steel}\frac{L}{A_x}$$
[4-30]

*and*
$$A_x = \frac{\pi}{4}\left(OD^2 - ID^2\right)$$
[4-31]

*where:*  OD = pipe outside diameter
ID = pipe inside diameter

The pipe resistance for a length of standard pipe can be calculated using Table B-1 in Appendix B.

*Example Calculation:*

Calculate the resistance of a 1 km length of 20 in. diameter schedule 30 pipe. From Table B-1 for Steel Pipe Data (Appendix B). The pipe dimensions are as follows:

*where:*     $OD$  =  50.8 cm
              $ID$  =  $OD - 2$ (wall thickness)
                   =  50.8 cm $- 2$ (1.27 cm)
              $ID$  =  48.26 cm

From Equation 4-31:

$$A_x \quad = \quad \frac{\pi}{4}\left[\left(50.8\,\text{cm}\right)^2 - \left(48.26\,\text{cm}\right)^2\right]$$

$$\begin{aligned}
&= \quad 0.785\,[2581\ \text{cm}^2 - \ 2329\ \text{cm}^2] \\
A_x &= \quad 0.785\,[252\ \text{cm}^2] \\
A_x &= \quad 198\ \text{cm}^2
\end{aligned}$$

Substituting for $A_x$ in Equation 4-30 and assuming $\rho_{steel} = 18 \times 10^{-6}$ $\Omega$-cm (a conservative value compared to Table B-1) gives:

$$R_p \quad = \quad \frac{18 \times 10^{-6}\ \Omega\text{-cm} \ \times \ 10^5\ \text{cm}}{198\ \text{cm}^2}$$

$$R_p \quad = \quad 0.009\ \Omega \quad or \ \ 9\ \text{m}\Omega\ \text{per kilometer}$$

# 4.5  Calculating System Capacity and Life

To determine the amount of anode material needed for a cathodic protection system it is usual to determine the electrochemical capacity required. Electrochemical capacity is simply the amount of cathodic protection current required multiplied by the anticipated service life of the system, as shown in Equation 4-32.

$$C_{cp} \ = \ I_{cp} \times L \quad\quad\quad\quad\quad\quad\quad [4\text{-}32]$$

*where:*

$I_{cp}$  =  cathodic protection current required
$L$  =  required service life
$C_{cp}$  =  CP system electrochemical capacity

For example, a cathodic protection system requiring 2 A of current for a service life of 15 years requires 30 A-y of electrochemical capacity.

Once the electrochemical capacity is determined, the minimum weight of any anode material can be determined from either Equation 4-33 or 4-34.

$$W_{ta,min} = \frac{C_{cp} \times C_r}{U \times E} \tag{4-33}$$

$$W_{ta,min} = \frac{C_{cp}}{C_a \times U \times E} \tag{4-34}$$

*where:*

$C_r$ = theoretical consumption rate of anode material
$C_a$ = theoretical capacity of anode material
$W_{ta,min}$ = minimum weight required
$U$ = utilization factor
$E$ = electrochemical efficiency

Besides the theoretical values of consumption and capacity, the calculated weight must have an allowance for anode efficiency (E) and utilization factor (U).

As an anode is consumed, it reaches a point when it can no longer provide the minimum cathodic protection current even though it is not yet fully consumed. This is addressed by the utilization factor, which typically ranges from 0.5 to 0.9 depending on the type of system and its operating condition.

Actual anode consumption rates and capacities are always less than the theoretical values as calculated from Faraday's law (see Chapter 1). Thus it is typical to assign an estimate of efficiency for each anode material depending on the application and operating conditions based on experience.

Table 4-6 contains typical consumption rates and electrochemical capacities for various anode materials. Note that the capacity is the inverse of the consumption rate.

**Table 4-6:  Typical Consumption Rate and Capacities of Different Anode Materials
in Soils or Fresh Waters**

| | | Theoretical Consumption Rate | | Theoretical Capacity | | Typical Efficiency[1] |
|---|---|---|---|---|---|---|
| | | kg/A-y | Lb./A-y | A-y/kg | A-y/lb | % |
| Galvanic Anode Material | Magnesium | 3.98 | 8.76 | 0.250 | 0.114 | 50 |
| | Zinc | 10.76 | 23.50 | 0.093 | 0.042 | 90 |
| | Aluminum | 2.94 | 6.49 | 0.340 | 0.155 | 85-95 |
| Impressed Current Anode | Graphite/Carbon | 0.1 to 1.0 | 0.22 to 2.2 | 10.1 to 1.0 | 4.5 to 0.45 | [2] [3] |
| | High Silicon Iron | 0.25 to 1.0 | 0.55 to 2.2 | 4.0 to 1.0 | 1.8 to 0.45 | [2] [3] |
| | Steel | 9.1 | 20 | 0.11 | 0.05 | 90 |

Note:   Platinum clad and mixed metal oxide coated anodes are quantified by thickness of the
surface film rather than by weight.

(1)  Efficiency of galvanic anodes is dependent on the anode current density.
(2)  Source:  Jakobs, J.A., A Comparison of Anodes for Impressed Current Systems, NACE
Canadian Region, Western Conference, Feb. 1980.
(3)  See Table 2-13 for consumption rate in different environments.

### Example Calculation

*Given:*   A required system capacity of 30 A-y.
What is the minimum weight of magnesium anode alloy required?
Assume a utilization factor of 0.85 and an efficiency of 50%.

$$W_{ta,min} \;=\; \frac{C_{cp} \times C_r}{U \times E}$$

$$W_{ta,min} \;=\; \frac{30 \, A\text{-}y \; \times \; 3.98 \, kg/A\text{-}y}{0.85 \; \times \; 0.5}$$

$$W_{ta,min} \;=\; 281 \, kg$$

## 4.6   Calculation of System Life

By substituting Equation 4-32 for system capacity in Equations 4-33 and 4-34 and
rearranging, system life can be calculated by the two resulting Equations 4-35 and
4-36 using theoretical anode consumption rate and theoretical anode capacity
respectively.

$$L = \frac{W_t \times U \times E}{I_{cp} \times C_r}$$  [4-35]

$$L = \frac{W_t \times C_a \times U \times E}{I_{cp}}$$  [4-36]

*where:*

L = anode life (yr)
$I_{cp}$ = cathodic protection current (A)
$W_t$ = weight (kg)
$C_r$ = theoretical consumption rate (kg/A-yr)
$C_a$ = theoretical capacity (A – y/kg)
U = utilization factor
E = efficiency (%)

Notes:
1. Apply efficiency to Table 4-6.
2. Efficiency included in $C_a$ from Figure 2-20.
3. 50% efficiency included in Table 2-10.

## Example Calculation

*Given:* A magnesium anode weighing 17 lb has a 50 mA output.
Assuming a utilization factor of 0.9 and an efficiency of
50%, what will be its service life?

Using Equation 4-35 and a theoretical consumption rate of 8.76 lb./A-y
(from Table 4-6).

$$L = \frac{W_t \times U \times E}{I_{cp} \times C_r}$$

$$L = \frac{17\,\text{lb.} \times 0.9 \times 0.5}{0.05\,\text{A} \times 8.76\,\text{lb/A - y.}}$$

$$L = 17.5\ \text{y}$$

## 4.7 Calculating Number of Anodes

Once the minimum total weight of anode material has been determined, the minimum number of anodes is calculated using Equation 4-37.

$$N \;=\; \frac{W_{t,\,min}}{W_{t,\,anode}} \qquad\qquad \text{[4-37]}$$

### *Example Calculation*

*Given:* From the previous example the minimum total weight of magnesium required was 281 kg. Choosing a #20D2 (20 lb) from Table I (Appendix A), how many anodes are required?

$$N_{min} \;=\; \frac{281\,kg \;\times\; 2.2\,lb/kg}{20\,lb}$$

$$N_{min} \;=\; 31 \text{ anodes}$$

This is the minimum number of anodes required from a weight basis, but the current output of each anode must be enough to supply the total current of 2A. The minimum number of anodes required on a current basis, given that each anode will produce 50 mA, is as follows:

$$N_{min} \;=\; \frac{I_t}{50\,mA} \;=\; \frac{2000\,mA}{50\,mA} \;=\; 40 \text{ anodes}$$

Hence the minimum number of 20 lb anodes required to satisfy both the current and life requirement is 40.

# 4.8 Calculating System Driving Voltage

## 4.8.1 *Galvanic (Sacrificial) System*

As seen previously, a galvanic system can be depicted on a polarization diagram such as Figure 4-19.
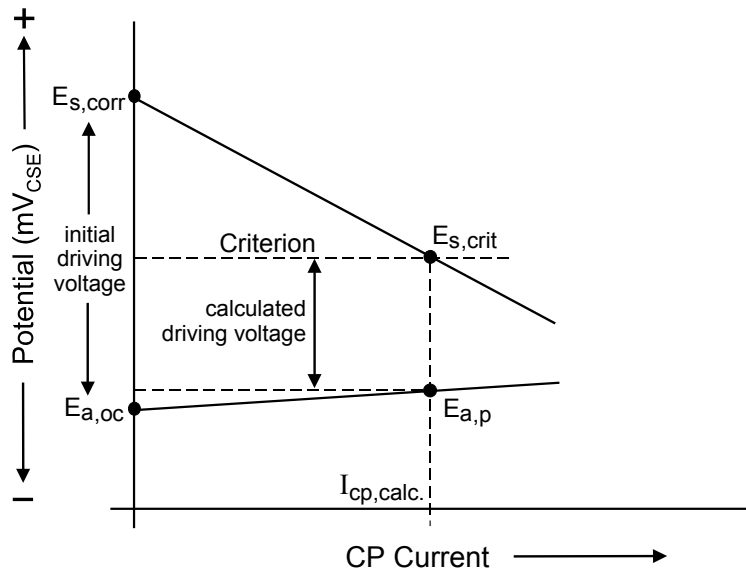


**Figure 4-19: Polarization Diagram for a Galvanic Cathodic Protection System**

The initial driving voltage (i.e., the original EMF) is the difference between the galvanic anode open circuit potential ($E_{a,oc}$) and the structure corrosion potential ($E_{s,corr}$). But the intended operating driving voltage is $E_{a,p} - E_{s,crit}$ which is substantially different from the initial driving voltage due to the amount of the original voltage used up in polarization at the anode and cathode.

For cathodic protection design purposes, the design driving voltage is the difference between the anode polarized potential ($E_{a,p}$) and the chosen cathodic protection criterion ($E_{s,crit}$).

For example, if the chosen criterion is $-850$ mV$_{cse}$ and the polarized potential for a high potential magnesium anode is $-1700$ mV$_{cse}$ (e.g., 50 mV allowance for polarization from an open circuit potential of $-1750$ mV$_{cse}$), then the driving voltage ($E_{cp}$) will be:

$$
\begin{aligned}
E_{a,p} &= E_{a,oc} - \text{anode polarization} \\
E_{cp} &= E_{a,p} - E_{s,crit} \\
E_{cp} &= (1700\ \text{mV} - 850\ \text{mV}) \\
E_{cp} &= 850\ \text{mV}
\end{aligned}
$$

## 4.8.2   Impressed Current System

The operation of an impressed current system can also be represented on a polarization diagram such as Figure 4-20.
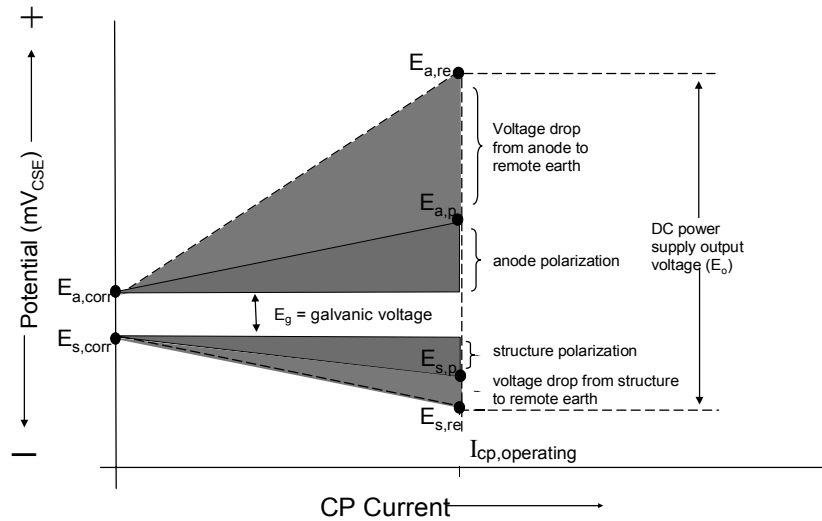


**Figure 4-20:  Polarization Diagram for an Impressed Current Cathodic Protection System (cable resistances ($R_c$) are ignored)**

Applying Ohm's law to the impressed current system, which is a series circuit, the required power supply voltage ($E_o$) is equal to the sum of the voltage drops (including polarization and back voltage) around the circuit as in Equation 4-38.

$$E_o \ = \ I_{cp} \, (R_{a,re} \ + \ R_{s,re} \ + \ R_c) \ + \ E_b \qquad\qquad \text{[4-38]}$$

*where:*

$$
\begin{aligned}
I_{cp} \quad &= \quad \text{required cathodic protection current} \\
R_{s,re} \quad &= \quad \text{resistance of the structure to remote earth} \\
R_{a,re} \quad &= \quad \text{resistance of anode or groundbed to remote earth} \\
R_c \quad &= \quad \text{sum of all cable resistances} \\
\Delta E_{a,p} \quad &= \quad \text{total polarization at anode} \\
\Delta E_{s,p} \quad &= \quad \text{total polarization at structure} \\
E_g \quad &= \quad \text{galvanic voltage} \\
E_b \quad &= \quad \Delta E_{a,p} + \Delta E_{s,p} \ + E_g
\end{aligned}
$$

Galvanic voltage ($E_g$) is the difference in potential between the corrosion potential of the structure ($E_{corr}$) and the corrosion potential of the anode or groundbed ($E_{corr}$). The semi-inert impressed current anodes have corrosion potentials that are more positive than steel structures (e.g., graphite could be up to 1.0 V positive to steel).

The term "back voltage" is used to account for anticipated anode and structure polarization plus the galvanic voltage difference.

# 4.9   Sample Cathodic Protection Designs

The examples that follow demonstrate typical calculations used in designing both galvanic and impressed current systems. These examples illustrate concepts only and are not intended as complete design procedures.

## 4.9.1   Galvanic Anodes

### 4.9.1(a)  Example No. 1

Given the following information, design a galvanic anode system for a 30 cm nominal by 6 km long FBE coated steel pipline.

- Soil resistivity is 5,500 $\Omega$-cm
- $i_{cp}$ required is 30 $\mu A/m^2$
- Pipeline is electrically isolated at both ends
- Specific coating resistance is $10^4$ $\Omega$-$m^2$
- Minimum design life is 15 years
- Actual pipe OD is 32.4 cm (12.75 in) (See Table B-1)

**Step 1**:        **Calculate Total current Required ($I_{cp}$)**

$$I_{cp} \quad = \quad i_{cp} \text{ x } A_t$$
$$i_{cp} \quad = \quad 30 \ \mu A/m^2$$
$$A_t \quad = \quad \pi dL$$
$$= \quad 3.14 \text{ x } 0.324 \text{ m x } 6,000 \text{ m}$$
$$= \quad 6,107 \text{ m}^2$$

*therefore:*
$$I_{cp} \quad = \quad 30 \text{ x } 10^{-6} \text{ A/m}^2 \text{ x } 6,107 m^2$$
$$= \quad 0.183A = 183 \text{ mA}$$

**Step 2:**        Choose a Magnesium Anode and Calculate its Resistance

- Choose a high potential #17D3 anode.
- Calculate resistance of the anode ($R_{a,h}$) placed horizontally at a depth of 1.2 m

$$R_{a,h} = \frac{\rho}{2\pi L} \left( \ln \frac{2L}{d} \right)$$

*where:*

$$L = 30 \text{ in x } \frac{2.54 cm}{in} = 76.2 \text{ cm}$$

$$d = 6 \text{ in x } \frac{2.54 cm}{in} = 15.2 \text{ cm}$$

$$R_{a,h} = \frac{5500 \text{ ohm - cm}}{6.28 \text{ x } 76.2 \text{ cm}} \left( \ln \frac{152.4 \text{ cm}}{15.2 \text{ cm}} \right)$$

$$= 11.5 \ \Omega \ (\ln 10)$$
$$= 11.5 \ \Omega \text{ x } 2.30 = 26.5 \ \Omega$$

**Step 3:       Calculate Anode Current Output**

$$Ia = \frac{E_{p,a} - E_{p,s}}{R_{a,h} + R_p}$$

w*here:*
$$\begin{aligned} E_{p,a} &= -1.7 \ V_{cse} \\ E_{p,s} &= -0.85 \ V_{cse} \\ R_{a,h} &= 26.5 \ \Omega \\ R_p &= \text{pipe resistance} \end{aligned}$$

- Calculate pipe resistance

$$R_p = \frac{r'}{A_t} = \frac{\text{specific coating resistance}}{\text{total pipe surface area}}$$

$$= \frac{10^4 \Omega - m^2}{3.14 \text{ x } 0.324m \text{ x } 6,000m} = 1.64 \ \Omega$$

- Calculate anode current output

$$I_a = \frac{1.7V - \left( -0.850V \right)}{26.5\Omega + 1.64\Omega} = \frac{0.850V}{28.1\Omega}$$

$$I_a = 30 \text{ mA}$$

**Step 4:        Calculate Number of Anodes Required Based Current Demand**

$$\text{N -} \frac{I_{cp}}{I_a} = \frac{183\,\text{mA}}{30\,\text{mA}} = 6.1 \rightarrow 7 \text{ anodes}$$

**Step 5:        Calculate Anode Life Based on Anode Current Density**

$$L = \frac{W \times U \times E \times Ca}{I_a}$$

w*here:*

| | | |
|---|---|---|
| W | = | 17 lb |
| U | = | 0.85 |
| E | = | 1.0 |
| $I_a$ | = | 30 mA |
| Ca | = | actual capacity from Fig 2-20 based on anode current density |

- Calculate anode current density

$$i_a = \frac{I_a}{A}$$

*where:*

| | | |
|---|---|---|
| $A_a$ | = | surface area of anode |
| $A_a$ | = | 2 (W + H) L |

*where:*

| | | | | |
|---|---|---|---|---|
| W | = | width of anode | = | 3.5 in |
| H | = | height of anode | = | 3.75 in |
| L | = | length of anode | = | 26 in |

*therefore:*

| | | |
|---|---|---|
| $A_a$ | = | 2 (3.5 + 3.75) 26 |
| | = | 377 $\text{in}^2$ = 2.6 $\text{ft}^2$ |

*therefore:*

$$i_a = \frac{30\text{mA}}{2.6\text{ft}^2} = 11.5\,\text{mA}/\text{ft}^2$$

- Determine magnesium capacity from Fig 2-20 for $i_a$ = 11.5 mA/ft$^2$

$$Ca \quad = \quad 300 \text{ A-hr/lb}$$

Converting to capacity for a year

$$Ca \quad = \quad 300 \; \frac{\text{A - hr}}{\text{lb}} \; \text{x} \; \frac{\text{yr}}{8766 \text{ hr}} = 0.034 \text{ A - } \frac{\text{yr}}{\text{lb}}$$

*therefore:*

$$L \quad = \quad \frac{17 \text{ lb x } 0.85 \text{ x } 1.0 \text{ x } 0.034 \text{ A - yr/lb}}{0.030 \text{ A}}$$

$$= \quad 16.4 \text{ yr}$$

Note to student:  Repeat design to achieve a 20 year life.

$$L \quad = \quad \frac{30.8 \text{ kg} \; \times \; 0.85 \times 0.5}{0.1 \text{ A} \; \times \; 3.98 \text{ kg/A - y.}} \quad = \quad 32.9 \text{ y}$$

## 4.9.1(b)  Example No. 2

The pipe to be protected is 2,000 feet of 4-in. ID steel (OD = 4.500 in. = 11.43 cm). It is coated and the coating is 98.5% effective. The pipe is electrically isolated and the estimated current requirement is 2 mA/ft$^2$ (21.54 mA/m$^2$) of exposed metal. Soil resistivity is 3,500 Ω-cm. Assume the desired pipe-to-soil polarized potential = −1.00 V$_{cse}$. Life of CP system must be 20 years. Assume pipe resistance is negligible and the CP system utilization factor is 0.85.

**General steps:**

- Determine current required
- Start with an anode size
- Calculate resistance to ground of one anode
- Determine the current output of one anode
- Determine the number of high potential magnesium anodes required based on the current required
- Determine the life of the anodes. Determine the weight of anode material needed based on the desired life.
- Determine number of anodes required and locations

## 1.    Calculate Current Required

*In Metric Units:*

$$\text{Total Surface Area} = \pi dL = \frac{\pi 11.43 \text{cm}}{\frac{100 \text{cm}}{\text{m}}} \times 609.6 \text{m} = 218.9 \text{ m}^2$$

*In Imperial Units:*

$$\text{Total Surface Area} = \pi dL = \frac{\pi 4.500 \text{in}}{\frac{12 \text{in}}{\text{ft}}} \times 2000 \text{ft} = 2356 \text{ ft}^2$$

$$
\begin{aligned}
\text{Coating effectiveness} &= \text{98.5\% or 1.5\% bare} = 0.015 \\
\text{Surface Area to protect} &= 2356 \text{ ft}^2 \times 0.015 = 35.3 \text{ ft}^2 \\
&= 218.9 \times 0.015 = 3.28 \text{ m}^2
\end{aligned}
$$

*therefore:*   At 21.5 mA/m$^2$, <u>current required</u> = 3.28 m$^2$ × 21.5 mA/m$^2$ =71 mA

***or***

*therefore:*   At 2 mA/ft$^2$, <u>current required</u> = 35.3 ft$^2$ × 2 mA/ft$^2$ = 71 mA

For a 7.7 kg (17 lb) high potential magnesium anode with dimensions of: 30 in. 76.2 cm [2.5 ft] long, 15.2 cm [6 in] diameter.

## 2.    Calculate the Resistance of a Single Vertical Anode

Using Equation 4-18:

$$R_v = \frac{\rho}{2\pi L}\left(\ln\frac{8L}{d} - 1\right) = \frac{3500 \; \Omega\text{-cm}}{2\pi 76.2 \text{ cm}}\left[\ln\left(\frac{8 \times 76.2 \text{ cm}}{15.2 \text{ cm}}\right) - 1\right]$$

$$
\begin{aligned}
&= 7.31 \times 2.69 \\
R_V &= 19.7 \; \Omega
\end{aligned}
$$

## 3.    Calculate the Resistance of the Anode Lead Wire

10 ft (3.048 m) of #12 lead wire → R = 1.62 Ω/1000 ft
= (5.32 Ω/1000 m)

*Using Metric*

$$R_{WIRE} = 3.05 \, m \times \frac{5.32 \, \Omega}{1000 \, m} = 0.016 \, \Omega$$

*Using Imperial*

$$R_{WIRE} = 10 \, ft \times \frac{1.62 \, \Omega}{1000 \, ft} = 0.016 \, \Omega$$

## 4.    Total Resistance of Anode and Wire:

$$R_{ANODE} = 19.7 \, \Omega + 0.016 \, \Omega = 19.7 \, \Omega$$

## 5.    Calculate the Current Output of a Single Anode

$$E_p \text{ of magnesium anode} = -1.70 \, V_{cse}$$

$$\text{Driving potential} = \Delta E = -1.70 \, V - (-1.00 \, V) = -0.7 \, V$$

*therefore:*

$$I_{anode} = \frac{\Delta E}{R} = \frac{0.7 \, V}{19.7 \, \Omega} = 0.036 \, A = 36 \, mA$$

## 6.  Calculate Life and Number of Anodes Needed

$$\text{Number} = \frac{71 \text{ mA needed}}{36 \text{ mA}/\text{anode}} = 2 \text{ anodes minimum required}$$

But we need to make sure the anode mass is available for the 20-year proposed design life. Assume the capacity is 0.250 A-y/kg (from Table 4-6).

*therefore:*

$$L = \frac{W_t \times C_a \times U \times E}{I_{cp}}$$

$$= \frac{7.7 \text{ kg} \times 0.250 \text{ A - yr/kg} \times 0.85 \times 0.5}{0.036 \text{ A}}$$

$$L = 22.7 \text{ y}$$

This would be the life of the system at 50% efficiency, but for 50% efficiency the anode current density must exceed 20 $\mu$A/cm$^2$, otherwise the life will be proportionately less.

> **Group Activity:**
>
> Calculate the anode current density assuming anode surface area is
> 2.46 ft$^2$ using Figure 2-20 and recalculate anode life.

## *4.9.2  Impressed Current System*

### 4.9.2(a)  Example No. 1

Known from field data and calculations:

*Given:*

Current requirement ($I_{cp}$)  =  15 A

Pipe-to-earth resistance ($R_{p,re}$ )  =  1 $\Omega$

Soil resistivity testing  =

| Layer (ft) | Layer Resistivity ($\Omega$–cm) |
|---|---|
| 0 - 5 ft  (0 - 1.5 m) | 30,000 |
| 5 - 10 ft  (1.5 - 3.0 m) | 20,000 |
| 10 - 15 ft  (3.0 - 4.5 m) | 5,000 |
| 15 - 20 ft  (4.5 - 6.0 m) | 10,000 |

## *Design Calculations:*

### Rectifier Option 1:  Try an output voltage of 20 volts

$$
\begin{aligned}
\text{Driving Volts (E}_{cp}) \ &= \ \text{Rectifier output} \ - \ \text{(Back voltage)} \\
&= \ 20\,\text{V} - 2\,\text{V} \\
&= \ 18\,\text{V}
\end{aligned}
$$

$$
\text{Max. R}_{gb,re} \ = \ \frac{E_{cp}}{I_{cp}} - R_{p,re} \ = \ \frac{18\,\text{V}}{15\,\text{A}} - 1 \ = \ 0.2\ \Omega
$$

From experience, this very low groundbed resistance would be impractical to try to attain. It would be better to use a larger voltage rectifier.

### Rectifier Option 2:  Try an output voltage of 40 volts

$$
\begin{aligned}
\text{Driving Volts (E}_{cp}) \ &= \ \text{Rectifier output} \ - \ \text{Back voltage} \\
&= \ 40\,\text{V} - 2\,\text{V} \\
&= \ 38\,\text{V}
\end{aligned}
$$

$$
\text{Max. R}_{gb,re} \ = \ \frac{E_{cp}}{I_{cp}} - R_{p,re} \ = \ \frac{38\,\text{V}}{15\,\text{A}} - 1 \ = \ 1.5\,\Omega
$$

This resistance is attainable with a reasonable anode system design.

### Anode System Option 1:

Calculate the anode-to-remote earth resistance for a system consisting of 15 impressed current anodes 20.3 cm (8 in.) by 2.13 m (7 ft) in a low-resistivity carbon backfill column, spaced 4.57 m (15 ft) apart and placed vertically at a depth of approximately 3.0 – 4.6 m (10 - 15 ft).

Using Equation 4-22, the vertical anode resistance would be:

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

$$=\frac{5,000\ \Omega-cm}{2\partial15\ anodes\ \times213cm}\left\{\left(\ln\frac{8\times213\ cm}{20.3}\right)-\ 1+\left(\frac{2\times213\ cm}{457cm}\ \ln(0.656\ \times15\ anodes)\right)\right\}$$

$$= \quad 0.248\ \{\ln(84)-1\ +\ 0.933\ \ln(9.84)\}$$
$$= \quad 0.249\ \{3.431\ +\ 2.133\}$$
$$= \quad 1.39\ \Omega$$

This configuration would work, but using this many anodes may cost more than a deep anode system. The decision is made to investigate the economics for using a deep anode system instead of a surface system.

**Anode System Option 2:**

Local geological surveys indicate a good clay stratum at depths between 38 and 61 m (125 and 200 ft). A carbon backfill column, 25.4 cm (10 in.) by 22.86 m (75 ft), containing the appropriate number of anodes for 15 A (based on the current density rating of the anode) will be used. Calculate the anode-to-remote earth resistance of this system assuming the clay stratum has a resistivity of 2,000 Ω-cm.

A deep anode system-to-remote earth resistance is calculated as if the "active zone" were one long single anode.

Using Equation 4-18 and metric units, the resistance of a single vertical groundbed is:

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

$$=\frac{2,000\ \Omega\text{-}cm}{2\pi2286\ cm}\left\{\left(\ln\frac{8\times2286\ cm}{25.4}\right)-1\right\}$$

$$=\ 0.1392\ \{\ln(720)-1\}$$
$$R_v\ =\ 0.78\ \Omega$$

Due to the low resistance, let's keep the 40-volt rectifier and shorten the length of carbon backfill column to 15.24 m (50 ft).

The anode-to-earth resistance using Equation 4-18 and metric now becomes:

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

$$= \frac{2000\ \Omega\text{-cm}}{2\partial 1524\ \text{cm}}\left\{\left(\ln\frac{8\times 1524\ \text{cm}}{25.4}\right)-1\right\}$$

$$= 0.209\ \{\ln(480)-1\}$$
$$R_v = 1.08\ \Omega$$

## 4.9.2(b)  Example No. 2

Design an impressed current cathodic protection system for 3048 meters (10,000 feet) of 20.32 cm (8 in.) ID, 21.9 cm (8.625 in.) OD coated steel pipe. Coating effectiveness is 99%. Use a surface groundbed. Soil resistivity is 4,000 $\Omega$-cm and the estimated current requirement is 21.5 mA/m$^2$ (2 mA/ft$^2$) of bare pipe. Pipe-to-ground resistance was measured as 0.3 $\Omega$ ($R_{p,re}$).

**General steps:**

- Determine current requirement
- Determine anode resistance
- Select appropriate wire size
- Determine cable resistance, $R_C$
- Determine pipe-to-soil resistance, $R_{p,re}$
- Decide if resistance is reasonable.
- Determine number of anodes required if resistance is not reasonable
- Determine total resistance based on number of anodes, $R_T$
- Determine rectifier size – voltage and amperage

1. **Calculate Current Required**

*Using metric units in meters*

$$\text{Total surface area} = \pi dL = \pi(0.219\ \text{m})\times 3048\ \text{m} = 2097\ \text{m}^2$$

$$\text{Actual bare surface area} = 2097\,\text{m}^2\frac{100-99}{100} = 20.97\ \text{m}^2$$

$$\text{Current required} = 20.97\ \text{m}^2\times 21.5\ \text{mA/m}^2 = 451\ \text{mA}$$

Assume that over the life of the pipeline, the current required to protect the structure will increase by 5 times to 2.3 A.

## 2.  Calculate Minimum Anode Weight Required

Anodes:   Using 21 kg (48 lb) high silicon cast iron anodes having a consumption rate ($C_r$) of 1 kg/A-y

$$C_r = \frac{2\ lb}{A - yr}$$

$$W_t = C_r \times I_{cp} \times L$$

*where:*        $C_r$ = consumption rate (lb/A-y)
                    $I_{cp}$ = current (A)
                    L = life (y)
                    $W_t$ = total weight of anode material required (lb)

*For 20 year life using metric:*

$$W_T = 1\ kg/A/y \times 2.3\ A \times 20\ y = 46\ kg$$

$$N = 46\ kg \div 21\ kg/anode = 2.2 = 3\ anodes$$

## 3.  Calculate Groundbed Resistance

The next step is to calculate the groundbed-to-remote earth resistance of multiple vertical anodes.

*Using Equation 4-22*

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

*where:*

$\rho$ = 4000 Ω-cm
L = 213.4 cm
d = 20.3 cm
S = 609.6 cm
N = 3 anodes (minimum)

$$R_N = \frac{4000\,\Omega\text{-}cm}{2 \times \pi \times 3 \times 213.4\,cm}\left[\ln\frac{8 \times 213.4\,cm}{20.3\,cm} - 1 + \left(\frac{2 \times 213.4\,cm}{609.6\,cm} \times \ln 0.656(3)\right)\right]$$

$$R_N \;=\; 1.0\,[4.43 - 1 \;+\; (0.7 \times 0.68)]$$

$$R_N \;=\; 3.9\,\Omega$$

For 2.3 A at 3.9 Ω, the rectifier voltage will need to be:

$$\begin{aligned}
E \;&=\; (I_T \times R_T) \\
&=\; 2.3\,A\,(3.9\,\Omega) + 2\,V\ (\text{back voltage}) \\
&=\; 11\,V
\end{aligned}$$

Calculate the anode-to-remote earth resistance using 4 anodes at 609.6 cm (20 feet) spacing.

*Using Equation 4-22:*

$$R_N = \frac{4,000\,\Omega\text{-}cm}{2 \times \pi \times 4 \times 213.4\,cm}\left[\ln\frac{8 \times 213.4\,cm}{20.32\,cm} - 1 + \left(\frac{2 \times 213.4\,cm}{609.6\,cm} \times \ln 0.656(4)\right)\right]$$

$$R_N \;=\; 0.746\,[\ln(84) - 1 \;+\; (0.7 \times \ln(2.624))]$$

$$R_N \;=\; 0.746\,[4.431 - 1 + 0.675]$$

$$R_N \;=\; 3.06\,\Omega$$

$$\begin{aligned}
E_{RECT} \;&=\; I_T \times R_N + 2V\ (\text{back voltage}) \\
&=\; (2.3\,A \times 3.06\,\Omega) + 2 \\
&=\; 9.04\,V
\end{aligned}$$

## 4.   Calculate Cable Resistances

Plan a surface single groundbed at the midpoint of the pipeline:
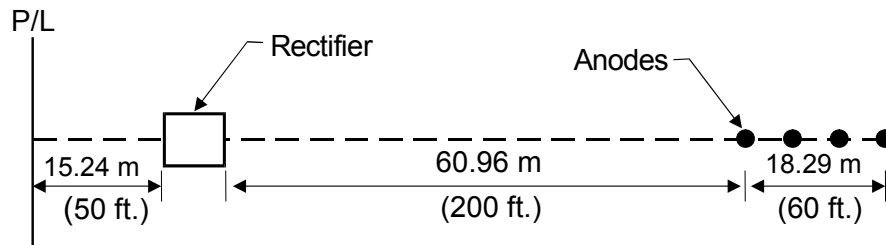


**Figure 4-21:  Single Groundbed Design**

Experience has shown that No. 6 AWG cable works well for this area.  The resistance of No. 6 AWG cable is 1.322 Ω/1000 m (0.403 Ω/1,000 ft).

*Cable resistance ($R_C$) in Imperial:*

| | | |
|---|---|---|
| Negative cable | = | 15.24 m (50 ft) |
| Positive cable | = | 60.96 m (200 ft) |
| Cable in groundbed | = | 18.29 m ÷ 2 = 9.1 m (60 ft ÷ 2 = 30 ft) |
| TOTAL CABLE | = | 85.3 m (280 ft) |

*Cable resistance ($R_C$):*

$$R_C = 85.3 \times \frac{1.322\ \Omega}{1,000\ m}$$

$$R_C = 0.11\ \Omega$$

**or**

$$R_C = 280\ ft \times \frac{0.403\ \Omega}{1,000\ ft}$$

$$R_C = 0.11\ \Omega$$

*Do we need to consider pipe longitudinal resistance, $R_P$?*

| | | |
|---|---|---|
| Pipe OD | = | 8 5/8 in = 8.625 in. (21.9 cm) |
| Pipe ID | = | 8.000 in. (20.32 cm) |
| Length | = | 10,000 ft. (3048 m) |

$$\rho_{steel} = 18\ \mu\Omega\text{-cm} = (18 \times 10^{-6}\ \Omega\text{-cm}) = 0.000018\ \Omega\text{-cm}$$

The longitudinal resistance of the pipe can be calculated using the following formula:

$$R = \frac{\rho L}{A} \qquad \text{[4-39]}$$

*where:*

$\rho$ = resistivity ($\Omega$-cm)
L = length (cm)
A = cross-sectional area ($cm^2$)

In this pipe example the cross-sectional area is:

$$A = \frac{\pi}{4}(OD^2 - ID^2) \qquad \text{[4-40]}$$

*where:*

A = cross-sectional area of the pipe ($cm^2$)
OD = pipe outside diameter, (cm)
D = pipe inside diameter, (cm)

*Using Equations 4-39 and 4-40 in metric units for ½ of the total pipe length:*

$$R_P(one\ direction) = \frac{\rho L}{\frac{\pi}{4}\left(OD^2 - ID^2\right)} = \frac{18 \times 10^{-6}\ \Omega\text{-cm} \times 15.25 \times 10^4\ cm}{\frac{\pi}{4}\left[(21.9\ cm)^2 - (20.32\ cm)^2\right]}$$

$$= \frac{2.75\ \Omega\text{-cm}^2}{52.4\ cm^2} = 0.052\ \Omega$$

Since the two directions of pipe length are in parallel with the rectifier, the total longitudinal resistance of the pipe is one-half of this value (e.g. 0.026$\Omega$).

Total circuit resistance:
$$R_T = R_N + R_{p,re} + R_C + R_P$$
*where:*

$R_T$ = Total circuit resistance ($\Omega$)
$R_N$ = Multiple anode resistance ($\Omega$)
$R_{p,re}$ = Pipe-to-electrolyte contact resistance ($\Omega$)
$R_C$ = Cable resistance ($\Omega$)
$R_P$ = Pipe resistance ($\Omega$)
$R_T$ = 3.06 + 0.30 + 0.11 + 0.026
= 3.496 $\Omega$ (use 4 $\Omega$)

5.    **Determining Rectifier Output Rating**

Rectifier voltage output ($E_O$):

$$E_O = (I \times R_T) + 2.0 \text{ V (Back voltage)}$$
$$= (2.3 \text{ A} \times 4.0 \text{ } \Omega) + 2.0 \text{ V (Back voltage)}$$
$$= 11.2 \text{ Volts}$$

Note:   Spare voltage capacity allowance for anode deterioration still needs to be considered.

# 4.10   Design of Performance Monitoring Facilities

Test facilities are an integral part of a complete cathodic protection design so that the system performance can be adequately monitored for industry regulations and practices. For pipelines, test leads to accommodate the surveys outlined in Chapter 5 are generally included:

a)  at frequent intervals (e.g., < 2 km)
b)  at crossings with foreign structures
c)  at points of electrical isolation
d)  at some galvanic anode locations
e)  at casings
f)  at current spans upstream and downstream of DC power supplies
g)  near sources of electrical interference
h)  at location of stray current discharge to earth

# 4.11   Current Distribution

## 4.11.1   Introduction

The amount of polarization and therefore the level of cathodic protection depend on the current density applied across the electrolyte/structure interface. To achieve uniform protection at all locations on the structure under constant conditions requires uniform, or ideal, current density on all protected surfaces. However, ideal current distribution is virtually impossible to obtain in practice due to non-uniformity of the electrolyte, characteristics of the structure, and placement of the cathodic protection anodes.

The relative resistance of each current path in the cathodic protection circuit determines the current in that path and the resulting current density at the structure surface. The resistance of a current path is related to the path length (L), cross-sectional area (A), and material resistivity (ρ) according to the expression in Equation 4-41.

$$R = \frac{\rho L}{A}$$
[4-41]

where:          $R$ = resistance ($\Omega$)
                $\rho$ = resistivity ($\Omega$-cm)
                $L$ = length of current path (cm)
                $A$ = cross-sectional area (cm$^2$)

In Equation 4-41 the cross-sectional area is the area perpendicular to the current direction. This equation is only valid for a system where the cross-sectional area is constant in the current direction. For electrodes in the earth, the cross-sectional area is constantly increasing as the current approaches remote earth; therefore, the simple relationship of Equation 4-41 is not valid.

For a cylindrical anode placed vertically in a homogeneous soil, the current distributes radially from the anode as shown in Figure 4-22. The total anode current ($I_{A)}$) is equal to the sum of an infinite number of radial currents ($I_a$).
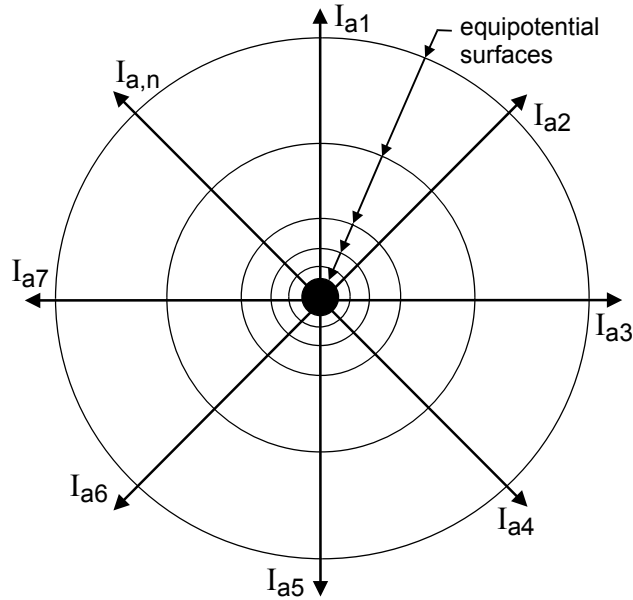
**Figure 4-22:  Typical Current Distribution with a Vertical Cylindrical Anode**

All of the current paths have equal lengths and cross-sectional areas to remote earth; thus, all paths have equal resistances if the soil resistivity is homogeneous. Equation 4-42 gives the total resistance ($R_T$) to remote earth.

$$\frac{1}{R_T} = \frac{1}{R_{a1}} + \frac{1}{R_{a2}} + \frac{1}{R_{a3}} + ... + \frac{1}{R_{an}} \qquad [4\text{-}42]$$

*where:*
$$R_T = \text{total resistance of anode } (\Omega)$$
$$R_{an} = \text{resistance of individual path } (\Omega)$$
$$n = \text{path number}$$

Figure 4-23 depicts the current paths from the anode to remote earth and the distribution of current to the structure from remote earth.
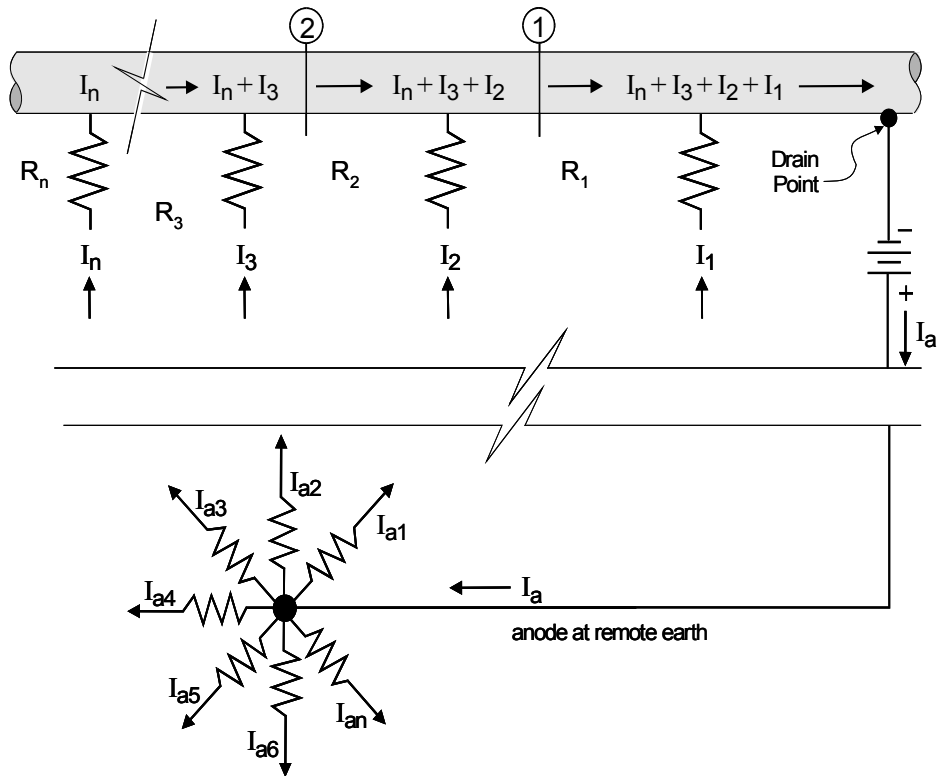
**Figure 4-23: Current Path Resistances for Ideal Current Distribution**

To complete the path for ideal current distribution, the current must enter the structure from remote earth. The resistance of the structure to remote earth is composed of an infinite number of individual parallel leakage resistances ($R_L$) that are equal in value in the ideal case. Assuming the internal resistance of the structure is zero, all current paths between the anode and cathode (structure) have equal resistances and therefore equal currents. This ideal circuit produces uniform (ideal) current density on the structure. Under ideal current distribution, the magnitude of cathodic protection current in the structure increases linearly toward the drain point (i.e., the point of negative connection to the structure) as illustrated in Figure 4-24.
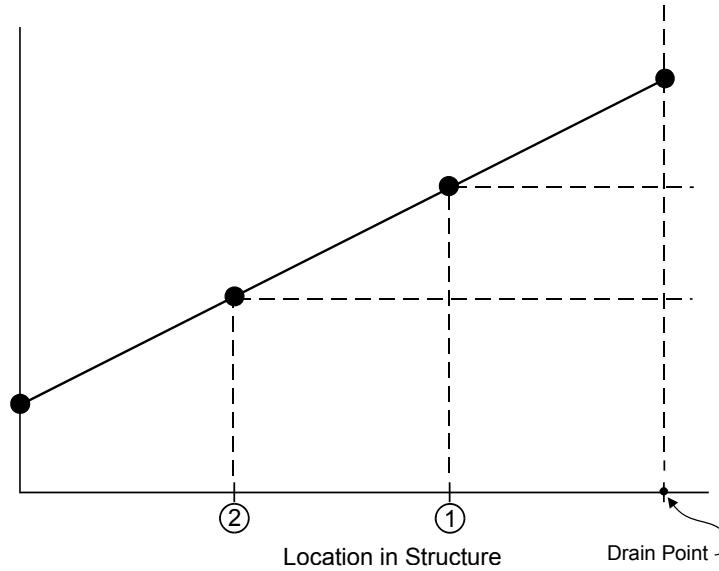
**Figure 4-24:  Current in Structure under Ideal Conditions**

Because the assumptions made to produce ideal current distribution are unrealistic, plus the fact that CP equipment cannot be located at remote earth, ideal current distribution cannot be achieved in practice.

**Table 4-7:  Some Factors That Affect Relative Current Distribution**

| Factors Affecting Current Distribution |
| --- |
| Current attenuation (structure has finite resistance) |
| Variations in electrolyte resistivity |
| Anode-to-structure and anode-to-anode spacing |
| Variations in electrolyte geometry and resistivity |
| Protective coatings |
| Polarization |

## *4.11.2   Attenuation*

In Figure 4-23, ideal current distribution is obtained in homogeneous soil with anodes remote from the structure and a structure resistance equal to zero. Structure resistance alters the ideal linear current distribution shown in Figure 4-24 so that it is no longer linear with distance but is logarithmic in nature. For structures such as pipelines and cables, the structure resistance can be significant

as modeled in Figure 4-25. Figure 4-26 illustrates the nonlinear tapering of the current and voltage along the structure known as *attenuation*.

When the structure resistance is included, the individual path resistance increases with distance from the drain point.
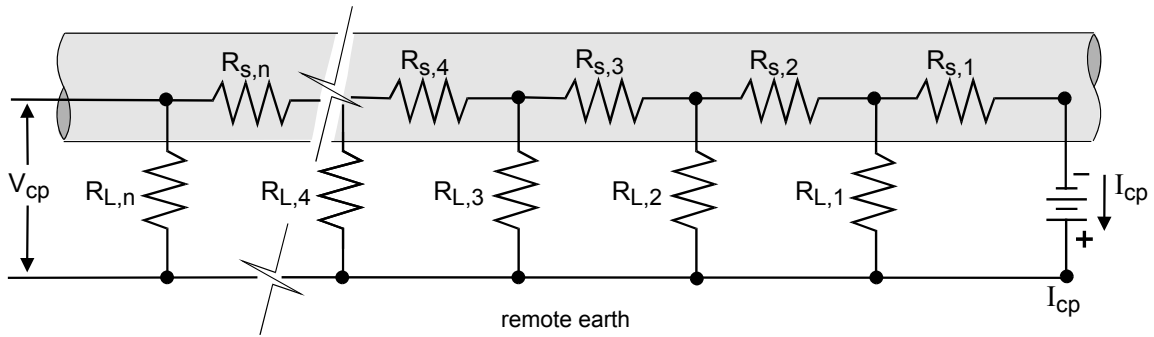


**Figure 4-25:  Current Path Resistance Including Resistance of Pipeline**

Even in homogeneous soil, the current density remote from the drain point will be less than the current density near the drain point. It follows then that the structure potential will also attenuate away from the drain point.
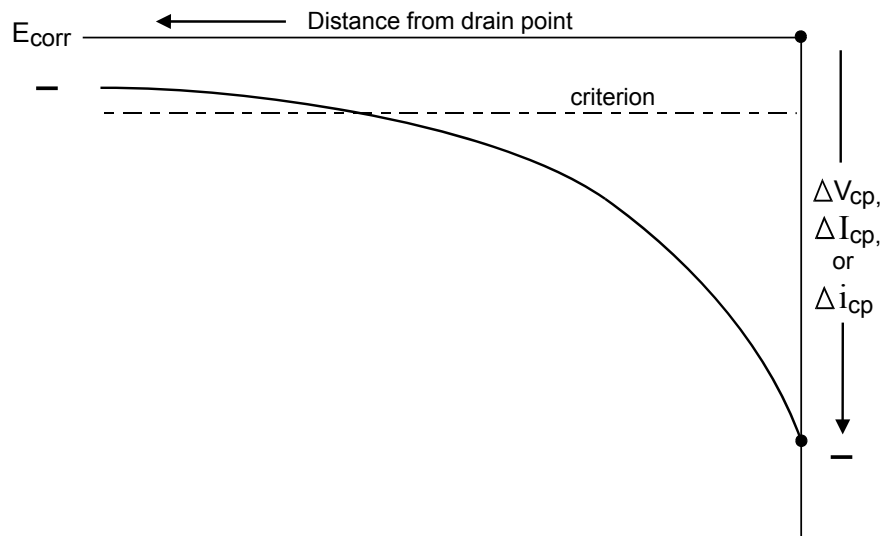


**Figure 4-26:  Current and Voltage Attenuation Away from the Drain Point**

The shape of the attenuation curve is governed by the relative values of the structure longitudinal resistance ($R_s$) in ohms per unit length and the structure leakage resistance to remote earth ($R_L$) in ohms per unit length. More specifically, these two parameters determine the structure attenuation constant ($\alpha$) that governs the rate of attenuation.

The attenuation constant is related to the two structure resistance parameters as indicated in Equation 4-43.

$$\alpha \ = \ \sqrt{\dfrac{R_S}{R_L}} \qquad\qquad\qquad [4\text{-}43]$$

*where:*      $\alpha$ = attenuation constant
$R_S$ = longitudinal resistance of structure ($\Omega$)
$R_L$ = leakage resistance of structure ($\Omega$)

The attenuation constant controls the rate at which the current and voltage are reduced with distance from the drain point. As shown in Figure 4-27, a small attenuation constant ($\alpha$) will result in a small amount of attenuation with distance, whereas a large attenuation constant will result in much greater attenuation with distance from the drain point.
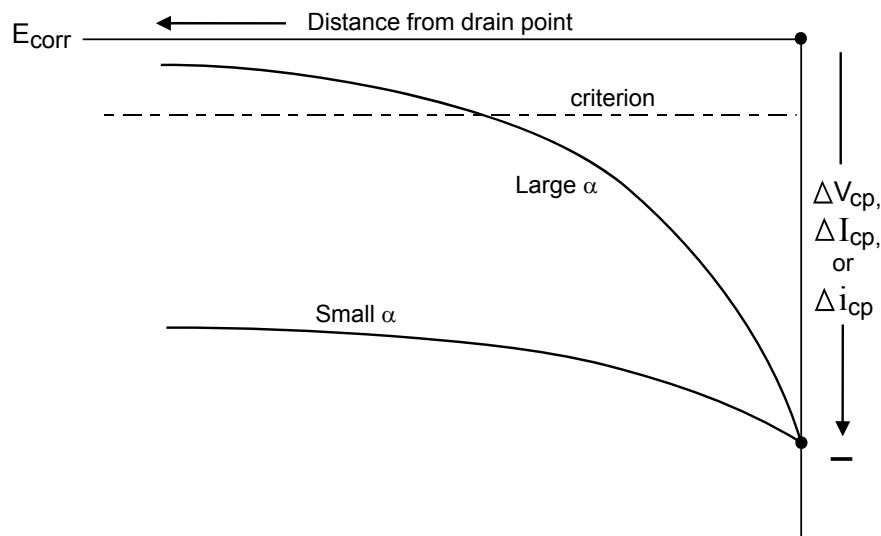


**Figure 4-27:  Effect of the Attenuation Constant $\alpha$ on Attenuation Characteristics**

When $R_s$ is large with respect to $R_L$, $\alpha$ will be relatively large. When $R_s$ is small with respect to $R_L$, $\alpha$ will be relatively small. The attenuation constant will be large if, for example, the coating is poor, the resistivity of the environment is low, or the longitudinal resistance of the pipe is high.

Assuming the structure is infinitely long, the current ($I_x$) in the structure at any distance (x) from the structure drain point is related to total cathodic protection current ($I_o$) as seen in Equation 4-44.

$$I_x \;=\; I_0 e^{-\alpha x} \qquad\qquad [4\text{-}44]$$

*where:*      $I_x$  =  current at point $x$ (A)
              $I_0$  =  current at drain point (A)
              $\alpha$  =  attenuation constant
              $x$  =  distance from drain point (unit lengths)

The structure voltage ($V_x$) with respect to remote earth at any distance (*x*) from the drain point in a structure that is infinitely long is related to the drain point voltage ($V_o$) as seen in Equation 4-45.

$$V_x \;=\; V_0 e^{-\alpha x} \qquad\qquad [4\text{-}45]$$

*where:*      $V_x$  =  voltage-to-remote earth at point $x$ (V)
              $V_0$  =  voltage-to-remote earth at drain point (V)

Since the cross-sectional area (A) of a structure such as a pipeline or cable is constant along the length of the structure, the longitudinal structure resistance can be calculated using Equations 4-30 and 4-31 (see Section 4.4.6). The resistivity ($\rho$) is the resistivity of the structure metal (e.g., steel is 18 x $10^{-6}$ $\Omega$-cm) and the length (L) is a unit length along the structure.

The leakage resistance ($R_L$) per unit length for a bare structure can be estimated by Equation 4-23.

$$R_L \;=\; \frac{\rho}{2\pi L}\; \ln\!\left(\frac{L^2}{td}\right) \qquad\qquad [4\text{-}46]$$

*where:*      $\rho$  =  soil resistivity ($\Omega$-cm)
              t  =  depth of burial (cm)
              D  =  diameter of pipe (cm)
              L  =  unit length of pipe (cm)

## 4.11.3   Effect of Coating on Current Distribution

Properly selected and applied protective coatings have a dramatically beneficial effect on current distribution and reduce the total current requirements. The principal effect of the coating involves its high electrical resistivity, which increases the structure leakage resistance ($R_L$) thereby minimizing current attenuation.

The $R_L$ as shown in Figure 4-28 is the sum of the leakage resistance of the coating ($R_{L,C}$) and the leakage resistance to remote earth of the steel structure ($R_{L,E}$).

*That is:*   $R_L = R_{L,c} + R_{L,e}$
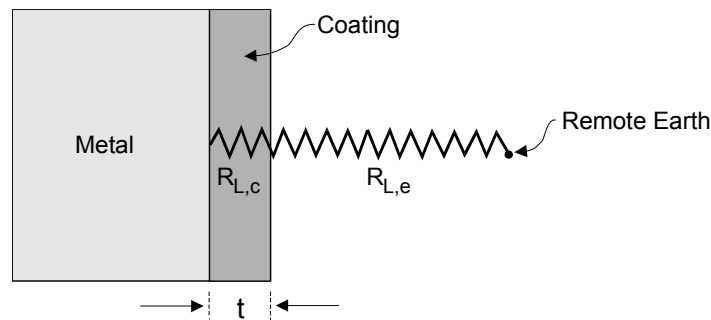


**Figure 4-28:  Leakage Resistance to Remote Earth of a Coated Structure**

The leakage resistance of the coating is a function of its electrical resistivity, thickness, and surface area exposed to the electrolyte. Therefore, modifying Equation 4-41 by changing the length (L) to thickness (t) produces Equation 4-47, which can be used to calculate the resistance of the coating for a given surface area ($A_s$).

$$R_{L,C} = \frac{\rho_c\, t}{A_s} \qquad\qquad [4\text{-}47]$$

*where:*   $R_{L,C}$  =  leakage resistance of coating ($\Omega$)
              $\rho_c$  =  coating electrical resistivity
                 t  =  coating thickness
               $A_s$  =  coated surface area

Typical coating resistivities are on the order of $10^{10}$ to $10^{12}$ $\Omega$-cm, and coating thickness are on the order of 0.005 to 0.015 cm. Accordingly, the coating leakage resistance ($R_{L,C}$) for one square meter of a coating from Equation 4-47 would be as follows:

$$R_{L,C} = \frac{\left(10^{10}\,\Omega - cm\right)\left(0.005\,cm\right)}{10^4\,cm^2} = 5000\,\Omega$$

The value of the leakage resistance of the structure ($R_{L,E}$) to remote earth can be approximated by assuming the surface is a disk with an area of one square meter. The resistance-to-remote earth of the soil side of the disk is given by Equation 4-48. In this case, the leakage resistance for one side of a bare metal disk ($R_{L,E}$) can be calculated using Equation 4-48.

$$R_{L,E} = \frac{\rho_s}{4\,r} \qquad\qquad [4-48]$$

*where:*        $\rho_s$ = soil resistivity
                r = radius of disk

Given a disk with a surface area of $10^4$ cm$^2$ (i.e., 1 m$^2$), the radius can be determined by rearranging the surface area equation for a circle and solving for radius (r). This is given in Equation 4-49 below.

$$r = \sqrt{\frac{A_s}{\pi}} \qquad\qquad [4-49]$$

*where:*        r = radius
          $A_s$ = surface area

Using the value for $A_s$, we find that the radius is as given in Equation 4-49.

$$r = \sqrt{\frac{10^4\,cm^2}{\pi}} = 56.4\,cm$$

Therefore, for a soil resistivity of 1,000 $\Omega$-cm solving Equation 4-48, we have:

$$R_{L,E} = \frac{1000\,\Omega - cm}{4\left(56.4\,cm\right)} = 4.4\,\Omega$$

The total leakage resistance ($R_L$) is therefore:

*where:*
$$
\begin{aligned}
R_L &= R_{L,c} + R_{L,e} \\
&= 5000\ \Omega\ +\ 4.4\ \Omega \\
&= 5004.4\ \Omega
\end{aligned}
$$

This example shows that the coating leakage resistance ($R_{L,C}$) is the dominant component of the structure leakage resistance ($R_L$). A good coating significantly increases the leakage resistance resulting in a small $\alpha$ and therefore less attenuation and better current distribution.

The leakage resistance of most coatings can be expected to decrease in service because coatings deteriorate with time. For this reason, it is important to measure the leakage resistance structure periodically. Equation 4-50 determines the average leakage resistance to remote earth of all or a portion of the structure.

$$R_L = \frac{\Delta V_s}{\Delta I_{test}} \qquad\qquad [4\text{-}50]$$

*where:*
$$
\begin{aligned}
R_L &= \text{average leakage resistance } (\Omega) \\
\Delta V_s &= \text{average potential change (V)} \\
\Delta I_{test} &= \text{average test current change (A)}
\end{aligned}
$$

The average potential change of the structure to remote earth ($\Delta V_s$) is measured with a reference electrode placed remote from the structure with the test current switched on and off. The average change in test current ($\Delta I_{test}$) is the difference between the applied test current as it changes from one value to another. Normally, the test current is simply switched on and off; therefore, the change in test current is equal to the test current value with the switch on. Both of these values, $\Delta E_s$ and $\Delta I_{test}$ must be instantaneous values obtained immediately after the switch is opened or closed.

The specific leakage resistance ($r'$) for the coating is related to the average total leakage resistance as shown by Equation 4-51.

$$r' = R_L A_S \qquad\qquad [4\text{-}51]$$

*where:*   $r'$ = specific leakage resistance
$R_L$ = average total leakage resistance
$A_S$ = total surface area tested

The specific leakage resistance, therefore, is typically expressed in units of $\Omega\text{-m}^2$ ($\Omega\text{-ft}^2$). Coating quality can be rated on the basis of comparing the specific coating resistance or conductance in 1000 $\Omega\text{-cm}$ soil to ranges established from experience, as shown previously in Table 4-8.

**Table 4-8:  Specific Leakage Resistances and Conductances**

| Long Pipelines with Few Fittings | Average Specific Coating Conductance $g'$ | | Average Specific Coating Resistance $r'_c$ | |
|---|---|---|---|---|
| **Quality of Work** | **Siemens/ft²** | **Siemens/m²** | **Ω-ft²** | **Ω-m²** |
| Excellent | $<1 \times 10^{-5}$ | $<1 \times 10^{-4}$ | $>10^5$ | $>10^4$ |
| Good | $1 \times 10^{-5}$ to $5 \times 10^{-5}$ | $1 \times 10^{-4}$ to $5 \times 10^{-4}$ | $2 \times 10^4$ to $10^5$ | $2 \times 10^3$ to $10^4$ |
| Fair | $5 \times 10^{-5}$ to $1 \times 10^{-4}$ | $5 \times 10^{-4}$ to $1 \times 10^{-3}$ | $10^4$ to $2 \times 10^4$ | $10^3$ to $2 \times 10^3$ |
| Poor | $>1 \times 10^{-4}$ | $>1 \times 10^{-3}$ | $<10^4$ | $<10^3$ |
| Bare Pipe (2 to 12 in.) (5 to 30cm) | $4 \times 10^{-3}$ to $2 \times 10^{-2}$ | $4 \times 10^{-2}$ to $2 \times 10^{-1}$ | 50 to 250 | 5 to 25 |

| Gas or Water Distribution with Many Fittings | Average Specific Coating Conductance $g'$ | | Average Specific Coating Resistance $r'_c$ | |
|---|---|---|---|---|
| **Quality of Work** | **Siemens/ft²** | **Siemens/m²** | **Ω-ft²** | **Ω-m²** |
| Excellent | $<5 \times 10^{-5}$ | $<5 \times 10^{-4}$ | $>2 \times 10^4$ | $>2 \times 10^3$ |
| Good | $5 \times 10^{-5}$ to $1 \times 10^{-4}$ | $5 \times 10^{-4}$ to $1 \times 10^{-3}$ | $10^4$ to $2 \times 10^4$ | $10^3$ to $2 \times 10^3$ |
| Fair | $1 \times 10^{-4}$ to $5 \times 10^{-4}$ | $1 \times 10^{-3}$ to $5 \times 10^{-3}$ | $2 \times 10^3$ to $10^4$ | $2 \times 10^2$ to $10^3$ |
| Poor | $>5 \times 10^{-4}$ | $>5 \times 10^{-3}$ | $<2 \times 10^3$ | $<2 \times 10^2$ |
| Bare Pipe (2 to 12 in.) (5 to 30 cm) | $4 \times 10^{-3}$ to $2 \times 10^{-2}$ | $4 \times 10^{-2}$ to $2 \times 10^{-1}$ | 50 to 250 | 5 to 25 |

### 4.11.4 Effect of Anode-to-Structure Spacing on Current Distribution

In homogeneous soil, the shorter current paths between the anode and structure carry larger currents than the longer current paths. For example in Figure 4-29,
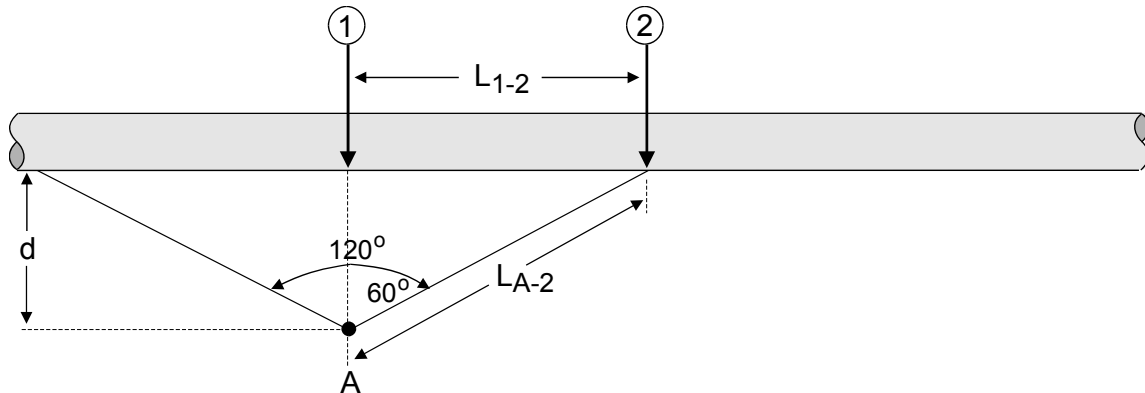


**Figure 4-29: Current Distribution with a Close Anode-to-Structure Spacing**

the current path A-1, between a vertical anode and a vertical steel sheet, is shorter than current path A-2. When the angle between A-1 and A-2 is 60°, then the length of the current path A-2 is given by Equation 4-52.

$$\cos \theta \ = \ \frac{d}{L_{A\text{-}2}} \qquad\qquad [4\text{-}52]$$

*and*

$$\cos 60 \ = \ \frac{d}{L_{A\text{-}2}}$$

$$0.5 \ = \ \frac{d}{L_{A\text{-}2}}$$

$$L_{A\text{-}2} = \ 2d$$

The current path $L_{A\text{-}2}$ is twice the perpendicular distance (d), and therefore the current density ($i_{①}$) at location ① would be expected to be double that at location ②.

In an attempt to achieve uniform current distribution, a second anode can be located at a distance $2L_{1\text{-}2}$ from the first anode as shown in Figure 4-30. The current density ($i_{②}$) will now be doubled, each anode contributing equal currents.
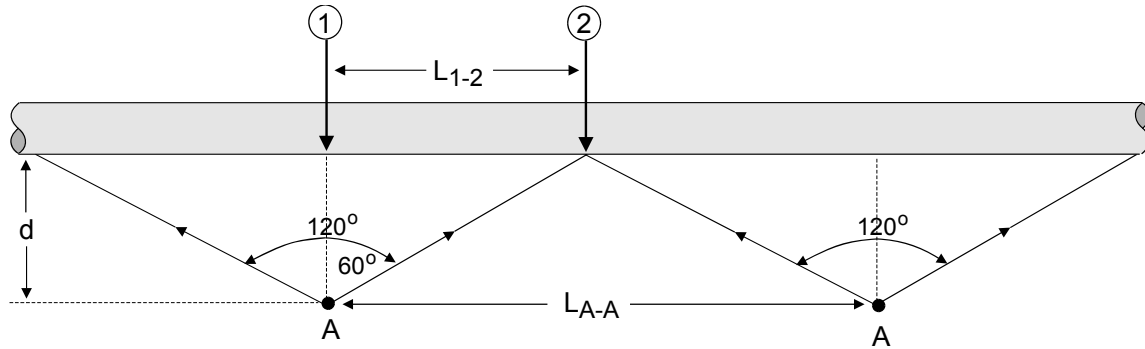
**Figure 4-30:  Anode-to-Anode Spacing to Achieve Relatively Uniform Current Distribution with Close Anode-to-Structure Spacing**

Distance (L) can be calculated from Equation 4-53

$$L = d \tan \theta \qquad\qquad \text{[4-53]}$$

Therefore the anode-to-anode separation distance ($L_{A-A}$) will be:

$$L_{A-A} = 2\, d \tan \theta$$

For example, if the anode-to-structure spacing (d) is 1 m, the anode-to-anode spacing $L_{A-A}$ will be:

$$
\begin{aligned}
L_{A-A} &= 2 \times 1\text{ m} \times \tan 60 \\
&= 2 \times 1\text{ m} \times 1.73 \\
&= 3.5\text{ m}
\end{aligned}
$$

Close distributed anode systems are often used to protect specific piping runs such as in petrochemical and chemical plants where the piping cannot be electrically isolated form other structures located in the immediate vicinity of the piping.

Close distributed impressed current anodes are widely used to protect existing underground storage tanks as shown in Figure 4-31.
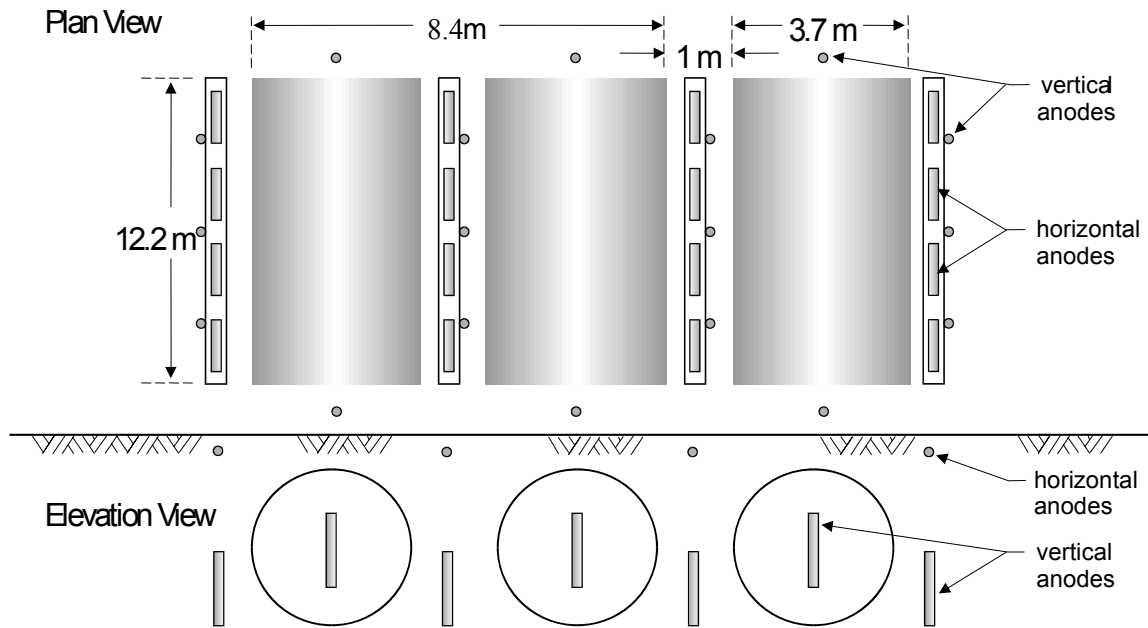
**Figure 4-31: Distributed Impressed Current Anodes around Underground Storage Tanks**

In this anode arrangement both horizontally and vertically installed anodes are used to provide relatively uniform current distribution.

## 4.11.5   Effect of Structure Arrangement on Current Distribution

One of the current distribution problems presented by the array of underground storage tanks in Figure 4-31 is the difficulty of providing sufficient current to the facing surfaces of the tanks. Because the soil current paths between tanks are constricted, these paths have a higher resistance than the current paths to the outside tank surfaces. This problem can also exist in a run of multiple parallel pipelines. The relative current density to the facing surfaces is a function of the diameter of the structures and the separation distance between the structures as shown in Figure 4-32.
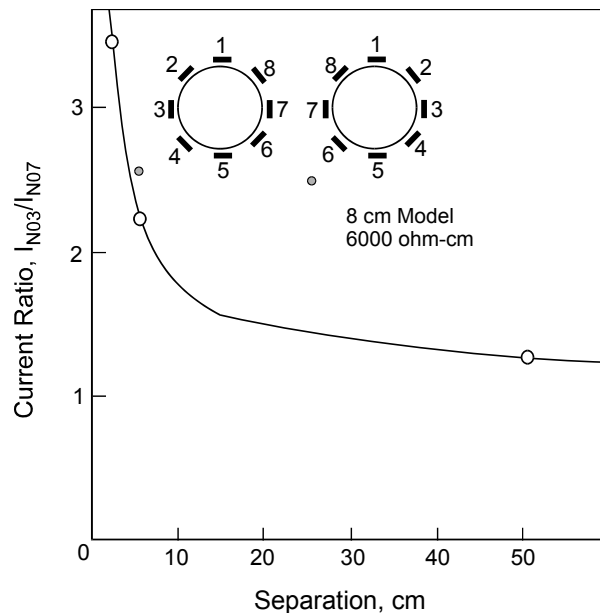
**Figure 4-32:  Current Max/Min Ratio for Two Parallel Structures**

Source:  Status of Cathodic Protection of Pipelines Under Some Particular Situations,
Keije Nunomura, Katsumi Masamura and Iwao Matsushima, NACE Corrosion '81 Conference,
Paper #81, Apr. 1981.

Note that the $I_{max}/I_{min}$ ratio only drops below 2 when the separation distance between the structures is equal to or exceeds the diameter of the structures.

## 4.11.6  *Effect of Electrolyte Resistivity Variation on Current Distribution*

When the electrolyte resistivity is uniform and the structure resistance is not negligible, the highest current density will occur at the point on the structure closest to the anode. Conversely, the lowest current density will be at the most remote structure surface. Most soil resistivities, however, are seldom uniform, and when there are extreme variations in electrical resistivity along the structure, the current distribution can be seriously affected. For example, in Figure 4-33 where the electrical resistivity of swamp ($\rho_{SW}$) is much less than the electrical resistivity of the adjacent soil ($\rho_S$), a disproportionate amount of the cathodic protection current will follow the swamp path. This results in a higher current density on the structure surfaces exposed to the swamp and a lower current density on the remaining structure surfaces. In extreme cases like this, where $\rho_S \gg \rho_{SW}$, better current distribution can be obtained by installing the groundbed

in the higher resistivity soil, although the groundbed resistance will be much greater.
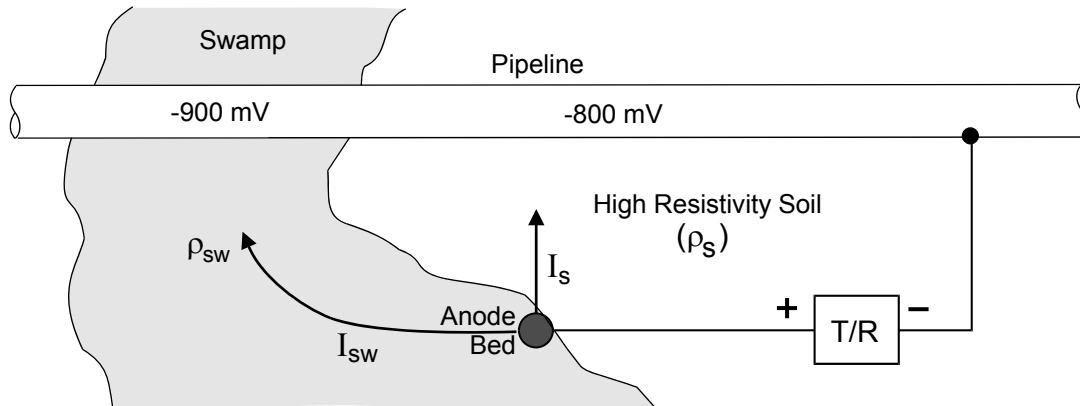


**Figure 4-33:  Localized Low Resistivity Path in a High Resistivity Soil**

A similar variation in electrolyte resistivity occurs due to soil or moisture stratification. Any structure, such as the well casing in Figure 4-34, that traverses strata of various resistivities will receive non-uniform current distribution. The largest current density need not appear on the surfaces exposed to the lowest resistivity environment, which in this case is brine, because the path resistance is also a function of the path length and cross-sectional area. The relative proximity of the anode to the fresh water and clay, each with similar electrical resistivities, means that the current densities would be similar, differing because the clay strata are farther from the anode. The current density on the structure exposed to the sandy loam above the water table may not be high despite the anode proximity because the sandy loam will have a low moisture content and relatively high electrical resistivity. Furthermore, the sandy loam would be reasonably well aerated, and its polarization level would be less than for a similar current density in the clay or fresh water strata.
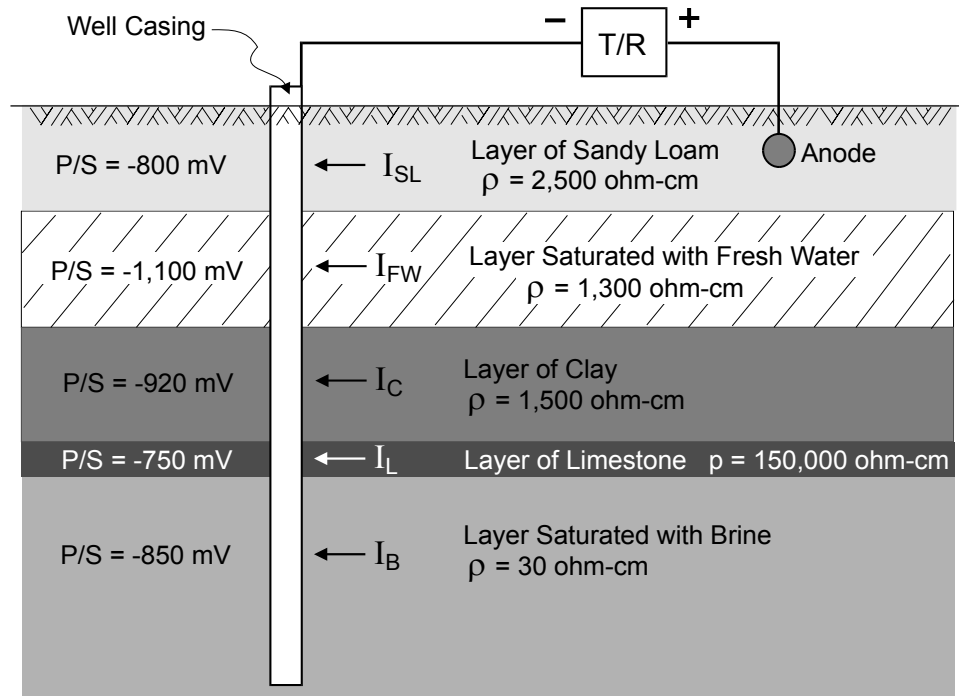
**Figure 4-34:  Current Distribution on a Well Casing with Variable Resistivities**

The current density in the brine layer is as large as that in the low moisture content sandy loam because the current path through the limestone layer is short and the cross-sectional area large resulting in a relatively low resistance path. The polarized potential is greater in the brine layer than in the dry sandy loam because the brine environment is relatively deaerated.

Where the current density on a structure in a high resistivity electrolyte is insufficient for complete protection, current distribution can be improved by installing additional anodes. Positioning of the anodes is also a critical factor in improving the current distribution.

### 4.11.7   Effect on Current Distribution of Holidays on a Coated Structure

Although the path resistance from remote earth to a holiday or to the coated surface adjacent to the holiday is essentially the same, the current densities through the coating are orders of magnitude less than at the holiday. Nevertheless on well coated pipelines, most of the cathodic protection current passes through the coating rather than the holidays.

Consider a 30 cm diameter pipeline that is 20 m long and has a dielectric coating with a specific resistance of $10^4$ $\Omega$-m$^2$ in 4000 $\Omega$-cm soil. Assuming there is a single 1 cm diameter circular holiday as shown in Figure 4-35, the current to both the holiday and through the coated surface can be calculated. Note a 1 cm diameter holiday is 0.0004% of the total surface area of the 20 m length of pipe that is realistic for new coated piping (see Figure 4-6).
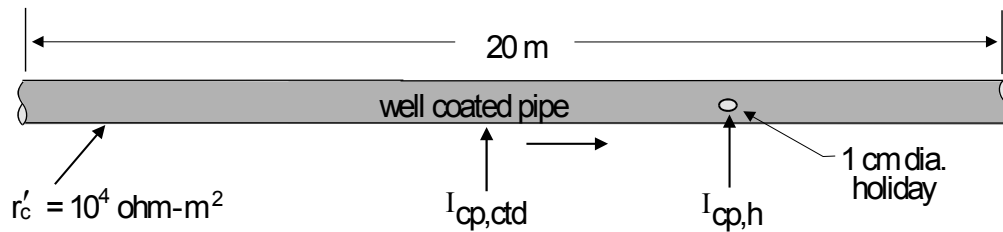


**Figure 4-35: Cathodic Protection Current Distribution to a Well Coated Pipe with a Holiday**

The leakage resistance ($R_L$) of the coated pipe to remote earth is given by Equation 4-54.

$$R_L = \frac{r'_C}{A_{s,p}}$$     [4-54]

*where the surface area of the pipe:*

$$A_{s,p} \;=\; \pi dL \;=\; 3.14 \times .3 \text{ m} \times 20 \text{ m} \;=\; 18.84 \text{ m}^2$$

*therefore:*     $$R_L \;=\; \frac{10^4 \Omega - \text{m}^2}{18.84 \text{ m}^2} \;=\; 0.53 \times 10^3 \Omega$$

Assuming an applied CP voltage of 300 mV between the pipe and remote earth, then from Ohm's law and Equation 4-8:

$$I_{cp,ctd} \;=\; \frac{300 \, mV}{0.53 \times 10^3 \, \Omega} \;=\; 0.565 \text{ mA}$$

and the current density through the coated surface

$$i_{cp,ctd} \;=\; \frac{0.565 \text{ mA}}{18.84 \text{ m}^2} \;=\; 0.033 \frac{\text{mA}}{\text{m}^2}$$

$$= \quad 33 \ \mu A/m^2 \ = \ 33 \times 10^{-4} \ \mu A/cm^2$$

The holiday resistance to remote earth can be calculated using Equation 4-55 for a circular disk.

$$R_h \ = \ \frac{\rho}{2d} \qquad\qquad [4\text{-}55]$$

*then:*
$$R_h \ = \ \frac{4000 \ \Omega\text{-}cm}{2 \ cm} \ = \ 2000 \ \Omega$$

*and from Ohm's law:*
$$I_{cp,h} \ = \ \frac{300 \ mV}{R_h} \ = \ \frac{300 \ mV}{2000 \ \Omega}$$

$$= \ 0.15 \ mA$$

*then:*
$$i_{cp,h} \ = \ \frac{0.15 \ mA}{A_h} \ = \ \frac{0.15 \ mA}{\dfrac{\pi}{4} d^2}$$

$$= \ \frac{0.15 \ mA \ \times \ 4}{3.14 \ cm^2} \ = \ 0.191 \ \frac{mA}{cm^2}$$

$$= \ 191 \ \mu A/cm^2$$

The ratio of the holiday current density ($i_{cp.h}$) and coating current density ($i_{cp,ctd}$) is therefore:

$$\frac{i_{cp,h}}{i_{cp,ctd}} \ = \ \frac{191 \ \mu A/cm^2}{33 \times 10^{-4} \ \mu A/cm^2} \ = \ 5.8 \times 10^4$$

Even though the current density at the holiday is over 4 orders of magnitude greater than through the coating, the total current through the coating (0.565 mA) is almost 4 times greater than at the holiday. Thus on well coated pipelines most of the cathodic protection current passes through the coating not through the holidays.

## 4.11.8   Effect of Polarization (Time) on Current Distribution

Calculations of current distribution do not normally incorporate polarization effects because they are difficult to calculate. When current is initially applied in the absence of significant polarization, the distribution of cathodic protection current is solely determined by the relative resistances of the current paths. This initial distribution of current is referred to as primary current distribution.

With time and the buildup of cathodic reaction products such as calcareous deposits, the polarized potential becomes more negative resulting in less attenuation and improved current distribution as indicated in Figure 4-36.
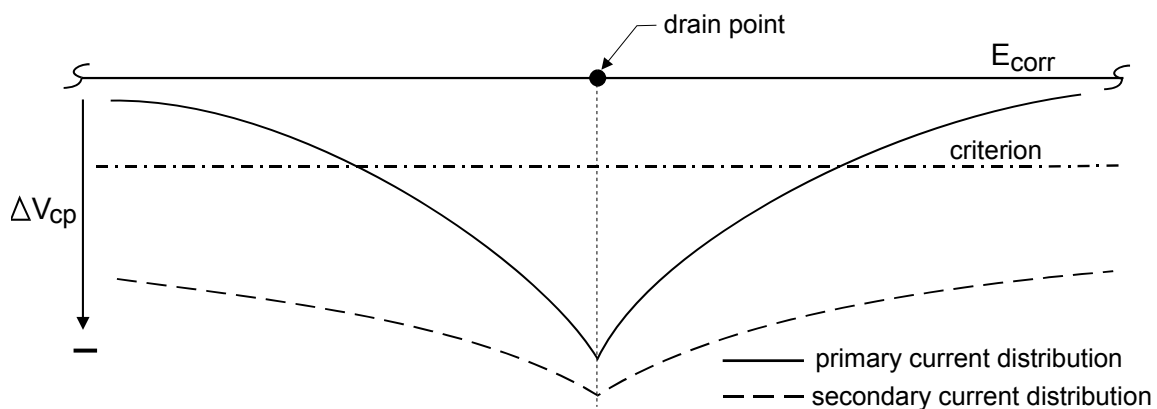


**Figure 4-36:  Effect of Polarization with Time on Attenuation Profile**

Polarization is enhanced on structures in some soils and in seawater because of the formation of calcium and magnesium deposits at the holidays in the coating. These deposits reduce the diffusion of oxygen to the surface, help maintain the high surface pH, and, in low resistivity electrolytes, increase the resistance of the holiday current path. Thus when a cathodic protection system is initially turned on there is a primary distribution current based on electrical circuit resistances, but as polarization increases with time there is a secondary distribution of cathodic protection current due to the polarization back voltage (see Figure 4-20).

## 4.11.9   Summary of Current Distribution Factors

The most difficult aspect of a cathodic protection design is achieving relatively uniform current distribution on the structure being protected, due to the many factors affecting current distribution as summarized in Table 4-9.

**Table 4-9:  Summary of the Effect of Various Factors on Current Distribution**

| Factor | Effect on Current Distribution |
|---|---|
| **Electrolyte Resistivity** | |
| Increase | Improves |
| Decrease | Diminishes |
| Variable | Diminishes |
| **Structure Resistivity** | |
| Increase | Diminishes |
| Decrease | Improves |
| Variable | Diminishes |
| **Coating Quality** | |
| Poor | Diminishes |
| Excellent | Improves |
| **Distance between Anode and Structure** | |
| Small | Diminishes |
| Large | Improves |
| **Polarization** | |
| Large | Improves |
| Small | Diminishes |

Many of these factors can be addressed in designing a cathodic protection system, particularly in the choice of system, anode-to-structure spacing, and placement of the anodes. As illustrated in Figure 4-37, there are many options from which to choose.
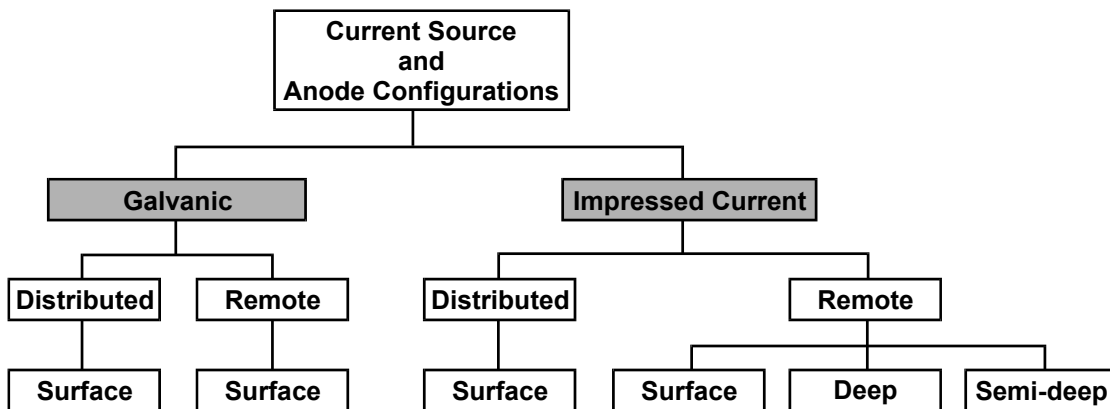
**Figure 4-37:  Typical Anode Arrangements**

## Team Project

Design a cathodic protection system with a 20 year minimum life for a 30 cm diameter coated high pressure natural gas pipeline located in a semi-urban area, given the following conditions:

- pipe is electrically isolated at both ends
- average soil resistivity is 4,700 $\Omega$-cm to a depth of 4 m then 21,000 $\Omega$-cm
- specific coating resistance in 4,700 $\Omega$-cm soil is $6 \times 10^4$ $\Omega$-m$^2$
- a minimum cathodic protection voltage of 300 mV must be applied to the pipe.

Produce a design sketch showing cathodic protection current source(s), type of anode, etc. as per the design flow chart of Figure 4-1. Omit calculation of system cost. State advantages and disadvantages of your design. The instructor will choose the pipe length.

## 5.0 Introduction

The effectiveness of a cathodic protection system ultimately is confirmed by whether or not it controls corrosion adequately. Although corrosion can be identified on some pipelines using smart pigs, determining corrosion rate directly is generally not a simple process. Hence indirect methods of assessing the adequacy of a cathodic protection system must be relied upon. The principal method is the measurement of the structure potential for comparison to the selected criterion. System currents are also measured as an additional performance parameter. Indeed, for oil and gas pipelines, potentials must be measured routinely for compliance with government regulations.

## 5.1 The Potential Measurement

A structure-to-electrolyte potential measurement involves using a high resistance input meter connected between the structure or structure test lead and a portable reference electrode placed in contact with the electrolyte, as illustrated for a pipeline in Figure 5-1.
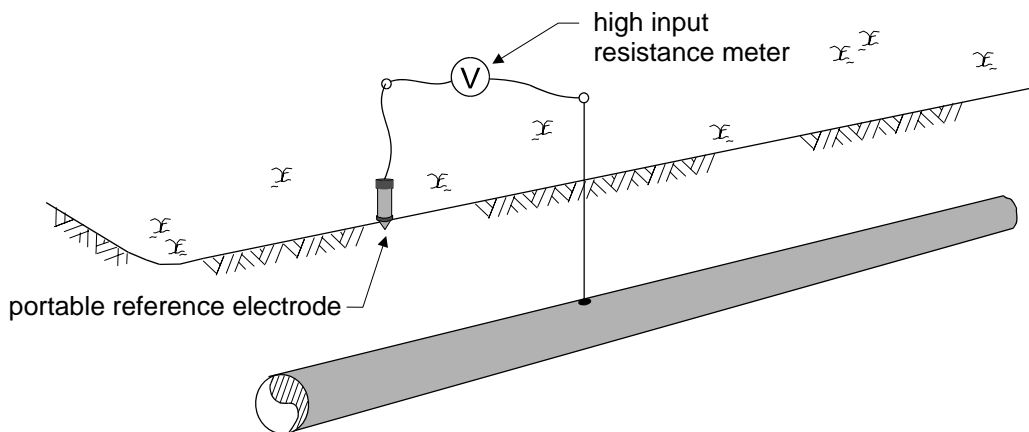


**Figure 5-1:  Illustration of a Typical Pipe-to-Soil Potential Measurement**

It is assumed that that the potential of the reference electrode does not change while moving from location to location, otherwise an error is introduced into the measurement. To ensure measurement accuracy and reproducibility, the reference electrode must be maintained in good condition.

## 5.1.1   Copper-Copper Sulfate Reference Electrode

Table 5-1 lists maintenance items for the saturated copper-copper sulfate electrode (CSE) shown in Figure 5-2.
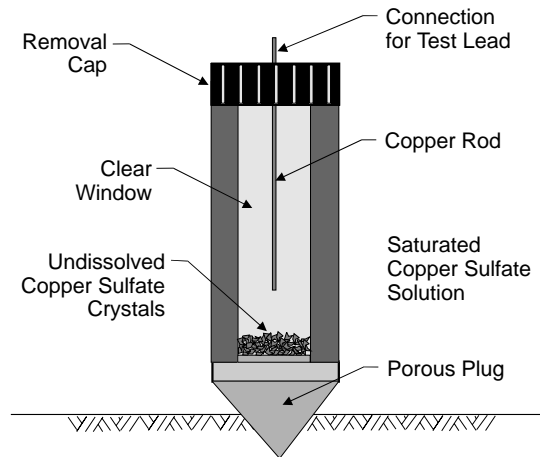


**Figure 5-2:  Copper-Copper Sulfate Reference Electrode**

**Table 5-1:  List of Copper-Copper Sulfate Maintenance Items**

| Use and Care of CSE |
|---|
| • Keep clean |
| • Cap when not in use |
| • Clean porous plug |
| • Keep free of contamination, especially by Cl$^-$ |
| • Keep spares in field |
| • Keep in calibration (versus SCE) |
| • Record temperature when in use |
| • Shield from direct sunlight |
| • Copper sulfate crystals must be present to ensure a saturated solution |

Two important items on the maintenance list are the need to prevent contamination especially by chloride and the requirement for the solution to be saturated with copper ions. Variations in these conditions can significantly change the reference electrode potential as shown in Figures 5-3a and 5-3b. As the concentration of chloride ions increases the reference electrode potential shifts in the negative direction. As the concentration of copper sulfate decreases, the

reference electrode potential also shifts electronegatively. In both cases the measured structure potential would be more electropositive. Typically a silver-silver chloride reference is used to measure potentials on structures in seawater or brine solutions.
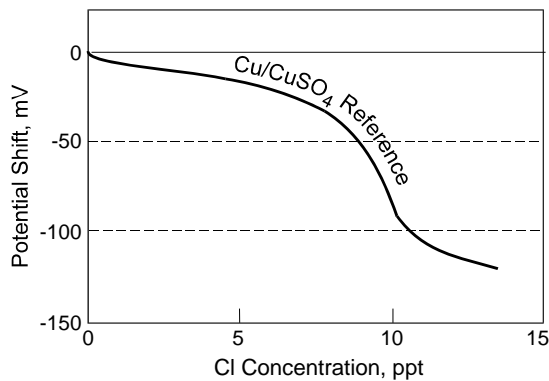


**Figure 5-3a: Effect of Cl⁻ Concentration on CSE Potential[1]**
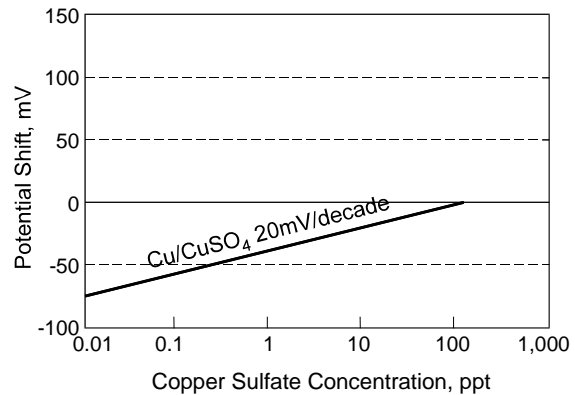
**Fig-5-3b: Effect of Copper-Sulfate Concentration on CSE Potential[2]**

In addition, another important factor is the reference electrode temperature. The copper sulfate reference electrode has a temperature coefficient of about 0.9 mV/ºC as indicated in Table 1-3. Thus the expression for the copper sulfate electrode potential with respect to a standard hydrogen electrode (SHE) at any temperature ($E_{cse,t}$) is given in Equation 5-1.

$$E_{cse,t} \; = \; E_{cse,25ºC} \; + \; 0.9 \text{ mV/ºC (T} - 25 \text{ ºC)} \qquad \text{[5-1]}$$

Centigrade degrees can be converted to degrees Fahrenheit using the following relationship:

$$ºF \; = \; \left(ºC \times \frac{9}{5}\right) + 32 \qquad \text{[5-2]}$$

Therefore for 25ºC:

$$ºF \; = \; \left(25ºC \times \frac{9}{5}\right) + 32 \; = \; 45 + 32$$

---

[1] *Ansuini, F.J. and Dimond, J.R., Factors Affecting the Accuracy of Reference Electrodes, MP, Vol. 33, No. 11, Nov. 1994, p.16.*

[2] *Ibid. 1*

$$°F = 77°F$$

Since the equivalent temperature coefficient is 0.5 mV/ºF, the temperature compensation in Equation 5-1 can be written as follows:

$$E_{cse,t} = E_{cse,77°F} + 0.5 \text{ mV/°F (T} - 77 \text{ °F)} \qquad [5\text{-}3]$$

For example at 25ºC, the copper-copper sulfate reference electrode potential is +0.316 $V_{she}$. At 5ºC the potential would be:

$$
\begin{aligned}
E_{cse,5°C} &= +316 \text{ mV}_{she} + 0.9 \text{ mV/°C [5°C} - 25°C] \\
&= +316 \text{ mV}_{she} + 0.9 \text{ mV/°C [}-20°C] \\
&= +316 \text{ mV}_{she} - 18 \text{ mV} \\
E_{se,5°C} &= +298 \text{ mV}_{she}
\end{aligned}
$$

This means a $-850$ mV$_{cse}$ structure potential measured at 25ºC would be equal to a $-832$ mV$_{cse}$ potential measured with the reference electrode temperature at 5ºC. Conversely, a $-850$ mV$_{cse}$ structure potential measured at 25ºC would be equal to a $-868$ mV$_{cse}$ with the reference electrode temperature at 45ºC. Accordingly, when potentials are measured the temperature of the reference electrode should also be noted.

## 5.1.2   Buried Reference Electrodes

In some situations, it is desirable to use a buried or permanently immersed reference electrode such as at a crossing between two cathodically protected pipelines, between underground storage tanks beneath a reinforced concrete slab, inside a water storage tank, etc. These references, sometimes labeled "permanent" reference electrodes have a finite design life normally stipulated by the manufacturer.

Reference electrodes intended for burial or immersion are commercially available from a number of manufacturers. For underground use CSE, SSC, and zinc reference electrodes are available. For extended service life, these electrodes are normally prepackaged in a bentonite/sulfate rich backfill similar to that used with magnesium and zinc galvanic anodes.

## *5.1.3   Polarity Considerations*

There are two common practices for connecting the voltmeter between the reference electrode and the structure whose potential is being measured as shown in Figures 5-4a and 5-4b.
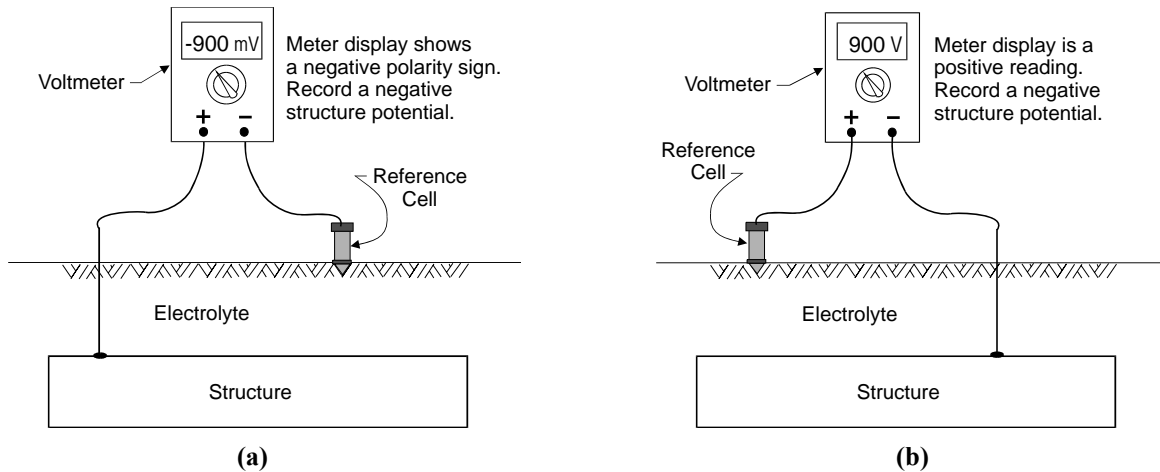


**Figure 5-4:  Structure-to-Soil Potential Measurements**

As long as the meter polarity sign, which appears in the display, is interpreted properly it does not matter which method is used. The polarity sign should be interpreted as follows. For Figure 5-4a, the negative polarity indicator means the polarity of the pipe with respect to the reference is opposite to the polarity markings on the meter terminals. Therefore the pipe, which is connected to the positive terminal, is not positive but negative and the structure potential is written as:

$$V_m = -900 \text{ mV/ref}$$

For Figure 5-4b, the lack of a polarity indicator in the display (on some meters a positive sign will appear) means the polarity of the pipe agrees with the polarity markings on the meter. Since the pipe is connected to the negative terminal the pipe potential is written as:

$$V_m = -900 \text{ mV/ref}$$

The structure potential measurement recorded above must have four distinct components: a polarity sign, a numerical magnitude, a unit of measurement, and the reference used. This notation is a short form for the statement: *"The structure*

*potential is negative 900 millivolts with respect to the reference electrode."* Hence if one component is missing from the notation, the statement is incoherent.

## 5.1.4 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 following electrical circuit.



where:

$R_m$ = voltmeter input resistance

$R_{t,l}$ = test lead resistance

$R_{p,e}$ = pipe-to-earth resistance

$R_{r,e}$ = reference-to-earth resistance

$I_m$ = meter current

$E_{true} = E_p - E_{ref}$
    but $E_{ref}$ is assumed to be zero
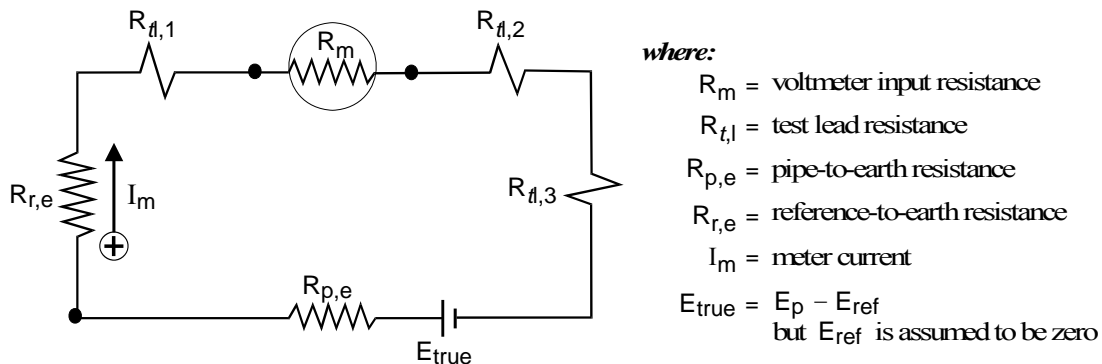
**Figure 5-5: Electrical Schematic of the Pipe-to-Soil Measurement Circuit**

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.

$$E_{true} = I_m R_t \qquad\qquad [5\text{-}4]$$

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

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

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

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

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

*then:* Divide both sides by $E_{true}$

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

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

*and after substitution:*

$$\frac{V_m}{E_{true}} = \frac{I_m (R_t - R_{circ})}{I_m (R_t)}$$

*and:* $R_t - R_{circ} = R_m$

$$\frac{V_m}{E_{true}} = \frac{R_m}{R_t} \qquad \text{[5-5]}$$

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 $E_{true}$ = 1,000 mV, each test lead resistance of 0.01 ohm, a pipe-to-earth resistance ($R_{p,e}$) of 10 ohms, a reference electrode resistance to earth ($R_{r,e}$) of 100 kΩ, and a meter resistance of 1 MΩ. 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 5-5*

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

$$V_m = \frac{1.0\,M\Omega}{1.1\,M\Omega} \times 1000\ mV = 909\ mV$$

This is an error of:

$$\frac{1000 - 909}{1000} \times 100 = 9\%$$

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 drop across the voltmeter ($V_m$) will approach the true potential difference between the reference and pipe as the ratio of the voltmeter resistance to total measurement circuit resistance approaches one (i.e., $R_m/R_t$ → 1). That is, 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 5-6a and 5-6b).



a) dry soil or frozen ground                                    b) asphalt or concrete
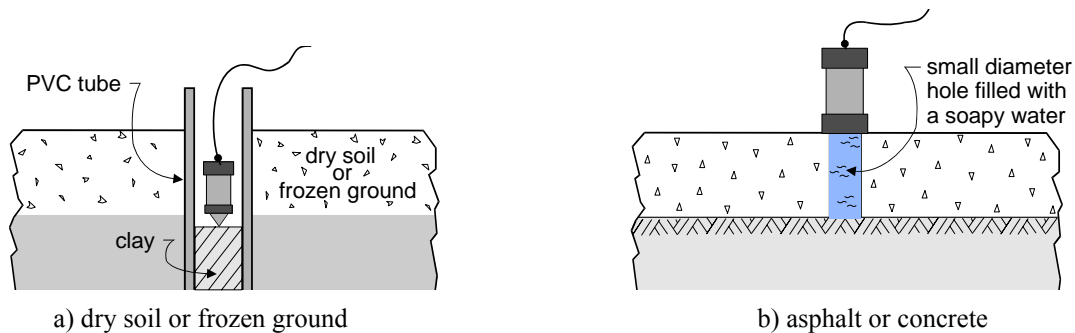
**Figure 5-6: Methods of Minimizing Reference Electrode Contact Resistance**

In Figure 5-6a, 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 5-6.

$$E_{true} \quad = \quad \frac{V_h \ (1-K)}{1-K \ \dfrac{V_h}{V_l}} \qquad \text{[5-6]}$$

*where:*

$\begin{aligned}
E_{true} &= \text{true potential (V)}\\
K &= \text{input resistance ratio } R_l/R_h\\
R_l &= \text{lowest input resistance}\\
R_h &= \text{highest input resistance}\\
V_l &= \text{voltage measured with lowest input resistance}\\
V_h &= \text{voltage measured with highest input resistance}
\end{aligned}$

*For example:* If a potential difference ($V_l$) of –650 $mV_{cse}$ was measured with an input resistance ($R_l$) of 1.0 MΩ and a potential difference of –800$mV_{cse}$ ($V_h$) was measured with an input resistance ($R_h$) of 10 MΩ, then the true potential ($E_{true}$) would be calculated as follows:

$$E_{true} \quad = \quad \frac{-800 \ mV \ (1 \ - \ 0.1)}{1 \ - \ 0.1 \left( \dfrac{-800 \ mV}{-650 \ mV} \right)}$$

$$= \quad \frac{-720 \ mV}{1 \ - \ 0.123} \quad = \quad \frac{-720 \ mV}{0.877} \quad = \quad -821 \ mV_{cse}$$

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

In addition, the total circuit resistance ($R_t$) can be determined using Equation 5-5.

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

$$= \frac{10\,\text{M}\Omega \times 821\,\text{mV}}{800\,\text{mV}}$$

$$R_t = 10.3\,\text{M}\Omega$$

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

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

# 5.2  Voltage Drop Errors External to the Metering Circuit

## 5.2.1  Voltage Drop Errors in the Potential Measurement due to Current in the Earth

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 5-7.
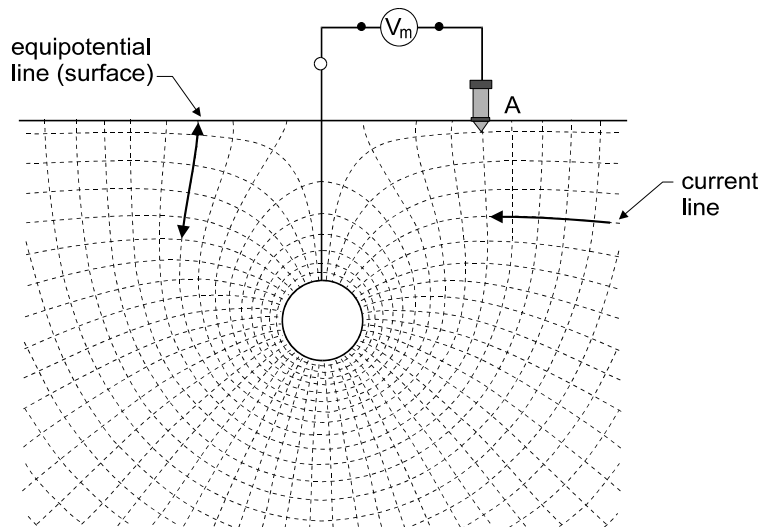


**Figure 5-7:  Voltage and Current Lines around a Bare Pipeline Receiving
Cathodic Protection Current**
Source:  Parker, Marshall and Peattie, Edward, Pipeline Corrosion and Cathodic Protection, 3rd Edition, Gulf Publishing Co., Houston, TX, p.25

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 × 10 mV = 100 mV. The soil at the pipe surface is –100 mV with respect to the soil at the reference electrode.
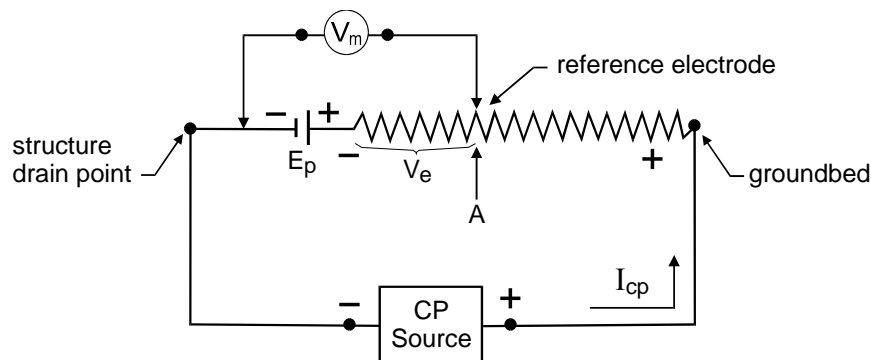


**Figure 5-8: Electrical Schematic Illustrating Soil Voltage Drop in the Potential Measurement**

For the pipe-to-soil measurement shown in Figure 5-7 and illustrated in Figure 5-8, the potential difference ($V_m$) indicated on the voltmeter will be given by the Equation 5-7.

$$V_m = E_p + V_e \qquad [5\text{-}7]$$

*where:*    $V_e$ = voltage drop in the earth

If the current direction was away from the pipe, then Equation 5-8 would apply.

$$V_m = E_p - V_e \qquad [5\text{-}8]$$

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

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

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 5-9 and 5-10.
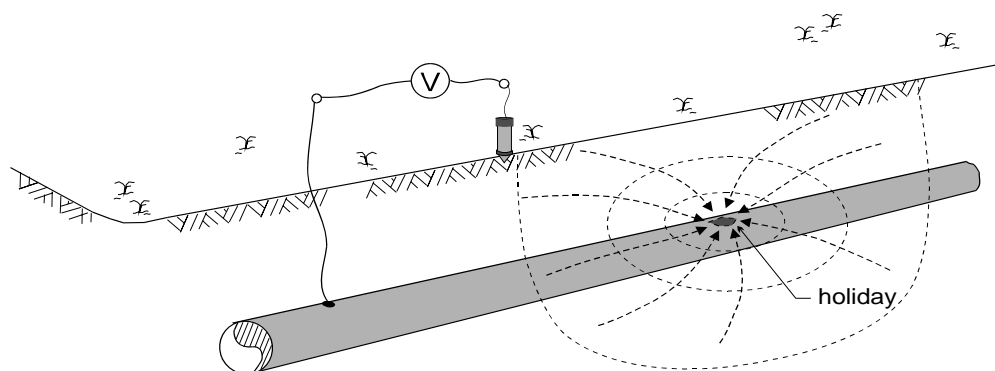


**Figure 5-9:  Current and Voltage Lines around a Holiday on a Coated Pipeline**
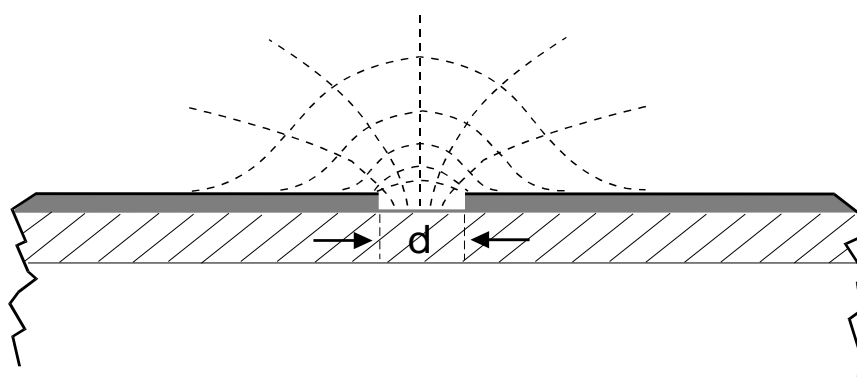


**Figure 5-10:  Current and Voltage Lines in Immediate Vicinity of a Holiday**

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 diameter holiday, 95% of the voltage occurs within a radius of 10 cm from the holiday.[3]

## 5.2.2 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 5-11, there will be an IR drop error ($V_p$) in the potential measurement.
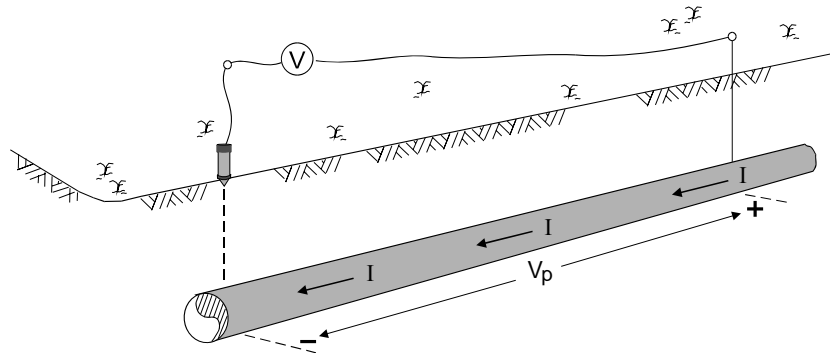


**Figure 5-11: Voltage Drop in a Pipeline Carrying Current**

When a connection to a current-carrying conductor is made as illustrated, the voltage drop error will be additive or subtractive depending on the direction of the current. This situation is illustrated in the electrical schematic of Figure 5-12.
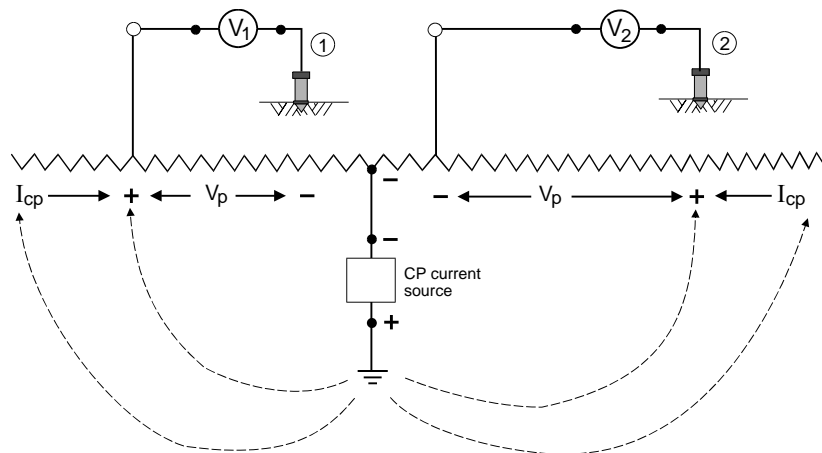


**Figure 5-12: Electrical Schematic to Illustrate Potential Measurement Error due to CP Current in a Pipeline**

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

NACE

At location ① the potential difference ($V_m$) measured by the voltmeter will be the pipe potential ($E_p$) less the pipe voltage drop ($V_p$) as follows:

$$V_m \; = \; E_p \; - \; V_p \qquad\qquad [5\text{-}9]$$

But for location ② with the current in the opposite direction, the $V_p$ error will be additive rather than subtractive and:

$$V_m \; = \; E_p \; + \; V_p \qquad\qquad [5\text{-}10]$$

## 5.3   Methods of Minimizing Voltage Drop Errors in the Potential Measurement

A typical potential measurement on a pipeline can include both earth and pipe voltage drops so that the potential difference between a pipe and a reference electrode can be expressed as in Equation 5-11:

$$V_m \; = \; E_p \; \pm \; V_e \; \pm \; V_p \qquad\qquad [5\text{-}11]$$

Whether the error is additive or subtractive depends on the direction of current. Equation 5-11 can also be written in terms of current and resistance according to Ohm's law as follows:

$$V_m \; = \; E_p \; \pm \; I_e\,(R_e) \; \pm \; I_p\,(R_p) \qquad\qquad [5\text{-}12]$$

Examination of either equation indicates it is the polarized potential of the pipe ($E_p$) that is required for comparison to industry potential criteria (e.g., $-850\ \text{mV}_{cse}$). The ideal situation is to have $V_m = E_p$ with no IR drop error.

### 5.3.1   Current Interruption Method

If the only current producing the voltage drops is the cathodic protection current, Equation 5-12 can be rewritten to

$$V_m \; = \; E_p \; \pm \; I_{cp} \bullet R_e \; \pm \; I_{cp} \bullet R_p \qquad\qquad [5\text{-}13]$$

Then it is apparent that if $I_{cp} = 0$, $V_m$ would equal $E_p$ since the IR drop terms go to zero.

$$V_m = E_p \pm \cancel{I_{cp}R_e}^{\circ} \pm \cancel{I_{cp}R_p}^{\circ} \qquad [5\text{-}14]$$

In this method, the cathodic protection current is interrupted momentarily and a potential recorded immediately after interruption, which is referred to as an *instant-off potential* or just *off potential*. The interruption for convenience is accomplished using a cyclic interrupter inserted in the cathodic protection circuit and adjusted so that the ON half-cycle time is at least twice the OFF half-cycle time (e.g., 10 seconds ON and 5 seconds OFF). It is advisable to keep the OFF half-cycle time to a minimum so the structure doesn't depolarize significantly during the course of the survey. This potential response is shown in Figure 5-13.
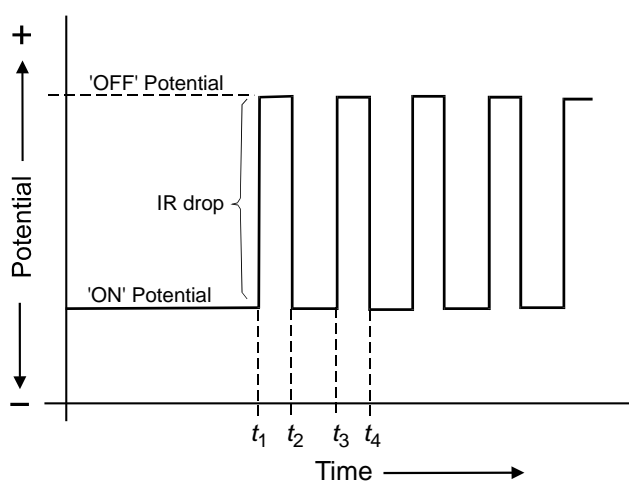


**Figure 5-13:  Graphical Illustration of the Current Interruption Method of
Minimizing Voltage Drop Error in the Potential Measurement**

The interrupter is started at $t_1$ and interrupts the current for $t_1$-$t_2$ and turns the current on at $t_2$. The ON half-cycle $t_2$ to $t_3$ should be at least twice the $t_1$-$t_2$ half-cycle. The sudden change in potential from ON to OFF is the disappearance of the IR drop in the measurement. This IR drop reappears when the current is switched back on.

The instant-off potential is considered equal to the polarized potential because it is assumed the potential across the structure-electrolyte interface is stored momentarily in the double-layer capacitance.

The current interruption technique is widely used when conducting close interval potential surveys. The example data in Figure 5-14 indicates that subcriterion potentials are located in sections A and B. In section A the instant-off potentials are subcriterion but the on-potential is more negative than $-850$ mV$_{cse}$, whereas in

section B both the on and instant-off potentials are subcriterion. After a close interval survey has been completed, on-potentials at each location where the instant-off potential is more negative than the $-850 \text{ mV}_{cse}$ criterion can be used as a second-hand criterion for future surveys providing there are no changes in the soil conditions such as moisture, aeration, pH, etc. or in the pipe operating temperature.
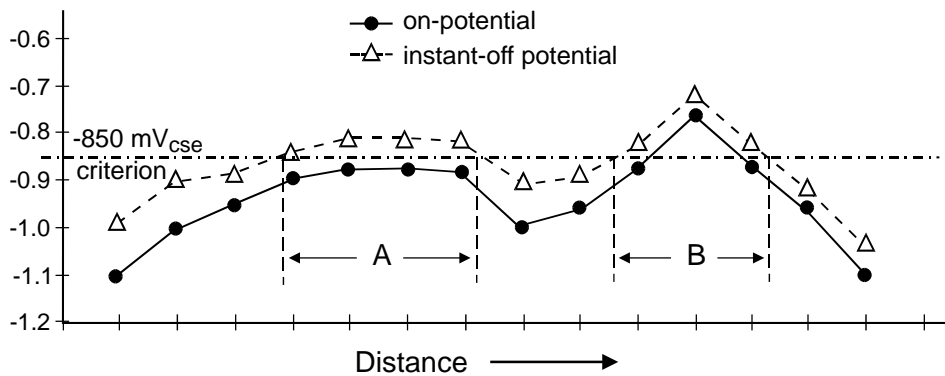


**Figure 5-14: Example of Close Interval Potential Survey Data Plotted Versus Distance for Both ON and Instant-Off Potentials**

Using the Randle's circuit model of electrode interface in Figure 5-15, it can be seen that the potential across the interface ($E_p$) is across the parallel combination of the double layer capacitance and the polarization resistance. Before the current is interrupted, the voltmeter measures the polarized potential plus the voltage drop across the electrolyte resistance ($R_e$). When the current is zero, $I_{cp}R_e$ will be zero and the voltmeter will measure the polarized potential ($E_p$)
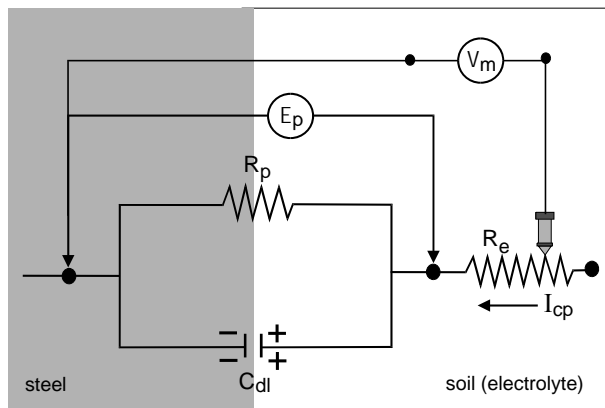


**Figure 5-15: Illustration of Current Interruption Technique for Minimizing Voltage Drop Errors Using Randle's Model of the Electrode/Electrolyte Interface**

If there is significant inductance in the cathodic protection circuit or if the current is large, a positive spike may appear in the potential upon interruption as shown in Figure 5-16.
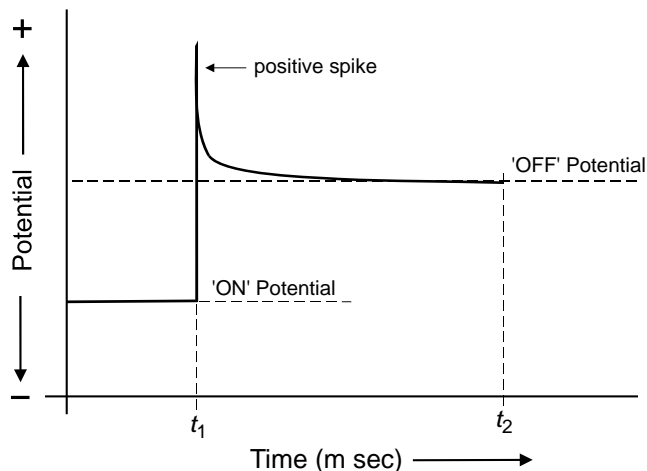


**Figure 5-16: Illustration of Positive Spike in Potential When CP Current is Interrupted**

Typically the spike time lasts less than 300 milliseconds[4] after which the off-potential can be recorded without incorporating this transient spike error in the potential measurement. Therefore, if $t_2$ is the time when the off-potential is being measured, then $t_1$-$t_2$ > 300 milliseconds. If a shorter measurement time period is contemplated, the potential-time waveform should be captured on an electronic oscilloscope to determine the magnitude and time duration of any switching transient.

When there are multiple current sources, simultaneous interruption of all the current sources achieved using synchronized interrupters is used for convenience, but it is not essential. Individual sources can be interrupted and the IR drop contribution of each can be recorded separately and the totaled IR drop subtracted from the on-potential. This is quite an arduous procedure for a long pipeline with many widely spaced rectifiers and many test point locations, but is more practical in a process plant were travel time is not an issue or where simultaneous interruption of rectifiers may be impractical.

As indicated in Equation 5-14, the current interruption technique reduces both the soil and structure IR drop components to zero, but for accuracy all currents must

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[4] Thompson, N.G., and Lawson, K.M., Causes and Effects of the Spiking Phenomenon, PRCI, Report #PR186-006, Jan 1992, p 94.

be interrupted, including stray currents. This is not possible however in some cases if telluric currents or transit stray currents are present.

Also, the accuracy of this technique is compromised if there are recirculating currents present. A recirculating current is a post-interruption current between highly polarized and lesser polarized areas on a structure as depicted in Figure 5-17 or between parallel pipelines where one pipeline is more highly polarized than the other.
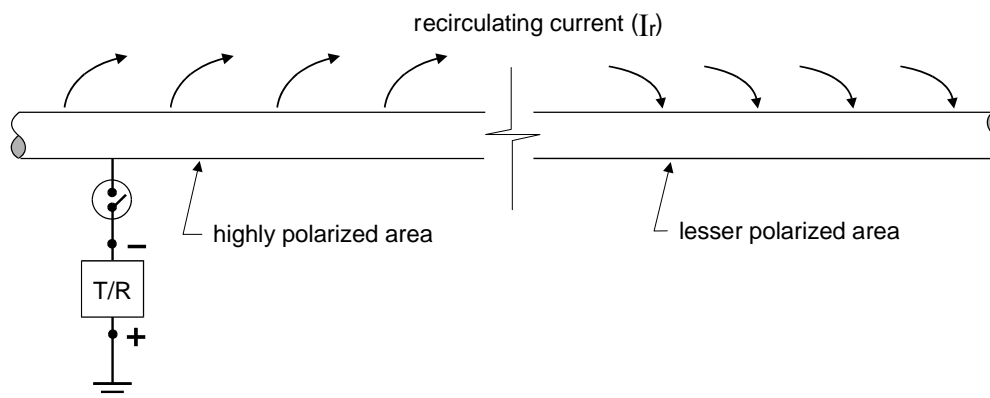


**Figure 5-17:  Illustration of Recirculating Current Activity after the Interruption of CP Current**

As would be expected, the piping closest to the transformer-rectifier and groundbed will be polarized to a greater extent than remote piping surfaces. Off potentials measured along the pipeline in the highly polarized areas will be more electropositive than the true potential. This is due to the IR drop created by the recirculating current ($I_r$) flowing away from the pipe (i.e., $V_m = E_p - I_rR_e$). Conversely, in the recirculating current pick-up region, the off-potential will be more negative than its true potential (i.e., $V_m = E_p + I_rR_e$), which might mask an otherwise subcriterion condition. Potential shifts due to recirculating currents are typically in the order of 0 to $\pm150$ mV.[5]

## 5.3.2   Stepwise Current Reduction Method of Determining the Amount of Soil IR Drop in the On-Potential

The stepwise current reduction technique involves recording the potential shift in the pipe-to-soil potential measurement and a side drain potential measurement as

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[5] *Thompson, N.G. and Lawson, K.M., Most Accurate Method for Measuring an Off-Potential, PRCI Final Report on Contract PR-186-9203, March, 1994, p.ix.*

the cathodic protection current is reduced. The test arrangement is illustrated in Figure 5-18.
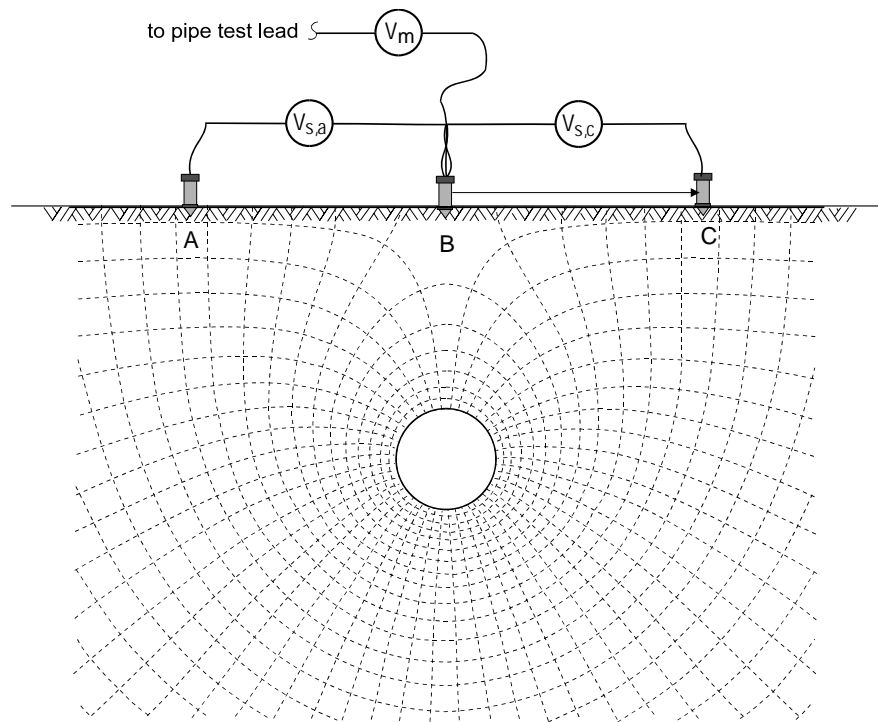


**Figure 5-18:  Field Test Arrangement for the Stepwise Current Reduction Method
of Determining the Amount of IR drop in the On-Potential**

It is understood that the on-potential recorded on the voltmeter ($V_m$) is

$$V_m = E_p + I_{cp} \bullet R_e$$

And that 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 5-19.
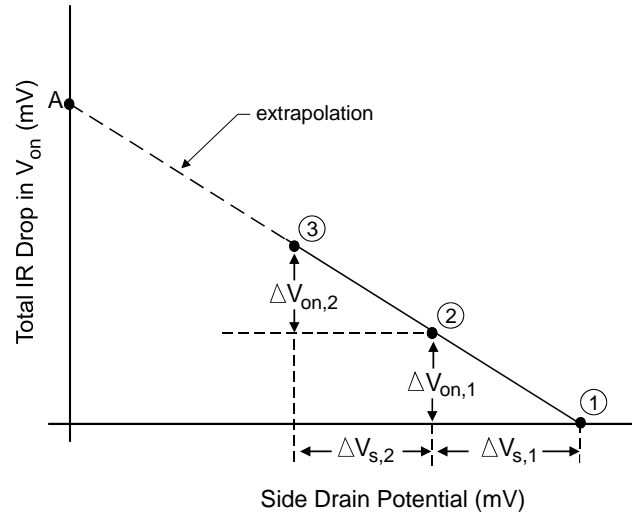
**Figure 5-19:  Data Plot for Stepwise Current Reduction Technique**

Step ①    Plot $V_{s,a}$ or $V_{s,c}$ on the abscissa with full current

Step ②    Reduce $I_{cp}$, calculate $\Delta V_{s1}$, and $\Delta V_{on,1}$;
plot $\Delta V_{s1}$ and $\Delta V_{on,1}$ to obtain point ②

Step ③    Repeat Step ② and plot $\Delta V_{s2}$ 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 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.

$$i.e., \quad E_p \;=\; V_{m,b} - A$$

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.

### 5.3.3   Reference Electrode Placement Close to the Structure

The voltage drop ($IR_e$) included in the on-potential measurement is the voltage drop in the earth between the surface of the structure and the reference electrode position as previously illustrated in Figure 5-7. If the reference electrode could be moved closer to the pipe, as shown in Figure 5-20, the on-potential ($V_{on}$) would approach the polarized potential ($E_p$) in value since the $IR_e$ drop would approach zero.
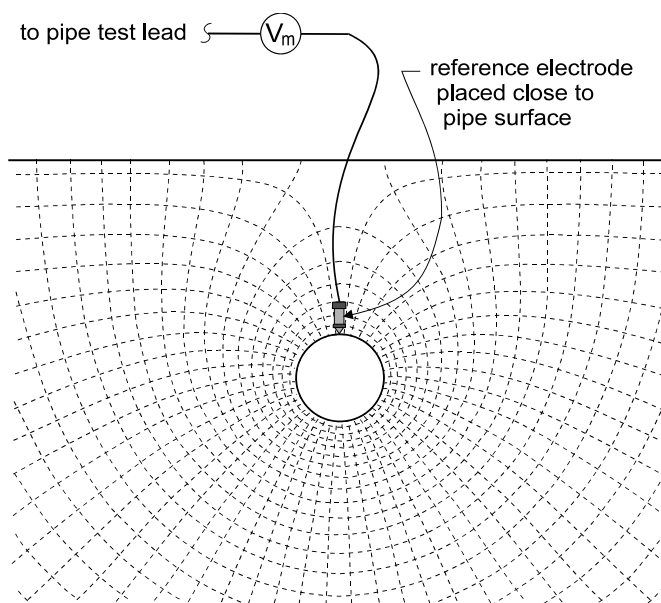


**Figure 5-20:  Reference Electrode Placed Close to Pipe Surface to Minimize IR Drop Error in Potential Measurement**

The reference should not be placed too close to the surface or the surface will be shielded from cathodic protection current. It is usually recommended that the reference be no closer than two diameters of the reference.

This technique is not very practical for buried pipelines but is applicable to underwater structures and to piping appurtenances such as valves and risers as illustrated in Figure 5-21.
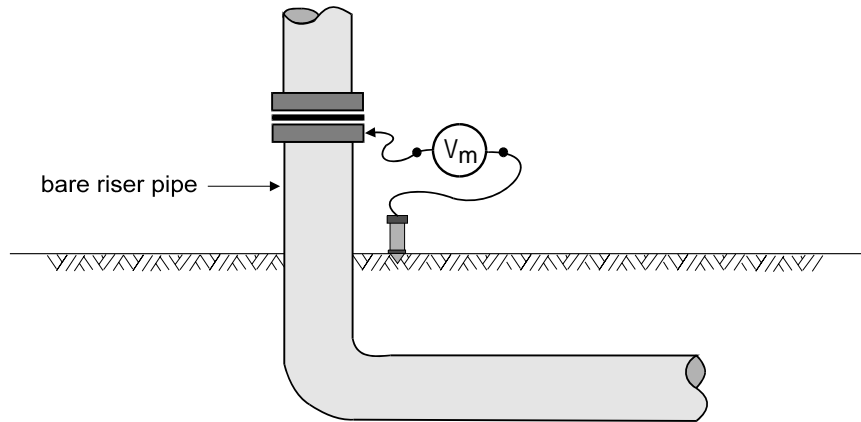


**Figure 5-21:  Reference Electrode Placed Close to a Bare Riser Pipe**

If the reference is placed close to a coated pipeline the amount of IR drop reduction will be minimal as depicted in Figure 5-22.
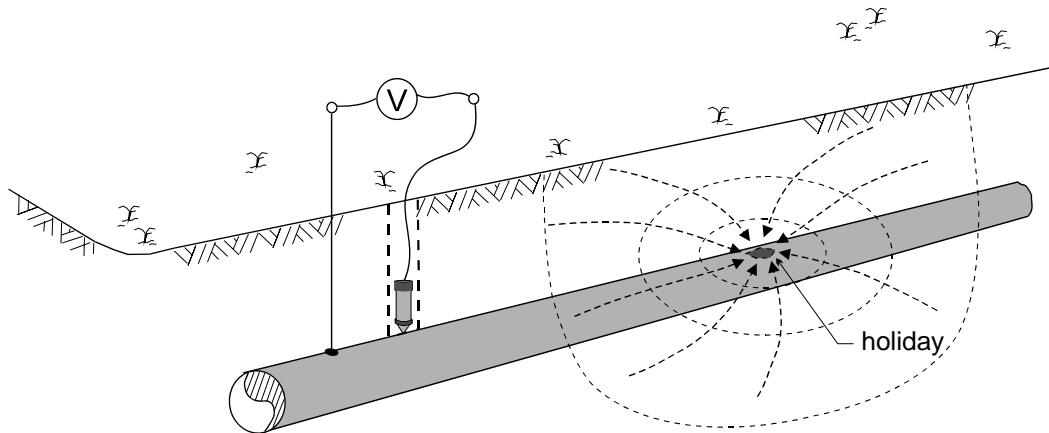


**Figure 5-22:  Reference Electrode Placed Close to a Coated Pipe Surface**

The reference electrode would have to be placed extremely close to a sizable coating holiday before the $IR_e$ drop reduction would be significant, which is generally impractical.

An alternative to placing the reference close to the structure is to install a plastic tube filled with soil from grade next to the pipe surface as shown in Figure 5-23.
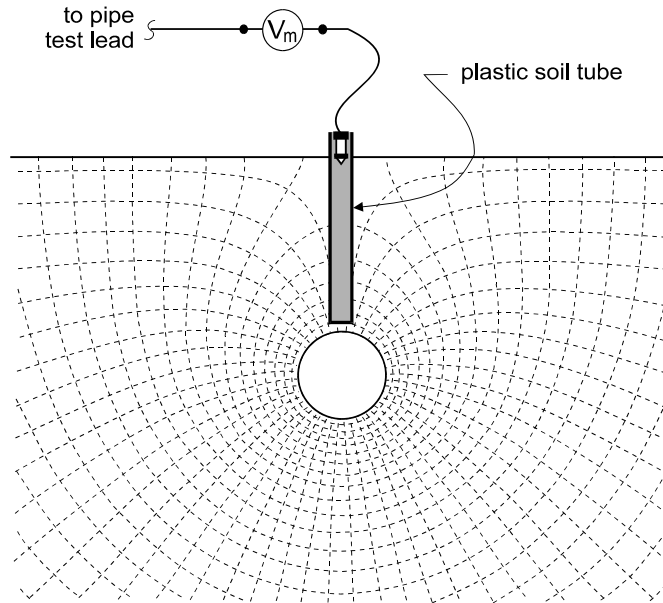


**Figure 5-23:  Using a Soil Tube to Minimize IR$_e$ Drop in a Potential Measurement on Bare Pipe**

As there can be no cathodic protection current in the soil tube, there can be no IR$_e$ drop between the reference and the bottom of the tube, thus minimizing the IR$_e$ drop error in the measurement.

## 5.3.4   *Using Coupons to Minimize Voltage Drop Errors in the Potential Measurement*

A cathodic protection coupon is intended to simulate a small portion of the pipe surface, which on a coated pipe would be a holiday. Coupons are made from an alloy similar to that of the structure. They are typically 10 to 100 cm$^2$ in surface area and are installed in conditions similar to those a coating holiday would experience. A coupon is placed near the structure with its test lead routed into a test station and connected to a pipe test lead as shown in Figure 5-24.
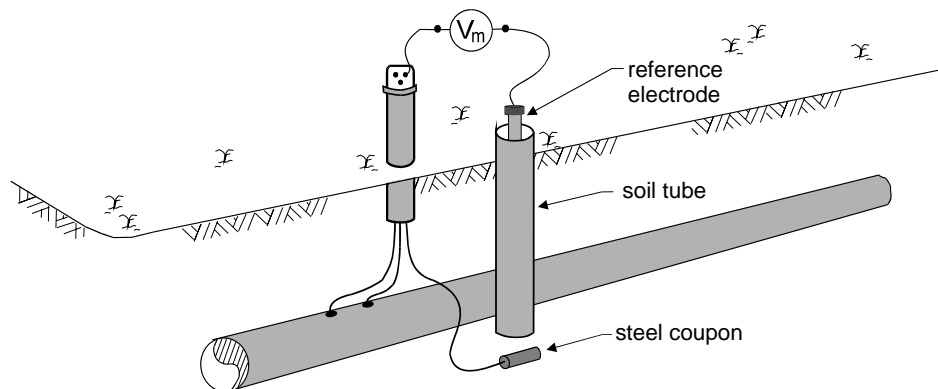
**Figure 5-24:  Using a Steel Coupon to Simulate a Holiday on a Pipeline**

To measure the polarized potential of the coupon, the coupon is momentarily disconnected from the pipeline and its instant-disconnect potential is recorded with respect to the portable reference electrode placed in the soil tube positioned above the coupon. The measured coupon polarized potential ($E_{p,cpn}$) is considered to be the same as a nearby holiday having the same surface area as the coupon and exposed to the same soil conditions. It should be noted that the coupon polarized potential will not necessarily be the same as the pipe polarized potential at this location since the pipe potential represents a number of holidays of differing surface areas rather than a single holiday. Nevertheless, it is assumed that if the coupon polarized potential ($E_{p,cpn}$) is equal to or more negative than $-850$ mV$_{cse}$, any holiday of similar surface area or smaller will be equally as well protected.

The ability of a coupon to monitor the effectiveness of a cathodic protection system was evaluated in a series of field tests at eight pipeline field sites by the Pipeline Research Council International Inc. (PRCI).[6]  The cathodic protection coupon arrangement used exclusively in the testing program consists of two steel rods, each having a surface area of 9 cm$^2$ (1.4 in$^2$) integrated into a plastic test station as shown in Figure 5-25.

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[6] *Thompson, N.G. and Lawson, K.M., Development of Coupons for Monitoring Cathodic Protection Systems, PRCI Contract PR-186-9220, Catalog No. L51888, Final Report, Dec. 2001.*

**NACE**
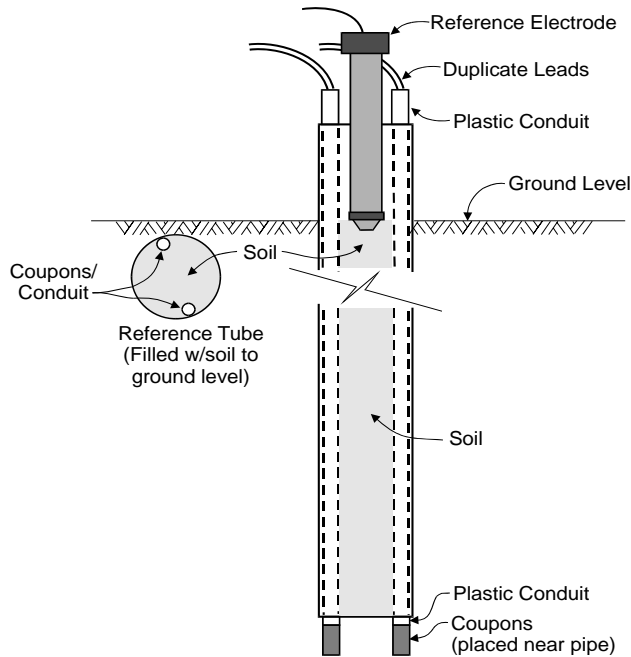
**Figure 5-25:  Schematic of an Integrated Coupon Test Station**
Source:  Thompson, N.G. and Lawson, K.M., Development of Coupons for Monitoring Cathodic Protection Systems,
PRCI Contract PR-186-9220, Catalog No. L51888, Final Report, Dec. 2001.

Tests were conducted that compared the coupon instant-disconnect potential with the instant-off potential with the coupon and ICCP system interrupted. The vast majority of these two potential measurements were within ±25 mV as indicated in Figure 5-26.
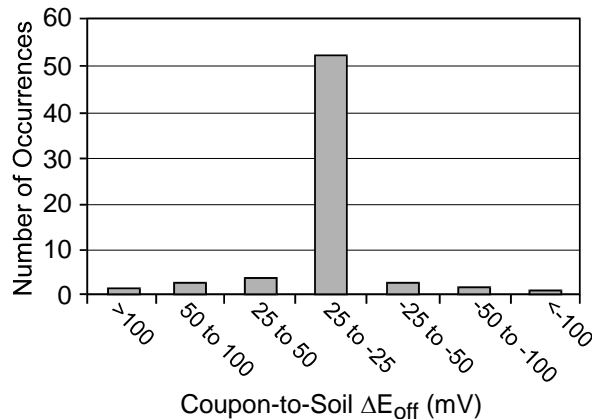


**Figure 5-26:  Difference between Coupon Disconnected Potential and
Coupon-Pipe Potential with ICCP Interrupted**
Source:  Thompson, N.G. and Lawson, K.M., Development of Coupons for Monitoring Cathodic Protection Systems,
PRCI Contract PR-186-9220, Catalog No. L51888, Final Report, Dec. 2001.

The merits of placing the portable electrode in the soil tube versus on grade were also explored. As shown in Figure 5-27, the potentials with the reference on grade

were often more negative, indicating a measurement error due to the IR drop between the coupon and the on-grade reference.
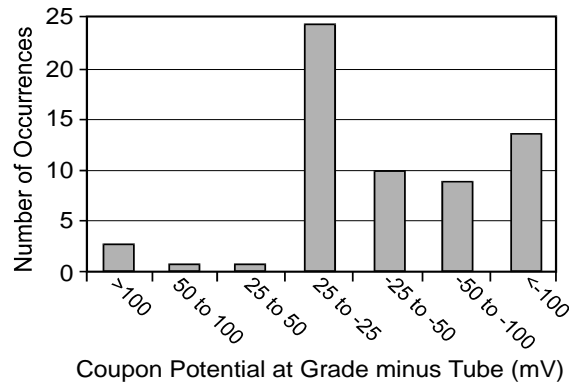


**Figure 5-27:  Difference between Coupon Disconnected Potential Measured with Reference on Grade versus in the Soil Tube**
Source:  Thompson, N.G. and Lawson, K.M., Development of Coupons for Monitoring Cathodic Protection Systems, PRCI Contract PR-186-9220, Catalog No. L51888, Final Report, Dec. 2001.

Although it is understood that a coupon does not represent the pipe but rather a holiday of similar surface area in similar soil conditions, the correlation between the coupon instant-disconnect potential and the pipe instant-off potential, as shown in Figure 5-28, was very strong even though there was considerable scatter in the data. Hence, it can be assumed that if a coupon is adequately polarized the pipe exposed at a holiday, having a surface area equal to or less than the coupon, will be as equally well protected.
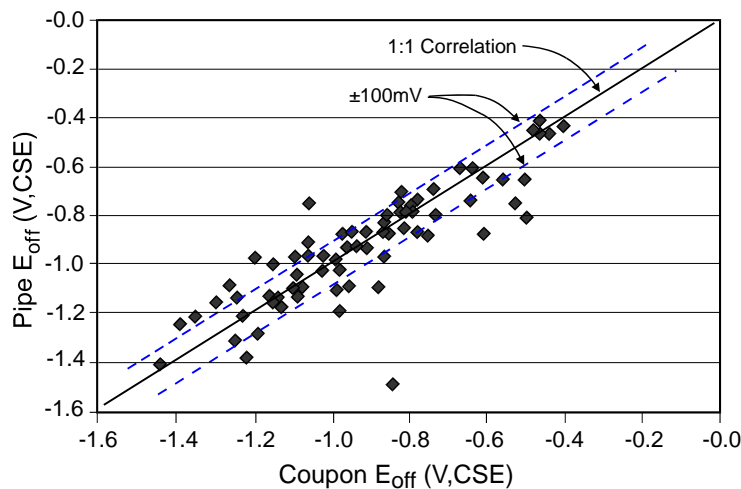


**Figure 5-28:  Pipe versus Coupon Off-Potential**
Source:  Thompson, N.G. and Lawson, K.M., Development of Coupons for Monitoring Cathodic Protection Systems, PRCI Contract PR-186-9220, Catalog No. L51888, Final Report, Dec. 2001.

The number of coupons used for monitoring the level of cathodic protection on pipelines on a worldwide basis is probably around 10,000. Typically these cathodic protection coupons have been installed for one or more of the following reasons:

- To monitor a polarized potential with a minimum of IR drop in the measurement

- On pipelines subject to transient or static stray currents. Note that if a continuous recording of a polarized potential is required, an integrated coupon reference electrode probe may be required.

- To eliminate errors due to long line recirculating currents when the cathodic protection current is interrupted.

- To measure a representative polarized potential on pipelines with direct connected galvanic anodes or with impressed current systems whose outputs cannot easily be synchronously interrupted.

- On parallel interconnected pipelines to avoid measurement error caused by the proximity of the paralleling pipeline.

- On structures where use of an on-grade reference is likely to produce a measurement error such as under reinforced concrete slabs, at a crossing with other pipelines, at the bottom elevation of closely spaced underground storage tanks, etc.

- On structures exhibiting potentials that are marginally protected to assess the merits of installing additional cathodic protection.

- To measure cathodic protection current magnitude and density.

- To measure AC interference current density.

A soil tube is often included with the coupon arrangement so the portable reference electrode can be placed inside to avoid any voltage drop error in the coupon-to-soil potential measurement when the coupon is disconnected. Coupon test stations are commercially available where the coupon and the soil tube are an integral part of the test station.

In dynamic stray current locations where a recording of the polarized pipe-to-soil potential with time is required, disconnecting the coupon to measure its polarized potential is impractical. For these measurements, vertical IR drop-free coupons

are available and indispensable in determining the true impact of stray current activity. This is a photo of one such arrangement where the coupon does not need to be repeatedly interrupted to record a polarized potential.
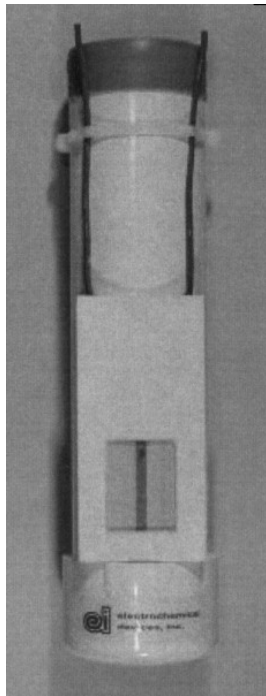


**Figure 5-29a: Photo of a Vertical IR Drop Coupon**

**Figure 5-29b: Vertical IR Drop Coupon Schematic**

Source: Photo and schematic courtesy of Electrochemical Devices Inc.

The coupon is embedded in the face of the test station post with a vertical porous plug slot in the middle of the coupon. With a portable reference electrode placed inside the post, there is no IR drop between it and the coupon. Therefore there is no need to disconnect the coupon or interrupt the cathodic protection current to obtain a reasonably accurate coupon polarized potential.

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**Experiment 5-1**

To demonstrate various methods of minimizing IR drop error in a potential measurement.

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## 5.4  Measurement of Polarization Potential Shift

One of the cathodic protection criteria involves polarizing a steel structure by at least 100 mV from its corrosion potential ($E_{corr}$). Since polarization is a function of time, the amount of polarization can be determined either in the formation of polarization or the decay of polarization as shown in Figure 5-30.
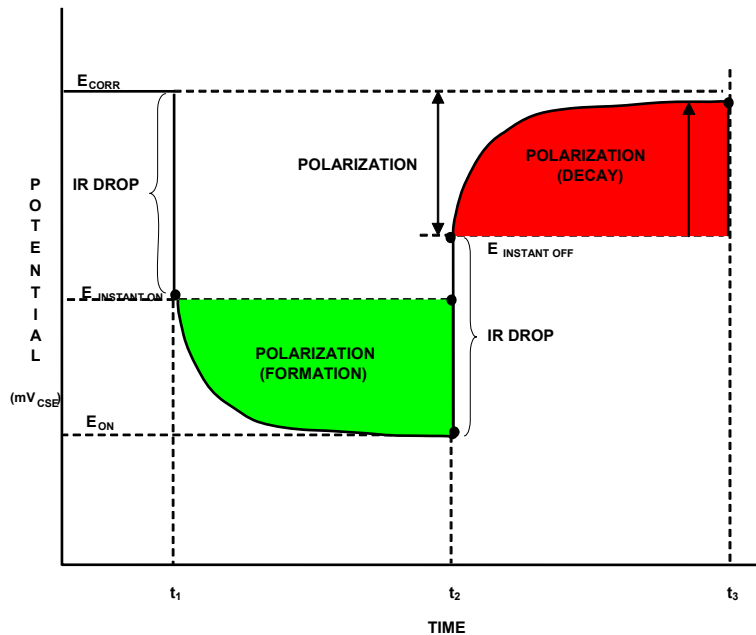


**Figure 5-30:  Potential versus Time Plot for Determining Polarization Potential Shift**

Polarization formation can be determined in two ways. First, the difference between the instant-on potential measured at $t_1$ is compared to the on-potential ($E_{on}$) measured at $t_2$. If the difference is equal to or exceeds 100 mV then the structure is considered cathodically protected. Second, when the cathodic protection current is interrupted at $t_2$ and the instant-off potential (e.g., polarized potential) is measured, if the difference between the instant-off potential and the corrosion potential ($E_{corr}$) is equal to or exceeds 100 mV then the structure is considered cathodically protected. These two cases can be summarized respectively as follows:

$$E_{on} \ - \ E_{instant\text{-}on} \ \geq \ 100 \text{ mV} \qquad\qquad [5\text{-}15]$$

$$E_{instant\text{-}off} \ - \ E_{corr} \ \geq \ 100 \text{ mV} \qquad\qquad [5\text{-}16]$$

Polarization formation methods can only be used at the time a system has been energized since the corrosion potential is likely to change with time and soil conditions. Also, if the instant-on potential is going to be used to determine the amount of polarization shift the system must be energized through an interrupter where the ON half-cycle is very short compared to the OFF half-cycle to avoid polarization being included in the instant-on potential.

To determine the amount of polarization by the polarization decay method, the current when turned off at $t_2$ must remain off for a period of time until the difference between the instant-off potential and the decayed off potential equals or exceeds 100 mV or until the change in potential ($\Delta E$) approaches zero (i.e., $\Delta E/\Delta t \rightarrow 0$).  Therefore, Equation 5-17 must be satisfied for protection to be confirmed.

$$E_{instant\text{-}off} - E_{decayed\text{-}off} \geq 100mV \qquad\qquad [5\text{-}17]$$

If the 100 mV criterion is met at a location, then the on-potential at that location can be used as a proxy criterion as long as the soil conditions, pipe operating temperature, and coating conditions remain the same.

The decay method is often applied when the structure instant-off potential is not equal to or more negative than the potential criterion (e.g., –850 mV$_{cse}$) since in many soils the potential criterion is overly conservative. The fact that the cathodic protection system is turned off for several days or weeks is a significant disadvantage although not particularly detrimental to pipeline integrity.[7] If coupons are being used, however, it is only necessary to disconnect the coupon rather than the cathodic protection system.

Verifying adequate cathodic protection using the 100 mV polarization shift criterion usually results in a lesser current requirement than for the –850 mV$_{cse}$ polarized potential criterion and often avoids expensive remedial action that would normally be required to restore the structure to the potential criterion.

Note that where there are significant recirculating currents upon interruption of the cathodic protection current, IR drop errors in the "decayed-off" potential measurement will result. At the least negative locations, the time to full depolarization will be extended until the recirculating current being picked up in these locations has reduced to zero. This can take up to 175 hours.[8]

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[7] *Thompson, N.G. and Lawson, K.M., Impact of Short-Term Depolarization on Pipelines, PRCI Contract #PR-186-9611, Catalog #L51801, Final Report, Feb. 1999.*
[8] *Ibid. 5.*

## 5.5  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 5-31.

### 5.5.1  Using an Ammeter to Measure Current
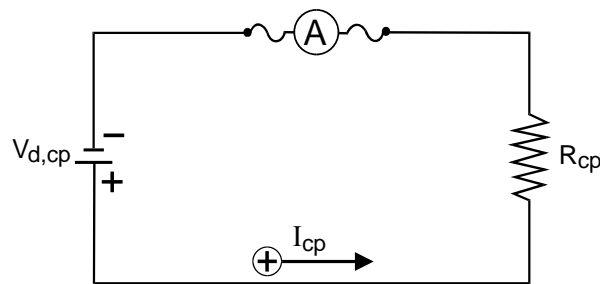


**Figure 5-31:  Measurement of CP Current Using an Ammeter**

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., $R_m << R_{cp}$) to prevent measurement error.

For example, in Figure 5-31 from Ohm's law:

$$I_{cp} = \frac{V_{d,cp}}{R_{cp}}$$                                              [5-18]

but with the ammeter inserted in series in the series circuit, the current measured on the ammeter ($I_m$) is given by:

$$I_m = \frac{V_{d,cp}}{R_{cp} + R_m} \qquad [5\text{-}19]$$

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 milliampere 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 0.1ohm, 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 5-32, an appreciable error can occur.
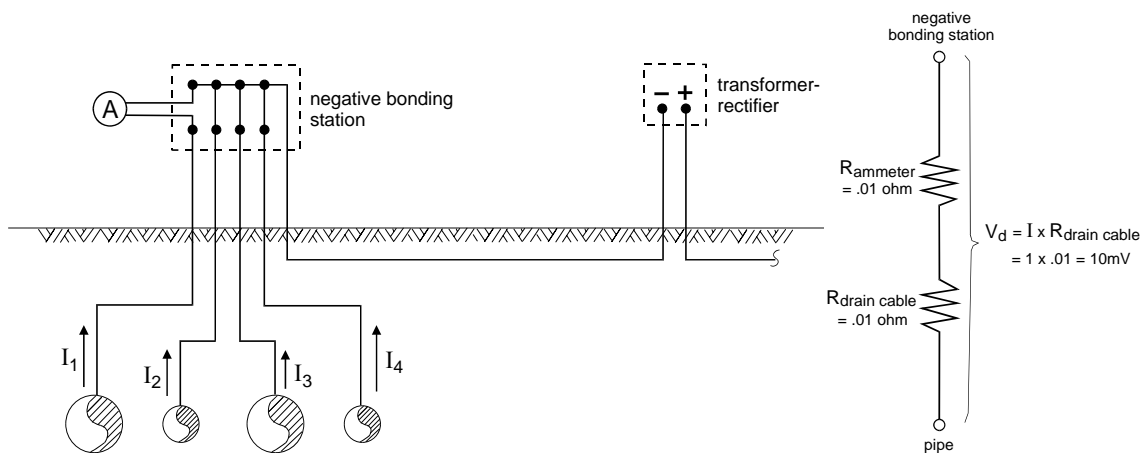


**Figure 5-32:  Current Measurement in Parallel Drain Conductors**

If the shunt resistance inside the ammeter is 0.01 ohm and the resistance of the negative return cable is 0.01 ohm, 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 shunt table in Appendix D.)

### 5.5.2    *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 5-33.
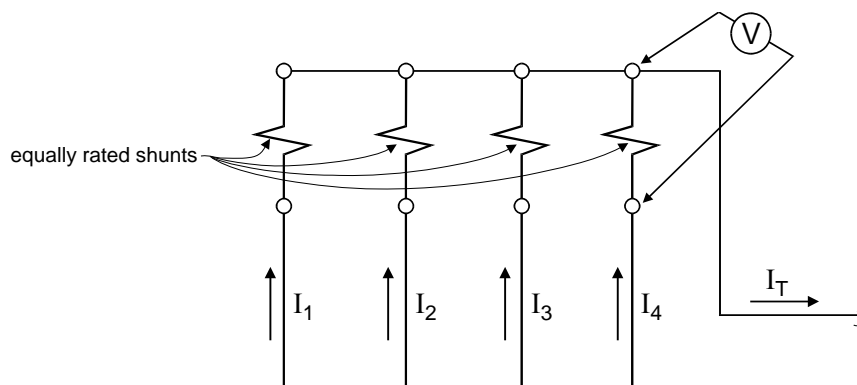


**Figure 5-33:  Use of Shunts for Current Measurements in Parallel Conductors**

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:

$$V_{shunt} \quad = \quad I_{cp} \times R_{shunt} \qquad\qquad\qquad [5\text{-}20]$$

$$= \quad 5\,mA \quad \times \quad \frac{V_{rating}}{I_{rating}}$$

$$= \quad 5\,mA \quad \times \quad \frac{.050\,V}{5\,A}$$

$$V_{shunt} \quad = \quad 0.05 \; mV$$

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 ohm is more appropriate. (See shunt table in Appendix D.)

## 5.5.3  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 5-34.
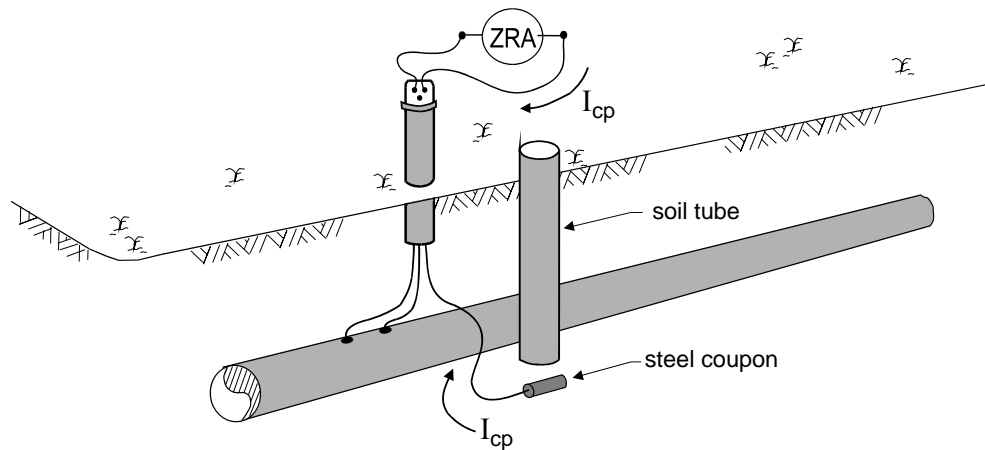


**Figure 5-34:  Current Measurement Using a Zero Resistance Ammeter (ZRA)**

If the coupon has a surface area of 10 cm$^2$ and a current density of 10 $\mu$A/cm$^2$ the coupon current ($I_{cp}$) would be:

$$I_{cpn} \quad = \quad 10 \ \mu A/cm^2 \ \times 10 \ cm^2$$

$$I_{cpn} \quad = \quad 100 \ \mu A \ or \ 0.1 \ mA$$

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 ohms is required to measure in the 10 mV range. Under these circumstances, a zero resistance ammeter should be used.

## 5.5.4   Clamp-on Ammeter

A relatively noninvasive method of measuring current in a conductor is by using a clamp-on ammeter as illustrated in Figure 5-35.
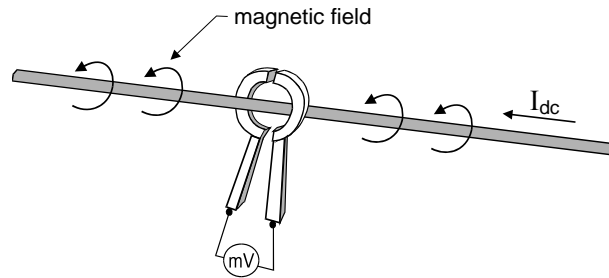


**Figure 5-35:  Using a Clamp-on Ammeter to Measure Current**

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 5-36 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.
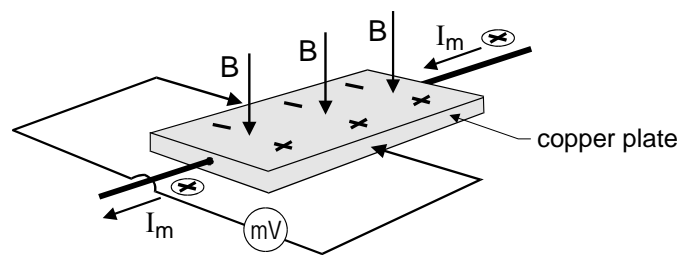


**Figure 5-36:  Schematic of the Hall Effect for Conventional Current Direction**

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 milliamperes. When there are multiple current-carrying conductors in a congested area, the accuracy is reduced if there is magnetic interference from adjacent conductors.

## 5.5.5   *Pipeline Current Measurements*

Pipeline currents can be measured with a clamp made up of a number of turns of wire as shown in Figure 5-37.
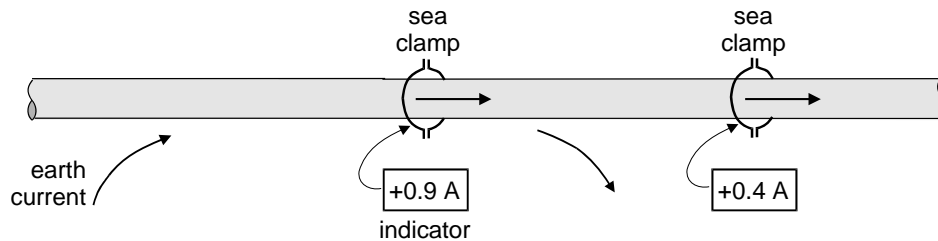
Earth current leaving subject pipeline is 0.9 - 0.4 = 0.5 A.

**Figure 5-37:  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

Pipeline current can also be measured using the four-wire span illustrated in Figure 5-38. 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.
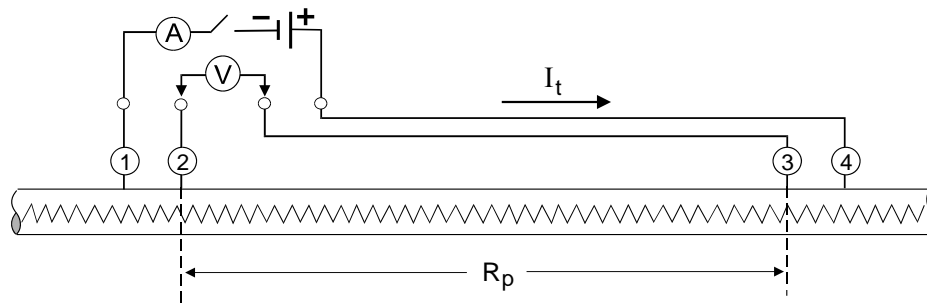
**Figure 5-38:  Calibrating a Pipeline Current Span**

The resistance of the pipe between test leads ② and ③ is calculated from Ohm's law:

$$R_p = \frac{\Delta V_{2\text{-}3}}{\Delta I_t}$$

[5-21]

The result can be anticipated prior to the test by referring to the pipe table in Appendix B.

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,*  $V_{2-3}$  =  +21 mV (before test current applied)

$V_{2-3}$  =  −19 mV (after test current applied)

$I_t$  =  10 A

The resistance ($R_p$) of the pipe section being tested is:

$$R_p = \frac{+21\,mV - (-19\,mV)}{10\,A}$$

$$R_p = \frac{+40\,mV}{10\,A} = 4\,m\Omega$$

Therefore the current calibration factor is:     $\dfrac{10A}{40\,mv} = 0.25 A/mV$

and the residual current magnitude is:

$$I_{residual} = 21\,mV \times 0.25\,A/mV = 5.25\,A$$

with a direction from 2 to 3.

# 5.6  Close Interval Potential Survey

When measuring a potential at one location, the amount of pipe sampled in the measurement is considered the length of pipe encompassed by a 120º arc centered on the reference electrode as shown in Figure 5-39.[9]
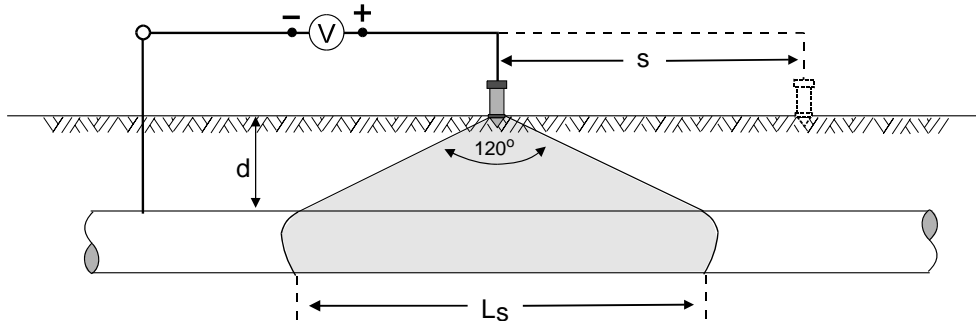


**Figure 5-39:  Length of Pipe Sampled in a Pipe-to-Soil Potential Measurement**

To determine the potential over the entire pipeline surface requires that the reference electrode be moved along the centerline of the pipe route and placed at regular intervals. For bare pipe, the interval distance is a function of pipe depth (d) to top of pipe as shown in Figure 5-40.
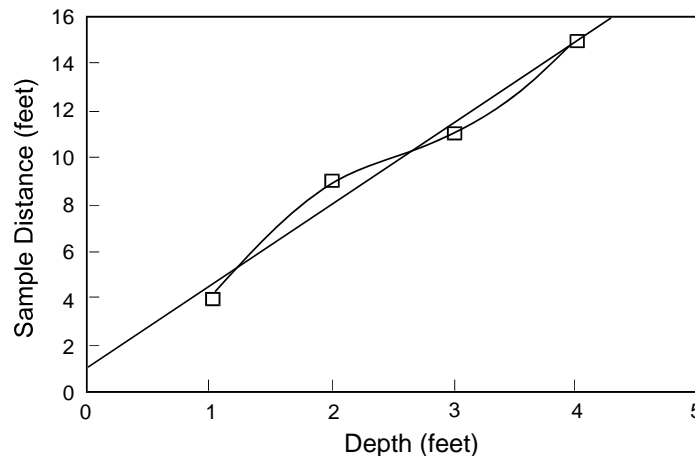


**Figure 5-40:  Length of Bare Pipe Over Which Potentials are Averaged
as a Function of Burial Depth**

Source:  Thompson, N.G. and Lawson, K.M., Improved Pipe-to-Soil Potential Survey Methods,
PRCI Final Report PR-186-807, April, 1991, p.4-2

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[9]  Pearson, J.M., Concepts and Methods of Cathodic Protection, Part 2, The Petroleum Engineer, April, 1994, p. 200.

This figure shows that field test data on a bare 24 in. pipeline verified the predictions of a finite element model. Hence, the length of pipeline sampled ($L_s$) in a potential measurement is given by the equation

$$L_s \ = \ 3.5d \ + 1 \qquad\qquad\qquad [5\text{-}22]$$

*where:*

$$d \ = \ \text{pipe depth}$$

Therefore for a pipeline buried at a 3 ft (0.92 m) depth, the length of pipe surveyed would be:

$$
\begin{aligned}
L_s \ &= \ 3.5 \times 3 \ + 1 \\
&= \ 11 \text{ ft (3.35 m)}
\end{aligned}
$$

Accordingly, the reference electrode spacing interval should be no greater than 11 ft (3.35 m).

The percentage of the circumferential area sampled on a bare pipe is not only a function of pipe depth but also of pipe diameter as shown in Figure 5-41.
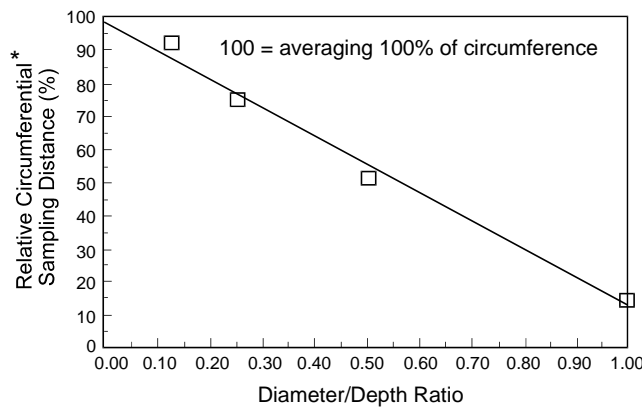


$$\ast \quad \frac{E_{(top\ pipe\ surface)} \ - \ E_{(ground\ level)}}{E_{(top\ pipe\ surface)} \ - \ E_{(average)}} \quad x \quad 100\%$$

**Figure 5-41:  Relative Circumferential Sampling Distance as a
Function of Pipe Diameter-to-Pipe Depth Ratio**

Source:  Thompson, N.G. and Lawson, K.M., Improved Pipe-to-Soil Potential Survey Methods,
PRCI Final Report PR-186-807, April 1991, p 4-4.

This figure illustrates that the percentage of circumferential surface sampled on a bare pipe increases as the pipe diameter/pipe depth ratio decreases.

For coated pipe, the length of pipe sampled depends on the size and location of the holidays in the coating. A finite element analysis[10] suggests the important parameter in determining the potential measured with respect to a reference electrode at grade is the ratio of coating resistivity to earth resistivity ($\rho_{ctg}/\rho_e$). This model predicted that only relatively large holidays (20 to 200 in.$^2$ or 130 to 1300 cm$^2$) are detectible at ground level on a pipeline with a $\rho_{ctg}/\rho_e$ ratio equal to 40. It also predicted that potential changes on a pipeline located beneath a high resistivity environment can be shielded from ground level potential measurements (e.g., coated piping directionally drilled through bedrock).

When conducting a close-interval potential survey, it is good practice to keep the reference electrode lead as short and as well insulated as possible. If there is a break in the reference electrode lead insulation and the test lead comes in contact with groundwater, as illustrated in Figure 5-42, an error in the potential measurement will result.
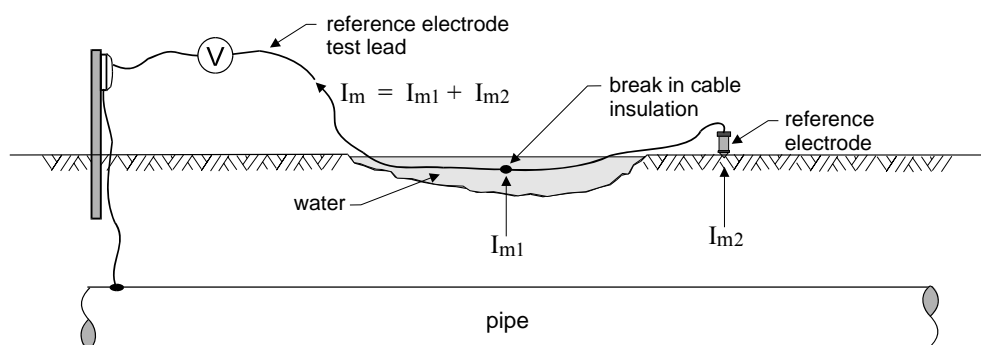


**Figure 5-42: Error in Potential Measurement Introduced by Reference Electrode Lead Conductor Contacting the Earth**

Essentially, the meter senses a reference potential that is a combination of the actual reference electrode potential and the test lead conductor potential. Both contribute metering current. Thus the reference electrode lead should be kept short and well insulated. A break in the insulation on the voltmeter to pipe wire will not affect the potential measurement significantly because of the relative low resistance of the pipeline to earth compared to the test lead.

Potential measurement errors can accumulate in close-interval survey data due to current in the pipeline. As shown in Figure 5-43, the measured potential at each

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[10] *Thompson, N.G. and Lawson, K.M., Improved Pipe-to-Soil Potential Survey Methods, PRCI Final Report PR-186-807, April 1991, p4-4.*

placement location becomes more electropositive when the current direction is the same as the survey direction.
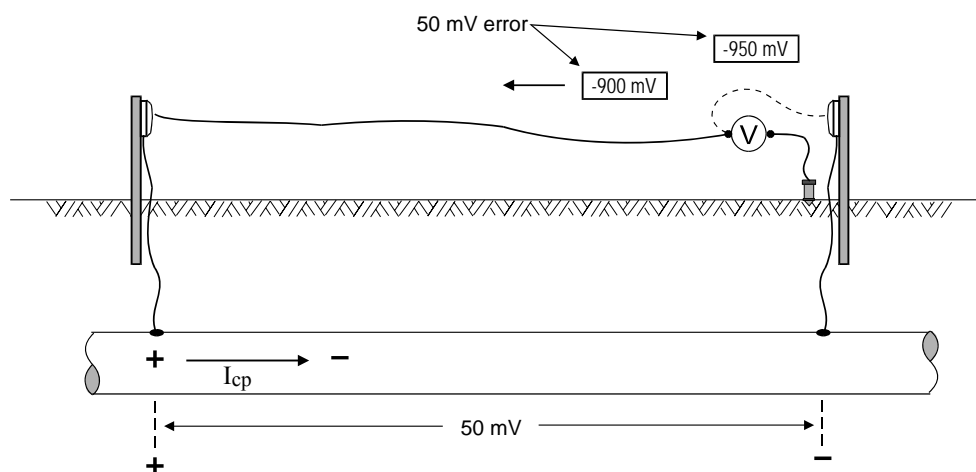


**Figure 5-43:  Error in Potential Measurement Introduced by Current in the Pipeline**

The amount of error accumulated can be determined by switching the point of connection at the last reference electrode position (i.e., at test station #2) and observing the potential. The difference in the two potentials should be linearly distributed with distance back to test station #1. For instance, the potential measurement at the halfway point between the two test stations would be increased in the negative direction by 25 mV. The voltage drop in the pipeline can also be determined by simply connecting the voltmeter leads to the two test stations.

If the pipe current is not steady state but is fluctuating with time, as could be the situation with telluric or other dynamic stray currents, a more complex method of identifying and correcting for this measurement error is required (see Chapter 3).

The presence of parallel interconnected pipelines as illustrated in Figure 5-44 can also produce errors in potential measurements.
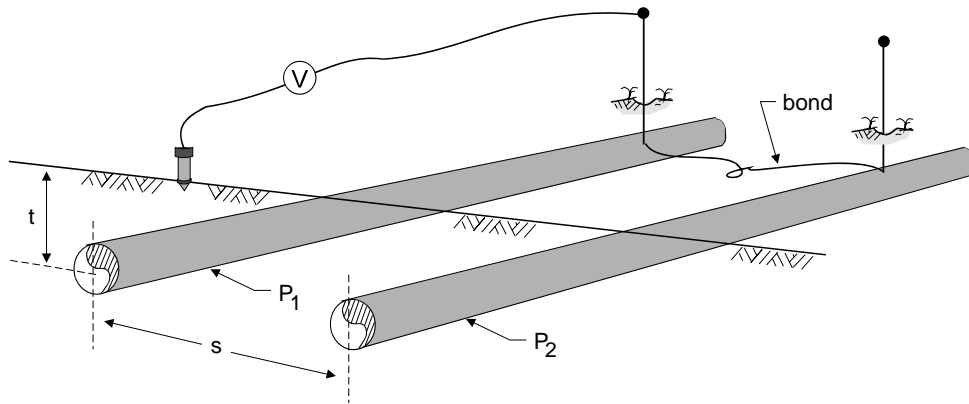
**Figure 5-44:  Error in Potential Measurement due to Interaction with a
Parallel Interconnected Pipeline**

The proximity of an adjacent pipeline can introduce errors in the potential measurement if there is a significant difference in the coating quality of each pipeline or in the level of polarization. First, there is the possibility of a recirculating current upon interruption of the cathodic protection current. Second the potential measurement with the reference located over $P_1$ will also be influenced by the potential on $P_2$. The magnitude of the error will increase as depth (t) increases and the pipeline separation distance (s) decreases.

The relative impact of a paralleling pipeline on the potential measurement is summarized in Table 5-2.[11]

**Table 5-2:  Summary of Relative Interaction for Two Paralleling Pipelines on
Potential Measurements**

| Pipeline Coating Quality on Pipe of Interest | Relative Interaction From Other Pipeline | |
|---|---|---|
| | on-potential | off-potential |
| bare | significant | not significant |
| bare | significant | not significant |
| bare | not significant | not significant |
| coated | marginally significant | marginally significant |
| poorly coated | not significant | not significant |
| well coated | significant | significant |

Where the interaction is significant or unknown, the inter-pipeline bonds should be interrupted synchronously along with the rectifiers.

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[11] *Thompson, N.G., Lawson, K.M., Multiple Pipelines in Right-of-Way:  Improved Pipe-to-Soil Potential Survey Methods, PRCI Contract PR-186-9105, Final Report, Oct. 1993, p.94.*

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## 5.7   Coating Condition Surveys

Since a close-interval potential survey is unlikely to identify coating holidays having a surface area less than about 20 cm$^2$, other means of identifying coating holidays and general coating conditions are used. One such survey technique relies on detection of the voltage gradient produced at a holiday by a signal current.

### 5.7.1   Voltage Gradient Method of Detecting Holidays in a Pipe Coating

The principle of this technique involves detecting a voltage difference on the earth surface using two or more portable electrodes separated by a short distance as illustrated in Figure 5-45.
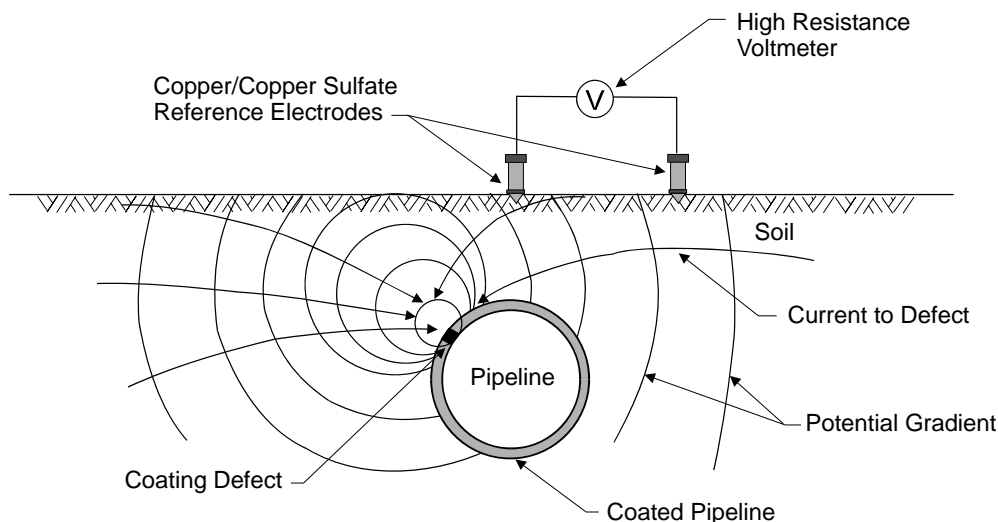


**Figure 5-45:  Coating Holiday Detection Using Voltage Gradient Method**

A signal generator is connected between the pipe and ground at a test point location. When the signal current passes from the pipeline to earth at a holiday, a voltage gradient is created in the soil radially from the holiday. Separated surface electrodes located either transverse to the pipe or along the pipe axis will detect a change in potential between them as they pass over the gradient.

The magnitude of the voltage gradient at any point in the earth is given by Equation 5-23.

$$V_g \quad = \quad \rho_e\, i \qquad\qquad [5\text{-}23]$$

*where:*

$V_g$  =  voltage gradient (V/unit length)
$\rho_e$  =  earth resistivity
$i$  =  current density at point of interest

The magnitude of the voltage difference depends on the signal current magnitude, the soil resistivity, and the holiday size.

Larger holidays will produce a larger potential difference ($V_{g1} - V_{g2}$) between the surface electrodes. Because of this, the surface area of the holiday can be estimated. The signal can be either DC (e.g., DCVG) or AC (Pearson, C-scan, etc.).

## 5.7.2  Coating Conductance Method of Evaluating Coating Quality

The quality of a coating can be determined by evaluating the coating conductance ($G_c$) or the specific coating resistance ($r'_c$) of a pipeline coating. The test method consists of applying an interrupt DC current between the pipe and earth, using either an existing rectifier or a temporary test current. (See TM0102-2002 in Appendix F.)  With the current interrupted, the pipe-to-soil potential and pipeline current are measured at two different locations (i.e., opposite ends of the pipe section of interest) as shown in Figure 5-46. Current would normally be measured with a current span or sometimes through a bond around an isolating fitting.
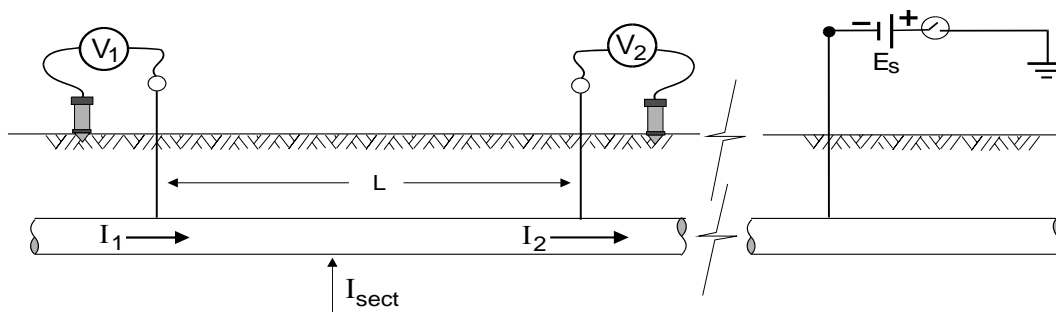


**Figure 5-46:  Arrangement for a Pipeline Coating Resistance (Conductance) Test**

An example of a data set and coating resistance calculations are as follows:

|       | $V_{on}$ | $V_{off}$ | $\Delta V$ | $I_{on}$ | $I_{off}$ | $\Delta I$ |
|-------|----------|-----------|------------|----------|-----------|------------|
| TS #1 | −2.00    | −0.90     | 1.10       | 2.8      | 0.10      | 2.70       |
| TS #2 | −1.65    | −0.85     | 0.80       | 3.0      | 0.20      | 2.80       |

The average resistance ($R_{sect}$) of the section of pipe is determined by Ohm's law as follows:

$$R_{sect} = \frac{\Delta V_{ave}}{I_{sect}} \qquad [5\text{-}24]$$

*where:*

$$\Delta V_{ave} = \frac{\Delta V_1 + \Delta V_2}{2}$$

$$I_{sect} = \Delta I_2 - \Delta I_1$$

Substituting field data into Equation 5-24 gives:

$$R_{sect} = \frac{\dfrac{1.10\,V + 0.80\,V}{2}}{2.80\,A - 2.70\,A} = \frac{0.95\,V}{0.1\,A}$$

$$R_{sect} = 9.5\,\Omega$$

To determine the coating quality for the section of pipe tested, the specific coating resistance ($r'_c$) must be calculated based on a soil resistivity of 1,000 $\Omega$-cm using Equation 5-25.

$$r'_c = R_{sect@1000\,\Omega\text{-cm}} \times A_s \qquad [5\text{-}25]$$

*where:*

$$R_{sect@1000\,\Omega\text{-cm}} = R_{sect} \times \frac{1000}{\rho test}$$

$$A_s = \pi d L_s = \text{the surface area of the pipe section}$$

For a 60 cm diameter pipe, 2 km long in 6500 $\Omega$-cm soil, the specific coating resistance in 1000 $\Omega$-cm soil will be:

$$r'_c = 9.5\,\Omega \times \frac{1000\,\Omega\text{-cm}}{6500\,\Omega\text{-cm}} \times 3.14 \times 0.6\,\text{m} \times 2000\,\text{m}$$

$$r'_c = 1.46\,\Omega \times 3768\,\text{m}^2$$
$$r'_c = 5507\,\Omega\text{-m}^2$$

The specific coating conductance ($g'_c$) can then be calculated from Equation 5-26.

$$g'_c = \frac{1}{r'_c} \qquad\qquad [5\text{-}26]$$

*therefore:*

$$g'_c = \frac{1}{5507\,\text{ohm-m}^2} = 1.82 \times 10^{-4}\,\text{S/m}^2$$

The resulting specific coating conductance can be compared to Table 5-3 to estimate coating quality. For a specific coating conductance of $1.82 \times 10^{-4}$ S/m$^2$, the coating on the test section would be rated "good" if the pipeline has few fittings in the test section or "excellent" if there are valves or fittings within the test section.

**Table 5-3:  Typical Specific Leakage Conductance for Dielectric Protective Coatings in 1000 Ω-cm Soil**

| Long Pipelines with Few Fittings | Average Specific Coating Conductance | | Average Specific Coating Resistance $r'_c$ | |
|---|---|---|---|---|
| Quality of Work | $g'$ Siemans/ft$^2$ | $g'$ Siemans/m$^2$ | Ω-ft$^2$ | Ω-m$^2$ |
| Excellent | $<1 \times 10^{-5}$ | $<1 \times 10^{-4}$ | $>10^5$ | $>10^4$ |
| Good | $1 \times 10^{-5}$ to $5 \times 10^{-5}$ | $1 \times 10^{-4}$ to $5 \times 10^{-4}$ | $2 \times 10^4$ to $10^5$ | $2 \times 10^3$ to $10^4$ |
| Fair | $5 \times 10^{-5}$ to $1 \times 10^{-4}$ | $5 \times 10^{-4}$ to $1 \times 10^{-3}$ | $10^4$ to $2 \times 10^4$ | $10^3$ to $2 \times 10^3$ |
| Poor | $>1 \times 10^{-4}$ | $>1 \times 10^{-3}$ | $<10^4$ | $<10^3$ |
| Bare Pipe (2 to 12") (5 to 30 cm) | $4 \times 10^{-3}$ to $2 \times 10^{-2}$ | $4 \times 10^{-2}$ to $2 \times 10^{-1}$ | 50 to 250 | 5 to 25 |

| Gas or Water Distribution with Many Fittings | Average Specific Coating Conductance | | Average Specific Coating Resistance $r'_c$ | |
|---|---|---|---|---|
| Quality of Work | $g'$ Siemans/ft$^2$ | $g'$ Siemans/m$^2$ | Ω-ft$^2$ | Ω-m$^2$ |
| Excellent | $<5 \times 10^{-5}$ | $<5 \times 10^{-4}$ | $>2 \times 10^4$ | $>2 \times 10^3$ |
| Good | $5 \times 10^{-5}$ to $1 \times 10^{-4}$ | $5 \times 10^{-4}$ to $1 \times 10^{-3}$ | $10^4$ to $2 \times 10^4$ | $10^3$ to $2 \times 10^3$ |
| Fair | $1 \times 10^{-4}$ to $5 \times 10^{-4}$ | $1 \times 10^{-3}$ to $5 \times 10^{-3}$ | $10^4$ to $2 \times 10^4$ | $2 \times 10^2$ to $10^3$ |
| Poor | $>5 \times 10^{-4}$ | $>5 \times 10^{-3}$ | $<2 \times 10^3$ | $<2 \times 10^2$ |
| Bare Pipe (2 to 12") (5 to 30 cm) | $4 \times 10^{-3}$ to $2 \times 10^{-2}$ | $4 \times 10^{-2}$ to $2 \times 10^{-1}$ | 50 to 250 | 5 to 25 |

# 5.8  Troubleshooting Cathodic Protection Systems

When subcriterion polarized potentials are measured on a structure, the remedial solution may simply be increasing the output of the cathodic protection system or adding additional current sources. Such a measure ultimately costs money whether it is for increased consumption of the anodes or for purchasing and installing additional materials. The exact cause of subcriterion potentials should be determined before arbitrary current additions are implemented.

There are many methods of identifying malfunctions in a cathodic protection system. For discussion purposes, the troubleshooting procedure has been applied independently to four fundamental factors of a cathodic protection system:

- polarization changes
- resistance changes
- power supply changes
- stray current effects

## 5.8.1  Polarization Changes

### 5.8.1(a)  Structure Depolarization

Depolarization of the structure is one of the most common causes of loss of protection because so many possible factors result in depolarization. Any circumstance that speeds up the charge transfer across the structure electrolyte interface will result in cathode depolarization as depicted in Figure 5-47 for a galvanic cathodic protection system.
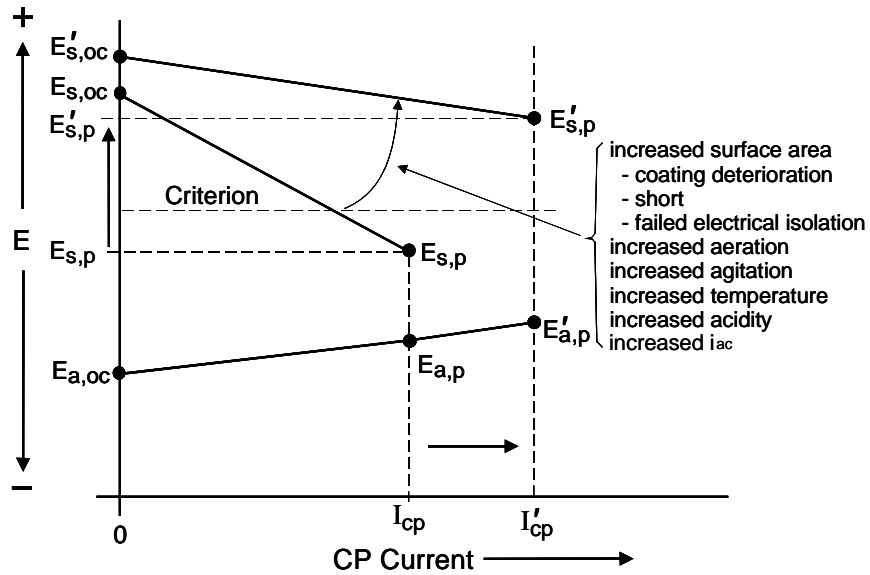
**Figure 5-47: Structure Depolarization in a Galvanic CP System**

The key symptom of depolarization is the cathodic protection current increase from $I_{cp}$ to $I'_{cp}$ along with an electropositive shift in structure potential. This effect will be more apparent on a galvanic protection system than on an impressed current system because most of the driving voltage in the latter is used up in the earth near the anode, not in polarization.

Coating deterioration, a metallic contact with a foreign structure, or a failed isolating fitting provide more structure surface resulting in less energy needed to transfer charge and therefore less polarization.

Increased temperature increases the rate of the two predominant reduction reactions:

$$H^+ + e^- \rightarrow H^O$$

*and,*

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$
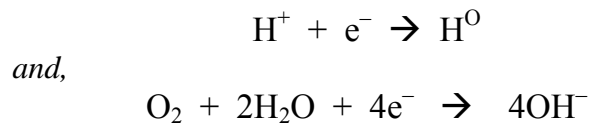
Increased aeration, agitation, and acidity provide more reactants to the reduction reactions increasing the reaction rate. Agitation also sweeps away the products of the reduction reaction allowing the reaction to proceed more readily.

## *5.8.2   Anode Polarization*

Anode polarization is a malfunction that is more common on impressed current systems than on galvanic systems, but in either case, as illustrated in Figures 5-48 and 5-49, the symptoms are the same.
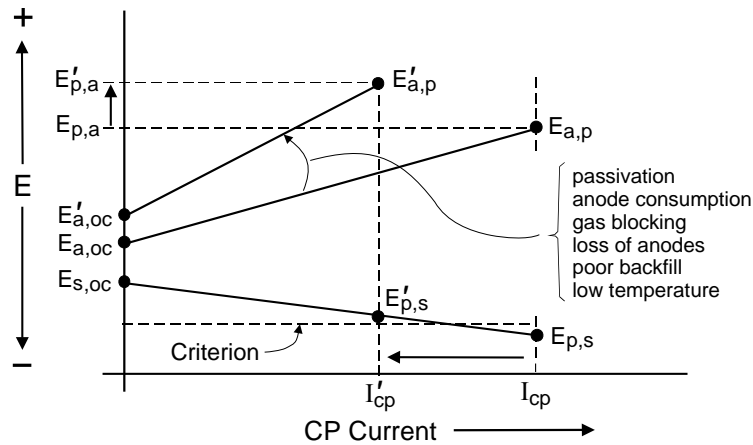


**Figure 5-48:  Increased Anode Polarization in an Impressed Current System**
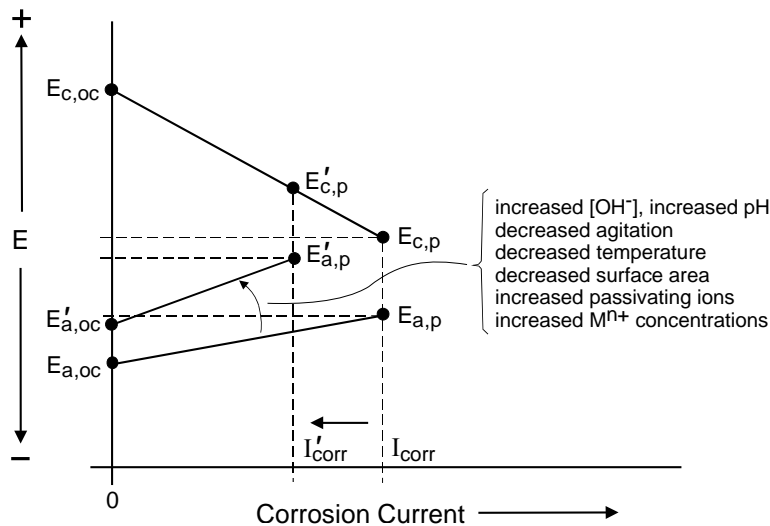


**Figure 5-49:  Increased Anode Polarization in a Galvanic System**

Anode polarization is characterized by a positive shift in the anode polarized potential ($E_{a,p}$) and usually a positive shift in the anode's open circuit potential ($E_{a,oc}$). This causes a reduction in current output. The key symptom is the positive

shift in anode potential, which for identification purposes requires that the anode potential be measured routinely as part of survey procedures.

Any factor that slows the oxidation reaction will cause anode polarization. Anode polarization can occur gradually as the anode is consumed resulting in a smaller surface area for charge transfer in the oxidation reaction or as the products of the oxidation reaction build up around the anode.

In impressed current systems anode polarization can occur abruptly if one or more anodes in a group are lost due to cable or splice failure or if a vent becomes plugged resulting in gas blockage.

Inadequate or poor quality backfill around the anode can cause anode polarization since without the proper backfill or the proper quantity, passive films may form on the anode surface.

A lower temperature, especially below freezing conditions, will slow the oxidation reaction and produce more anode polarization.


## 5.8.3   Increased Resistance

Any increase in resistance in a cathodic protection circuit will result in less current and hence less polarization at both the anode and structure, as illustrated in Figures 5-50 and 5-51.
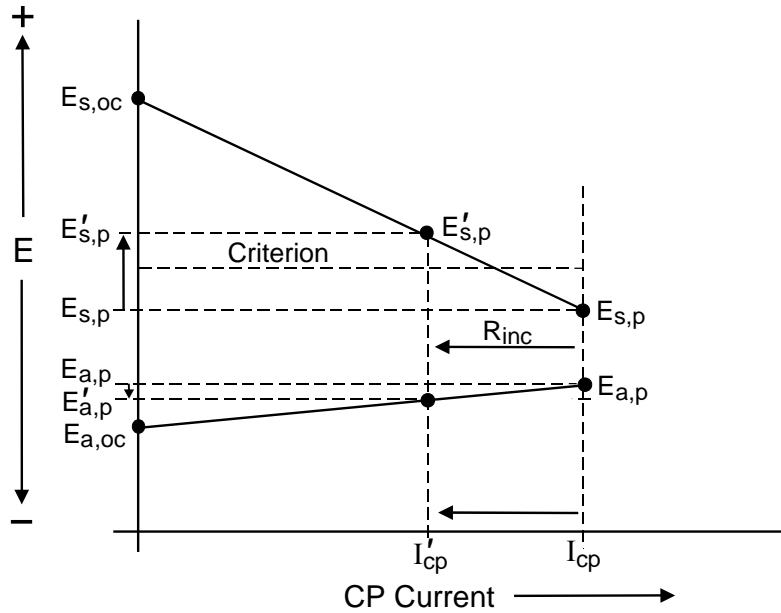
**Figure 5-50:  Increased Resistance in a Galvanic CP System**
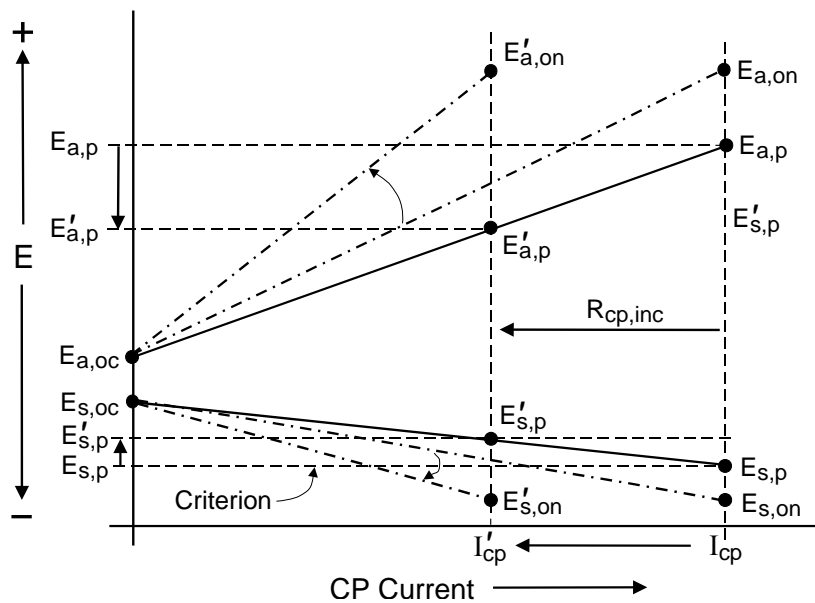


**Figure 5-51:  Increased Resistance in an Impressed Current System**

Besides a decrease in current, an increase in resistance results in a more negative polarized anode potential ($E'_{a,p}$). This is the key symptom and distinguishes the cause of subcriterion potentials from anode polarization where the polarized potential of the anode shifts in the positive direction. The increase in resistance can be in either the earth or metal current paths. The resistance increase can occur

in the bulk soil or can be localized at the anode or structure. Bulk earth resistivity increases with decreasing moisture and lower temperature, especially if the temperature drops below freezing (see Figures 1-35 and 1-36).

Gradual increase in circuit resistance will occur as anode consumption progresses due to decreasing anode geometry.

Sudden changes in resistance are usually due to broken and corroded cables or corroded splices. Cables and splices on the positive side of an impressed current system are particularly vulnerable to corrosion when and where the insulation has been damaged or where the splice has not been insulated properly. A localized resistance increase around a pipeline can result if the pipe backfill provides a drainage path for water as might occur on a hillside. The high temperature of piping downstream of a compressor station can result in localized drying of the soil adjacent to the pipe surface.

Localized drying of the soil around an impressed current anode can occur if the anode current density is too high. Typically, anode current densities should be limited to 50 µA/cm$^2$ (50 mA/ft$^2$) in low permeability soils such as clay[12].

Although the above events have been treated independently, it is not uncommon for a combination of these circumstances to be present. Very permeable well drained soils change in resistivity seasonally and allow more dissolved oxygen to contact structure surfaces creating a depolarization–increased resistance combination as illustrated in Figure 5-52. Similarly, high temperature can both dry out the soil and cause depolarization.

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[12] Haanestead, J.W. and Stapp, J., HVDC Ground Electrode Design, EPRI, Report #1467-1, August 1981, p. 7-38.

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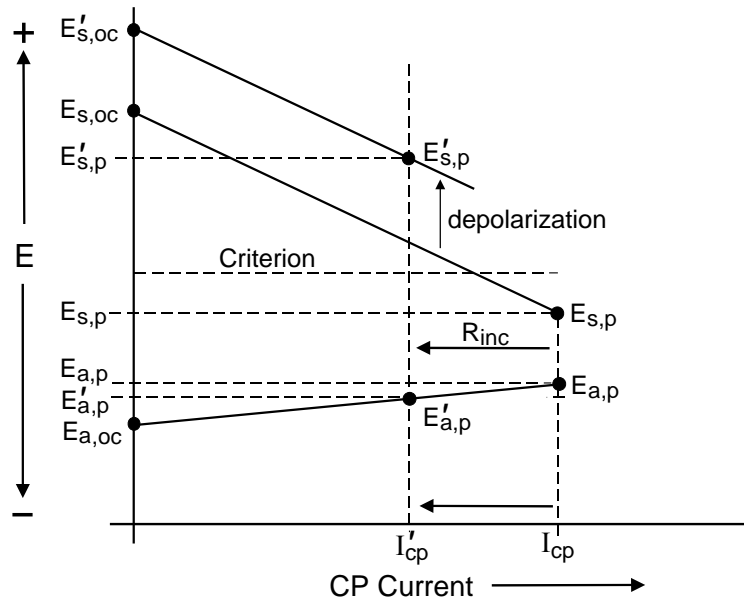
**Figure 5-52:  Seasonal Effects on a Galvanic CP System due to Drying of the Soil Resulting in Increased Resistance and Depolarization**

When soil dries, its resistance increases because the moisture between soil particles constitutes the principle ionic current paths. Furthermore, as the soil dries out, the earth becomes better aerated resulting in a reduction in polarization. Note that the key symptoms in this situation are the more electronegative polarized potentials of the galvanic anode and a more electropositive open circuit potential ($E_{corr,s}$) of the structure.

## 5.8.4  Power Supply Changes

A decrease in the driving voltage in a cathodic protection system will result in a decrease in current and structure polarization. This is more common in an impressed current system than in a galvanic system due to the vulnerability of the power supplies to damage and outages.

One of the more serious problems associated with DC power supplies is the reverse connection of the output terminals such that the positive terminal is connected to the structure. This is not uncommon since electricians are taught that for DC circuits the line side is positive and negative is ground. On well coated pipelines corrosion leaks can occur in a matter of months. It is therefore advisable when any work at a transformer-rectifier involves disconnecting cables, either internally or externally, that a pipe-to-soil potential be measured at the pipeline

test lead nearest to the power supply location immediately after the work has been completed.

Often a DC power supply is turned off for a variety of reasons and not re-energized. Transformer-rectifiers should not be connected to an AC circuit that is routinely interrupted.

Failure of a single phase transformer-rectifier as schematically illustrated in Figure 5-53 can occur for any one of the following reasons:

- Loss of input power
- Blown fuses
- Failed diodes
- Failed transformer windings
- Short circuit lightning arrestors
- Direct short in CP circuit
- Open connections and broken cables
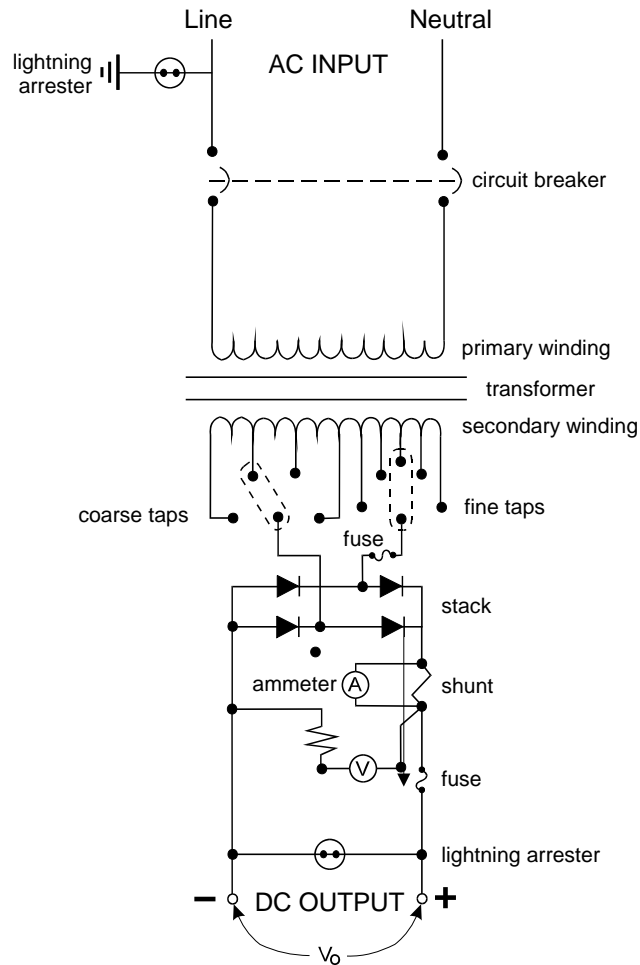
**Figure 5-53:  Typical Single Phase Tap Set Transformer-Rectifier**

When checking rectifier outputs on a routine basis, four basic situations require investigation:

- Zero current and voltage outputs
- Zero current output with unchanged output voltage
- Significant current change with unchanged voltage
- Significant changes in both voltage and current outputs

Note that output voltage and currents may not be precisely zero. There may be back voltage due to the potential difference between the pipe and groundbed or residual currents due to stray current activity.

## 5.8.4(a)  Zero Current and Voltage Outputs

For the case of zero output for both current and voltage, either there is no input power to the unit or an open circuit within the rectifier is indicated. First, determine if input AC voltage is present. If not, the problem is external to the rectifier. If AC voltage is present at the input terminals, an open circuit exists within the rectifier. However, the open circuit may be due to a tripped circuit breaker at the rectifier input.

The component causing the open circuit can be located by realizing that the rectifier voltage must exist across the open circuit element. If it is determined that the input circuit breaker has tripped, a high current or overload has occurred. This high current could have been a temporary problem, perhaps due to a lightning surge, or a permanent short circuit. The best method of proceeding is to reduce the voltage output tap to a low level and reset the circuit breaker. If the circuit breaker does not trip again, the problem was probably temporary and full output voltage can be restored. If the circuit breaker does trip, a permanent short circuit is indicated.

To determine if the short circuit is external to the rectifier, disconnect one of the DC output connection leads and reset the breaker. If the short circuit is external to the rectifier, the circuit breaker will not trip. If the short circuit is internal to the rectifier, the circuit breaker will again trip. 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.

The sequence of short circuit location is shown in Figure 5-54.
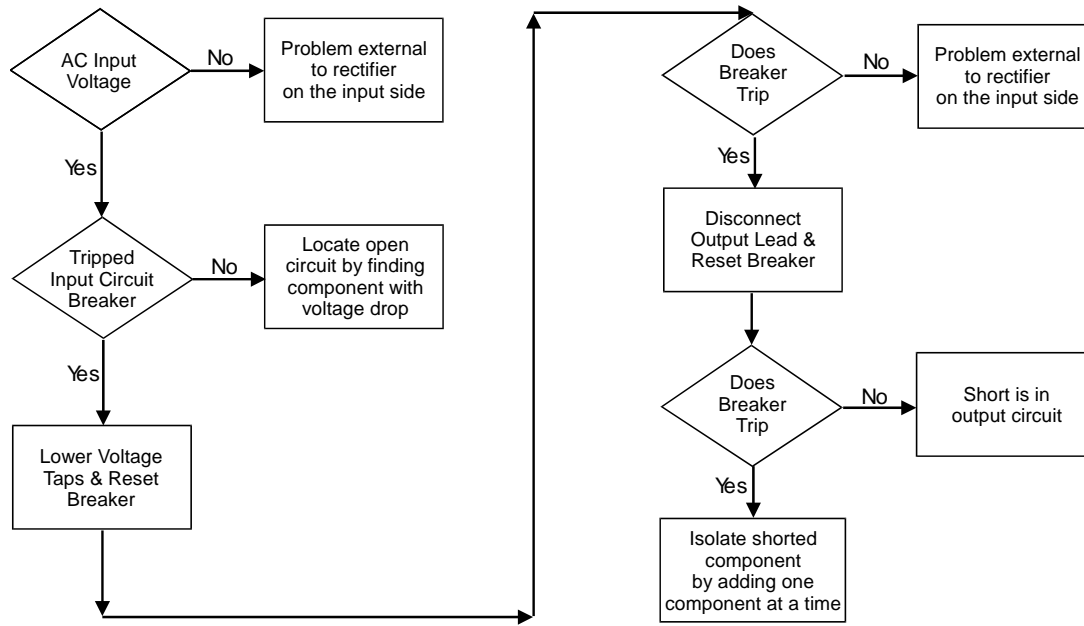
**Figure 5-54: Locating a Short Circuit in an ICCP System**

## 5.8.4(b)  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:

- An open fuse in the output circuit
- An open positive or negative lead wire
- A failed groundbed

If an open fuse in the output circuit is found, a short exists (or has existed) in the output circuit.

## 5.8.4(c)  Significant Current Change with Unchanged Voltage

If the DC current output significantly changes with no change in the output voltage, the output circuit resistance has changed. If the current output has significantly increased, a lower circuit resistance is indicated. This could be due to system additions, shorts to other underground structures, or major coating damage. If the current output significantly decreased, a higher circuit resistance is indicated. Some of the possible causes might include installation of inline isolators, groundbed deterioration, discontinuity due to disconnection of a system

component, or anode gas blockage. Seasonal variations in soil conditions, such as drying or frost, can also increase the current resistance.

## 5.8.4(d)  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.

## 5.8.4(e)  Transformer-Rectifier Efficiency

A transformer-rectifier with selenium stacks may lose efficiency as the rectifier elements age. Transformer-rectifier efficiency should be determined routinely by comparing input and output power as per Equations 5-27 and 5-28.

$$\text{T/R efficiency} = \frac{P_{dc,out}}{P_{ac,in}} \times 100 \qquad [5\text{-}27]$$

*where:* $\qquad P_{dc,out} = E_{dc} \times I_{dc}$

*and:* $\qquad P_{ac,in} = \dfrac{3600\,NK}{t} \qquad\qquad [5\text{-}28]$

*where:* $\quad N =$ number of revolutions of wattmeter disc
$\qquad\quad K =$ wattmeter constant on meter nameplate
$\qquad\quad t =$ time in which revolutions were counted (sec.)

The efficiency can be used to determine the average AC power consumption over a specific time period using Equation 5-29.

$$W = \frac{I_{dc} \times E_{dc} \times t}{1000 \times \text{Eff.}} \qquad [5\text{-}29]$$

*where:* $\quad W =$ total ac power consumption (kW-h)
$\qquad\quad I_{dc} =$ average dc current output (A)
$\qquad\quad E_{dc} =$ average dc voltage output (V)
$\qquad\quad t =$ length of period (h)

If the calculated input power read on the wattmeter differs from that calculated, a temporary power supply outage during the period would be suspected.

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Furthermore the total time (*t*) the rectifier has been operating can be determined by Equation 5-30, which is just a rearrangement of Equation 5-29.

$$t = \frac{W \times 1000 \times Eff}{I_o \times E_o}$$
[5-30]

Much of the power lost in the transformer-rectifiers is across the diodes and the transformer. Therefore a transformer-rectifier with a center-tapped secondary and only two diodes will have a higher efficiency than a bridge connected rectifying element with four diodes.

Also three phase power supplies, although more expensive, are much more efficient than single phase. The extra expense is often justified where three phase power is available once the CP system power requirements exceed about 2 kilowatts.

## 5.8.5   Cathodic Protection Troubleshooting Flow Chart

The sequence of steps involve in troubleshooting the operation of a cathodic protection system can be summarized in a flow chart such as Figure 5-55. Prior to the potential measurement, it is assumed that both the meter and reference electrode have been calibrated and the potential previously recorded at the measurement location was equal to or more electronegative than the criterion.
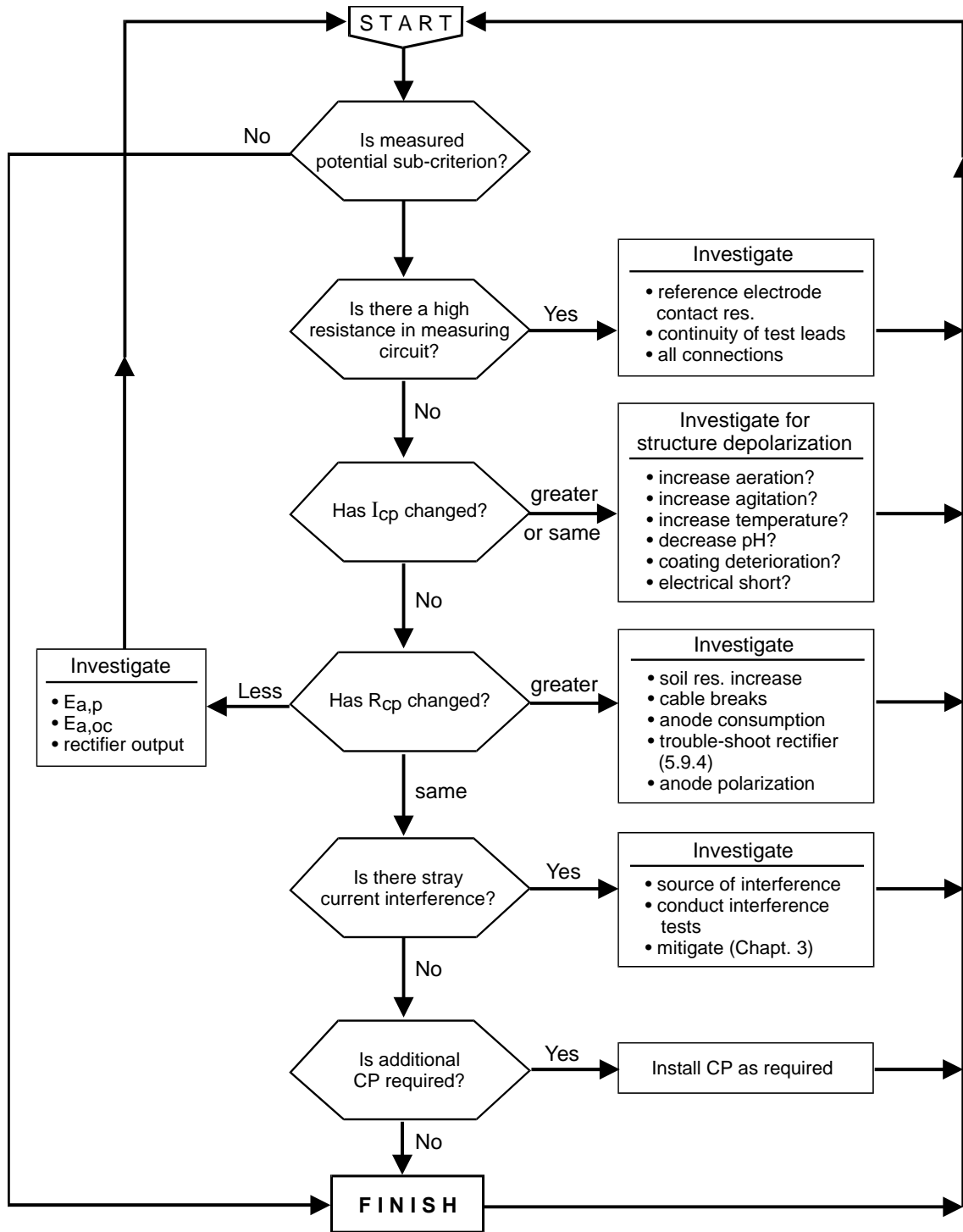
**Figure 5-55:  Cathodic Protection Troubleshooting Flow Chart**

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> # *Class Exercise 5-1*
> # **Evaluating Cathodic Protection Performance**

The following problems are presented for the student to exercise his performance-evaluation skills. Plot the data on semi-log graph paper.

Given the following cathodic protection data, state the reason(s) the design objective was not achieved.

## *Problem 1:*

| Potentials (mV) | | Current (mA) |
|---|---|---|
| $E_{corr,\ structure}$ | $= -550$ | |

**Design:**

| | | |
|---|---|---|
| $E_{corr,\ anode}$ | $= -1,500$ | $= 100$ |
| $E_{structure}$ | $= -1,000$ | |
| $E_{anode}$ | $= -1,300$ | |

**Actual:**

| | | |
|---|---|---|
| $E_{structure}$ | $= -700$ | $= 1,000$ |
| $E_{anode}$ | $= -1,200$ | |

## *Problem 2:*

| Potentials (mV) | | Current (mA) |
|---|---|---|
| $E_{corr,\ structure}$ | $= -550$ | |

**Design:**

| | | |
|---|---|---|
| $E_{corr,\ anode}$ | $= -1,500$ | $= 100$ |
| $E_{structure}$ | $= -1,000$ | |
| $E_{anode}$ | $= -1,300$ | |

**Actual:**

| | | |
|---|---|---|
| $E_{structure}$ | $= -600$ | $= 15$ |
| $E_{anode}$ | $= -650$ | |
| $E_{corr,\ anode}$ | $= -1,100$ | |

## *Problem 3:*

| Potentials (mV) | | Current (mA) |
|---|---|---|
| $E_{corr\ structure}$ | $= -550$ | |
| **Design:** | | |
| $E_{oc,\ anode}$ | $= -1,500$ | $= 100$ |
| $E_{structure}$ | $= -1,000$ | |
| $E_{anode}$ | $= -1,300$ | |
| **Actual:** | | |
| $E_{structure}$ | $= -700$ | $= 20$ |
| $E_{anode}$ | $= -1,450$ | |
| $E_{oc\ anode}$ | $= -1,500$ | |

## *Problem 4:*

The corrosion potential of a steel structure is –500 mV. When the cathodic protection is applied using an impressed current system, the structure potential shifts to –960 mV. Upon interrupting the current, the instant-off potential is –610 mV. If all potentials are measured with respect to a copper/copper sulfate reference electrode, which cathodic protection criteria are satisfied?

## *Problem 5:*

A fixed-voltage rectifier is set to operate at an output of 30 V and 15 A. During routine surveillance the rectifier is found to be 30 V and 7A. What malfunction(s) could have occurred?

## *Group Case Study:*

The figure below shows the plan and polarized potential profile for a portion of a coated and cathodically protected pipeline. List at least seven possible causes for the apparent lack of protection in the vicinity of the road crossing.
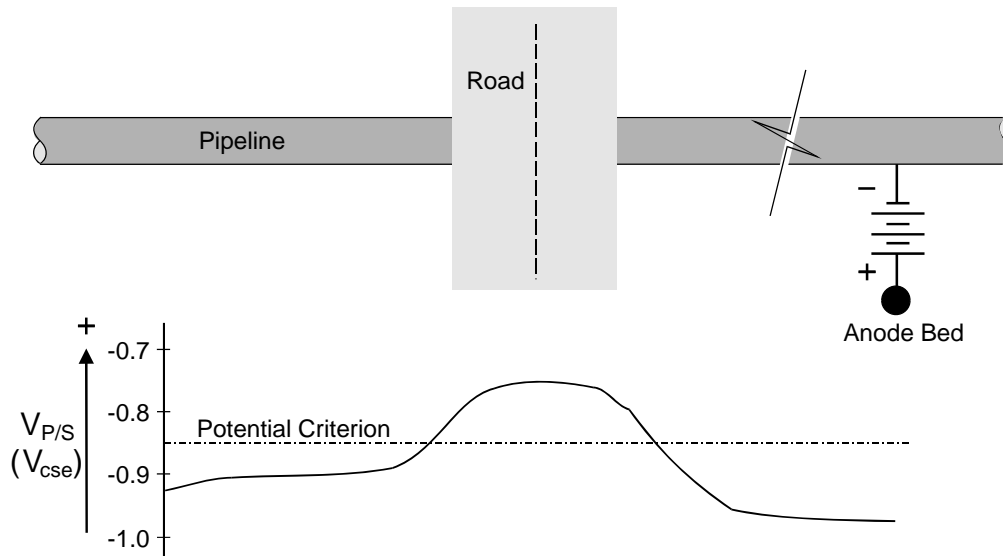
**Exercise Schematic 5-1:**
**Plan and Potential Profile for an Underground Cathodically**
**Protected Pipeline**

## *Experiment 5-1*
# To Demonstrate Four Methods of Minimizing IR Drop Error in a Potential Measurement
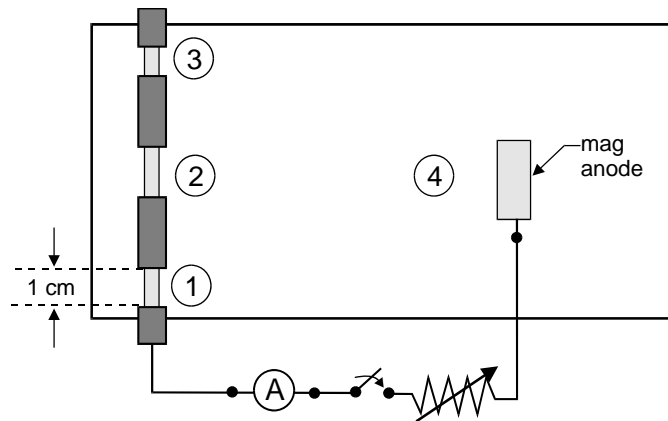


**Experiment Schematic 5-1**

## Procedure

### Step A:  Setup

1.  Fill tub to a depth of 5 cm with water from a cold water tap.
2.  Tape the steel rod with plastic tape leaving 3 uncoated sections, each 1 cm long, as shown on the schematic.
3.  Place rod in tub and connect the rod to the magnesium anode through an ammeter and switch.
4.  Close the switch and wait for 5 minutes for the structure to reach a steady state polarization level.

### Step B:  Current Interruption Method

1.  Measure potential of steel rod with top of reference electrode touching the top of the water at locations ① through ④ with the current on and momentarily interrupted. Do not allow the interruption time to exceed 5 seconds.
2.  Record the potentials in Results Table.
3.  Calculate the IR drop at each measurement location.

## Step C:  Reference Placed Close to Structure Holiday

1.  With switch closed, measure the structure potential with reference placed close to each of the 3 holidays. Close means a distance equal to 2 diameters of the reference (approximately 1 cm).
2.  Record the potentials in Table 5-2.
3.  Compare results to the instant-off potentials measured in Step A.

## Step D:  Stepwise Current Reduction Method
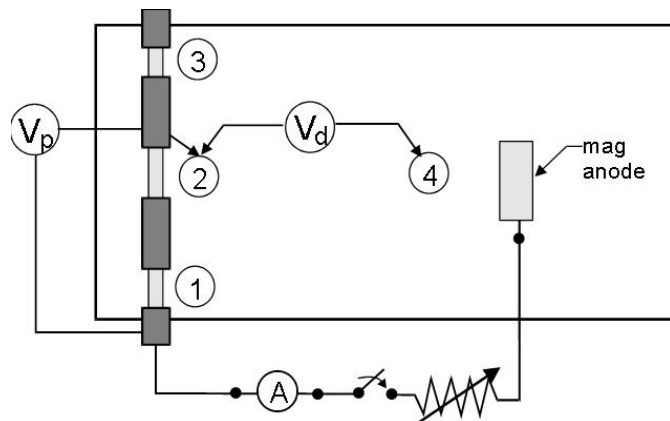


**Experiment Schematic 5-2**

1.  Place reference electrodes at locations ② and ④.
2.  Measure and record structure potential with respect to the reference touching the top of the water at location ②.
3.  Measure and record side drain voltage drop ($V_d$) between ② and ④.
4.  Insert 10 ohm resistor in series with the ammeter and repeat steps D2 and D3.
5.  Insert 100 ohm resistor in series with the ammeter and repeat steps D2 and D3.
6.  Calculate the change in the structure potentials $\Delta V_s$ and side drain ($V_d$) IR drops after step 4 and 5.
7.  Plot data on quad paper with the change in structure potential ($\Delta V_s$) on the ordinate and the change in side drain potential ($\Delta V_{2,4}$) on the abscissa (see Figure 5-19).
8.  Linearly extrapolate the curve to intersect the ordinate and estimate the total IR drop.
9.  Subtract the IR drop from the full current on-potential to obtain a calculated off-potential.
10. Compare with potential at ② in steps B and C.

## Step E:  Use of a Cathodic Protection Coupon and Reference Tube



Steel Rod

5/8" dia. PVC reference tube

coated coupon rod

Magnesium Anode

bare end of coupon rod (1/8" dia.)
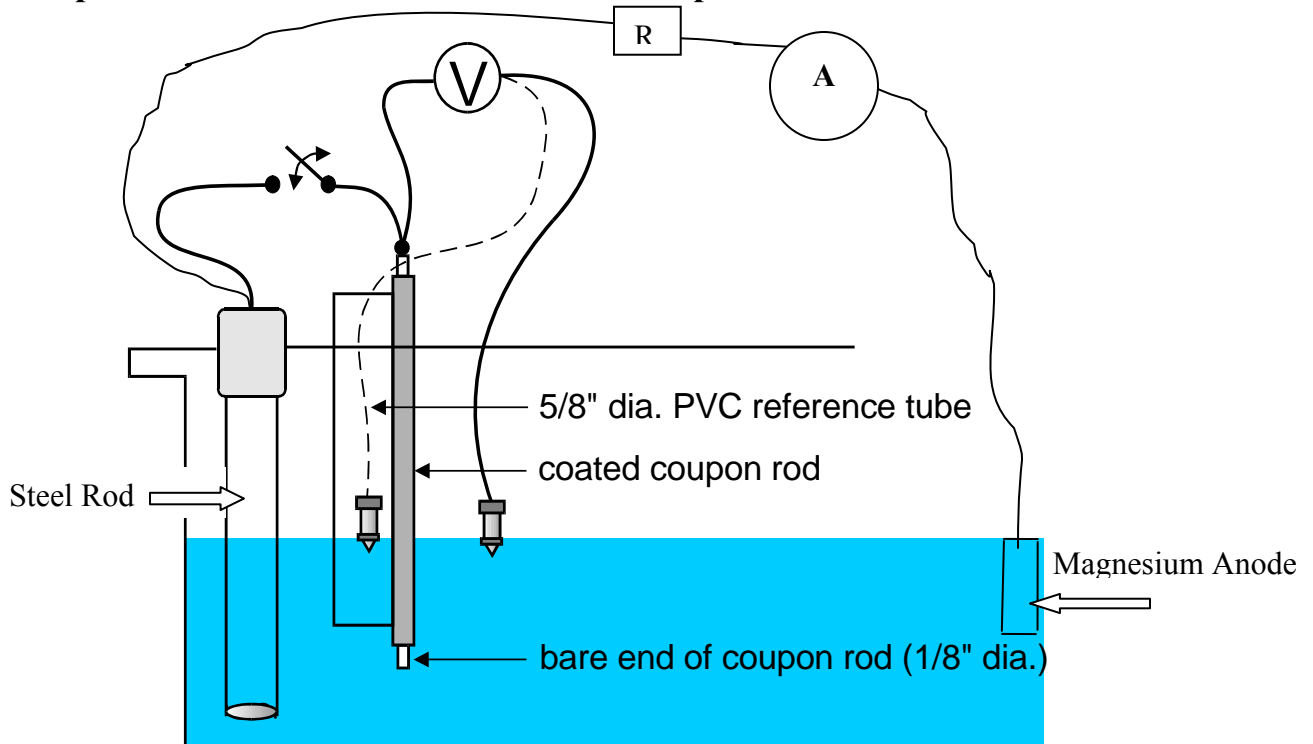
**Experiment Schematic 5-3**

1. Insert integrated coupon/reference cube as per schematic 5-3 and connect the coupon to the steel rod through a switch. Allow several minutes to polarize.
2. Place reference electrode touching top of water adjacent to the tube. Measure and record the potential of the coupon with the coupon connected and disconnected.
3. Place reference electrode inside reference tube so reference touches top of water inside the tube. Measure and record the potential of the coupon with the coupon connected to the structure and disconnected.

## Step F:  Compare the Following IR Drop Mitigated Data

1. B instant-off potentials at locations ① to ④.
2. C on-potentials at locations ① to ④.
3. D-9 calculated polarized potential at ②.
4. E coupon instant-disconnect potential.

Which is the most effective technique?

# Results Table

| Step | Structure-to-Electrolyte Potentials (mV/CSE) Reference Electrode Location | | | | | $I_{cp}$ | Remarks |
|------|---|---|---|---|---|---|---|
|  | ① | ② | ③ | ④ | Other |  |  |
| **B** |  |  |  |  |  |  |  |
| ON |  |  |  |  |  |  |  |
| OFF |  |  |  |  |  |  |  |
| IR$_{calc.}$ |  |  |  |  |  |  |  |
| **C** |  |  |  |  |  |  |  |
| ON |  |  |  |  |  |  |  |
| **D** |  | **V$_{S,2}$** |  | **V$_{2,4}$** |  |  |  |
| Full I$_{cp}$ |  |  |  |  | (1) |  |  |
| 10 Ω |  |  |  |  |  |  |  |
| Calc. ΔV$_S$ |  |  | Calc. ΔV$_{2,4}$ |  |  |  |  |
| 100 Ω |  |  |  |  |  |  |  |
| Calc. ΔV$_S$ |  |  | Calc. ΔV$_{2,4}$ |  |  |  |  |
| **E** | Water Surface | | Inside Ref. Tube | |  |  |  |
|  |  | Coupon |  | Coupon |  |  |  |
| Cpn connected |  |  |  |  |  |  |  |
| Cpn disconnected |  |  |  |  |  |  |  |

## Table I
## Packaged Magnesium Anodes

*The first number in the anode designation refers to the weight in pounds. The letter indicates the anode shape. The final number represents the approximate width in inches.
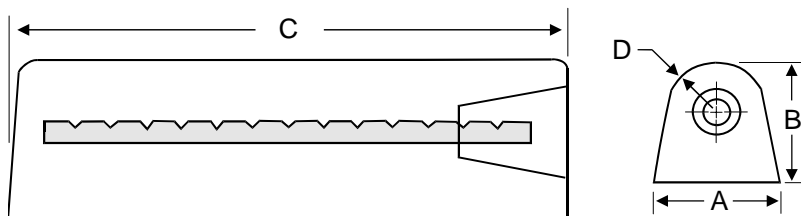


| ANODE TYPE* | MAGNESIUM CASTING DIMENSIONS (in.) | | | | PACKAGE DIMENSIONS (in.) & WEIGHT (lb.) | | | |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | Length | Width | Backfill Wt. | Total Wt. |
| 3D3 | 3-1/2" | 3-3/4" | 5" | 1-1/2" | 6-1/2" | 6" | 6# | 9# |
| 5D3 | 3-12" | 3-3/4" | 8-1/2" | 1-1/2" | 13-1/2" | 6" | 9# | 14# |
| 9D3 | 3-1/2" | 3-3/4" | 13-5/16" | 1-1/2" | 17" | 6" | 15# | 24# |
| 9D2 | 2-3/4" | 3" | 27" | 1-1/8" | 33" | 6" | 15# | 24# |
| 17D3 | 3-1/2" | 3-3/4" | 25-7/8" | 1-1/2" | 30" | 6" | 25# | 42# |
| 17D2 | 2-3/4" | 3" | 50" | 1-1/8" | 60" | 6" | 25# | 42# |
| 20D2 | 2-3/4" | 3" | 59-3/4" | 1-1/8" | 62" | 5" | 50# | 70# |
| 24D4 | 4-3/4" | 4-1/2" | 22-1/4" | 2" | | | | |
| 32D3 | 3-1/2" | 3-3/4" | 45-1/4" | 1-1/2" | 48" | 6" | 40# | 72# |
| 32D5 | 5-1/2" | 5-3/4" | 20-9/16" | 2-7/16" | 30" | 8" | 38# | 70# |
| 40D3 | 3-1/2" | 3-3/4" | 59-3/4" | 1-1/2" | 62" | 6" | 50# | 90# |
| 48D5 | 5-1/2" | 5-3/4" | 31-1/16" | 2-7/16" | 34" | 8" | 48# | 96# |

## Table II
## Zinc Packaged Ground Anodes

| TYPE | WEIGHT | SIZE |
|------|--------|------|
| ZA5 | 5 | 1.4" $\times$ 1.4" $\times$ 110" |
| ZA6 | 6 | 1.4" $\times$ 1.4" $\times$ 112" |
| ZA9 | 9 | 1.4" $\times$ 1.4" $\times$ 118" |
| ZA12 | 12 | 1.4" $\times$ 1.4" $\times$ 224" |
| ZA18 | 18 | 1.4" $\times$ 1.4" $\times$ 336" |
| ZA24 | 24 | 2" $\times$ 2" $\times$ 24" |
| ZA30 | 30 | 1.4" $\times$ 1.4" $\times$ 660" |
| ZA48 | 48 | 2" $\times$ 2" $\times$ 48" |
| ZA60 | 60 | 2" $\times$ 2" $\times$ 60" |
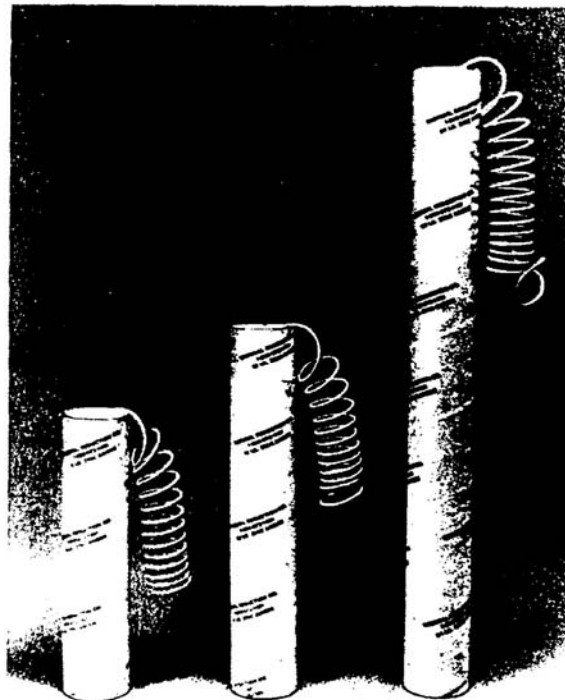
## Table IIIA
## High Silicon Iron Tubular Anodes

| TYPE | DIMENSIONS (Inches) | | | | WEIGHT (lbs.) | AREA (sq.ft.) |
|------|-----|-----|-----|-----|--------|---------|
|      | D   | L   | A   | H   |        |         |
| 2284 | 2.2 | 84  | 2.6 | 8   | 46     | 4.2     |
| 2684 | 2.6 | 84  | 3.0 | 8   | 64     | 4.9     |
| 3884 | 3.8 | 84  | 4.2 | 8   | 87     | 7.0     |
| 4884L | 4.8 | 84 | 5.2 | 8   | 112    | 8.8     |
| 4884H | 4.8 | 84 | 5.2 | 8   | 177    | 8.8     |
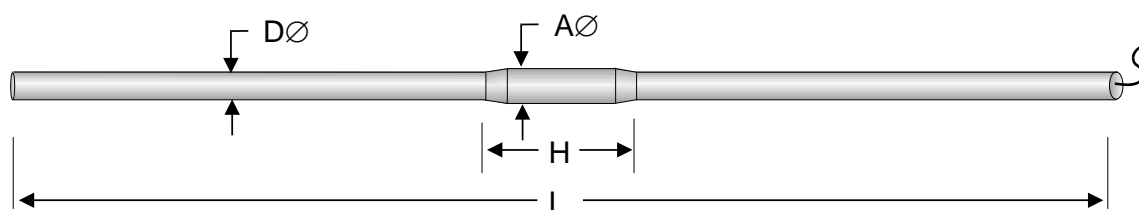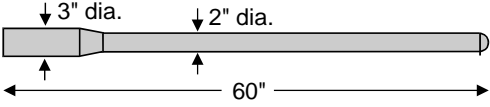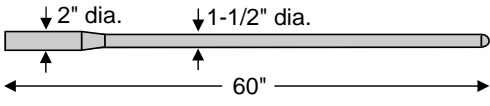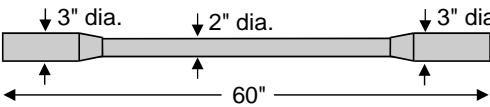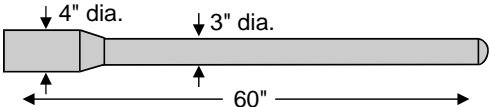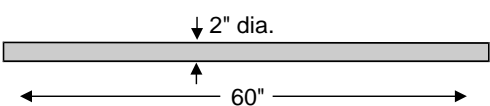


When ordering Compression Wedges Specify:  Style 1 (Crimp) or Style 2 (Solder)

### SHIPPING INFORMATION

| Anode Type | TUBE ANODES PER CRATE | | GROSS WEIGHT (lbs.) | |
|------------|-------------|-------------|-------------|-------------|
|            | Small Crate | Large Crate | Small Crate | Large Crate |
| 2284  | 45 | 63 | 2190 | 3018 |
| 2684  | 40 | 56 | 2800 | 3872 |
| 3084  | 21 | 35 | 1947 | 3165 |
| 4884L | 15 | 20 | 1845 | 2420 |
| 4884H | 15 | 20 | 2745 | 3620 |

## Table IIIB
## High Silicon Iron Solid Chill Cast Anodes

| TYPE | STYLE | DIMENSIONS | WEIGHT (lbs.) | AREA (sq.ft.) |
|------|-------|------------|---------------|---------------|
| EHA | 1 (PIN) 2 (LEAD) | 3" dia.  2" dia.  60" | 44 | 2.6 |
| EHK | 2 (LEAD) | 2" dia.  1-1/2" dia.  60" | 26 | 2.0 |
| EHM | 1 (PIN) 2 (LEAD) | 3" dia.  2" dia.  3" dia.  60" | 60 | 2.7 |
| EHR | 1 (PIN) 2 (LEAD) | 4" dia.  3" dia.  60" | 110 | 4.0 |
| SHA | 2 (LEAD) | 2" dia.  60" | 43 | 2.6 |

### SHIPPING INFORMATION

| Anode Type | SOLID ANODES PER CRATE | | GROSS WEIGHT (lbs.) | |
|------------|------------|-------------|-------------|-------------|
|            | Small Crate | Large Crate | Small Crate | Large Crate |
| EHA, SHA | 50 | 80 | 2350 | 3720 |
| EHM | 45 | -- | 2800 | -- |
| EHK | 70 | 126 | 1990 | 3502 |
| EHR | 24 | -- | 2740 | -- |

## Table IV
## Concentric Stranded Copper Single Conductors
## Direct Burial Service Suitably Insulated

| Size AWG | Overall Diameter Not including Insulation (inches) | Approx. weight Not Including Insulation (lbs./M ft.) | Maximum Breaking Strength (lbs.) | Maximum D.C. Resistance @ 20ºC Ohms/1000 ft. | Max. Allowable D.C. Current Capacity (Amperes) |
|---|---|---|---|---|---|
| 14 | 0.0726 | 12.68 | 130 | 2.5800 | 15 |
| 12 | 0.0915 | 20.16 | 207 | 1.6200 | 20 |
| 10 | 0.1160 | 32.06 | 329 | 1.0200 | 30 |
| 8 | 0.1460 | 50.97 | 525 | 0.6400 | 45 |
| 6 | 0.1840 | 81.05 | 832 | 0.4030 | 65 |
| 4 | 0.2320 | 128.90 | 1320 | 0.2540 | 85 |
| 3 | 0.2600 | 162.50 | 1670 | 0.2010 | 100 |
| 2 | 0.2920 | 204.90 | 2110 | 0.1590 | 115 |
| 1 | 0.3320 | 258.40 | 2660 | 0.1260 | 130 |
| 1/0 | 0.3730 | 325.80 | 3350 | 0.1000 | 150 |
| 2/0 | 0.4190 | 410.90 | 4230 | 0.0795 | 175 |
| 3/0 | 0.4700 | 518.10 | 5320 | 0.0631 | 200 |
| 4/0 | 0.5280 | 653.30 | 6453 | 0.0500 | 230 |
| 250 MCM | 0.5750 | 771.90 | 7930 | 0.0423 | 255 |

## Table V
## Typical Platinum Clad Niobium (Copper-cored) Anode Specification

| Diameter inches | % Nb | Nb Thickness inches | Resistance microhm/ft | Pt Thickness $\mu$-in. (2X)** | | Anode Life* AY/ft. (2X) | |
|---|---|---|---|---|---|---|---|
| .750 | 20 | .038 | 22 | 300 | | 373 | |
| .500 | 20 | .025 | 50 | 200 | | 166 | |
| .375 | 20 | .019 | 89 | 150 | (300) | 93 | (186) |
| .250 | 20 | .013 | 201 | 100 | (200) | 41 | (82) |
| .188 | 20 | .009 | 356 | 75 | (150) | 22 | (44) |
| .125 | 20 | .006 | 806 | 50 | (100) | 10 | (20) |
| .125 | 40 | .013 | 1025 | 50 | (100) | 10 | (20) |
| .093 | 40 | .010 | 1822 | 38 | (75) | 5.5 | (11) |
| .063 | 40 | .007 | 4102 | 25 | (50) | 2.5 | (5) |

*Based on 0.08 g/Amp-Year
**Double Platinum Thickness

## Table VI
## Graphite Cylindrical Anodes

| Anode Size | Anode Weight |
|------------|--------------|
| 3" x 30"   | 14 lb        |
| 3" x 60"   | 27 lb        |
| 4" x 80"   | 68 lb        |

## Table B-1: Steel Pipe Data for Corrosion Calculations

Resistivity of steel = 5.292E-06 ohms-in/1.344E-05 ohms-cm

| Nominal Size | Nominal Size | Schedule Number | OD | | Wall Thickness | | Weight Per ft  Per m | | Linear Res Per ft  Per m | |
|---|---|---|---|---|---|---|---|---|---|---|
| Inch | Cm | | Inch | Cm | Inch | Cm | lbs | kg | ohms | ohms |
| 4 | 10 | 40 | 4.500 | 11.4 | 0.237 | 0.602 | 10.79 | 4.90 | 2.001E-05 | 6.582E-05 |
| 6 | 15 | | 6.625 | 16.8 | 0.188 | 0.476 | 12.89 | 5.85 | 1.675E-05 | 5.493E-05 |
| 6 | 15 | | 6.625 | 16.8 | 0.219 | 0.556 | 14.97 | 6.80 | 1.442E-05 | 4.731E-05 |
| 6 | 15 | | 6.625 | 16.8 | 0.250 | 0.635 | 17.02 | 7.73 | 1.268E-05 | 4.160E-05 |
| 6 | 15 | 40 | 6.625 | 16.8 | 0.280 | 0.711 | 18.98 | 8.62 | 1.138E-05 | 3.732E-05 |
| 6 | 15 | 80 | 6.625 | 16.8 | 0.432 | 1.097 | 28.58 | 12.97 | 7.556E-06 | 2.478E-05 |
| 6 | 15 | 120 | 6.625 | 16.8 | 0.562 | 1.427 | 36.40 | 16.52 | 5.932E-06 | 1.946E-05 |
| 8 | 20 | 20 | 8.625 | 21.9 | 0.250 | 0.635 | 22.37 | 10.15 | 9.654E-06 | 3.167E-05 |
| 8 | 20 | 30 | 8.625 | 21.9 | 0.277 | 0.704 | 24.70 | 11.21 | 8.742E-06 | 2.867E-05 |
| 8 | 20 | 40 | 8.625 | 21.9 | 0.322 | 0.616 | 28.58 | 12.97 | 7.561E-0 | 2.480E-05 |
| 8 | 20 | 60 | 8.625 | 21.9 | 0.406 | 1.031 | 35.64 | 16.18 | 6.058E-06 | 1.987E-05 |
| 10 | 25 | 20 | 10.750 | 27.3 | 0.250 | 0.635 | 28.04 | 12.73 | 7.701E-06 | 2.526E-05 |
| 10 | 25 | 30 | 10.750 | 27.3 | 0.307 | 0.780 | 34.25 | 15.55 | 6.305E-06 | 2.068E-05 |
| 10 | 25 | 40 | 10.750 | 27.3 | 0.365 | 0.927 | 40.49 | 18.38 | 5.333E-06 | 1.749E-05 |
| 10 | 25 | 60 | 10.750 | 27.3 | 0.500 | 1.270 | 54.74 | 24.85 | 3.944E-06 | 1.294E-05 |
| 12 | 30 | 20 | 12.750 | 32.4 | 0.250 | 0.635 | 33.38 | 15.15 | 6.468E-06 | 2.122E-05 |
| 12 | 30 | 30 | 12.750 | 32.4 | 0.330 | 0.638 | 43.78 | 19.88 | 4.932E-06 | 1.618E-05 |
| 12 | 30 | | 12.750 | 32.4 | 0.375 | 0.953 | 49.57 | 22.51 | 4.356E-06 | 1.429E-05 |
| 12 | 30 | 40 | 12.750 | 32.4 | 0.406 | 1.031 | 53.53 | 24.30 | 4.033E-06 | 1.323E-05 |
| 12 | 30 | | 12.750 | 32.4 | 0.500 | 1.270 | 65.43 | 29.70 | 3.300E-06 | 1.082E-05 |
| 14 | 36 | 10 | 14.000 | 35.6 | 0.250 | 0.635 | 36.72 | 16.67 | 5.880E-06 | 1.929E-05 |
| 14 | 36 | 20 | 14.000 | 35.6 | 0.312 | 0.792 | 45.62 | 20.71 | 4.733E-06 | 1.552E-05 |
| 14 | 36 | 30 | 14.000 | 35.6 | 0.375 | 0.953 | 54.58 | 24.78 | 3.956E-06 | 1.298E-05 |
| 16 | 41 | 10 | 16.000 | 40.6 | 0.250 | 0.635 | 42.06 | 19.10 | 5.134E-06 | 1.684E-05 |
| 16 | 41 | 20 | 16.000 | 40.6 | 0.312 | 0.792 | 52.28 | 23.74 | 4.130E-06 | 1.355E-05 |
| 16 | 41 | 30 | 16.000 | 40.6 | 0.375 | 0.953 | 62.59 | 28.42 | 3.450E-06 | 1.132E-05 |
| 16 | 41 | 40 | 16.000 | 40.6 | 0.500 | 1.270 | 82.78 | 37.58 | 2.608E-06 | 8.555E-06 |

## Table B-1, *cont'd*:  Steel Pipe Data for Corrosion Calculations
Resistivity of steel  =  5.292E-06 ohms-in/1.344E-05 ohms-cm

| Nominal Size | Nominal Size | Schedule Number | OD | | Wall Thickness | | Weight Per ft  Per m | | Linear Res Per ft  Per m | |
|---|---|---|---|---|---|---|---|---|---|---|
| Inch | Cm | | Inch | Cm | Inch | Cm | lbs | kg | ohms | ohms |
| 18 | 46 | 10 | 18.000 | 45.7 | 0.250 | 0.635 | 47.40 | 21.52 | 4.555E-06 | 1.494E-05 |
| 18 | 46 | 20 | 18.000 | 45.7 | 0.312 | 0.792 | 56.95 | 26.76 | 3.663E-06 | 1.201E-05 |
| 18 | 46 | 30 | 18.000 | 45.7 | 0.437 | 1.110 | 61.98 | 37.22 | 2.634E-06 | 8.639E-06 |
| 18 | 46 | | 18.000 | 45.7 | 0.500 | 1.270 | 93.47 | 42.43 | 2.310E-06 | 7.577E-06 |
| 20 | 51 | 10 | 20.000 | 50.8 | 0.250 | 0.635 | 52.74 | 23.94 | 4.094E-06 | 1.343E-06 |
| 20 | 51 | 20 | 20.000 | 50.8 | 0.375 | 0.953 | 78.61 | 35.69 | 2.747E-06 | 9.009E-06 |
| 20 | 51 | 30 | 20.000 | 50.8 | 0.500 | 1.270 | 104.15 | 47.28 | 2.073E-06 | 6.800E-06 |
| 24 | 61 | 10 | 24.000 | 61.0 | 0.250 | 0.635 | 63.42 | 28.79 | 3.404E-06 | 1.117E-05 |
| 24 | 61 | 20 | 24.000 | 61.0 | 0.375 | 0.953 | 94.64 | 42.96 | 2.282E-06 | 7.484E-06 |
| 24 | 61 | | 24.000 | 61.0 | 0.500 | 1.270 | 125.51 | 56.98 | 1.720E-06 | 5.643E-06 |
| 30 | 76 | | 30.000 | 76.2 | 0.250 | 0.635 | 79.45 | 36.07 | 2.718E-06 | 8.915E-06 |
| 30 | 76 | | 30.000 | 76.2 | 0.375 | 0.953 | 118.67 | 53.88 | 1.820E-06 | 5.968E-06 |
| 30 | 76 | | 30.000 | 76.2 | 0.500 | 1.270 | 157.56 | 71.53 | 1.370E-06 | 4.495E-06 |
| 36 | 91 | | 36.000 | 91.4 | 0.250 | 0.635 | 95.47 | 43.34 | 2.262E-06 | 7.418E-06 |
| 36 | 91 | | 36.000 | 91.4 | 0.375 | 0.953 | 142.70 | 64.79 | 1.513E-06 | 4.963E-06 |
| 36 | 91 | | 36.000 | 91.4 | 0.500 | 1.270 | 189.60 | 86.08 | 1.139E-06 | 3.735E-06 |
| 42 | 107 | | 42.000 | 106.7 | 0.250 | 0.635 | 111.49 | 50.62 | 1.937E-06 | 6.352E-06 |
| 42 | 107 | | 42.000 | 106.7 | 0.375 | 0.953 | 166.74 | 75.70 | 1.295E-06 | 4.248E-06 |
| 42 | 107 | | 42.000 | 106.7 | 0.500 | 1.270 | 221.65 | 100.63 | 9.742E-06 | 3.195E-06 |
| 46 | 122 | | 48.000 | 121.9 | 0.250 | 0.635 | 127.52 | 57.89 | 1.693E-06 | 5.554E-06 |
| 46 | 122 | | 48.000 | 121.9 | 0.375 | 0.953 | 190.77 | 86.61 | 1.132E-06 | 3.712E-06 |
| 46 | 122 | | 48.000 | 121.9 | 0.500 | 1.270 | 253.70 | 115.18 | 8.511E-06 | 2.792E-06 |
| 54 | 137 | | 54.000 | 137.2 | 0.250 | 0.635 | 143.54 | 65.17 | 1.504E-06 | 4.934E-06 |
| 54 | 137 | | 54.000 | 137.2 | 0.375 | 0.953 | 214.81 | 97.52 | 1.005E-06 | 3.297E-06 |
| 54 | 137 | | 54.000 | 137.2 | 0.500 | 1.270 | 285.74 | 129.73 | 7.557E-06 | 2.479E-06 |
| 60 | 152 | | 60.000 | 152.4 | 0.250 | 0.635 | 159.56 | 72.44 | 1.353E-06 | 4.439E-06 |
| 60 | 152 | | 60.000 | 152.4 | 0.375 | 0.953 | 238.84 | 108.43 | 9.040E-06 | 2.965E-06 |

## U.S. Customary/Metric Conversions
## for Units Commonly Used in Corrosion-Related Literature

| | |
|---|---|
| 1 A/ft$^2$ | = 10.76 A/m$^2$ |
| 1 acre | = 4,047 m$^2$ = 0.4047 ha |
| 1 A-h/lb | = 2.205 A-h/kg |
| 1 Angstrom | = 10$^{-4}$ μm = 10$^{-10}$ m = 0.1 nm |
| 1 atm | = 101.325 kPa |
| 1 bar | = 100kPa |
| 1 bbl, oil (U.S.) | = 159.0 L |
| 1 bpd (oil) | = 159 L/d |
| 1 BTU | = 1,055 J |
| 1 BTU/ft$^2$ | = 11,360 J/m$^2$ |
| 1 BTU/ft$^2$/h | = 3.152 W/m$^2$ (K-factor) |
| 1 BTU/ft$^2$/h/F | = 5.674 W/m$^2$-K |
| 1 BTU/ft$^2$/h/F/in. | = 0.144 W/m-K |
| 1 BTU/h | = 0.2931 W |
| 1 cfm | = 28.3 L/min = 0.0283 m$^3$/min = 40.75 m$^3$/d |
| 1 cup | = 236.6 mL |
| 1 cycle/s | = 1 Hz |
| 1 ft | = 0.3048 m |
| 1 ft$^2$ | = 0.0929 m$^2$ = 929 cm$^2$ |
| 1 ft$^3$ | = 0.02832 m$^3$ = 28.32 L |
| 1 ft-lb (force) | = 1.356 J |
| 1 ft-lb (torque) | = 1.356 N-m |
| 1 ft/s | = 0.3048 m/s |
| 1 gal (Imp.) | = 4.546 L = 0.004546 m$^3$ |
| 1 gal (U.S.) | = 3.785 L = 0.003785 m$^3$ |
| 1 gal/bag (U.S.) | = 89 mL/kg (water/cement ratio) |
| 1 grain | = 0.06480 g = 64.80 mg |
| 1 grain/ft$^3$ | = 2.212 g/m$^3$ |
| 1 grain/100 ft$^3$ | = 22.12 mg/m |
| 1 hp | = 0.7457 kW |
| 1 microinch | = 0.0254 μm = 25.4 nm |
| 1 in. | = 2.54 cm = 25.4 mm |
| 1 in.$^2$ | = 6.452 cm$^2$ |
| 1 in.$^3$ | = 16.387 cm$^2$ = 0.01639 L |
| 1 in.-lb (torque) | = 0.113 N·m |
| 1 in. mercury | = 3.387 kPa |
| 1 in. water | = 248.8 Pa |

| | |
|---|---|
| 1 kg/mm$^2$ | = 9.807 MPa |
| 1 kilocalorie | = 4.184 kJ |
| 1 knot | = 0.515 m/s |
| 1 ksi | = 6.895 MPa |
| 1 lb | = 453.6 g = 0.4536 kg |
| 1 lb/ft$^2$ | = 47.88 Pa |
| 1 lb/ft$^3$ | = 0.01602 g/cm$^3$ |
| 1 lb/100 U.S. gal | = 1.1981 g/L |
| 1 lb/1,000 bbl | = 2.852 mg/L |
| 1 mA/in$^2$ | = 0.155 mA/cm$^2$ |
| 1 mA/ft$^2$ | = 10.76 mA/m$^2$ |
| 1 MBPD (oil) | = 159 kL/d |
| 1 mile | = 1.609 km |
| 1 sq. mile | = 2.590 km$^2$ |
| 1 mi. (naut.) | = 1.852 km |
| 1 mil | = 0.0254 mm = 25.4 μm |
| 1 MMCFD | = 2.83 × 10$^4$ m$^3$/d |
| 1 mm mercury | = 0.1333 kPa |
| 1 mph | = 1.609 km/h |
| 1 mpy | = 0.0254 mm/y = 25.4 μm/y |
| 1 N/mm$^2$ | = 1 Pa |
| 1 oz | = 28.35 g |
| 1 oz fluid (Imp.) | = 28.41 mL |
| 1 oz fluid (U.S.) | = 29.57 mL |
| 1 oz/ft$^2$ | = 2.992 Pa |
| 1 oz/U.S. gal | = 7.49 g/L |
| 1 part/1,000 bbl | = 2.32 mg/L |
| 1 psi | = 0.006895 MPa = 6.895 kPa |
| 1 qt (Imp.) | = 1.1365 L |
| 1 qt (U.S.) | = 0.9464 L |
| 1 teaspoon (tsp) | = 4.929 mL |
| 1 ton (short) | = 907.2 kg |
| 1 torr | = 133.3 Pa |
| 1 U.S. bag cement | = 42.63 kg (94 lb) |
| 1 yd | = 0.914 m |
| 1 yd$^2$ | = 0.8361 m$^2$ |
| 1 yd$^3$ | = 0.7646 m$^3$ |

| **Do Not Use** | **Use Instead** | |
|---|---|---|
| are | 1 are | = 1 dam$^2$ = 100 m$^2$ |
| candle | 1 candle | = 1 cd |
| candlepower | 1 candlepower | = 1 cd |
| fermi | 1 fermi | = 1 fm = 10$^{-15}$ m |
| gamma | 1 gamma | = 1 nT |
| micron | 1 micron | = 1 μm = 10$^{-6}$ m |
| millimicron | 1 millimicron | = 1 nm = 10$^{-9}$ m |
| mho | 1 mho | = 1S |
| γ (mass) | 1 γ | = 1 μg |
| λ (volume) | 1 λ | = mm$^3$ = 1 μL = 1mm$^3$ |

**Miscellaneous Units Not to Be Used**
calorie
conventional millimeter of mercury
grade (1 grade = (π/200) rad)
kilogram-force
langley ( 1 langley = 1 cal/cm$^2$)
metric carat
metric horsepower
millimeter, centimeter, or meter of water
standard atmosphere (atm = 101.325 kPa)
technical atmosphere (1 at = 98.0665 kPa)

## Table D-1:  Shunt Types and Values

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

# NACE GLOSSARY OF CORROSION-RELATED TERMS



## ABRASIVE
Small particles of material that are propelled at high velocity to impact a surface during abrasive blast cleaning.

## ABRASIVE BLAST CLEANING
Cleaning and roughening of a surface produced by the high-velocity impact of an abrasive that is propelled by the discharge of pressurized fluid from a blast nozzle or by a mechanical device such as a centrifugal blasting wheel.  (Also referred to as *Abrasive Blasting*.)

## ACCELERATOR
A chemical substance that increases the rate at which a chemical reaction (e.g., curing) would otherwise occur.

## ACRYLIC
Type of resin polymerized from acrylic acid, methacrylic acid, esters of these acids, or acrylonitrile.

## ACTIVATOR
A chemical substance that initiates and accelerates a chemical reaction (e.g., curing). Heat and radiation may also serve as activators for some chemical reactions.

## ACTIVE
(1)  The negative direction of electrode potential.  (2)  A state of a metal that is corroding without significant influence of reaction product.

## AERATION CELL
[See *Differential Aeration Cell*.]

## AIR DRYING
Process by which an applied wet coat converts to a dry coating film by evaporation of solvent or reaction with oxygen as a result of simple exposure to air without intentional addition of heat or a curing agent.

## AIRLESS SPRAYING
Process of spraying coating liquids using hydraulic pressure, not air pressure, to atomize.

## ALKYD
Type of resin formed by the reaction of polyhydric alcohols and polybasic acids, part of which is derived from saturated or unsaturated oils or fats.

## ALLIGATORING
Pronounced wide cracking over the surface of a coating, which has the appearance of alligator hide.

## AMPHOTERIC METAL
A metal that is susceptible to corrosion in both acid and alkaline environments.

## ANAEROBIC
Free of air or uncombined oxygen.

## ANION
A negatively charged ion that migrates through the electrolyte toward the anode under the influence of a potential gradient.

## ANODE
The electrode of an electrochemical cell at which oxidation occurs.  Electrons flow away from the anode in the external circuit.  Corrosion usually occurs and metal ions enter the solution at the anode.

## ANODE CAP
An electrical insulating material placed over the end of the anode at the lead wire connection.

## ANODE CORROSION EFFICIENCY
The ratio of the actual corrosion (mass loss) of an anode to the theoretical corrosion (mass loss) calculated from the quantity of electricity that has passed between the anode and cathode using Faraday's law.

## ANODIC INHIBITOR
A chemical substance that prevents or reduces the rate of the anodic or oxidation reaction.

## ANODIC POLARIZATION
The change of the electrode potential in the noble (positive) direction caused by current across the electrode/electrolyte interface.  [*See Polarization*.]

## ANODIC PROTECTION
Polarization to a more oxidizing potential to achieve a reduced corrosion rate by the promotion of passivity.

## ANODIZING
Oxide coating formed on a metal surface (generally aluminum) by an electrolytic process.

## ANOLYTE
The electrolyte adjacent to the anode of an electrochemical cell.

## ANTIFOULING
Preventing fouling. [See *Fouling*.]

# NACE GLOSSARY OF CORROSION-RELATED TERMS

## ATTENUATION
Electrical losses in a conductor caused by current flow in the conductor.

## AUGER ELECTRON SPECTROSCOPY
Analytical technique in which the sample surface is irradiated with low-energy electrons and the energy spectrum of electrons emitted from the surface is measured.

## AUSTENITIC STEEL
A steel whose microstructure at room temperature consists predominantly of austenite.

## AUXILIARY ELECTRODE
An electrode, usually made from a noncorroding material, which is commonly used in polarization studies to pass current to or from a test electrode.

## B

## BACKFILL
Material placed in a hole to fill the space around the anodes, vent pipe, and buried components of a cathodic protection system.

## BARRIER COATING
(1) A coating that has a high resistance to permeation of liquids and/or gases. (2) A coating that is applied over a previously coated surface to prevent damage to the underlying coating during subsequent handling

## BEACH MARKS
The characteristic markings on the fracture surfaces produced by fatigue crack propagation (also known as *clamshell marks, conchoidal marks*, and *arrest marks*).

## BETA CURVE
A plot of dynamic (fluctuating) interference current or related proportional voltage (ordinate) versus the corresponding structure-to-electrolyte potentials at a selected location on the affected structure (abscissa).

## BINDER
The nonvolatile portion of the vehicle of a formulated coating material.

## BITUMINOUS COATING
An asphalt or coal-tar compound used to provide a protective coating for a surface.

## BLAST ANGLE
(1) The angle of the blast nozzle with reference to the surface during abrasive blast cleaning. (2) The angle of the abrasive particles propelled from a centrifugal blasting wheel with reference to the surface being abrasive blast cleaned.

## BLOWDOWN
(1) Injection of air or water under high pressure through a tube to the anode area for the purpose of purging the annular space and possibly correcting high resistance caused by gas blockage. (2) In conjunction with boilers or cooling towers, the process of discharging a significant portion of the aqueous solution in order to remove accumulated salts, deposits, and other impurities.

## BLUSHING
Whitening and loss of gloss of a coating, usually organic, caused by moisture (also known as *blooming*).

## BRACELET ANODES
Galvanic anodes with geometry suitable for direct attachment around the circumference of a pipeline. These may be half-shell bracelets consisting of two semi-circular sections or segmented bracelets consisting of a large number of individual anodes.

## BRITTLE FRACTURE
Fracture with little or no plastic deformation.

## BRUSH-OFF BLAST CLEANED SURFACE
A brush-off blast cleaned surface, when viewed without magnification, shall be free of all visible oil, grease, dirt, dust, loose mill scale, loose rust, and loose coating. Tightly adherent mill scale, rust, and coating may remain on the surface. Mill scale, rust, and coating are considered tightly adherent if they cannot be removed by lifting with a dull putty knife. [See NACE No. 4/SSPC-SP 7.]

## C

## CALCAREOUS COATING
A layer consisting of calcium carbonate and other salts deposited on the surface. When the surface is cathodically polarized as in cathodic protection, this layer is the result of the increased pH adjacent to the protected surface.

## CALCAREOUS DEPOSIT
[See *Calcareous Coating.*]

## CASE HARDENING

Hardening a ferrous alloy so that the outer portion, or case, is made substantially harder than the inner portion, or core. Typical processes are carburizing, cyaniding, carbo-nitriding, nitriding, induction hardening, and flame hardening.

## CASEIN PAINT

Water-thinned paint with vehicle derived from milk.

## CATALYST

A chemical substance, usually present in small amounts relative to the reactants, that increases the rate at which a chemical reaction (e.g., curing) would otherwise occur, but is not consumed in the reaction.

## CATHODE

The electrode of an electrochemical cell at which reduction is the principal reaction. Electrons flow toward the cathode in the external circuit.

## CATHODIC CORROSION

Corrosion resulting from a cathodic condition of a structure, usually caused by the reaction of an amphoteric metal with the alkaline products of electrolysis.

## CATHODIC DISBONDMENT

The destruction of adhesion between a coating and the coated surface caused by products of a cathodic reaction.

## CATHODIC INHIBITOR

A chemical substance that prevents or reduces the rate of the cathodic or reduction reaction.

## CATHODIC POLARIZATION

The change of the electrode potential in the active (negative) direction caused by current across the electrode/electrolyte interface. [See *Polarization.*]

## CATHODIC PROTECTION

A technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

## CATHOLYTE

The electrolyte adjacent to the cathode of an electrochemical cell.

## CATION

A positively charged ion that migrates through the electrolyte toward the cathode under the influence of a potential gradient.

## CAVITATION

The formation and rapid collapse of cavities or bubbles within a liquid which often results in damage to a material at the solid/liquid interface under conditions of severe turbulent flow.

## CELL

[See *Electrochemical Cell.*]

## CEMENTATION

The introduction of one or more elements into the surface layer of a metal by diffusion at high temperature. (Examples of cementation include carburizing [introduction of carbon], nitriding [introduction of nitrogen], and chromizing [introduction of chromium].)

## CHALKING

The development of loose, removable powder (pigment) at the surface of an organic coating, usually caused by weathering.

## CHECKING

The development of slight breaks in a coating which do not penetrate to the underlying surface.

## CHEMICAL CONVERSION COATING

An adherent reaction product layer on a metal surface formed by reaction with a suitable chemical to provide greater corrosion resistance to the metal and increase adhesion of coatings applied to the metal. (Example is an iron phosphate coating on steel, developed by reaction with phosphoric acid.)

## CHEVRON PATTERN

A V-shaped pattern on a fatigue or brittle-fracture surface. The pattern can also be one of straight radial lines on cylindrical specimens.

## CHLORIDE STRESS CORROSION CRACKING

Cracking of a metal under the combined action of tensile stress and corrosion in the presence of chlorides and an electrolyte (usually water).

## COAT

One layer of a coating applied to a surface in a single continuous application to form a uniform film when dry.

## COATING

A liquid, liquefiable, or mastic composition that, after application to a surface, is converted into a solid protective, decorative, or functional adherent film.

# NACE GLOSSARY OF CORROSION-RELATED TERMS

## COATING SYSTEM
The complete number and types of coats applied to a substrate in a predetermined order. (When used in a broader sense, surface preparation, pretreatments, dry film thickness, and manner of application are included.)

## COLD LAP
(1) Discontinuity caused by solidification of the meniscus of a partially cast anode as a result of interrupted flow of the casting stream. The solidified meniscus is covered with metal when the flow resumes. Cold laps can occur along the length of an anode. (2) A protective film consisting of one or more coats, applied in a predetermined order by prescribed methods to an as-specified dry film thickness, including any reinforcing material that may be specified.

## COLD SHUT
Horizontal surface discontinuity caused by solidification of a portion of a meniscus during the progressive filling of a mold, which is later covered with more solidifying metal as the molten metal level rises. Cold shuts generally occur at corners remote from the point of pour.

## COMMERCIAL BLAST CLEANED SURFACE
A commercial blast cleaned surface, when viewed without magnification, shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products, and other foreign matter. Random staining shall be limited to no more than 33 percent of each unit area (approximately 58 cm$^2$ [9.0 in.$^2$]) of surface and may consist of light shadows, slight streaks, or minor discolorations caused by stains of rust, stains of mill scale, or stains of previously applied coating. [See NACE No. 3/SSPC-SP 6.]

## CONCENTRATION CELL
An electrochemical cell, the electromotive force of which is caused by a difference in concentration of some component in the electrolyte. (This difference leads to the formation of discrete cathodic and anodic regions.)

## CONCENTRATION POLARIZATION
That portion of polarization of a cell produced by concentration changes resulting from passage of current though the electrolyte.

## CONDUCTIVE COATING
(1) A coating that conducts electricity. (2) An electrically conductive, mastic-like material used as an impressed current anode on reinforced concrete surfaces.

## CONDUCTIVE CONCRETE
A highly conductive cement-based mixture containing coarse and fine coke and other material used as an impressed current anode on reinforced concrete surfaces.

## CONDUCTIVITY
(1) A measure of the ability of a material to conduct an electric charge. It is the reciprocal of resistivity. (2) The current transferred across a material (e.g., coating) per unit potential gradient.

## CONTACT CORROSION
[See *Galvanic Corrosion.*]

## CONTINUITY BOND
A connection, usually metallic, that provides electrical continuity between structures that can conduct electricity.

## CONTINUOUS ANODE
A single anode with no electrical discontinuities.

## CONVERSION COATING
[See *Chemical Conversion Coating.*]

## CORROSION
The deterioration of a material, usually a metal, that results from a reaction with its environment.

## CORROSION FATIGUE
Fatigue-type cracking of metal caused by repeated or fluctuating stresses in a corrosive environment characterized by shorter life than would be encountered as a result of either the repeated or fluctuating stress alone or the corrosive environment alone.

## CORROSION INHIBITOR
A chemical substance or combination of substances that, when present in the environment, prevents or reduces corrosion.

## CORROSION POTENTIAL (E$_{corr}$)
The potential of a corroding surface in an electrolyte relative to a reference electrode under open-circuit conditions (also known as *rest potential, open-circuit potential*, or *freely corroding potential*).

## CORROSION RATE
The rate at which corrosion proceeds.

## CORROSION RESISTANCE
Ability of a material, usually a metal, to withstand corrosion in a given system.

## CORROSIVENESS
The tendency of an environment to cause corrosion.

## COUNTER ELECTRODE
[See *Auxiliary Electrode.*]

## COUNTERPOISE
A conductor or system of conductors arranged beneath a power line, located on, above, or most frequently, below the surface of the earth and connected to the footings of the towers or poles supporting the power line.

## COUPLE
[See *Galvanic Couple.*]

## CRACKING (OF COATING)
Breaks in a coating that extend through to the substrate.

## CRAZING
A network of checks or cracks appearing on the surface of a coating.

## CREEP
Time-dependent strain occurring under stress.

## CREVICE CORROSION
Localized corrosion of a metal surface at, or immediately adjacent to, an area that is shielded from full exposure to the environment because of close proximity of the metal to the surface of another material.

## CRITICAL HUMIDITY
The relative humidity above which the atmospheric corrosion rate of some metals increases sharply.

## CRITICAL PITTING POTENTIAL ($E_p$, $E_{pp}$)
The lowest value of oxidizing potential (voltage) at which pits nucleate and grow. The value depends on the test method used.

## CURING
Chemical process of developing the intended properties of a coating or other material (e.g., resin) over a period of time.

## CURING AGENT
A chemical substance used for curing a coating or other material (e.g., resin). [Also referred to as *Hardener.*]

## CURRENT
(1) A flow of electric charge. (2) The amount of electric charge flowing past a specified circuit point per unit time, measured in the direction of net transport of positive charges. (In a metallic conductor, this is the opposite direction of the electron flow.)

## CURRENT DENSITY
The current to or from a unit area of an electrode surface.

## CURRENT EFFICIENCY
The ratio of the electrochemical equivalent current density for a specific reaction to the total applied current density.

## D

## DC DECOUPLING DEVICE
A device used in electrical circuits that allows the flow of alternating current (AC) in both directions and stops or substantially reduces the flow of direct current (DC).

## DEALLOYING
The selective corrosion of one or more components of a solid solution alloy (also known as *parting* or *selective dissolution*).

## DECOMPOSITION POTENTIAL
The potential (voltage) on a metal surface necessary to decompose the electrolyte of an electrochemical cell or a component thereof.

## DECOMPOSITION VOLTAGE
[See *Decomposition Potential.*]

## DEEP GROUNDBED
One or more anodes installed vertically at a nominal depth of 15 m (50 ft) or more below the earth's surface in a drilled hole for the purpose of supplying cathodic protection.

## DEPOLARIZATION
The removal of factors resisting the current in an electrochemical cell.

## DEPOSIT ATTACK
Corrosion occurring under or around a discontinuous deposit on a metallic surface (also known as *poultice corrosion*).

## DEZINCIFICATION

A corrosion phenomenon resulting in the selective removal of zinc from copper-zinc alloys. (This phenomenon is one of the more common forms of dealloying.)

## DIELECTRIC COATING

A coating that does not conduct electricity.

## DIELECTRIC SHIELD

An electrically nonconductive material, such as a coating, sheet or pipe, that is placed between an anode and an adjacent cathode, usually on the cathode, to improve current distribution in a cathodic protection system.

## DIFFERENTIAL AERATION CELL

An electrochemical cell, the electromotive force of which is due to a difference in air (oxygen) concentration at one electrode as compared with that at another electrode of the same material.

## DIFFUSION-LIMITED CURRENT DENSITY

The current density that corresponds to the maximum transfer rate that a particular species can sustain because of the limitation of diffusion (often referred to as *limiting current density*).

## DISBONDMENT

The loss of adhesion between a coating and the substrate.

## DISSIMILAR METALS

Different metals that could form an anode-cathode relationship in an electrolyte when connected by a metallic path.

## DOUBLE LAYER

The interface between an electrode or a suspended particle and an electrolyte created by charge-charge interaction leading to an alignment of oppositely charged ions at the surface of the electrode or particle. The simplest model is represented by a parallel plate condenser.

## DOUBLER PLATE

An additional plate or thickness of steel used to provide extra strength at the point of anode attachment to an offshore platform.

## DRAINAGE

Conduction of electric current from an underground or submerged metallic structure by means of a metallic conductor.

## DRIVING POTENTIAL

Difference in potential between the anode and the steel structure.

## DRYING OIL

An oil capable of conversion from a liquid to a solid by slow reaction with oxygen in the air.



## ELASTIC DEFORMATION

Changes of dimensions of a material upon the application of a stress within the elastic range. Following the release of an elastic stress, the material returns to its original dimensions without any permanent deformation.

## ELASTIC LIMIT

The maximum stress to which a material may be subjected without retention of any permanent deformation after the stress is removed.

## ELASTICITY

The property of a material that allows it to recover its original dimensions following deformation by a stress below its elastic limit.

## ELECTRICAL INTERFERENCE

Any electrical disturbance on a metallic structure in contact with an electrolyte caused by stray current(s).

## ELECTRICAL ISOLATION

The condition of being electrically separated from other metallic structures or the environment.

## ELECTRO-OSMOSIS

The migration of water through a semipermeable membrane as a result of a potential difference caused by the flow of electric charge through the membrane.

## ELECTROCHEMICAL CELL

A system consisting of an anode and a cathode immersed in an electrolyte so as to create an electrical circuit. The anode and cathode may be different metals or dissimilar areas on the same metal surface.

## ELECTROCHEMICAL EQUIVALENT

The mass of an element or group of elements oxidized or reduced at 100% efficiency by the passage of a unit quantity of electricity.

---

## ELECTROCHEMICAL POTENTIAL

The partial derivative of the total electrochemical free energy of a constituent with respect to the number of moles of this constituent where all other factors are kept constant. It is analogous to the chemical potential of a constituent except that it includes the electrical as well as chemical contributions to the free energy.

## ELECTRODE

A conductor used to establish contact with an electrolyte and through which current is transferred to or from an electrolyte.

## ELECTRODE POTENTIAL

The potential of an electrode in an electrolyte as measured against a reference electrode. (The electrode potential does not include any resistance losses in potential in either the electrolyte or the external circuit. It represents the reversible work to move a unit of charge from the electrode surface through the electrolyte to the reference electrode.)

## ELECTROKINETIC POTENTIAL

A potential difference in a solution caused by residual, unbalanced charge distribution in the adjoining solution, producing a double layer. The electrokinetic potential is different from the electrode potential in that it occurs exclusively in the solution phase. This potential represents the reversible work necessary to bring a unit charge from infinity in the solution up to the interface in question but not through the interface (also known as *zeta potential*).

## ELECTROLYTE

A chemical substance containing ions that migrate in an electric field.

## ELECTROLYTIC CLEANING

A process for removing soil, scale, or corrosion products from a metal surface by subjecting the metal as an electrode to an electric current in an electrolytic bath.

## ELECTROMOTIVE FORCE SERIES

A list of elements arranged according to their standard electrode potentials, the sign being positive for elements whose potentials are cathodic to hydrogen and negative for those anodic to hydrogen.

## ELLIPSOMETRY

An optical analytical technique employing plane-polarized light to study films.

## EMBRITTLEMENT

Loss of ductility of a material resulting from a chemical or physical change.

## EMF SERIES

[See *Electromotive Force Series.*]

## ENAMEL

(1) A paint that dries to a hard, glossy surface. (2) A coating that is characterized by an ability to form a smooth, durable film.

## END EFFECT

The more rapid loss of anode material at the end of an anode, compared with other surfaces of the anode, resulting from higher current density.

## ENDURANCE LIMIT

The maximum stress that a material can withstand for an infinitely large number of fatigue cycles.

## ENVIRONMENT

The surroundings or conditions (physical, chemical, mechanical) in which a material exists.

## ENVIRONMENTAL CRACKING

Brittle fracture of a normally ductile material in which the corrosive effect of the environment is a causative factor.

Environmental cracking is a general term that includes all of the terms listed below. The definitions of these terms are listed elsewhere in the *Glossary:*
Corrosion Fatigue
Hydrogen Embrittlement
Hydrogen-Induced Cracking ⎯ (Stepwise Cracking)
Hydrogen Stress Cracking
Liquid Metal Cracking
Stress Corrosion Cracking
Sulfide Stress Cracking

The following terms have been used in the past in connection with environmental cracking but are now obsolete and should not be used:
Caustic Embrittlement
Delayed Cracking
Liquid Metal Embrittlement
Season Cracking
Static Fatigue
Sulfide Corrosion Cracking
Sulfide Stress Corrosion Cracking

## EPOXY
Type of resin formed by the reaction of aliphatic or aromatic polyols (like bisphenol) with epichlorohydrin and characterized by the presence of reactive oxirane end groups.

## EQUILIBRIUM POTENTIAL
The potential of an electrode in an electrolyte at which the forward rate of a given reaction is exactly equal to the reverse rate; the electrode potential with reference to a standard equilibrium, as defined by the Nernst equation.

## EROSION
The progressive loss of material from a solid surface due to mechanical interaction between that surface and a fluid, a multicomponent fluid, or solid particles carried with the fluid.

## EROSION-CORROSION
A conjoint action involving corrosion and erosion in the presence of a moving corrosive fluid or a material moving through the fluid, leading to accelerated loss of material.

## EXCHANGE CURRENT
The rate at which either positive or negative charges are entering or leaving the surface when an electrode reaches dynamic equilibrium in an electrolyte.

## EXFOLIATION CORROSION
Localized subsurface corrosion in zones parallel to the surface that result in thin layers of uncorroded metal resembling the pages of a book.

## EXTERNAL CIRCUIT
The wires, connectors, measuring devices, current sources, etc., that are used to bring about or measure the desired electrical conditions within an electrochemical cell. It is this portion of the cell through which electrons travel.

## F

## FATIGUE
The phenomenon leading to fracture of a material under repeated or fluctuating stresses having a maximum value less than the tensile strength of the material.

## FATIGUE STRENGTH
The maximum stress that can be sustained for a specified number of cycles without failure.

## FAULT CURRENT
A current that flows from one conductor to ground or to another conductor due to an abnormal connection (including an arc) between the two. A fault current flowing to ground may be called a ground fault current.

## FERRITE
The body-centered cubic crystalline phase of iron-based alloys.

## FERRITIC STEEL
A steel whose microstructure at room temperature consists predominantly of ferrite.

## FILIFORM CORROSION
Corrosion that occurs under a coating in the form of randomly distributed thread-like filaments.

## FILM
A thin, not necessarily visible layer of material.

## FINISH COAT
[See *Topcoat*.]

## FORCED DRAINAGE
Drainage applied to underground or submerged metallic structures by means of an applied electromotive force or sacrificial anode.

## FOREIGN STRUCTURE
Any metallic structure that is not intended as a part of a system under cathodic protection.

## FOULING
An accumulation of deposits. This includes accumulation and growth of marine organisms on a submerged metal surface and the accumulation of deposits (usually inorganic) on heat exchanger tubing.

## FRACTOGRAPHY
Descriptive treatment of fracture, especially in metals, with specific reference to photographs of the fracture surface.

## FRACTURE MECHANICS
A quantitative analysis for evaluating structural reliability in terms of applied stress, crack length, and specimen geometry.

## FREE MACHINING
The machining characteristics of an alloy to which an ingredient has been introduced to give small broken chips, lower power consumption, better surface finish, and longer tool life.

## FRETTING CORROSION
Deterioration at the interface of

two contacting surfaces under load which is accelerated by their relative motion.

## FURAN
Type of resin formed by the polymerization or polycondensation of furfuryl, furfuryl alcohol, or other compounds containing a furan ring.

G

## GALVANIC ANODE
A metal that provides sacrificial protection to another metal that is more noble when electrically coupled in an electrolyte. This type of anode is the electron source in one type of cathodic protection.

## GALVANIC CORROSION
Accelerated corrosion of a metal because of an electrical contact with a more noble metal or nonmetallic conductor in a corrosive electrolyte.

## GALVANIC COUPLE
A pair of dissimilar conductors, commonly metals, in electrical contact in an electrolyte.

## GALVANIC CURRENT
The electric current between metals or conductive nonmetals in a galvanic couple.

## GALVANIC SERIES
A list of metals and alloys arranged according to their corrosion potentials in a given environment.

## GALVANOSTATIC
Refers to an experimental technique whereby an electrode is maintained at a constant current in an electrolyte.

## GENERAL CORROSION
Corrosion that is distributed more or less uniformly over the surface of a material.

## GRAPHITIC CORROSION
Deterioration of gray cast iron in which the metallic constituents are selectively leached or converted to corrosion products, leaving the graphite intact.

## GRAPHITIZATION
The formation of graphite in iron or steel, usually from decomposition of iron carbide at elevated temperatures. [Should not be used as a term to describe graphitic corrosion.]

## GRIT
Small particles of hard material (e.g., iron, steel, or mineral) with irregular shapes that are commonly used as an abrasive in abrasive blast cleaning.

## GRIT BLASTING
Abrasive blast cleaning using grit as the abrasive.

## GROUNDBED
One or more anodes installed below the earth's surface for the purpose of supplying cathodic protection.

H

## HALF-CELL
A pure metal in contact with a solution of known concentration of its own ion, at a specific temperature, develops a potential that is characteristic and reproducible; when coupled with another half-cell, an overall potential that is the sum of both half-cells develops.

## HALF-CELL POTENTIAL
The potential in a given electrolyte of one electrode of a pair relative to a standard state or a reference state. Potentials can only be measured and expressed as the difference between the half-cell potentials of a pair of electrodes.

## HAND TOOL CLEANING
Removal of loose rust, loose mill scale, and loose paint to degree specified, by hand chipping, scraping, sanding, and wire brushing. [See SSPC-SP 2.]

## HARDENER
[See *Curing Agent*.]

## HEAT-AFFECTED ZONE
That portion of the base metal that is not melted during brazing, cutting, or welding, but whose microstructure and properties are altered by the heat of these processes.

## HEAT TREATMENT
Heating and cooling a solid metal or alloy in such a way as to obtain desired properties. Heating for the sole purpose of hot working is not considered heat treatment.

## HIGH-PRESSURE WATER CLEANING
Water cleaning performed at pressures from 34 to 70 MPa (5,000 to 10,000 psig).

## HIGH-PRESSURE WATER JETTING

Water jetting performed at pressures from 70 to 170 MPa (10,000 to 25,000 psig).

## HIGH-TEMPERATURE HYDROGEN ATTACK

A loss of strength and ductility of steel by high-temperature reaction of absorbed hydrogen with carbides in the steel, resulting in decarburization and internal fissuring.

## HOLIDAY

A discontinuity in a protective coating that exposes unprotected surface to the environment.

## HYDROGEN BLISTERING

The formation of subsurface planar cavities, called hydrogen blisters, in a metal resulting from excessive internal hydrogen pressure. Growth of near-surface blisters in low-strength metals usually results in surface bulges.

## HYDROGEN EMBRITTLEMENT

A loss of ductility of a metal resulting from absorption of hydrogen.

## HYDROGEN-INDUCED CRACKING

Stepwise internal cracks that connect adjacent hydrogen blisters on different planes in the metal, or to the metal surface (also known as *stepwise cracking*).

## HYDROGEN OVERVOLTAGE

Overvoltage associated with the liberation of hydrogen gas.

## HYDROGEN STRESS CRACKING

Cracking that results from the presence of hydrogen in a metal in combination with tensile stress. It occurs most frequently with high-strength alloys.

# I

## IMPINGEMENT CORROSION

A form of erosion-corrosion generally associated with the local impingement of a high-velocity, flowing fluid against a solid surface.

## IMPRESSED CURRENT

An electric current supplied by a device employing a power source that is external to the electrode system. (An example is direct current for cathodic protection.)

## IMPRESSED CURRENT ANODE

An electrode, suitable for use as an anode when connected to a source of impressed current, which is generally composed of a substantially inert material that conducts by oxidation of the electrolyte and, for this reason, is not corroded appreciably.

## IMPULSE DIELECTRIC TEST

A method of applying voltage to an insulated wire through the use of electric pulses (usually 170 to 250 pulses per second) to determine the integrity of the wire's insulation.

## INCLUSION

A nonmetallic phase such as an oxide, sulfide, or silicate particle in a metal.

## INORGANIC ZINC-RICH COATING

Coating containing a metallic zinc pigment (typically 75 wt% zinc or more in the dry film) in an inorganic vehicle.

## INSTANT-OFF POTENTIAL

The polarized half-cell potential of an electrode taken immediately after the cathodic protection current is stopped, which closely approximates the potential without IR drop (i.e., the polarized potential) when the current was on.

## INTERCRYSTALLINE CORROSION

[See *Intergranular Corrosion.*]

## INTERDENDRITIC CORROSION

Corrosive attack of cast metals that progresses preferentially along paths between dendrites.

## INTERFERENCE BOND

An intentional metallic connection, between metallic systems in contact with a common electrolyte, designed to control electrical current interchange between the systems.

## INTERFERENCE CURRENT

[See *Stray Current.*]

## INTERGRANULAR CORROSION

Preferential corrosion at or along the grain boundaries of a metal (also known as *intercrystalline*

*corrosion*).

## INTERGRANULAR STRESS CORROSION CRACKING
Stress corrosion cracking in which the cracking occurs along grain boundaries.

## INTERNAL OXIDATION
The formation of isolated particles of oxidation products beneath the metal surface.

## INTUMESCENCE
The swelling or bubbling of a coating usually caused by heating. [The term is commonly used in aerospace and fire-protection applications.]

## ION
An electrically charged atom or group of atoms.

## IR DROP
The voltage across a resistance in accordance with Ohm's Law.

## IRON ROT
Deterioration of wood in contact with iron-based alloys.

## K

## KNIFE-LINE ATTACK
Intergranular corrosion of an alloy along a line adjoining or in contact with a weld after heating into the sensitization temperature range.

## L

## LAMELLAR CORROSION
[See *Exfoliation Corrosion.*]

## LANGELIER INDEX
A calculated saturation index for calcium carbonate that is useful in predicting scaling behavior of natural water.

## LINE CURRENT
The direct current flowing on a pipeline.

## LINING
A coating or layer of sheet material adhered to or in intimate contact with the interior surface of a container used to protect the container against corrosion by its contents and/or to protect the contents of the container from contamination by the container material.

## LIQUID METAL CRACKING
Cracking of a metal caused by contact with a liquid metal.

## LONG-LINE CURRENT
Current though the earth between an anodic and a cathodic area that returns along an underground metallic structure.

## LOW-CARBON STEEL
Steel having less than 0.30% carbon and no intentional alloying additions.

## LOW-PRESSURE WATER CLEANING
Water cleaning performed at pressures less than 34 MPa (5,000 psig).

## LUGGIN PROBE
A small tube or capillary filled with electrolyte, terminating close to the metal surface of an electrode under study, which is used to provide an ion-conducting path without diffusion between the electrode under study and a reference electrode.

## M

## MARTENSITE
A hard supersaturated solid solution of carbon in iron characterized by an acicular (needle-like) microstructure.

## METAL DUSTING
The catastrophic deterioration of a metal exposed to a carbonaceous gas at elevated temperature.

## METALLIZING
The coating of a surface with a thin metal layer by spraying, hot dipping, or vacuum deposition.

## MILL SCALE
The oxide layer formed during hot fabrication or heat treatment of metals.

## MIXED POTENTIAL
A potential resulting from two or more electrochemical reactions occurring simultaneously on one metal surface.

## MODULUS OF ELASTICITY

A measure of the stiffness or rigidity of a material. It is actually the ratio of stress to strain in the elastic region of a material. If determined by a tension or compression test, it is also called Young's Modulus or the coefficient of elasticity.

# N

## NATURAL DRAINAGE

Drainage from an underground or submerged metallic structure to a more negative (more anodic) structure, such as the negative bus of a trolley substation.

## NEAR-WHITE BLAST CLEANED SURFACE

A near-white blast cleaned surface, when viewed without magnification, shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products, and other foreign matter. Random staining shall be limited to not more than 5% of each unit area of surface (approximately 58 cm$^2$ [9.0 in.$^2$]), and may consist of light shadows, slight streaks, or minor discolorations caused by stains of rust, stains of mill scale, or stains of previously applied coating. [See NACE No. 2/SSPC-SP 10.]

## NEGATIVE RETURN

A point of connection between the cathodic protection negative cable and the protected structure.

## NERNST EQUATION

An equation that expresses the exact electromotive force of an electrochemical cell in terms of the activities of products and reactants of the cell.

## NERNST LAYER

The diffusion layer at the surface of an electrode in which the concentration of a chemical species is assumed to vary linearly from the value in the bulk solution to the value at the electrode surface.

## NOBLE

The positive direction of electrode potential, thus resembling noble metals such as gold and platinum.

## NOBLE METAL

(1) A metal that occurs commonly in nature in the free state. (2) A metal or alloy whose corrosion products are formed with a small negative or a positive free-energy change.

## NOBLE POTENTIAL

A potential more cathodic (positive) than the standard hydrogen potential.

## NORMALIZING

Heating a ferrous alloy to a suitable temperature above the transformation range (austenitizing), holding at temperature for a suitable time, and then cooling in still air to a temperature substantially below the transformation range.

# O

## OPEN-CIRCUIT POTENTIAL

The potential of an electrode measured with respect to a reference electrode or another electrode in the absence of current.

## ORGANIC ZINC-RICH COATING

Coating containing a metallic zinc pigment (typically 75 wt% zinc or more in the dry film) in an organic resin.

## OVERVOLTAGE

The change in potential of an electrode from its equilibrium or steady-state value when current is applied.

## OXIDATION

(1) Loss of electrons by a constituent of a chemical reaction. (2) Corrosion of a metal that is exposed to an oxidizing gas at elevated temperatures.

## OXIDATION-REDUCTION POTENTIAL

The potential of a reversible oxidation-reduction electrode measured with respect to a reference electrode, corrected to the hydrogen electrode, in a given electrolyte.

## OXYGEN CONCENTRATION CELL

[See *Differential Aeration Cell.*]

# P

## PAINT

A pigmented liquid or resin applied to a substrate as a thin layer that is converted to an opaque solid film after application. It is commonly used

as a decorative or protective coating.

## PAINT SYSTEM
[See *Coating System.*]

## PARTING
[See *Dealloying.*]

## PASSIVATION
A reduction of the anodic reaction rate of an electrode involved in corrosion.

## PASSIVATION POTENTIAL
[See *Primary Passive Potential.*]

## PASSIVE
(1) The positive direction of electrode potential. (2) A state of a metal in which a surface reaction product causes a marked decrease in the corrosion rate relative to that in the absence of the product.

## PASSIVE-ACTIVE CELL
An electrochemical cell, the electromotive force of which is caused by the potential difference between a metal in an active state and the same metal in a passive state.

## PASSIVITY
The state of being passive.

## PATINA
A thin layer of corrosion product, usually green, that forms on the surface of metals such as copper and copper-based alloys exposed to the atmosphere.

## pH
The negative logarithm of the hydrogen ion activity written as:

$$pH = -log_{10} (a_H^+)$$

where $a_H^+$ = hydrogen ion activity = the molar concentration of hydrogen ions multiplied by the mean ion-activity coefficient.

## PICKLING
(1) Treating a metal in a chemical bath to remove scale and oxides (e.g., rust) from the surface. (2) Complete removal of rust and mill scale by acid pickling, duplex pickling, or electrolytic pickling. [See SSPC-SP 8.]

## PICKLING SOLUTION
A chemical bath, usually an acid solution, used for pickling.

## PIGMENT
A solid substance, generally in fine powder form, that is insoluble in the vehicle of a formulated coating material. It is used to impart color or other specific physical or chemical properties to the coating.

## PIPE-TO-ELECTROLYTE POTENTIAL
[See *Structure-to-Electrolyte Potential.*]

## PIPE-TO-SOIL POTENTIAL
[See *Structure-to-Electrolyte Potential.*]

## PITTING
Localized corrosion of a metal surface that is confined to a small area and takes the form of cavities called pits.

## PITTING FACTOR
The ratio of the depth of the deepest pit resulting from corrosion divided by the average penetration as calculated from mass loss.

## PLASTIC DEFORMATION
Permanent deformation caused by stressing beyond the elastic limit.

## PLASTICITY
The ability of a material to deform permanently (nonelastically) without fracturing.

## POLARIZATION
The change from the open-circuit potential as a result of current across the electrode/electrolyte interface.

## POLARIZATION ADMITTANCE
The reciprocal of polarization resistance.

## POLARIZATION CELL
A DC decoupling device consisting of two or more pairs of inert metallic plates immersed in an aqueous electrolyte. The electrical characteristics of the polarization cell are high resistance to DC potentials and low impedance of AC.

## POLARIZATION CURVE
A plot of current density versus electrode potential for a specific electrode/electrolyte combination.

## POLARIZATION DECAY
The decrease in electrode potential with time resulting from the interruption of applied current.

## POLARIZATION RESISTANCE
The slope (dE/di) at the corrosion potential of a potential (E)-current density (i) curve. (The measured slope is usually in good agreement with the true value of

the polarization resistance when the scan rate is low and any uncompensated resistance is small relative to the polarization resistance.)

## POLARIZED POTENTIAL

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

## POLYESTER

Type of resin formed by the condensation of polybasic and monobasic acids with polyhydric alcohols.

## POSTWELD HEAT TREATMENT

Heating and cooling a weldment in such a way as to obtain desired properties.

## POTENTIAL-pH DIAGRAM

A graphical method of representing the regions of thermodynamic stability of species for metal/electrolyte systems (also known as *Pourbaix diagram*).

## POTENTIODYNAMIC

Refers to a technique wherein the potential of an electrode with respect to a reference electrode is varied at a selected rate by application of a current through the electrolyte.

## POTENTIOKINETIC

[See *Potentiodynamic.*]

## POTENTIOSTAT

An instrument for automatically maintaining a constant electrode potential.

## POTENTIOSTATIC

Refers to a technique for maintaining a constant electrode potential.

## POT LIFE

The elapsed time within which a coating can be effectively applied after all components of the coating have been thoroughly mixed.

## POULTICE CORROSION

[See *Deposit Attack.*]

## POURBAIX DIAGRAM

[See *Potential-pH Diagram.*]

## POWER TOOL CLEANING

Removal of loose rust, loose mill scale, and loose paint to degree specified by power tool chipping, descaling, sanding, wire brushing, and grinding.  [See SSPC-SP 3.]

## PRECIPITATION HARDENING

Hardening caused by the precipitation of a constituent from a supersaturated solid solution.

## PRIMARY PASSIVE POTENTIAL

The potential corresponding to the maximum active current density (critical anodic current density) of an electrode that exhibits active-passive corrosion behavior.

## PRIME COAT

[See *Primer.*]

## PRIMER

A coating material intended to be applied as the first coat on an uncoated surface.  The coating is specifically formulated to adhere to and protect the surface as well as to produce a suitable surface

for subsequent coats.  [Also referred to *as Prime Coat.*]

## PROFILE

Anchor pattern on a surface produced by abrasive blasting or acid treatment.

## PROTECTIVE COATING

A coating applied to a surface to protect the substrate from corrosion.

R

## REDUCTION

Gain of electrons by a constituent of a chemical reaction.

## REFERENCE ELECTRODE

An electrode whose open-circuit potential is constant under similar conditions of measurement, which is used for measuring the relative potentials of other electrodes.

## REFERENCE HALF-CELL

[See *Reference Electrode.*]

## RELATIVE HUMIDITY

The ratio, expressed as a percentage, of the amount of water vapor present in a given volume of air at a given temperature to the amount required to saturate the air at that temperature.

## REMOTE EARTH

A location on the earth far enough from the affected structure that the soil potential gradients associated with currents entering the earth from the affected structure are

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# NACE GLOSSARY OF CORROSION-RELATED TERMS

insignificant.

## RESISTIVITY
(1) The resistance per unit length of a substance with uniform cross section. (2) A measure of the ability of an electrolyte (e.g., soil) to resist the flow of electric charge (e.g., cathodic protection current). Resistivity data are used to design a groundbed for a cathodic protection system.

## REST POTENTIAL
[See *Corrosion Potential*.]

## REVERSIBLE POTENTIAL
[See *Equilibrium Potential*.]

## RIMMED STEEL
An incompletely deoxidized steel. [Also called *Rimming Steel*.]

## RISER
(1) That section of pipeline extending from the ocean floor up to an offshore platform. (2) The vertical tube in a steam generator convection bank that circulates water and steam upward.

## RUST
Corrosion product consisting of various iron oxides and hydrated iron oxides. (This term properly applies only to iron and ferrous alloys.)

## RUST BLOOM
Discoloration indicating the beginning of rusting.

S

## SACKING
Scrubbing a mixture of a cement mortar over the concrete surface using a cement sack, gunny sack, or sponge rubber float.

## SACRIFICIAL ANODE
[See *Galvanic Anode*.]

## SACRIFICIAL PROTECTION
Reduction of corrosion of a metal in an electrolyte by galvanically coupling it to a more anodic metal (a form of cathodic protection).

## SCALING
(1) The formation at high temperatures of thick corrosion-product layers on a metal surface. (2) The deposition of water-insoluble constituents on a metal surface.

## SCANNING ELECTRON MICROSCOPE
An electron optical device that images topographical details with maximum contrast and depth of field by the detection, amplification, and display of secondary electrons.

## SENSITIZING HEAT TREATMENT
A heat treatment, whether accidental, intentional, or incidental (as during welding), that causes precipitation of constituents (usually carbides) at grain boundaries, often causing the alloy to become susceptible to intergranular corrosion or intergranular stress corrosion cracking.

## SHALLOW GROUNDBED
One or more anodes installed either vertically or horizontally at a nominal depth of less than 15 m (50 ft) for the purpose of supplying cathodic protection.

## SHIELDING
(1) Protecting; protective cover against mechanical damage. (2) Preventing or diverting cathodic protection current from its natural path.

## SHOP COAT
One or more coats applied in a shop or plant prior to shipment to the site of erection or fabrication.

## SHOT BLASTING
Abrasive blast cleaning using metallic (usually steel) shot as the abrasive.

## SHOT PEENING
Inducing compressive stresses in the surface layer of a material by bombarding it with a selected medium (usually steel shot) under controlled conditions.

## SIGMA PHASE
An extremely brittle Fe-Cr phase that can form at elevated temperatures in Fe-Cr-Ni and Ni-Cr-Fe alloys.

## SLIP
A deformation process involving shear motion of a specific set of crystallographic planes.

## SLOW STRAIN RATE TECHNIQUE
An experimental technique for evaluating susceptibility to environmental cracking. It involves pulling the specimen to failure in uniaxial tension at a controlled slow strain rate while the specimen is in the test environment and examining the specimen for evidence of environmental cracking.

## SLUSHING COMPOUND
Oil or grease coatings used to

provide temporary protection against atmospheric corrosion.

## SOLUTION HEAT TREATMENT

Heating a metal to a suitable temperature and holding at that temperature long enough for one or more constituents to enter into solid solution, then cooling rapidly enough to retain the constituents in solution.

## SOLVENT CLEANING

Removal of oil, grease, dirt, soil, salts, and contaminants by cleaning with solvent, vapor, alkali, emulsion, or steam. [See SSPC-SP 1.]

## SPALLING

The spontaneous chipping, fragmentation, or separation of a surface or surface coating.

## STANDARD ELECTRODE POTENTIAL

The reversible potential for an electrode process when all products and reactions are at unit activity on a scale in which the potential for the standard hydrogen reference electrode is zero.

## STANDARD JETTING WATER

Water of sufficient purity and quality that it does not impose additional contaminants on the surface being cleaned and does not contain sediments or other impurities that are destructive to the proper functioning of water jetting equipment.

## STEEL SHOT

Small particles of steel with spherical shape that are commonly used as an abrasive in abrasive blast cleaning or as a selected medium for shot peening.

## STEP POTENTIAL

The potential difference between two points on the earth's surface separated by a distance of one human step, which is defined as one meter, determined in the direction of maximum potential gradient.

## STEPWISE CRACKING

[See *Hydrogen-Induced Cracking.*]

## STRAY CURRENT

Current through paths other than the intended circuit.

## STRAY-CURRENT CORROSION

Corrosion resulting from current through paths other than the intended circuit, e.g., by any extraneous current in the earth.

## STRESS CORROSION CRACKING

Cracking of a material produced by the combined action of corrosion and tensile stress (residual or applied).

## STRESS RELIEVING (THERMAL)

Heating a metal to a suitable temperature, holding at that temperature long enough to reduce residual stresses, and then cooling slowly enough to minimize the development of new residual stresses.

## STRUCTURE-TO-ELECTROLYTE POTENTIAL

The potential difference between the surface of a buried or submerged metallic structure and the electrolyte that is measured with reference to an electrode in contact with the electrolyte.

## STRUCTURE-TO-SOIL POTENTIAL

[See *Structure-to-Electrolyte Potential.*]

## STRUCTURE-TO-STRUCTURE POTENTIAL

The potential difference between metallic structures, or sections of the same structure, in a common electrolyte.

## SUBSURFACE CORROSION

[See *Internal Oxidation.*]

## SULFIDATION

The reaction of a metal or alloy with a sulfur-containing species to produce a sulfur compound that forms on or beneath the surface of the metal or alloy.

## SULFIDE STRESS CRACKING

Cracking of a metal under the combined action of tensile stress and corrosion in the presence of water and hydrogen sulfide (a form of hydrogen stress cracking).

## SURFACE POTENTIAL GRADIENT

Change in the potential on the surface of the ground with respect to distance.

T

## TACK COAT

A thin wet coat applied to the surface that is allowed to dry just until it is tacky before application of a thicker wet coat. (Use of a tack coat allows application of thicker coats without sagging or runs.)

## TAFEL PLOT

A plot of the relationship between the change in potential (E) and the logarithm of the current density (log *i*) of an electrode when it is polarized in both the anodic and cathodic directions from its open-circuit potential.

## TAFEL SLOPE

The slope of the straight-line portion of the E log *i* curve on a Tafel plot. (The straight-line portion usually occurs at more than 50 mV from the open-circuit potential.)

## TARNISH

Surface discoloration of a metal resulting from formation of a film of corrosion product.

## THERMAL SPRAYING

A group of processes by which finely divided metallic or nonmetallic materials are deposited in a molten or semimolten condition to form a coating.

## THERMOGALVANIC CORROSION

Corrosion resulting from an electrochemical cell caused by a thermal gradient.

## THROWING POWER

The relationship between the current density at a point on a surface and its distance from the counterelectrode. The greater the ratio of the surface resistivity shown by the electrode reaction to the volume resistivity of the electrolyte, the better is the throwing power of the process.

## TOPCOAT

The final coat of a coating system. [Also referred to as *Finish Coat*.]

## TOUCH POTENTIAL

The potential difference between a metallic structure and a point on the earth's surface separated by a distance equal to the normal maximum horizontal reach of a human (approximately 1.0 m [3.3 ft]).

## TRANSPASSIVE

The noble region of potential where an electrode exhibits a higher-than-passive current density.

## TUBERCULATION

The formation of localized corrosion products scattered over the surface in the form of knob-like mounds called tubercles.

U-V-W

## ULTIMATE STRENGTH

The maximum stress that a material can sustain.

## ULTRAHIGH-PRESSURE WATER JETTING

Water jetting performed at pressures above 170 MPa (25,000 psig.)

## UNDERFILM CORROSION

[See *Filiform Corrosion*.]

## VEHICLE

The liquid portion of a formulated coating material.

## VOID

(1) A holiday, hole, or skip in a coating. (2) A hole in a casting or weld deposit usually resulting from shrinkage during cooling.

## WASH PRIMER

A thin, inhibiting primer, usually chromate pigmented, with a polyvinyl butyral binder.

## WATER CLEANING

Use of pressurized water discharged from a nozzle to remove unwanted matter (e.g., dirt, scale, rust, coatings) from a surface.

## WATER JETTING

Use of standard jetting water discharged from a nozzle at pressures of 70 MPa (10,000 psig) or greater to prepare a surface for coating or inspection.

## WEIGHT COATING

An external coating applied to a pipeline to counteract buoyancy.

## WHITE METAL BLAST CLEANED SURFACE

A white metal blast cleaned surface, when viewed without magnification, shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products, and other foreign matter. [See NACE No. 1/SSPC-SP 5.]

## WELD DECAY

Intergranular corrosion, usually of

stainless steel or certain nickel-base alloys, that occurs as the result of sensitization in the heat-affected zone during the welding operation. [This is not a preferred term.]

## WET FILM GAUGE
Device for measuring wet film thickness of a coating.

## WORKING ELECTRODE
The test or specimen electrode in an electrochemical cell.

## WROUGHT
Metal in the solid condition that is formed to a desired shape by working (rolling, extruding, forging, etc.), usually at an elevated temperature.

## X-Y-Z

## YIELD POINT
The stress on a material at which the first significant permanent or plastic deformation occurs without an increase in stress.  In some materials, particularly annealed low-carbon steels, there is a well-defined yield point from the straight line defining the modulus of elasticity.

## YIELD STRENGTH
The stress at which a material exhibits a specified deviation from the proportionality of stress to strain.  The deviation is expressed in terms of strain by either the offset method (usually at a strain of 0.2%) or the total-extension-under-load method (usually at a strain of 0.5%.)

# Standard Practice

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

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### Foreword

This standard practice presents procedures and practices for achieving effective control of external corrosion on buried or submerged metallic piping systems. These recommendations are also applicable to many other buried or submerged metallic structures. It is intended for use by corrosion control personnel concerned with the corrosion of buried or submerged piping systems, including oil, gas, water, and similar structures. This standard describes the use of electrically insulating coatings, electrical isolation, and cathodic protection (CP) as external corrosion control methods. It contains specific provisions for the application of CP to existing bare, existing coated, and new piping systems. Also included are procedures for control of interference currents on pipelines.

This standard should be used in conjunction with the practices described in the following NACE standards and publications, when appropriate (use latest revisions):

> SP0572[1]  RP0177[2]  RP0285[3]  SP0186[4]  SP0286[5]  SP0387[6]  SP0188[7]
> TPC 11[8]  TM0497[9]

For accurate and correct application of this standard, the standard must be used in its entirety. Using or citing only specific paragraphs or sections can lead to misinterpretation and misapplication of the recommendations and practices contained in this standard.

This standard does not designate practices for every specific situation because of the complexity of conditions to which buried or submerged piping systems are exposed.

This standard was originally published in 1969, and was revised by NACE Task Group (TG) T-10-1 in 1972, 1976, 1983, and 1992. It was reaffirmed in 1996 by NACE Unit Committee T-10A on Cathodic Protection, and in 2002 and 2007 by Specific Technology Group (STG) 35 on Pipelines, Tanks, and Well Casings. This standard is issued by NACE International under the auspices of STG 35, which is composed of corrosion control personnel from oil and gas transmission companies, gas distribution companies, power companies, corrosion consultants, and others concerned with external corrosion control of buried or submerged metallic piping systems.

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In NACE standards, the terms *shall*, *must*, *should*, and may are used in accordance with the definitions of these terms in the NACE Publications Style Manual, 4th ed., Paragraph 7.4.1.9. *Shall* and *must* are used to state mandatory requirements. The term should is used to state something considered good and is recommended but is not mandatory. The term may is used to state something considered optional.

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# NACE International
# Standard Practice

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

**Contents**

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**Section 1: General**

1.1 This standard presents acknowledged practices for the control of external corrosion on buried or submerged steel, cast iron, ductile iron, copper, and aluminum piping systems.

1.2 This standard is intended to serve as a guide for establishing minimum requirements for control of external corrosion on the following systems:

    1.2.1 New piping systems: Corrosion control by a coating supplemented with CP, or by some other proven method, should be provided in the initial design and maintained during the service life of the piping system, unless investigations indicate that corrosion control is not required. Consideration should be given to the construction of pipelines in a manner that facilitates the use of in-line inspection tools.

    1.2.2 Existing coated piping systems: CP should be provided and maintained, unless investigations indicate that CP is not required.

    1.2.3 Existing bare piping systems: Studies should be made to determine the extent and rate of corrosion on existing bare piping systems. When these studies indicate that corrosion will affect the safe or economic operation of the system, adequate corrosion control measures shall be taken.

1.3 The provisions of this standard should be applied under the direction of competent persons who, by reason of knowledge of the physical sciences and the principles of engineering and mathematics, acquired by education and related practical experience, are qualified to engage in the practice of corrosion control on buried or submerged metallic piping systems. Such persons may be registered professional engineers or persons recognized as corrosion specialists or CP specialists by NACE if their professional activities include suitable experience in external corrosion control of buried or submerged metallic piping systems.

1.4 Special conditions in which CP is ineffective or only partially effective sometimes exist. Such conditions may include elevated temperatures, disbonded coatings, thermal insulating coatings, shielding, bacterial attack, and unusual contaminants in the electrolyte. Deviation from this standard may be warranted in specific situations provided that corrosion control personnel in responsible charge are able to demonstrate that the objectives expressed in this standard have been achieved.

1.5 This standard does not include corrosion control methods based on chemical control of the environment, on the use of electrically conductive coatings, or on control of internal corrosion.

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**Section 2: Definitions [1]**

**Amphoteric Metal:** A metal that is susceptible to corrosion in both acid and alkaline environments.

**Anode:** The electrode of an electrochemical cell at which oxidation occurs. Electrons flow away from the anode in the external circuit. Corrosion usually occurs and metal ions enter solution at the anode.

**Anodic Polarization:** The change of the electrode potential in the noble (positive) direction caused by current across the electrode/electrolyte interface. (See *Polarization.*)

**Backfill:** Material placed in a hole to fill the space around the anodes, vent pipe, and buried components of a cathodic protection system.

**Beta Curve:** A plot of dynamic (fluctuating) interference current or related proportional voltage (ordinate) versus the corresponding structure-to-electrolyte potentials at a selected location on the affected structure (abscissa) (see Appendix A [nonmandatory]).

**Cable:** One conductor or multiple conductors insulated from one another.

**Cathode:** The electrode of an electrochemical cell at which reduction is the principal reaction. Electrons flow toward the cathode in the external circuit.

**Cathodic Disbondment:** The destruction of adhesion between a coating and the coated surface caused by products of a cathodic reaction.

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[1] Definitions in this section reflect common usage among practicing corrosion control personnel and apply specifically to how the terms are used in this standard. In many cases, in the interests of brevity and practical usefulness, the scientific definitions are abbreviated or paraphrased.

**Cathodic Polarization:** The change of electrode potential in the active (negative) direction caused by current across the electrode/electrolyte interface. See *Polarization*.

**Cathodic Protection:** A technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

**Coating:** A liquid, liquefiable, or mastic composition that, after application to a surface, is converted into a solid protective, decorative, or functional adherent film.

**Coating Disbondment:** The loss of adhesion between a coating and the pipe surface.

**Conductor:** A material suitable for carrying an electric current. It may be bare or insulated.

**Continuity Bond:** A connection, usually metallic, that provides electrical continuity between structures that can conduct electricity.

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

**Corrosion Potential ($E_{corr}$):** The potential of a corroding surface in an electrolyte relative to a reference electrode under open-circuit conditions (also known as *rest potential*, *open-circuit potential*, or *freely corroding potential*).

**Corrosion Rate:** The rate at which corrosion proceeds.

**Criterion:** Standard for assessment of the effectiveness of a cathodic protection system.

**Current Density:** The current to or from a unit area of an electrode surface.

**Diode:** A bipolar semiconducting device having a low resistance in one direction and a high resistance in the other.

**Distributed-Anode Impressed Current System:** An impressed current anode configuration in which the anodes are "distributed" along the structure at relatively close intervals such that the structure is within each anode's voltage gradient. This anode configuration causes the electrolyte around the structure to become positive with respect to remote earth.

**Electrical Isolation:** The condition of being electrically separated from other metallic structures or the environment.

**Electrical Survey**: Any technique that involves coordinated electrical measurements taken to provide a basis for deduction concerning a particular electrochemical condition relating to corrosion or corrosion control.

**Electrode:** A conductor used to establish contact with an electrolyte and through which current is transferred to or from an electrolyte.

**Electroosmotic Effect:** Passage of a charged particle through a membrane under the influence of a voltage. Soil or coatings may act as the membrane.

**Electrolyte:** A chemical substance containing ions that migrate in an electric field. For the purpose of this standard, electrolyte refers to the soil or liquid adjacent to and in contact with a buried or submerged metallic piping system, including the moisture and other chemicals contained therein.

**Foreign Structure:** Any metallic structure that is not intended as a part of a system under cathodic protection.

**Galvanic Anode:** A metal that provides sacrificial protection to another metal that is more noble when electrically coupled in an electrolyte. This type of anode is the electron source in one type of cathodic protection.

**Galvanic Series:** A list of metals and alloys arranged according to their corrosion potentials in a given environment.

**Groundbed:** One or more anodes installed below the earth's surface for the purpose of supplying cathodic protection.

**Holiday:** A discontinuity in a protective coating that exposes unprotected surface to the environment.

**Impressed Current**: An electric current supplied by a device employing a power source that is external to the electrode system. (An example is direct current for cathodic protection.)

**In-Line Inspection:** The inspection of a steel pipeline using an electronic instrument or tool that travels along the interior of the pipeline.

**Insulating Coating System:** All components of the protective coating, the sum of which provides effective electrical isolation of the coated structure.

**Interference:** Any electrical disturbance on a metallic structure as a result of stray current.

**Interference Bond:** An intentional metallic connection, between metallic systems in contact with a common electrolyte, designed to control electrical current interchange between the systems.

**IR Drop:** The voltage across a resistance in accordance with Ohm's Law.

**Isolation:** See *Electrical Isolation*.

**Line Current:** The direct current flowing on a pipeline.

**Long-Line Current:** Current through the earth between an anodic and a cathodic area that returns along an underground metallic structure.

**Mixed Potential:** A potential resulting from two or more electrochemical reactions occurring simultaneously on one metal surface.

**Pipe-to-Electrolyte Potential:** See Structure-to-Electrolyte Potential.

**Polarization:** The change from the open-circuit potential as a result of current across the electrode/electrolyte interface.

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

**Reference Electrode:** An electrode whose open-circuit potential is constant under similar conditions of measurement, which is used for measuring the relative potentials of other electrodes.

**Reverse-Current Switch:** A device that prevents the reversal of direct current through a metallic conductor.

**Shielding:** (1) Protecting; protective cover against mechanical damage. (2) Preventing or diverting the cathodic protection current from its intended path.

**Shorted Pipeline Casing:** A casing that is in direct metallic contact with the carrier pipe.

**Sound Engineering Practices:** Reasoning exhibited or based on thorough knowledge and experience, logically valid and having technically correct premises that demonstrate good judgment or sense in the application of science.

**Stray Current:** Current through paths other than the intended circuit.

**Stray-Current Corrosion:** Corrosion resulting from current through paths other than the intended circuit, e.g., by any extraneous current in the earth.

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

**Telluric Current:** Current in the earth as a result of geomagnetic fluctuations.

**Voltage:** An electromotive force or a difference in electrode potentials expressed in volts.

**Wire:** A slender rod or filament of drawn metal. In practice, the term is also used for smaller-gauge conductors (6 mm$^2$ [No. 10 AWG[2]] or smaller).

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## Section 3: Determination of Need for External Corrosion Control

3.1 Introduction

3.1.1 This section recommends practices for determining when an underground or submerged metallic piping system requires external corrosion control.

3.1.2 Metallic structures, buried or submerged, are subject to corrosion. Adequate corrosion control procedures should be adopted to ensure metal integrity for safe and economical operation.

3.2 The need for external corrosion control should be based on data obtained from one or more of the following: corrosion surveys, operating records, visual observations, test results from similar systems in similar environments, in-line inspections, engineering and design specifications, and

operating, safety, and economic requirements. The absence of leaks alone is insufficient evidence that corrosion control is not required.

3.2.1 Environmental and physical factors include the following:

3.2.1.1 Corrosion rate of the particular metallic piping system in a specific environment (see Appendix B [nonmandatory]);

3.2.1.2 Nature of the product being transported, the working temperature, temperature differentials within the pipeline causing thermal expansion and contraction, tendency of backfill to produce soil stress, and working pressure of the piping system as related to design specification;

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[2] American Wire Gauge.

3.2.1.3 Location of the piping system as related to population density and frequency of visits by personnel;

3.2.1.4 Location of the piping system as related to other facilities; and

3.2.1.5 Stray current sources foreign to the system.

3.2.2 Economic factors include the following:

3.2.2.1 Costs of maintaining the piping system in service for its expected life (see Appendix B [nonmandatory])

3.2.2.2 Contingent costs of corrosion (see Appendix C [nonmandatory]); and

3.2.2.3 Costs of corrosion control (see Appendix D [nonmandatory]).

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## Section 4: Piping System Design

4.1 Introduction

4.1.1 This section provides accepted corrosion control practices in the design of an underground or submerged piping system. A person qualified to engage in the practice of corrosion control should be consulted during all phases of pipeline design and construction (see Paragraph 1.3). These recommendations should not be construed as taking precedence over recognized electrical safety practices.

4.2 External Corrosion Control

4.2.1 External corrosion control must be a primary consideration during the design of a piping system. Materials selection and coatings are the first line of defense against external corrosion. Because perfect coatings are not feasible, CP must be used in conjunction with coatings. For additional information, see Sections 5 and 6.

4.2.2 New piping systems should be externally coated unless thorough investigation indicates that coatings are not required (see Section 5).

4.2.3 Materials and construction practices that create electrical shielding should not be used on the pipeline. Pipelines should be installed at locations where proximity to other structures and subsurface formations do not cause shielding.

4.3 Electrical Isolation

4.3.1 Isolation devices such as flange assemblies, prefabricated joint unions, or couplings should be installed within piping systems in which electrical isolation of portions of the system is required to facilitate the application of external corrosion control. These devices should be properly selected for temperature, pressure, chemical resistance, dielectric resistance, and mechanical strength. Installation of isolation devices should be avoided or safeguarded in areas in which combustible atmospheres are likely to be present. Locations at which electrical isolating devices should be considered include, but are not limited to, the following:

4.3.1.1 Points at which facilities change ownership, such as meter stations and well heads;

4.3.1.2 Connections to mainline piping systems, such as gathering or distribution system laterals;

4.3.1.3 Inlet and outlet piping of in-line measuring and pressure regulating stations;

4.3.1.4 Compressor or pumping stations, either in the suction and discharge piping or in the main line immediately upstream and downstream from the station;

4.3.1.5 Stray current areas;

4.3.1.6 The junction of dissimilar metals;

4.3.1.7 The termination of service line connections and entrance piping;

4.3.1.8 The junction of a coated pipe and a bare pipe; and

4.3.1.9 Locations at which electrical grounding is used, such as motorized valves and instrumentation.

4.3.2 The need for lightning and fault current protection at isolating devices should be considered. Cable connections from isolating devices to arresters should be short, direct, and of a size suitable for short-term high-current loading.

4.3.3 When metallic casings are required as part of the underground piping system, the pipeline should be electrically isolated from such casings. Casing insulators must be properly sized and spaced and be tightened securely on the pipeline to withstand insertion stresses without sliding on the pipe. Inspection should be made to verify that the leading insulator has remained in position. Concrete coatings on the carrier pipe could preclude the use of casing insulators. Consideration should be given to the use of support under the pipeline at each end of the casing to minimize settlement. The type of support selected

should not cause damage to the pipe coating or act as a shield to CP current.

4.3.4 Casing seals should be installed to resist the entry of foreign matter into the casing.

4.3.5 When electrical contact would adversely affect CP, piping systems should be electrically isolated from supporting pipe stanchions, bridge structures, tunnel enclosures, pilings, offshore structures, or reinforcing steel in concrete. However, piping can be attached directly to a bridge without isolation if isolating devices are installed in the pipe system on each side of the bridge to isolate the bridge piping electrically from adjacent underground piping.

4.3.6 When an isolating joint is required, a device manufactured to perform this function should be used, or, if permissible, a section of nonconductive pipe, such as plastic pipe, may be installed. In either case, these should be properly rated and installed in accordance with the manufacturer's instructions.

4.3.7 River weights, pipeline anchors, and metallic reinforcement in weight coatings should be electrically isolated from the carrier pipe and designed and installed so that coating damage does not occur and the carrier pipe is not electrically shielded.

4.3.8 Metallic curb boxes and valve enclosures should be designed, fabricated, and installed in such a manner that electrical isolation from the piping system is maintained.

4.3.9 Insulating spacing materials should be used when it is intended to maintain electrical isolation between a metallic wall sleeve and the pipe.

4.3.10 Underground piping systems should be installed so that they are physically separated from all foreign underground metallic structures at crossings and parallel installations and in such a way that electrical isolation could be maintained if desired.

4.3.11 Based on voltage rating of alternating current (AC) transmission lines, adequate separation should be maintained between pipelines and electric transmission tower footings, ground cables, and counterpoise. Regardless of separation, consideration should always be given to lightning and fault current protection of pipeline(s) and personnel safety (see NACE Standard RP0177[2]).

4.4 Electrical Continuity

4.4.1 Nonwelded pipe joints may not be electrically continuous. Electrical continuity can be ensured by the use of fittings manufactured for this purpose or by bonding across and to the mechanical joints in an effective manner.

4.5 Corrosion Control Test Stations

4.5.1 Test stations for potential, current, or resistance measurements should be provided at sufficient locations to facilitate CP testing. Such locations may include, but are not limited to, the following:

4.5.1.1 Pipe casing installations,

4.5.1.2 Metallic structure crossings,

4.5.1.3 Isolating joints,

4.5.1.4 Waterway crossings,

4.5.1.5 Bridge crossings,

4.5.1.6 Valve stations,

4.5.1.7 Galvanic anode installations,

4.5.1.8 Road crossings,

4.5.1.9 Stray-current areas, and

4.5.1.10 Rectifier installations.

4.5.2 The span of pipe used for line current test stations should exclude:

4.5.2.1 Foreign metallic structure crossings;

4.5.2.2 Lateral connections;

4.5.2.3 Mechanical couplings or connections such as screwed joints, transition pieces, valves, flanges, anode or rectifier attachments, or metallic bonds; and

4.5.2.4 Changes in pipe wall thickness and diameter.

4.5.3 Attachment of Copper Test Lead Wires to Steel and Other Ferrous Pipes

4.5.3.1 Test lead wires may be used both for periodic testing and for current-carrying purposes. As such, the wire/pipe attachment should be mechanically strong and electrically conductive.

4.5.3.2 Methods of attaching wires to the pipe include (a) thermit welding process, (b) soldering, and (c) mechanical means.

4.5.3.3 Particular attention must be given to the attachment method to avoid (a) damaging or penetrating the pipe, (b) sensitizing or altering of pipe properties, (c) weakening the test lead wire, (d) damaging internal or external pipe coatings, and (e) creating hazardous conditions in explosive environments.

4.5.3.4 Attachment by mechanical means is the least desirable method. Such a connection may

loosen, become highly resistant, or lose electrical continuity.

4.5.3.5 The connection should be tested for mechanical strength and electrical continuity. All exposed portions of the connection should be thoroughly cleaned of all welding slag, dirt, oils, etc.; primed, if needed; and coated with materials compatible with the cable insulation, pipe coating, and environment.

4.5.4 Attachment of Aluminum Test Lead Wire to Aluminum Pipes

4.5.4.1 Aluminum test lead wire, or aluminum tabs attached to aluminum wire, may be welded to aluminum pipe using the tungsten inert-gas shielded arc (TIG) or metal inert-gas shielded arc (MIG) process. Welded attachments should be made to flanges or at butt weld joints. Attachment at other sites may adversely affect the mechanical properties of the pipe because of the heat of welding.

4.5.4.2 Test lead wire may be attached to aluminum pipe by soldering. If low-melting-point soft solders are used, a flux is required. Flux residues may cause corrosion unless removed.

NOTE: The use of copper test lead wire may cause preferential galvanic attack on the aluminum pipe. When copper wire or flux is used, care must be taken to seal the attachment areas against moisture. In the presence of moisture, the connection may disbond and be damaged by corrosion.

4.5.4.3 Aluminum tabs to which test lead wires have been TIG welded can be attached by an

explosive bonding technique called high-energy joining.

4.5.4.4 Mechanical connections that remain secure and electrically conductive may be used.

4.5.5 Attachment of Copper Test Lead Wire to Copper Pipe.

4.5.5.1 Copper test lead wire, or copper tabs attached to copper wire, may be attached to copper pipe by one of the following methods. The relative thickness of the wire and the pipe wall dictates, in part, which of the methods can be used.

4.5.5.1.1 Arc welding (TIG, MIG, or shielded metal);

4.5.5.1.2 Electrical resistance (spot) welding;

4.5.5.1.3 Brazing;

4.5.5.1.4 Soldering; or

4.5.5.1.5 Mechanical connection.

4.5.5.2 Attention should be given to proper joining procedures to avoid possible embrittlement or loss of mechanical properties of the metals from the heat of welding or brazing.

4.5.5.3 A flux may be required, or self-produced, when brazing with some filler metals or soldering with some low-melting-point soft solders. Because flux residues may cause corrosion, they should be removed.

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## Section 5: External Coatings

5.1 Introduction

5.1.1 This section recommends practices for selecting, testing and evaluating, handling, storing, inspecting, and installing external coating systems for external corrosion control on piping systems.

The function of external coatings is to control corrosion by isolating the external surface of the underground or submerged piping from the environment, to reduce CP current requirements, and to improve current distribution.

5.1.2 External coatings must be properly selected and applied and the coated piping carefully handled and installed to fulfill these functions. Various types of external coatings can accomplish the desired functions.

5.1.2.1 Desirable characteristics of external coatings include the following:

5.1.2.1.1 Effective electrical insulator;

5.1.2.1.2 Effective moisture barrier;

5.1.2.1.3 Application to pipe by a method that does not adversely affect the properties of the pipe;

5.1.2.1.4 Application to pipe with a minimum of defects;
5.1.2.1.5 Good adhesion to pipe surface;

5.1.2.1.6 Ability to resist development of holidays with time;

5.1.2.1.7 Ability to resist damage during handling, storage, and installation;

5.1.2.1.8 Ability to maintain substantially constant electrical resistivity with time;

5.1.2.1.9 Resistance to disbonding;

5.1.2.1.10 Resistance to chemical degradation;

5.1.2.1.11 Ease of repair;

5.1.2.1.12 Retention of physical characteristics;

5.1.2.1.13 Nontoxic to the environment; and

5.1.2.1.14 Resistance to changes and deterioration during aboveground storage and long-distance transportation.

5.1.2.2 Typical factors to consider when selecting an external pipe coating include:

5.1.2.2.1 Type of environment;

5.1.2.2.2 Accessibility of piping system;

5.1.2.2.3 Operating temperature of piping system;

5.1.2.2.4 Ambient temperatures during application, shipping, storage, construction, installation, and pressure testing;

5.1.2.2.5 Geographical and physical location;

5.1.2.2.6 Type of external coating on existing pipe in the system;

5.1.2.2.7 Handling and storage;

5.1.2.2.8 Pipeline installation methods;

5.1.2.2.9 Costs; and

5.1.2.2.10 Pipe surface preparation requirements.

5.1.2.3 Pipeline external coating systems shall be properly selected and applied to ensure that adequate bonding is obtained. Unbonded coatings can create electrical shielding of the pipeline that could jeopardize the effectiveness of the CP system.

5.1.3 Information in this section is primarily by reference to other documents. It is important that the latest revision of the pertinent reference be used.

5.1.3.1 Table 1 is a listing of types of external coating systems, showing the appropriate references for material specifications and recommended practices for application.

5.1.3.2 Table 2 is a grouping of references for general use during installation and inspection, regardless of coating type.

5.1.3.3 Table 3 is a list of external coating system characteristics related to environmental conditions containing suggested laboratory test references for various properties.

5.1.3.4 Table 4 is a list of external coating system characteristics related to design and construction, with recommended laboratory tests for evaluating these properties.

5.1.3.5 Table 5 lists the references that are useful in field evaluation of external coating systems after the pipeline has been installed.

5.2 Storage, Handling, Inspection, and Installation

5.2.1 Storage and Handling

5.2.1.1 Coated pipe to be stored should be protected internally and externally from atmospheric corrosion and coating deterioration.

5.2.1.2 Damage to coating can be minimized by careful handling and by using proper pads and slings.

**TABLE 1**
**Generic External Coating Systems with Material Requirements**
**and Recommended Practices for Application[A]**

| Generic External Coating System | Reference |
|---|---|
| Coal Tar | ANSI[B]/AWWA[C] C 203[10] |
| Wax | NACE Standard RP0375[11] |
| Prefabricated Films | ANSI/AWWA C 214[12] |
| | ANSI/AWWA C 209[13] |
| Fusion-Bonded Epoxy Coatings | *Peabody's Control of Pipeline Corrosion*[14] |
| | ANSI/AWWA C 213[15] |
| | API[D] RP 5L7[16] |
| | CSA[E]Z245.20M[17] |
| | NACE Standard RP0394[18] |
| Polyolefin Coatings | NACE Standard RP0185[19] |
| | DIN[F] 30 670[20] |
| | ANSI/AWWA C 215[21] |

[A] NOTE: Many other references are available, and this table is not comprehensive. Listing does not constitute endorsement of any external coating system in preference to another. Omission of a system may be due to unavailability of reference standards or lack of data.
[B] American National Standards Institute (ANSI), 1819 L St. NW, Washington, DC 20036.
[C] American Water Works Association (AWWA), 6666 West Quincy Ave., Denver, CO 80235.
[D] American Petroleum Institute (API), 1220 L St. NW, Washington, DC 20005-4070.
[E] CSA International, 178 Rexdale Blvd., Toronto, Ontario, Canada M9W 1R3.
[F] Deutsches Institut fur Normung (DIN), Burggrafenstrasse 6, D-10787 Berlin, Germany.


**TABLE 2**
**References for General Use in the Installation and Inspection of External Coating Systems**
**for Underground Piping**

| Subject | Reference |
|---|---|
| Application of Organic Pipeline Coatings | ANSI/AWWA C 203[10] |
| | NACE Standard RP0375[11] |
| | *Peabody's Control of Pipeline Corrosion*[14] |
| | ANSI/AWWA C 213[15] |
| | API RP 5L7[16] |
| | CSA Z245.20M[17] |
| Film Thickness of Pipeline Coatings | ASTM[A] G 128[22] |
| Inspection of Pipeline Coatings | NACE Standard RP0274[23] |

[A] ASTM, 100 Barr Harbor Dr., West Conshohocken, PA 19428-2959.

**TABLE 3**
**External Coating System Characteristics Relative to Environmental Conditions[A]**

| Environmental Factor | Recommended Test Methods[B] |
|---|---|
| General underground exposure with or without CP | *Peabody's Control of Pipeline Corrosion*[14]<br>ANSI/AWWA C 213[15]<br>API RP 5L7[16]<br>CSA Z245.20M[17]<br>ASTM G 8[24]<br>ASTM G 19[25]<br>ASTM G 42[26]<br>ASTM G 95[27] |
| Resistance to water penetration and its effect on choice of coating thickness | ASTM G 9[28] |
| Resistance to penetration by stones in backfill | ASTM G 17[29]<br>ASTM D 2240[30]<br>ASTM G 13[31]<br>ASTM G 14[32] |
| Soil stress | *Underground Corrosion*[33]<br>ASTM D 427[34] |
| Resistance to specific liquid not normally encountered in virgin soil | ASTM D 543[35]<br>Federal Test Standard[C] No. 406A, Method 7011[36]<br>ASTM G 20[37] |
| Resistance to thermal effects | ASTM D 2304[38]<br>ASTM D 2454[39]<br>ASTM D 2485[40] |
| Suitability of supplementary materials for joint coating and field repairs | ASTM G 8[24]<br>ASTM G 19[25]<br>ASTM G 42[26]<br>ASTM G 95[27]<br>ASTM G 9[28]<br>ASTM G 18[41]<br>ASTM G 55[42] |
| Resistance to microorganisms | ASTM G 21[43]<br>Federal Test Standard No. 406A, Method 6091[44] |

[A] NOTE: Apply only those factors pertinent to the installation.
[B] No specific criteria are available. Comparative tests are recommended for use and evaluation as supplementary information only.
[C] Available from General Services Administration, Business Service Center, Washington, DC 20025.

**TABLE 4**
**External Coating System Characteristics Related to Design and Construction**

| Design and Construction Factor | Recommended Test Methods[A] |
|---|---|
| Yard Storage, Weathering | ASTM G 11[45] |
| Yard Storage, Penetration Under Load | ASTM G 17[29]<br>ASTM D 2240[30] |
| Handling Resistance, Abrasion | ASTM G 6[46] |
| Handling Resistance, Impact | ASTM G 13[31]<br>ASTM G 14[32] |
| Field Bending Ability | ASTM G 10[47] |
| Driving Ability (Resistance to Sliding Abrasion) | ASTM G 6[46]<br>ASTM D 2197[48] |
| Special Requirements for Mill-Applied Coating | ANSI/AWWA C 203[10]<br>NACE Standard RP0375[11]<br>ANSI/AWWA C 214[12]<br>ANSI/AWWA C 209[13]<br>*Peabody's Control of Pipeline Corrosion*[14]<br>ANSI/AWWA C 213[15]<br>API RP 5L7[16]<br>CSA Z245.20M[17]<br>NACE Standard RP0185[19]<br>DIN 30 670[20]<br>ANSI/AWWA C 215[21] |
| Special Requirements for Application of Coating Over the Ditch | ANSI/AWWA C 203[10]<br>NACE Standard RP0375[11]<br>ANSI/AWWA C 214[12]<br>ANSI/AWWA C 209[13]<br>*Peabody's Control of Pipeline Corrosion*[14]<br>ANSI/AWWA C 213[15]<br>API RP 5L7[16]<br>CSA Z245.20M[17] |
| Backfill Resistance | ASTM G 13[31]<br>ASTM G 14[32] |
| Resistance to Thermal Effects | ASTM G 8[24]<br>ASTM G 19[25]<br>ASTM G 42[26]<br>ASTM G 95[27]<br>ASTM D 2304[38]<br>ASTM D 2454[39]<br>ASTM D 2485[40] |
| Suitability of Joint Coatings and Field Repairs | *Peabody's Control of Pipeline Corrosion*[14]<br>ANSI/AWWA C 213[15]<br>API RP 5L7[16]<br>CSA Z245.20M[17]<br>ASTM G 8[24]<br>ASTM G 19[25]<br>ASTM G 42[26]<br>ASTM G 95[27]<br>ASTM G 9[28]<br>ASTM G 18[41]<br>ASTM G 55[42] |

[A] No specific criteria are available.  Comparative tests are recommended for use and evaluation as supplementary information only.

**TABLE 5**
**Methods for Evaluating In-Service Field Performance of External Coatings**

| Title or Subject of Method | Reference | Basis for Rating |
|---|---|---|
| (1) Rate of Change in Current Required for CP | *Underground Corrosion*[33] | Comparison of initial current requirement with subsequent periodic determination of current requirement |
| (2) Inspection of Pipeline Coating | NACE Standard RP0274[23] | (a) With CP: no active corrosion found<br>(b) Without CP: no new holidays showing active corrosion |
| (3) Cathodic Disbondment | ASTM G 8[24]<br>ASTM G 19[25]<br>ASTM G 42[26]<br>ASTM G 95[27] | Purpose is to obtain data relative to specific conditions for comparison with laboratory data |

5.2.2 Inspection

5.2.2.1 Qualified personnel should keep every phase of the coating operation and piping installation under surveillance.

5.2.2.2 Surface preparation, primer application, coating thickness, temperature, bonding, and other specific requirements should be checked periodically, using suitable test procedures, for conformance to specifications.

5.2.2.3 The use of holiday detectors is recommended to detect coating flaws that would not be observed visually. The holiday detector should be operated in accordance with the manufacturer's instructions and at a voltage level appropriate to the electrical characteristics of the coating system.

5.2.3 Installation

5.2.3.1 Joints, fittings, and tie-ins must be coated with a material compatible with the existing coating.

5.2.3.2 Coating defects should be repaired.

5.2.3.3 Materials used to repair coatings must be compatible with the existing pipe coating.

5.2.3.4 The ditch bottom should be graded and free of rock or other foreign matter that could damage the external coating or cause electrical shielding. Under difficult conditions, consideration should be given to padding the pipe or the ditch bottom.

5.2.3.5 Pipe should be lowered carefully into the ditch to avoid external coating damage.

5.2.3.6 Care should be taken during backfilling so that rocks and debris do not strike and damage the pipe coating.

5.2.3.7 Care shall be exercised when using materials such as loose wrappers, nonconducting urethane foam, and rock shield around pipelines as protection against physical damage or for other purposes, because these materials may create an electrical shielding effect that would be detrimental to the effectiveness of CP.

5.2.3.8 When a pipeline comes above ground, it must be cleaned and externally coated, or jacketed with a suitable material, for the prevention of atmospheric corrosion.

5.3 Methods for Evaluating External Coating Systems

5.3.1 Established Systems Proven by Successful Use

5.3.1.1 Visual and electrical inspection of in-service pipeline coatings should be used to evaluate the performance of an external coating system. These inspections can be conducted wherever the pipeline is excavated or at bell holes made for inspection purposes.

5.3.2 Established or Modified Systems for New Environments

5.3.2.1 This method is intended for use when external coating systems will continue to be used and are qualified under Paragraph 5.3.1, but when application will be extended to new environments or when it is desired to revise a system to make use of new developments, one of the following should be used:

5.3.2.1.1 The use of applicable material requirements, material specifications, standards, and recommended practices for application, as given in Table 1, is recommended.

5.3.2.1.2 The use of applicable references in Table 2 is recommended unless previously covered in applicable references in Table 1.

5.3.3 New External Coating System Qualification

5.3.3.1 The purpose of this method is to qualify a new external coating material by subjecting it to laboratory tests appropriate for the intended service. After laboratory tests have been conducted and indicate that the external coating system appears to be suitable, application and installation are conducted in accordance with recommended practices. In-service field performance tests are made to confirm the success of the previous steps. The steps of the method are (1) laboratory tests, (2) application under recommended practices, (3) installation under recommended practices, and (4) in-service field performance tests. If good results are obtained after five years, only Steps 2 and 3 are required thereafter.

5.3.3.1.1 Applicable sections of Tables 3 and 4 are recommended for the initial laboratory test methods.

5.3.3.1.2 Applicable sections of Tables 1 and 2 are recommended for conditional use during Steps 2 and 3.

5.3.3.1.3 During a period of five years or more, the use of the evaluation methods given in Table 5, Item 1 or 2 are recommended. The test method in Item 3 may be used as a supplementary means for obtaining data for correlation with laboratory tests.

5.3.4 Method for Evaluating an External Coating System by In-Service Field Performance Only

5.3.4.1 The purpose of this method is to qualify an external coating system when none of the first three methods given in Paragraph 5.3 has been or will be used. It is intended that this method should be limited to minor pilot installations.

5.3.4.1.1 The use of at least one of the first two methods given in Table 5 is recommended on the basis of at least one investigation per year for five consecutive years.

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## Section 6:  Criteria and Other Considerations for CP

6.1  Introduction

6.1.1 This section lists criteria and other considerations for CP that indicate, when used either separately or in combination, whether adequate CP of a metallic piping system has been achieved (see also Section 1, Paragraphs 1.2 and 1.4).

6.1.2 The effectiveness of CP or other external corrosion control measures can be confirmed by visual observation, by measurements of pipe wall thickness, or by use of internal inspection devices. Because such methods sometimes are not practical, meeting any criterion or combination of criteria in this section is evidence that adequate CP has been achieved. When excavations are made for any purpose, the pipe should be inspected for evidence of corrosion and coating condition.

6.1.3 The criteria in this section have been developed through laboratory experiments or verified by evaluating data obtained from successfully operated CP systems. Situations in which a single criterion for evaluating the effectiveness of CP may not be satisfactory for all conditions may exist. Often a combination of criteria is needed for a single structure.

6.1.4 Sound engineering practices shall be used to determine the methods and frequency of testing required to satisfy these criteria.

6.1.5 Corrosion leak history is valuable in assessing the effectiveness of CP. Corrosion leak history by itself, however, shall not be used to determine whether adequate levels of CP have been achieved unless it is impractical to make electrical surveys.

6.2  Criteria

6.2.1 It is not intended that persons responsible for external corrosion control be limited to the criteria listed below. Criteria that have been successfully applied on existing piping systems can continue to be used on those piping systems. Any other criteria used must achieve corrosion control comparable to that attained with the criteria herein.

6.2.2  Steel and Cast Iron Piping

6.2.2.1 External corrosion control can be achieved at various levels of cathodic polarization depending on the environmental conditions. However, in the absence of specific data that demonstrate that adequate CP has been achieved, one or more of the following shall apply:

6.2.2.1.1 A negative (cathodic) potential of at least 850 mV with the CP applied. This potential is measured with respect to a saturated copper/copper sulfate reference electrode contacting the electrolyte. Voltage

drops other than those across the structure-to-electrolyte boundary must be considered for valid interpretation of this voltage measurement.

NOTE: Consideration is understood to mean the application of sound engineering practice in determining the significance of voltage drops by methods such as:

6.2.2.1.1.1 Measuring or calculating the voltage drop(s);

6.2.2.1.1.2 Reviewing the historical performance of the CP system;

6.2.2.1.1.3 Evaluating the physical and electrical characteristics of the pipe and its environment; and

6.2.2.1.1.4 Determining whether or not there is physical evidence of corrosion.

6.2.2.1.2 A negative polarized potential (see definition in Section 2) of at least 850 mV relative to a saturated copper/copper sulfate reference electrode.

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

6.2.2.2  Special Conditions

6.2.2.2.1 On bare or ineffectively coated pipelines when long-line corrosion activity is of primary concern, the measurement of a net protective current at predetermined current discharge points from the electrolyte to the pipe surface, as measured by an earth current technique, may be sufficient.

6.2.2.2.2 In some situations, such as the presence of sulfides, bacteria, elevated temperatures, acid environments, and dissimilar metals, the criteria in Paragraph 6.2.2.1 may not be sufficient.

6.2.2.2.3 When a pipeline is encased in concrete or buried in dry or aerated high-resistivity soil, values less negative than the criteria listed in Paragraph 6.2.2.1 may be sufficient.

6.2.2.3  PRECAUTIONARY NOTES

6.2.2.3.1 The earth current technique is often meaningless in multiple pipe rights-of-way, in high-resistivity surface soil, for deeply buried pipe, in stray-current areas, or where local corrosion cell action predominates.

6.2.2.3.2 Caution is advised against using polarized potentials less negative than -850 mV for CP of pipelines when operating pressures and conditions are conducive to stress corrosion cracking (see references on stress corrosion cracking at the end of this section).

6.2.2.3.3 The use of excessive polarized potentials on externally coated pipelines should be avoided to minimize cathodic disbondment of the coating.

6.2.2.3.4 Polarized potentials that result in excessive generation of hydrogen should be avoided on all metals, particularly higher-strength steel, certain grades of stainless steel, titanium, aluminum alloys, and prestressed concrete pipe.

6.2.3  Aluminum Piping

6.2.3.1 The following criterion shall apply: a minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte. The formation or decay of this polarization can be used in this criterion.

6.2.3.2  PRECAUTIONARY NOTES

6.2.3.2.1 Excessive Voltages: Notwithstanding the minimum criterion in Paragraph 6.2.3.1, if aluminum is cathodically protected at voltages more negative than -1,200 mV measured between the pipe surface and a saturated copper/copper sulfate reference electrode contacting the electrolyte and compensation is made for the voltage drops other than those across the pipe-electrolyte boundary, it may suffer corrosion as the result of the buildup of alkali on the metal surface. A polarized potential more negative than -1,200 mV should not be used unless previous test results indicate that no appreciable corrosion will occur in the particular environment.

6.2.3.2.2 Alkaline Conditions: Aluminum may suffer from corrosion under high-pH conditions, and application of CP tends to increase the pH at the metal surface. Therefore, careful investigation or testing should be done before applying CP to stop pitting attack on aluminum in environments with a natural pH in excess of 8.0.

6.2.4  Copper Piping

6.2.4.1 The following criterion shall apply: a minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte. The formation or decay of this polarization can be used in this criterion.

6.2.5  Dissimilar Metal Piping

6.2.5.1 A negative voltage between all pipe surfaces and a stable reference electrode contacting the electrolyte equal to that required for the protection of the most anodic metal should be maintained.

6.2.5.2  PRECAUTIONARY NOTE

6.2.5.2.1 Amphoteric materials that could be damaged by high alkalinity created by CP should be electrically isolated and separately protected.

6.3  Other Considerations

6.3.1 Methods for determining voltage drop(s) shall be selected and applied using sound engineering practices. Once determined, the voltage drop(s) may be used for correcting future measurements at the same location, provided conditions such as pipe and CP system operating conditions, soil characteristics, and external coating quality remain similar. (Note: Placing the reference electrode next to the pipe surface may not be at the pipe-electrolyte interface. A reference electrode placed at an externally coated pipe surface may not significantly reduce soil voltage drop in the measurement if the nearest coating holiday is remote from the reference electrode location.)

6.3.2 When it is impractical or considered unnecessary to disconnect all current sources to correct for voltage drop(s) in the structure-to-electrolyte potential measurements, sound engineering practices should be used to ensure that adequate CP has been achieved.

6.3.3 When feasible and practicable, in-line inspection of pipelines may be helpful in determining the presence or absence of pitting corrosion damage. Absence of external corrosion damage or the halting of its growth may indicate adequate external corrosion control. The in-line inspection technique, however, may not be capable of detecting all types of external corrosion damage, has limitations in its accuracy, and may report as anomalies items that are not external corrosion. For example, longitudinal seam corrosion and general corrosion may not be readily detected by in-line inspection. Also, possible thickness variations, dents, gouges, and external ferrous objects may be detected as corrosion. The appropriate use of in-line inspection must be carefully considered.

6.3.4 Situations involving stray currents and stray electrical gradients that require special analysis may exist. For additional information, see Section 9, "Control of Interference Currents."

6.4  Alternative Reference Electrodes

6.4.1 Other standard reference electrodes may be substituted for the saturated copper/copper sulfate reference electrode. Two commonly used reference electrodes are listed below along with their voltage equivalent (at 25°C [77°F]) to -850 mV referred to a saturated copper/copper sulfate reference electrode:

6.4.1.1 Saturated KCl calomel reference electrode: -780 mV; and

6.4.1.2 Saturated silver/silver chloride reference electrode used in 25 ohm-cm seawater: -800 mV.

6.4.2 In addition to these standard reference electrodes, an alternative metallic material or structure may be used in place of the saturated copper/copper sulfate reference electrode if the stability of its electrode potential is ensured and if its voltage equivalent referred to a saturated copper/copper sulfate reference electrode is established.

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## Section 7:  Design of Cathodic Protection Systems

7.1 Introduction

7.1.1 This section recommends procedures for designing CP systems that will provide effective external corrosion control by satisfying one or more of the criteria listed in Section 6 and exhibiting maximum reliability over the intended operating life of the systems.

7.1.2 In the design of a CP system, the following should be considered:

7.1.2.1 Recognition of hazardous conditions prevailing at the proposed installation site(s) and the selection and specification of materials and installation practices that ensure safe installation and operation.

7.1.2.2 Specification of materials and installation practices to conform to the latest editions of applicable codes, National Electrical Manufacturers Association (NEMA)[7] standards, National Electrical Code (NEC),[8] appropriate international standards, and NACE standards.

7.1.2.3 Selection and specification of materials and installation practices that ensure dependable and economical operation throughout the intended operating life.

7.1.2.4 Selection of locations for proposed installations to minimize currents or earth potential gradients, which can cause detrimental effects on foreign buried or submerged metallic structures.

7.1.2.5 Cooperative investigations to determine mutually satisfactory solution(s) of interference problems (see Section 9).

7.1.2.6 Special consideration should be given to the presence of sulfides, bacteria, disbonded coatings, thermal insulating coatings, elevated temperatures, shielding, acid environments, and dissimilar metals.

7.1.2.7 Excessive levels of CP that can cause external coating disbondment and possible damage to high-strength steels as a result of hydrogen evolution should be avoided.

7.1.2.8 When amphoteric metals are involved, care should be taken so that high-pH conditions that could cause cathodic corrosion of the metal are not established.

7.2 Major objectives of CP system design include the following:

7.2.1 To provide sufficient current to the structure to be protected and distribute this current so that the selected criteria for CP are effectively attained;

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[7] National Electrical Manufacturers Association (NEMA), 1300 North 17th St., Suite 1752, Rosslyn, Virginia 22209.
[8] National Fire Protection Association, Batterymarch Park, Quincy, MA  02269.

7.2.2 To minimize the interference currents on neighboring underground structures (see Section 9);

7.2.3 To provide a design life of the anode system commensurate with the required life of the protected structure, or to provide for periodic rehabilitation of the anode system;

7.2.4 To provide adequate allowance for anticipated changes in current requirements with time;

7.2.5 To install anodes when the possibility of disturbance or damage is minimal; and

7.2.6 To provide adequate monitoring facilities to test and evaluate the system performance.

7.3 Information Useful for Design

7.3.1 Useful piping system specifications and information include the following:

    7.3.1.1 Route maps and atlas sheets;

    7.3.1.2 Construction dates;

    7.3.1.3 Pipe, fittings, and other appurtenances;

    7.3.1.4 External coatings;

    7.3.1.5 Casings;

    7.3.1.6 Corrosion control test stations;

    7.3.1.7 Electrically isolating devices;

    7.3.1.8 Electrical bonds; and

    7.3.1.9 Aerial, bridge, and underwater crossings.

7.3.2 Useful information on piping system site conditions includes the following:

    7.3.2.1 Existing and proposed CP systems;

    7.3.2.2 Possible interference sources (see Section 9);

    7.3.2.3 Special environmental conditions;

    7.3.2.4 Neighboring buried metallic structures (including location, ownership, and corrosion control practices);

    7.3.2.5 Structure accessibility;

    7.3.2.6 Power availability; and

    7.3.2.7 Feasibility of electrical isolation from foreign structures.

7.3.3 Useful information from field surveys, corrosion test data, and operating experience includes the following:

    7.3.3.1 Protective current requirements to meet applicable criteria;

    7.3.3.2 Electrical resistivity of the electrolyte;

    7.3.3.3 Electrical continuity;

    7.3.3.4 Electrical isolation;

    7.3.3.5 External coating integrity;

    7.3.3.6 Cumulative leak history;

    7.3.3.7 Interference currents;

    7.3.3.8 Deviation from construction specifications; and

    7.3.3.9 Other maintenance and operating data.

7.3.4 Field survey work prior to actual application of CP is not always required if prior experience or test data are available to estimate current requirements, electrical resistivity of the electrolyte, and other design factors.

7.4 Types of CP Systems

7.4.1 Galvanic Anode Systems

    7.4.1.1 Galvanic anodes can be made of materials such as alloys of magnesium, zinc, or aluminum. The anodes are connected to the pipe, either individually or in groups. Galvanic anodes are limited in current output by the anode-to-pipe driving voltage and the electrolyte resistivity.

7.4.2 Impressed Current Anode Systems

    7.4.2.1 Impressed current anodes can be of materials such as graphite, high-silicon cast iron, lead-silver alloy, precious metals, or steel. They are connected with an insulated cable, either individually or in groups, to the positive terminal of a direct-current (DC) source, such as a rectifier or generator. The pipeline is connected to the negative terminal of the DC source.

7.5 Considerations influencing selection of the type of CP system include the following:

7.5.1 Magnitude of protective current required;

7.5.2 Stray currents causing significant potential fluctuations between the pipeline and earth that may preclude the use of galvanic anodes;

7.5.3 Effects of CP interference currents on adjacent structures that may limit the use of impressed current CP systems;

7.5.4 Availability of electrical power;

7.5.5 Physical space available, proximity of foreign structures, easement procurement, surface conditions, presence of streets and buildings, river crossings, and other construction and maintenance concerns.

7.5.6 Future development of the right-of-way area and future extensions to the pipeline system;

7.5.7 Costs of installation, operation, and maintenance; and

7.5.8 Electrical resistivity of the environment.

7.6 Factors Influencing Design of CP Systems

7.6.1 Various anode materials have different rates of deterioration when discharging a given current density from the anode surface in a specific environment. Therefore, for a given current output, the anode life depends on the environment and anode material, as well as the anode weight and the number of anodes in the CP system. Established anode performance data may be used to calculate the probable deterioration rate.

7.6.2 Data on the dimensions, depth, and configuration of the anodes and the electrolyte resistivity may be used to calculate the resultant resistance to electrolyte of the anode system. Formulas and graphs relating to these factors are available in the bibliography literature and from most anode manufacturers.

7.6.3 Design of galvanic anode systems should consider anode-to-pipe potential, electrolyte resisivity, current output, and in special cases, anode lead-wire resistance. A separate design for each anode or anode system may not be necessary.

7.6.4 Galvanic anode performance in most soils can be improved by using special backfill material. Mixtures of gypsum, bentonite, and anhydrous sodium sulfate are most commonly used.

7.6.5 The number of impressed current anodes required can be reduced and their useful life lengthened by the use of special backfill around the anodes. The most common materials are coal coke, calcined petroleum coke, and natural or manufactured graphite.

7.6.6 In the design of an extensive distributed-anode impressed current system, the voltage and current attenuation along the anode-connecting (header) cable should be considered. In such cases, the design objective is to optimize anode system length, anode spacing and size, and cable size in order to achieve efficient external corrosion control at the extremities of the protected structure.

7.6.7 When it is anticipated that entrapment of gas generated by anodic reactions could impair the ability of the impressed current groundbed to deliver the required current, suitable provisions should be made for venting the anodes. For the same current output of the system, an increase in the surface area of the special backfill material or an increase in the number of anodes may reduce gas blockage.

7.6.8 When it is anticipated that electroosmotic effects could impair the ability of the impressed current groundbed to deliver the required current output, suitable provisions should be made to ensure adequate soil moisture around the anodes. Increasing the number of impressed current anodes or increasing the surface area of the special backfill materials may further reduce the electroosmotic effect.

7.7 Design Drawings and Specifications

7.7.1 Suitable drawings should be prepared to designate the overall layout of the piping to be protected and the location of significant items of structure hardware, corrosion control test stations, electrical bonds, electrical isolation devices, and neighboring buried or submerged metallic structures.

7.7.2 Layout drawings should be prepared for each impressed current CP installation, showing the details and location of the components of the CP system with respect to the protected structure(s) and to major physical landmarks. These drawings should include right-of-way information.

7.7.3 The locations of galvanic anode installations should be recorded on drawings or in tabular form, with appropriate notes on anode type, weight, spacing, depth, and backfill.

7.7.4 Specifications should be prepared for all materials and installation practices that are to be incorporated in construction of the CP system.

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### Section 8:  Installation of CP Systems

8.1 Introduction

8.1.1 This section recommends procedures that will result in the installation of CP systems that achieve protection of the structure.  The design considerations recommended in Sections 4 and 7 should be followed.

8.2 Construction Specifications

8.2.1 All construction work on CP systems should be performed in accordance with construction drawings and specifications.  The construction specifications should be in accordance with recommended practices in Sections 4 and 7.

8.3 Construction Supervision

8.3.1 All construction work on CP systems should be performed under the surveillance of trained and qualified personnel to verify that the installation is in strict accordance with the drawings and specifications. Exceptions may be made only with the approval of qualified personnel responsible for external corrosion control.

8.3.2 All deviations from construction specifications should be noted on as-built drawings.

8.4 Galvanic Anodes

8.4.1 Inspection, Handling, and Storage

8.4.1.1 Packaged anodes should be inspected and steps taken to ensure that backfill material completely surrounds the anode.  The individual container for the backfill material and anode should be intact.  If individually packaged anodes are supplied in waterproof containers, the containers must be removed before installation. Packaged anodes should be kept dry during storage.

8.4.1.2 Lead wire must be securely connected to the anode.  Lead wire should be inspected for assurance that it is not damaged.

8.4.1.3 Other galvanic anodes, such as the unpackaged "bracelet" or ribbon type, should be inspected to ensure that dimensions conform to

design specifications and that any damage during handling does not affect application. If a coating is used on bands and the inner side of bracelet anode segments, it should be inspected and, if damaged, repaired before the anodes are installed.

### 8.4.2 Installing Anodes

8.4.2.1 Anodes should be installed according to construction specifications.

8.4.2.2 Packaged galvanic anodes should be backfilled with appropriately compacted material. When anodes and special chemical backfill are provided separately, anodes should be centered in special backfill, which should be compacted prior to backfilling. Care should be exercised during all operations so that lead wires and connections are not damaged. Sufficient slack should exist in lead wires to avoid strain.

8.4.2.3 When anodes in bracelet form are used, external pipe coating beneath the anode should be free of holidays. Care should be taken to prevent damage to the external coating when bracelet anodes are installed. After application of concrete (if used) to pipe, all coating and concrete should be removed from the anode surface. If reinforced concrete is used, there must be no metallic contact between the anode and the reinforcing mesh or between the reinforcing mesh and the pipe.

8.4.2.4 When a ribbon-type anode is used, it can be trenched or plowed in, with or without special chemical backfill as required, generally parallel to the section of pipeline to be protected.

## 8.5 Impressed Current Systems

### 8.5.1 Inspection and Handling

8.5.1.1 The rectifier or other power source should be inspected to ensure that internal connections are mechanically secure and that the unit is free of damage. Rating of the DC power source should comply with the construction specification. Care should be exercised in handling and installing the power source.

8.5.1.2 Impressed current anodes should be inspected for conformance to specifications concerning anode material, size, length of lead cable, anode lead connection, and integrity of seal. Care should be exercised to avoid cracking or damaging anodes during handling and installation.

8.5.1.3 All cables should be carefully inspected to detect defects in insulation. Care should be taken to avoid damage to cable insulation. Defects in the cable insulation must be repaired.

8.5.1.4 Anode backfill material should conform to specifications.

### 8.5.2 Installation Provisions

8.5.2.1 A rectifier or other power source should be installed so that the possibility of damage or vandalism is minimized.

8.5.2.2 Wiring to rectifiers shall comply with local and national electrical codes and requirements of the utility supplying power. An external disconnect switch should be provided in the AC circuit. A rectifier case shall be properly grounded.

8.5.2.3 On thermoelectric generators, a reverse current device should be installed to prevent galvanic action between the anode bed and the pipe if the flame is extinguished.

8.5.2.4 Impressed current anodes can be buried vertically, horizontally, or in deep holes (see NACE Standard RP0572[1]) as indicated in construction specifications. Backfill material should be installed to ensure that there are no voids around anodes. Care should be exercised during backfilling to avoid damage to the anode and cable.

8.5.2.5 The cable from the rectifier negative terminal to the pipe should be connected to the pipe as described in Paragraph 8.6. Cable connections to the rectifier must be mechanically secure and electrically conductive. Before the power source is energized, it must be verified that the negative cable is connected to the structure to be protected and that the positive cable is connected to the anodes. After the DC power source has been energized, suitable measurements should be made to verify that these connections are correct.

8.5.2.6 Underground splices on the header (positive) cable to the groundbed should be kept to a minimum. Connections between the header and anode cables should be mechanically secure and electrically conductive. If buried or submerged, these connections must be sealed to prevent moisture penetration so that electrical isolation from the environment is ensured.

8.5.2.7 Care must be taken during installation of direct-burial cable to the anodes (positive cable) to avoid damage to insulation. Sufficient slack should be left to avoid strain on all cables. Backfill material around the cable should be free of rocks and foreign matter that might cause damage to the insulation when the cable is installed in a trench. Cable can be installed by plowing if proper precautions are taken.

8.5.2.8 If insulation integrity on the buried or submerged header cable, including splices, is not

maintained, this cable may fail because of corrosion.

8.6 Corrosion Control Test Stations, Connections, and Bonds (see Paragraph 4.5)

8.6.1 Pipe and test lead wires should be clean, dry, and free of foreign materials at points of connection when the connections are made. Connections of test lead wires to the pipe must be installed so they will remain mechanically secure and electrically conductive.

8.6.2 All buried or submerged lead-wire attachments should be coated with an electrically insulating material, compatible with the external pipe coating and wire insulation.

8.6.3 Test lead wires should be color coded or otherwise permanently identified. Wires should be installed with slack. Damage to insulation should be avoided and repairs made if damage occurs. Test leads should not be exposed to excessive heat and sunlight. Aboveground test stations are preferred. If test stations are flush with the ground, adequate slack should be provided within the test station to facilitate test connections.

8.6.4 Cable connections at bonds to other structures or across isolating joints should be mechanically secure, electrically conductive, and suitably coated. Bond connections should be accessible for testing.

8.7 Electrical Isolation

8.7.1 Inspection and electrical measurements should ensure that electrical isolation is adequate (see NACE SP0286[5]).

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## Section 9:  Control of Interference Currents

9.1 Introduction

9.1.1 This section recommends practices for the detection and control of interference currents. The mechanism and its detrimental effects are described.

9.2 Mechanism of Interference-Current Corrosion (Stray-Current Corrosion)

9.2.1 Interference-current corrosion on buried or submerged metallic structures differs from other causes of corrosion damage in that the direct current, which causes the corrosion, has a source foreign to the affected structure. Usually the interfering current is collected from the electrolyte by the affected structure from a DC source not metallically bonded to the affected structure.

9.2.1.1 Detrimental effects of interference currents usually occur at locations where the currents transfer between the affected structures and the electrolyte.

9.2.1.2 Structures made of amphoteric metals such as aluminum and lead may be subject to corrosion damage from a buildup of alkalinity at or near the metal surface collecting interference currents.

9.2.1.3 Coatings may become disbonded at areas where voltage gradients in the electrolyte force current onto the affected structure. However, as the external coating becomes disbonded, a larger area of metal may be exposed, which would increase the demand for a CP current. This disbondment may create shielding problems.

9.2.2 The severity of external corrosion resulting from interference currents depends on several factors:

9.2.2.1 Separation and routing of the interfering and affected structures and location of the interfering current source;

9.2.2.2 Magnitude and density of the current;

9.2.2.3 Quality of the external coating or absence of an external coating on the structures involved; and

9.2.2.4 Presence and location of mechanical joints having high electrical resistance.

9.2.3 Typical sources of interference currents include the following:

9.2.3.1 Direct current:  CP rectifiers, thermoelectric generators, DC electrified railway and transit systems, coal mine haulage systems and pumps, welding machines, and other DC power systems;

9.2.3.2 Alternating current:  AC power systems and AC electrified railway systems; and

9.2.3.3 Telluric current.

9.3 Detection of Interference Currents

9.3.1 During external corrosion control surveys, personnel should be alert for electrical or physical observations that could indicate interference from a foreign source such as the following:

9.3.1.1 Pipe-electrolyte potential changes on the affected structure caused by the foreign DC source;

9.3.1.2 Changes in the line current magnitude or direction caused by the foreign DC source;

9.3.1.3 Localized pitting in areas near or immediately adjacent to a foreign structure; and

9.3.1.4 Damage to external coatings in a localized area near an anode bed or near any other source of stray direct current.

9.3.2 In areas in which interference currents are suspected, appropriate tests should be conducted. All affected parties shall be notified before tests are conducted. Notification should be channeled through corrosion control coordinating committees, when they exist (see NACE Publication TPC 11[8]). Any one or a combination of the following test methods can be used.

9.3.2.1 Measurement of structure-electrolyte potentials with recording or indicating instruments;

9.3.2.2 Measurement of current flowing on the structure with recording or indicating instruments;

9.3.2.3 Development of beta curves to locate the area of maximum current discharge from the affected structure (see Appendix A); and

9.3.2.4 Measurement of the variations in current output of the suspected source of interference current and correlations with measurements obtained in Paragraphs 9.3.2.1 and 9.3.2.2.

9.4 Methods for Mitigating Interference Corrosion Problems

9.4.1 Interference problems are individual in nature and the solution should be mutually satisfactory to the parties involved. These methods may be used individually or in combination.

9.4.2 Design and installation of electrical bonds of proper resistance between the affected structures is a technique for interference control. The bond electrically conducts interference current from an affected structure to the interfering structure or current source.

9.4.2.1 Unidirectional control devices, such as diodes or reverse current switches, may be required in conjunction with electrical bonds if

fluctuating currents are present. These devices prevent reversal of current flow.

9.4.2.2 A resistor may be necessary in the bond circuit to control the flow of electrical current from the affected structure to the interfering structure.

9.4.2.3 The attachment of electrical bonds can reduce the level of CP on the interfering structure. Supplementary CP may then be required on the interfering structure to compensate for this effect.

9.4.2.4 A bond may not effectively mitigate the interference problem in the case of a cathodically protected bare or poorly externally coated pipeline that is causing interference on an externally coated pipeline.

9.4.3 CP current can be applied to the affected structure at those locations at which the interfering current is being discharged. The source of CP current may be galvanic or impressed current anodes.

9.4.4 Adjustment of the current output from interfering CP rectifiers may resolve interference problems.

9.4.5 Relocation of the groundbeds of cathodic protection rectifiers can reduce or eliminate the pickup of interference currents on nearby structures.

9.4.6 Rerouting of proposed pipelines may avoid sources of interference current.

9.4.7 Properly located isolating fittings in the affected structure may reduce or resolve interference problems.

9.4.8 Application of external coating to current pick-up area(s) may reduce or resolve interference problems.

9.5 Indications of Resolved Interference Problems

9.5.1 Restoration of the structure-electrolyte potentials on the affected structure to those values that existed prior to the interference.

9.5.2 Measured line currents on the affected structure that show that the interference current is not being discharged to the electrolyte.

9.5.3 Adjustment of the slope of the beta curve to show that current discharge has been eliminated at the location of maximum exposure (see Appendix A).

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## Section 10:  Operation and Maintenance of CP Systems

10.1  Introduction

10.1.1 This section recommends procedures and practices for energizing and maintaining continuous, effective, and efficient operation of CP systems.

10.1.1.1 Electrical measurements and inspection are necessary to determine that protection has been established according to applicable criteria and that each part of the CP system is operating properly.  Conditions that affect protection are subject to change. Correspondingly, changes may be required in the CP system to maintain protection.  Periodic measurements and inspections are necessary to detect changes in the CP system.  Conditions in which operating experience indicates that testing and inspections need to be made more frequently than recommended herein may exist.

10.1.1.2 Care should be exercised in selecting the location, number, and type of electrical measurements used to determine the adequacy of CP.

10.1.1.3 When practicable and determined necessary by sound engineering practice, a detailed (close-interval) potential survey should be conducted to:

(a)  assess the effectiveness of the CP system;

(b)  provide base line operating data;

(c)  locate areas of inadequate protection levels;

(d)  identify locations likely to be adversely affected by construction, stray currents, or other unusual environmental conditions; or

(e)  select areas to be monitored periodically.

10.1.1.4 Adjustments to a CP system should be accompanied by sufficient testing to assure the criteria remain satisfied and to reassess interference to other structures or isolation points.

10.2  A survey should be conducted after each CP system is energized or adjusted to determine whether the applicable criterion or criteria from Section 6 have been satisfied.

10.3 The effectiveness of the CP system should be monitored annually.  Longer or shorter intervals for monitoring may be appropriate, depending on the variability of CP factors, safety considerations, and economics of monitoring.

10.4   Inspection and tests of CP facilities should be made to ensure their proper operation and maintenance as follows:

10.4.1 All sources of impressed current should be checked at intervals of two months.  Longer or shorter intervals for monitoring may be appropriate.  Evidence of proper functioning may be current output, normal power consumption, a signal indicating normal operation, or satisfactory CP levels on the pipe.

10.4.2 All impressed current protective facilities should be inspected annually as part of a preventive maintenance program to minimize in-service failure.  Longer or shorter intervals for monitoring may be appropriate.  Inspections may include a check for electrical malfunctions, safety ground connections, meter accuracy, efficiency, and circuit resistance.

10.4.3 Reverse current switches, diodes, interference bonds, and other protective devices, whose failures would jeopardize structure protection, should be inspected for proper functioning at intervals of two months.  Longer or shorter intervals for monitoring may be appropriate.

10.4.4 The effectiveness of isolating fittings, continuity bonds, and casing isolation should be evaluated during the periodic surveys.  This may be accomplished by electrical measurements.

10.5 When pipe has been uncovered, it should be examined for evidence of external corrosion and, if externally coated, for condition of the external coating.

10.6 The test equipment used for obtaining each electrical value should be of an appropriate type.  Instruments and related equipment should be maintained in good operating condition and checked for accuracy.

10.7 Remedial measures should be taken when periodic tests and inspections indicate that CP is no longer adequate.  These measures may include the following:

10.7.1 Repair, replace, or adjust components of CP systems;

10.7.2 Provide supplementary facilities in which additional CP is necessary;

10.7.3 Thoroughly clean and properly coat bare structures if required to attain CP;

10.7.4 Repair, replace, or adjust continuity and interference bonds;

10.7.5 Remove accidental metallic contacts; and

10.7.6  Repair defective isolating devices.

10.8  An electrical short circuit between a casing and carrier pipe can result in inadequate CP of the pipeline outside the casing due to reduction of protective current to the pipeline.

10.8.1  When a short results in inadequate CP of the pipeline outside the casing, steps must be taken to restore CP to a level required to meet the CP criterion. These steps may include eliminating the short between the casing and carrier pipe, supplementing CP, or

improving the quality of the external coating on the pipeline outside the casing.  None of these steps will ensure that external corrosion will not occur on the carrier pipe inside the casing; however, a shorted casing does not necessarily result in external corrosion of the carrier pipe inside the casing.

10.9  When the effects of electrical shielding of CP current are detected, the situation should be evaluated and appropriate action taken.

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## Section 11:  External Corrosion Control Records

11.1  Introduction

11.1.1  This section describes external corrosion control records that will document in a clear, concise, workable manner data that are pertinent to the design, installation, operation, maintenance, and effectiveness of external corrosion control measures.

11.2  Relative to the determination of the need for external corrosion control, the following should be recorded:

11.2.1  Corrosion leaks, breaks, and pipe replacements; and

11.2.2  Pipe and external coating condition observed when a buried structure is exposed.

11.3  Relative to structure design, the following should be recorded:

11.3.1  External coating material and application specifications; and

11.3.2  Design and location of isolating devices, test leads and other test facilities, and details of other special external corrosion control measures taken.

11.4  Relative to the design of external corrosion control facilities, the following should be recorded:

11.4.1  Results of current requirement tests;

11.4.2  Results of soil resistivity surveys;

11.4.3  Location of foreign structures; and

11.4.4  Interference tests and design of interference bonds and reverse current switch installations.

11.4.4.1 Scheduling of interference tests, correspondence with corrosion control coordinating committees, and direct communication with the concerned companies.

11.4.4.2 Record of interference tests conducted, including location of tests, name of company involved, and results.

11.5  Relative to the installation of external corrosion control facilities, the following should be recorded:

11.5.1  Installation of CP facilities:

11.5.1.1  Impressed current systems:

11.5.1.1.1 Location and date placed in service;

11.5.1.1.2 Number, type, size, depth, backfill, and spacing of anodes;

11.5.1.1.3 Specifications of rectifier or other energy source; and

11.5.1.1.4 Cable size and type of insulation.

11.5.1.2  Galvanic anode systems:

11.5.1.2.1 Location and date placed in service;

11.5.1.2.2 Number, type, size, backfill, and spacing of anodes; and

11.5.1.2.3 Wire size and type of insulation.

11.5.2  Installation of interference mitigation facilities:

11.5.2.1  Details of interference bond installation:

11.5.2.1.1 Location and name of company involved;

11.5.2.1.2 Resistance value or other pertinent information; and

11.5.2.1.3 Magnitude and polarity of drainage current.

11.5.2.2 Details of reverse current switch:

11.5.2.2.1 Location and name of companies;

11.5.2.2.2 Type of switch or equivalent device; and

11.5.2.2.3 Data showing effective operating adjustment.

11.5.2.3 Details of other remedial measures.

11.6 Records of surveys, inspections, and tests should be maintained to demonstrate that applicable criteria for interference control and CP have been satisfied.

11.7 Relative to the maintenance of external corrosion control facilities, the following information should be recorded:

11.7.1 Maintenance of CP facilities:

11.7.1.1 Repair of rectifiers and other DC power sources; and

11.7.1.2 Repair or replacement of anodes, connections, wires, and cables.

11.7.2 Maintenance of interference bonds and reverse current switches:

11.7.2.1 Repair of interference bonds; and

11.7.2.2 Repair of reverse current switches or equivalent devices.

11.7.3 Maintenance, repair, and replacement of external coating, isolating devices, test leads, and other test facilities.

11.8 Records sufficient to demonstrate the evaluation of the need for and the effectiveness of external corrosion control measures should be maintained as long as the facility involved remains in service. Other related external corrosion control records should be retained for such a period that satisfies individual company needs.

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## Appendix A—Interference Testing

A beta curve is a plot of dynamic (fluctuating) interference current or related proportional voltage (ordinate) versus values of corresponding structure-to-soil potentials at a selected location on the affected structure (abscissa). If the correlation is reasonably linear, the plot will indicate whether the affected structure is receiving or discharging current at the location where the structure-to-soil potential was measured. Dynamic interference investigation involves many beta curve plots to search for the point of maximum interference-current discharge. Interference is resolved when the correlation of maximum current discharge has been changed to a correlation that shows that current pickup is being achieved in the exposure area by the corrective measures taken. These corrective measures may be accomplished by metallic bonding or other interference control techniques.

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## Appendix B—Method for Determining Probable Corrosion Rate and Costs of Maintaining Service

Maintenance of a piping system may include repairing corrosion leaks and reconditioning or replacing all or portions of the system.

In order to make estimates of the costs involved, it is necessary to determine the probability of corrosion or the rate at which corrosion is proceeding. The usual methods of predicting the probability or rate of corrosion are as follows:

(a) Study of corrosion history on the piping system in question or on other systems of the same material in the same general area or in similar environments. Cumulative leak-frequency curves are valuable in this respect.

(b) Study of the environment surrounding a piping system: resistivity, pH, and composition. Redox potential tests may also be used to a limited extent. Once the nature of the environment has been determined, the probable corrosiveness is estimated by reference to actual corrosion experience on similar metallic structures, when environmental conditions are similar. Consideration of possible environmental changes such as might result from irrigation, spillage of corrosive substances, pollution, and seasonal changes in soil moisture content should be included in such a study.

(c) Investigation for corrosion on a piping system by visual inspection of the pipe or by instruments that mechanically or electrically inspect the condition of the pipe. Condition of the piping system should be carefully determined and recorded each time a portion of the line is excavated for any reason.

(d) Maintenance records detailing leak locations, soil studies, structure-to-electrolyte potential surveys, surface potential surveys, line current studies, and wall thickness surveys used as a guide for locating areas of maximum corrosion.

(e) Statistical treatment of available data.

(f) Results of pressure testing. Under certain conditions, this may help to determine the existence of corrosion.

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## Appendix C—Contingent Costs of Corrosion

In addition to the direct costs that result from corrosion, contingent costs include:

(a) Public liability claims;

(b) Property damage claims;

(c) Damage to natural facilities, such as municipal or irrigation water supplies, forests, parks, and scenic areas;

(d) Cleanup of product lost to surroundings;

(e) Plant shutdown and startup costs;

(f)   Cost of lost product;

(g)   Loss of revenue through interruption of service;

(h)   Loss of contract or goodwill through interruption of service; and

(i)   Loss of reclaim or salvage value of piping system.

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## Appendix D—Costs of Corrosion Control

The usual costs for protecting buried or submerged metallic structures are for complete or partial CP or for external coatings supplemented with cathodic protection. Other corrosion control costs include:

(a)   Relocation of piping to avoid known corrosive conditions (this may include installing lines above ground);

(b)   Reconditioning and externally coating the piping system;

(c)   Use of corrosion-resistant materials;

(d)   Use of selected or inhibited backfill;

(e)   Electrical isolation to limit possible galvanic action; and

(f)   Correction of conditions in or on the pipe that might accelerate corrosion.

# Standard Practice

# Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems

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## Foreword

This standard practice presents guidelines and procedures for use during design, construction, operation, and maintenance of metallic structures and corrosion control systems used to mitigate the effects of lightning and alternating current (AC) power transmission systems. This standard is not intended to supersede or replace existing electrical safety standards. As shared right-of-way and utility corridor practices become more common, AC influence on adjacent metallic structures has greater significance, and personnel safety becomes of greater concern. This standard addresses problems primarily caused by proximity of metallic structures to AC-powered transmission systems.

The hazards of lightning and AC effects on aboveground pipelines, while strung along the right-of-way prior to installation in the ground, are of particular importance to pipeline construction crews. The effects of AC power lines on buried pipelines are of particular concern to operators of aboveground appurtenances and cathodic protection (CP) testers, CP designers, safety engineers, as well as maintenance personnel working on the pipeline.

Some controversy arose in the 1995 issue of this standard regarding the shock hazard stated in Section 5, Paragraph 5.2.1.1 and elsewhere in this standard. The reason for a more conservative value is that early work by George Bodier[1] at Columbia University and by other investigators has shown that the average hand-to-hand or hand-to-foot resistance for an adult male human body can range between 600 ohms and 10,000 ohms. A reasonable safe value for the purpose of estimating body currents is 1,500 ohms hand-to-hand or hand-to-foot. In other work by C.F. Dalziel[2] on muscular contraction, the inability to release contact occurs in the range of 6 to 20 mA for adult males. Ten mA hand-to-hand or hand-to-foot is generally established as the absolute maximum safe let-go current. Conservative design uses an even lower value. Fifteen volts of AC impressed across a 1,500-ohm load would yield a current flow of 10 mA; thus, the criterion within this standard is set at 15 volts. Prudent design would suggest an even lower value under certain circumstances.

Many are now concerned with AC corrosion on buried pipelines adjacent to or near overhead electric transmission towers. This subject is not quite fully understood, nor is there an industry consensus on this subject. There are reported incidents of AC corrosion on buried pipelines under specific conditions, and there are also many case histories of pipelines operating under the influence of induced AC for many years without any reports of AC corrosion. The members of NACE Task Group (TG) 025 agreed that any criteria for AC corrosion control should not be included in this standard. However, the mitigation measures implemented for safety and system protection, as outlined in this standard, can also be used for AC corrosion control.

This standard was originally published in July 1977 by Unit Committee T-10B on Interference Problems and was technically revised in 1983, 1995, 2000, and 2007. NACE continues to recognize the need for a standard on this subject. Future development and field experience should provide additional information, procedures, and devices for Specific Technology Group (STG) 05 on Cathodic/Anodic Protection to consider in future revisions of this standard. This standard was revised in 2007 by TG 025 on Alternating Current (AC) Power Systems, Adjacent: Corrosion Control and Related Safety Procedures to Mitigate the Effects. This standard is issued by NACE under the auspices of STG 05.

In NACE standards, the terms *shall*, *must*, *should*, and *may* are used in accordance with the definitions of these terms in the *NACE Publications Style Manual*, 4th ed., Paragraph 7.4.1.9. *Shall* and *must* are used to state mandatory requirements. The term *should* is used to state something good and is recommended but is not mandatory. The term *may* is used to state something considered optional.

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# NACE International
# Standard Practice

# Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems

**Contents**

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## Section 1:  General

1.1  This standard presents acknowledged practices for the mitigation of AC and lightning effects on metallic structures and corrosion control systems.

1.2  This standard covers some of the basic procedures for determining the level of AC influence and lightning effects to which an existing metallic structure may be subjected and outlines design, installation, maintenance, and testing procedures for CP systems on structures subject to AC influence, primarily caused by proximity of metallic structures to AC power transmission systems.  However, this standard is not intended to be a design guide or a "how-to" engineering manual to perform AC interference studies or mitigation designs.

1.3  This standard does not designate procedures for any specific situation.  The provisions of this standard should be applied under the direction of competent persons, who, by reason of knowledge of the physical sciences and the principles of engineering and mathematics, acquired by professional education and related practical experience, are qualified to engage in the practice of corrosion control on metallic structures.  Such persons may be registered professional engineers or persons recognized as being qualified and certified as corrosion specialists by NACE, if their professional activities include suitable experience in corrosion control on metallic structures and AC interference and mitigation.

1.4  This standard should be used in conjunction with the references contained herein.

## Section 2:  Definitions

2.1 Definitions presented in this standard pertain to the application of this standard only.  Reference should be made to other industry standards when appropriate.

**AC Exposure:**  Alternating voltages and currents induced on a structure because of the AC power system.

**AC Power Structures:**  The structures associated with AC power systems.

**AC Power System:**  The components associated with the generation, transmission, and distribution of AC.

**Affected Structure:**  Pipes, cables, conduits, or other metallic structures exposed to the effects of AC or lightning.

**Bond:**  A low-impedance connection (usually metallic) provided for electrical continuity.

**Breakdown Voltage:**  A voltage in excess of the rated voltage that causes the destruction of a barrier film, coating, or other electrically isolating material.

**Capacitive Coupling:**  The influence of two or more circuits upon one another, through a dielectric medium such as air, by means of the electric field acting between them.

**Circular Mil:**  A unit of area of round wire or cable equal to the square of the diameter in mils (1 mil = 0.001 inch).

**Coating Stress Voltage:**  Potential difference between the metallic surface of a coated structure and the earth in contact with the outer surface of the coating.

**Coupling:**  The association of two or more circuits or systems in such a way that energy may be transferred from one to another.

**Dead-Front Construction:**  A type of construction in which the energized components are recessed or covered to preclude the possibility of accidental contact with elements having electrical potential.

**Direct Current (DC) Decoupling Device:**  A device used in electrical circuits that allows the flow of AC in both directions and stops or substantially reduces the flow of DC.

**Earth Current:**  Electric current flowing in the earth.

**Electric Field:**  One of the elementary energy fields in nature.  It occurs in the vicinity of an electrically charged body.

**Electric Potential:**  The voltage between a given point and a remote reference point.

**Electrolytic Grounding Cell:**  A device consisting of two or more buried electrodes installed at a fixed spacing, commonly made of zinc, and resistively coupled through a prepared backfill mixture.  The electrical characteristics of a grounding cell include a small degree of resistance and a subsequent reduced voltage drop across the cell during a fault condition.

**Fault Current:**  A current that flows from one conductor to ground or to another conductor due to an abnormal connection (including an arc) between the two.  A fault current flowing to ground may be called a ground fault current.

**Fault Shield:** Shallow grounding conductors connected to the affected structure adjacent to overhead electrical transmission towers, poles, substations, etc., to provide localized protection to the structure and coating during a fault event from nearby electric transmission power systems.

**Ground:** An electrical connection to earth.

**Ground Current:** Current flowing to or from earth in a grounding circuit.

**Grounded:** Connected to earth or to some extensive conducting body that serves instead of the earth, whether the connection is intentional or accidental.

**Ground Electrode Resistance:** The ohmic resistance between a grounding electrode and remote earth.

**Gradient Control Mat:** A system of bare conductors connected to the affected structure and placed on or below the surface of the earth, usually at above grade or exposed appurtenances, arranged and interconnected to provide localized touch-and-step voltage protection. Metallic plates and grating of suitable area are common forms of ground mats, as well as conventional bare conductors closely spaced.

**Gradient Control Wire:** A continuous and long grounding conductor or conductors installed horizontally and parallel to the affected structure at strategic lengths and connected at regular intervals to provide protection to the structure and coating during steady-state and fault AC conditions from nearby electric transmission power systems.

**Grounding Grid:** A system of grounding electrodes consisting of interconnected bare conductors buried in the earth to provide a common electrical ground.

**Guarded:** Covered, fenced, enclosed, or otherwise protected by means of suitable covers or casings, barrier rails or screens, mats, or platforms; designed to limit the likelihood, under normal conditions, of dangerous approach or accidental contact by persons or objects. [3]

**Inductive Coupling:** The influence of two or more circuits upon one another by means of changing magnetic flux linking them together.

**Lightning:** An electric discharge that occurs in the atmosphere between clouds or between clouds and the earth.

**Load Current:** The current in an AC power system under normal operating conditions.

**Lumped Grounding:** Localized grounding conductors, either shallow or deep, connected to the affected structure at strategic locations to provide protection to the structure and coating during steady-state and fault AC conditions from nearby electric transmission power systems.

**Magnetic Field:** One of the elementary energy fields in nature. It occurs in the vicinity of a magnetic body or current-carrying medium.

**Over-Voltage Protector (Surge Arrester):** A device that provides high resistance to DC and high impedance to AC under normal conditions within the specified DC and AC threshold rating and "closes" or has a very low resistance and impedance during upset conditions.

**Polarization Cell:** A DC decoupling device consisting of two or more pairs of inert metallic plates immersed in an aqueous electrolyte. The electrical characteristics of the polarization cell are high resistance to DC potentials and low impedance of AC.

**Potential:** See *Electric Potential*.

**Potential Gradient:** Change in the potential with respect to distance.

**Reclosing Procedure:** A procedure that normally takes place automatically whereby the circuit breaker system protecting a transmission line, generator, etc., recloses one or more times after it has tripped because of abnormal conditions such as surges, faults, lightning strikes, etc.

**Reference Electrode:** An electrode whose open-circuit potential is constant under similar conditions of measurement, which is used for measuring the relative potentials of other electrodes.

**Remote Earth:** A location on the earth far enough from the affected structure that the soil potential gradients associated with currents entering the earth from the affected structure are insignificant.

**Resistive Coupling:** The influence of two or more circuits on one another by means of conductive paths (metallic, semi-conductive, or electrolytic) between the circuits.

**Shock Hazard:** A condition considered to exist at an accessible part in a circuit between the part and ground or other accessible part if the steady-state open-circuit AC voltage is 15 V or more (root mean square [rms]). For capacitive build-up situations, a source capacity of 5 mA or more is recognized as a hazardous condition. For short-circuit conditions, the permissible touch-and-step voltages should be determined in accordance with the methodology specified in accordance with IEEE[(1)] Standard 80. [4]

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[(1)] Institute of Electrical and Electronics Engineers (IEEE), Three Park Avenue, 17th Floor, New York: NY 10016-5997.

**Solid-State DC Decoupler:** A dry type of DC decoupling device comprising solid-state electronics. The electrical characteristics of a solid-state decoupler are high resistance to low voltage DC and low impedance to AC.

**Step Potential or Voltage:** The potential difference between two points on the earth's surface separated by a distance of one human step, which is defined as one meter, determined in the direction of maximum potential gradient.

**Stray Current:** Current through paths other than the intended circuit.

**Surface Potential Gradient:** Change in the potential on the surface of the ground with respect to distance.

**Switching Surge:** The transient wave of potential and current in an electric system that results from the sudden change of current flow caused by a switching operation, such as the opening or closing of a circuit breaker.

**Touch Potential or Voltage:** The potential difference between a metallic structure and a point on the earth's surface separated by a distance equal to the normal maximum horizontal reach of a human (approximately 1.0 m [3.3 ft]).

**Voltage:** The difference in electrical potential between two points.

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## Section 3: Exposures and Effects of Alternating Current and Lightning

3.1 Introduction

3.1.1 This section outlines the physical phenomena by which AC, AC power systems, and lightning may affect metallic structures.

3.2 Resistive Coupling (Electrolytic)

3.2.1 Grounded structures of an AC power system share an electrolytic environment with other underground or submerged structures. Coupling effects may transfer AC energy to a metallic structure in the earth in the form of alternating current or potential. Whenever a power system with a grounded neutral has unbalanced conditions, current may flow in the earth. Substantial currents in the earth may result from phase-to-phase-to-ground or phase-to-ground faults. A metallic structure in the earth may carry part of this current. Also, a structure in the earth coated with a dielectric material may develop a significant AC potential across the coating.

3.2.2 Resistive coupling is primarily a concern during a short-circuit condition on a power system, for example, when a large part of the current in a live conductor flows into the earth by means of the foundations and grounding system of a tower, pole, or substation. This current flow raises the electric potential of the earth near the structure, often to thousands of volts with respect to remote earth, and can result in a considerable stress voltage across the coating (see Paragraph 4.13) of a long metallic structure, such as a pipeline. This can lead to arcing that damages the coating, or even the structure itself. This difference in potential between the earth and the structure can represent an electric shock hazard. The effect of resistive coupling is usually concentrated in the vicinity of each of the first few power system poles or towers nearest the short-circuit location and near any substations involved in the short circuit. Under some circumstances, the electric potential of the structure

may be raised enough to transfer hazardous potentials over considerable distances, particularly if the structure is well coated. Resistive coupling effects are strongly dependent on a number of factors, the most important of which are:

(a) The total short-circuit current;

(b) The power line overhead ground wire type and length back to the source;

(c) The size of the foundations and grounding systems of the poles, towers, or substations through which the current is flowing;

(d) The electrical resistivity of the soil as a function of depth; and

(e) Separation distance between power systems and the affected metallic structure.

The electrical layering of the soil alone can easily change resistive coupling effects by an order of magnitude or more.

3.3 Capacitive Coupling

3.3.1 The electric field associated with power conductors cause a well defined current to flow continuously between a nearby aboveground metallic structure and the earth, whether that aboveground structure is grounded or simply suspended in the air. This current flows from the structure to the earth partially through the air as a displacement current and partially through conductive or semi-conductive paths such as deliberate grounds, wooden supports, or human beings touching the structure. The magnitude of the total current flowing from the structure is a function of the size of the structure, its proximity to the power conductors, the voltage level of the power conductors, and their geometrical arrangement. The total current flowing between the metallic structure and

earth distributes itself between the different available paths to earth in direct proportion to the relative conductivity of each path. For example, a 100-ohm ground rod would carry 10 times as much current to earth as a 1,000-ohm human being, thus reducing the magnitude of the available shock current by a factor of 10. Capacitive coupling is typically a hazard during construction with respect to electric shock or arcing when the structure is on insulating supports prior to lowering in or connecting to an adjacent section. Ground rods and bonding often provide sufficient protection. The need for additional grounding can be verified with a simple voltmeter test.

3.4 Inductive Coupling

3.4.1 AC flow in power conductors produces an alternating magnetic field around these conductors, thereby inducing AC potentials and current flow in an adjacent structure. The magnitude of the induced potential depends on many factors. The most important are:

(a) The overall separation distance between the structure and the power line;

(b) The length of exposure and the power line current magnitude;

(c) Changes in the arrangement of power line conductors or in separation distance;

(d) The degree to which current flowing in one power line conductor is balanced by the currents flowing in the others due to conductor arrangement and current distribution;

(e) The type of conductor used for the lightning shield wires on the power line;

(f) The coating resistance of the structure;

(g) The grounding present on the structure; and

(h) The soil resistivity as a function of depth.

Grounding is usually present to some degree because of leakage across the coating or anodes of the CP system connected to the structure. Induced voltages increase in magnitude during fault conditions. The coating stress voltages caused by the inductive coupling near a short-circuit location tend to reinforce those caused by resistive coupling; therefore, both factors must be considered. The same is true for touch-and-step voltages. Hazardous induced potentials can easily extend over distances of many kilometers (miles), both within a power line corridor and

beyond the extremities of the corridor. Considerable power may be transferred to a structure by means of inductive coupling and can result in currents of tens or even hundreds of amperes flowing in the structure during peak power system operating conditions, and thousands of amperes during short-circuit conditions. Potential peaks tend to occur at locations in which there are abrupt changes in the parameters. These are usually locations where power lines and structures deviate away from or cross one another at substations or at power line phase transposition locations. Installing grounding at one location can make matters significantly worse elsewhere; therefore, it is important to consider the whole system carefully when designing mitigation.

3.5 Power Arc

3.5.1 During a fault-to-ground on an AC power system, the AC power structures and surrounding earth may develop a high potential with reference to remote earth. A long metallic structure, whether coated or bare, tends to remain at remote earth potential if not running parallel to the AC power lines. Worse still, if the structure runs parallel to the AC power lines, the induced potential on the structure tends to be opposite in polarity to the earth potential near the fault location at any given instance in time. Either way, if the resulting voltage to which the structure is subjected exceeds the breakdown voltage of any circuit element, a power arc can occur, damaging the circuit elements. Elements of specific concern include coatings, isolating fittings, bonds, lightning arresters, and CP facilities. If the potential gradient in the earth is large enough to ionize the soil for a finite distance, a direct arc from the power system ground to the structure can occur within that distance and result in coating damage, arc burn, or puncture/failure of the structure.

3.6 Lightning

3.6.1 Lightning strikes to the power system can initiate fault current conditions. Lightning strikes to a structure or to earth in the vicinity of a structure can produce electrical effects similar to those caused by AC fault currents. Lightning may strike a metallic structure at some point remote from AC power systems, also with deleterious effects.

3.7 Switching Surges or Other Transients

3.7.1 A switching surge or other transient may generate abnormally high currents or potentials on a power system, causing a momentary increase in inductive and capacitive coupling on the affected structures.

## Section 4:  Design Considerations for Protective Devices

4.1  Introduction

4.1.1  This section describes various protective devices used to help mitigate AC effects on metallic structures subject to hazardous AC conditions, minimize damage to the structures, and reduce the electrical hazard to people coming in contact with these structures.

4.1.2  The methods listed can be used to mitigate the problems of power arcing, lightning arcing, resistive coupling, inductive coupling, and capacitive coupling.[3,4,5]  These methods may also be used to mitigate AC corrosion.

4.1.3  Design considerations should include steady-state conditions (including touch voltage and maximum pipe potentials during normal, emergency, and future loads) and fault conditions (including touch-and-step voltage, avoidance of pipe wall puncture and arc burns, and tolerable coating stress voltages).

4.1.4  Design mitigation objectives should be clearly defined.  As a minimum, the mitigation objectives should include the maximum steady-state voltage at above-grade portions and appurtenances, maximum pipe potential (ground potential rise [GPR]) for the normally buried and inaccessible portions, touch-and-step voltage criteria at above-grade portions and appurtenances during fault conditions, and the maximum coating stress voltage during fault conditions.

4.2  Fault Shields, Lumped Grounding, and Gradient Control Wires

4.2.1  Fault shields consist of shallow grounding conductors (i.e., electrodes) connected to the affected structure adjacent to overhead electrical transmission towers, poles, substations, etc.  They are intended to provide localized protection to the structure and coating during a fault event from a nearby electric transmission power system.  Fault shields can reduce the possibility of puncturing the coating or structure under fault conditions.

4.2.2  Lumped grounding consists of a localized conductor or conductors connected to the affected structure at strategic locations (e.g., at discontinuities). It is intended to protect the structure from both steady-state and fault AC conditions.  Lumped grounding systems may be installed in shallow or deep configurations, depending on the site-specific parameters.  Lumped grounding can reduce the steady-state touch voltages and the possibility of puncturing the coating or structure under fault conditions; however, grounding between the lumped

grounding locations may be required for complete protection.

4.2.3  Gradient control wires consist of a continuous and long grounding conductor or conductors installed horizontally and parallel to a structure (e.g., pipeline section) at strategic lengths and connected at regular intervals.  They are intended to provide protection to the structure and coating during steady-state and fault AC conditions from nearby electric transmission power systems.  Gradient control wires can reduce the steady-state voltages and the possibility of puncturing the coating or structure under fault conditions.

4.2.4  Among the factors that influence mitigation design is the extent to which the structure is affected and the magnitude of the electrical potential between the structure and earth.  These factors vary from one location to another and must be calculated or determined for each specific location.  A combination of the above methods may be utilized, depending on the specific AC mitigation requirements.

4.2.5  Electrodes constructed of materials that are cathodic to the protected structure must be connected to the structure through a DC decoupling device, unless both the structure and electrode are cathodically protected as a single unit.  Electrodes constructed of materials that are anodic to the protected structure may be connected directly to the structure; however, the CP design must be verified to be compatible with this type of circuitry.

4.2.6  Other types of systems can be designed for protection against faults on miscellaneous underground or aboveground structures.

4.3  Gradient Control Mats

4.3.1  Gradient control mats, bonded to the structure, are used to reduce electrical touch-and-step voltages in areas where people may come in contact with a structure subject to hazardous potentials.  Permanent mats bonded to the structure may be used at valves, metallic vents, CP test stations, and other aboveground metallic and nonmetallic appurtenances in which electrical contact with the affected structure is possible.

4.3.2  Gradient control mats should be large enough to extend through and beyond the entire area on which people may be standing when contacting the affected structure.  They should be installed close enough to the surface to adequately reduce touch-and-step voltages for individuals coming in contact with the structure.[6] Gradient control mats should be engineered to provide acceptable touch-and-step voltages during both load

and fault conditions, accounting for the local soil conditions.

4.3.3 Gradient control mats, regardless of materials of construction, must be bonded to the structure, preferably at more than one point. If CP of the structure becomes difficult because of shielding, a DC decoupling device may be installed. Connections to the structure should be made aboveground to allow a means of testing for effect of the gradient control mat in reducing AC potentials and its effectiveness on the CP system. Care should be taken to prevent the possible establishment of detrimental galvanic cells between the gradient control mat and structures that are not cathodically protected.

4.3.4 A bed of clean, well-drained gravel can reduce the shock hazard associated with touch-and-step voltages. Although an excellent practice, if hazardous conditions exist for pipeline applications, increasing the surface resistance should be used to augment the grounding system and not as a sole protection measure, as it may not be well maintained and kept clean. The thickness of the bed should be no less than 76 mm (3.0 in.). Gravel should be a minimum of 13 mm (0.50 in.) in diameter. The hazards of step voltages at the edge of a mat may be mitigated by extending the gravel beyond the perimeter of the grounding mat.

4.4 Independent Structure Grounds

4.4.1 Wherever a metallic structure subject to hazardous AC that is not electrically connected to an existing grounded structure is installed, it shall have an independent grounding system. This grounding system may consist of one or more ground rods and interconnecting wires. Care shall be taken to interconnect all components of the structure to be grounded properly. Factors considered in the design of the grounding system of an independent structure include the resistivity of the soil and the magnitude of the induced potential and current that the designer expects the structure to encounter under all possible conditions.

4.4.2 When an independent metallic structure or its grounding system is in close proximity to an existing grounded structure, an electrical hazard may develop for any person contacting both structures or their grounds simultaneously. In such cases, both grounding systems should be connected, either directly or through a DC decoupling device, unless it is determined that such a connection is undesirable. The electrical and CP designers should both be involved with this evaluation. For more details on designing systems for independent structures, see IEEE Standard 80.[4]

4.5 Bonding to Existing Structures

4.5.1 One available means of reducing induced AC potentials on a structure involves bonding the structure to the power system ground through adequately sized cables and decoupling devices. Such bonds may, under fault conditions, contribute to increased potentials and currents on the affected structure for the duration of the fault. If the bonded structure is aboveground, or well-insulated from earth, elevated potentials may be created and exist temporarily along the entire length of the bonded structure. In such instances, additional protective devices may be required outside the immediate area of the origin of electrical effects. Close coordination should be maintained with all other utilities in the area, especially with those utilities to which bond connections are proposed. The corresponding utilities shall be notified in advance of the need to bond to their structures and shall be furnished with details of the proposed bonding arrangements. A utility may prefer to have the connection to its structures made by its own personnel. Other methods of reducing AC potentials should be considered before committing to bonding. The increased hazards during fault conditions and extra installation requirements may make this method questionable from safety and economic perspectives.

4.5.2 Whenever such a bond is installed, full consideration must be given to mitigation of hazardous AC transferred to the influenced structure.

4.6 Distributed Anodes

4.6.1 Whenever distributed galvanic anodes are used as part of the grounding system to reduce the AC potential between a structure and earth, they should be installed in close proximity to the protected structure and away from power system grounds. Connecting anodes directly to the affected structure, without test connections, may be desirable. Direct connection reduces the number of points at which people can come in contact with the structure and offers the shortest path to ground. Should it be desirable for measurement purposes to open the circuit between the distributed grounding system and the structure, the test lead connection should be made in an accessible dead-front test box. When galvanic anodes are used as part of a grounding system, the useful life of the electrode material should be considered. Normal deterioration and consumption of the anode material increases the grounding system resistance.

4.7 Casings

4.7.1 Bare or poorly coated casings may be deliberately connected to a coated structure through a DC decoupling device to lower the impedance of the structure to earth during surge conditions and to avoid arcing between the structure and the casing.

4.8 Connector (Electrical and Mechanical) and Conductor Sizes

4.8.1 All anodes, bonds, grounding devices, and jumpers must have secure, reliable, low-resistance connections to themselves and to the devices to which they are attached. Structure members with rigid bolted, riveted, or welded connections may be used in lieu of a bonding cable for part or all of the circuit. Steady-state conductor sizing should consider the AC load with the mitigation applied. For adequate fault sizing of conductors, refer to Table 1 and Figures 1, 2, 3, and 4. For wire gauge conversions, refer to Table A1 in Appendix A (nonmandatory). All cables, connections, and structural members should be capable of withstanding the maximum anticipated magnitude and duration of the surge or fault currents with mitigation applied.

**Table 1:  Maximum 60 Hz Fault Currents—Grounding Cables[A]**

| Cable Size AWG[B] | Fault Time Cycles | rms[C] Amperes | | Cable Size AWG[B] | Fault Time Cycles | rms[C] Amperes | |
|---|---|---|---|---|---|---|---|
| | | Copper | Aluminum | | | Copper | Aluminum |
| 1 | 15 | 10,550 | 6,500 | 3/0 | 15 | 26,500 | 16,500 |
| | 30 | 7,500 | 4,600 | | 30 | 18,500 | 16,500 |
| | 60 | 5,300 | 3,200 | | 60 | 13,000 | 8,000 |
| 1/0 | 15 | 16,500 | 10,500 | 4/0 | 15 | 30,000 | 21,000 |
| | 30 | 11,500 | 7,500 | | 30 | 21,000 | 15,000 |
| | 60 | 8,000 | 5,300 | | 60 | 15,000 | 10,000 |
| 2/0 | 15 | 21,000 | 13,000 | 250 MCM[D] | 15 | 35,000 | 25,000 |
| | 30 | 15,000 | 9,000 | | 30 | 25,000 | 17,500 |
| | 60 | 10,000 | 6,500 | | | | |

[A] Based on 30°C (86°F) ambient and a total temperature of 175°C (347°F) established by the Insulated Cable Engineers Association (ICEA)[2] for short-circuit characteristic calculations for power cables.  Values are approximately 58% of fusing currents.
[B] American Wire Gauge (AWG)
[C] Root mean square
[D] MCM = 1,000 circular mils

4.8.2 Mechanical connections for the installation of permanent protective devices should be avoided when practical except when they can be inspected, tested, and maintained in approved aboveground enclosures. When practical, field connections to the structure or grounding device should be made by the exothermic welding process. However, compression-type connectors may be used for splices on connecting wires. Mechanical connectors may be used for temporary protective measures, but extreme care should be taken to avoid high-resistance contacts. Soft-soldered connections are not acceptable in grounding circuits.

Figure 1 is based on the assumption that no heat is radiated or conducted from the cable to the surrounding media during a fault period. Electrical energy released in the cable equals the heat energy absorbed by the cable. This is illustrated in Equation (1):

$$I^2 Rt = CFQ \qquad (1)$$

Where:

I = fault current in amperes
R = average AC resistance (in ohms) of conductor over temperature range $T_1$ to $T_2$ in °C (°F)
t = fault duration in seconds
Q = heat energy in kJ (BTU)
CF = conversion factor = 1,000 for SI units (1 W=J/s and 1,000 J/kJ) and 1,055 for U.S. units (1,055 W-s/BTU)

Q is calculated using Equation (2):

$$Q = CM (T_2 - T_1) \; [\text{Thermodynamics}] \qquad (2)$$

Where:

C = average specific heat in kJ/kg °C (BTU/lb °F) of annealed soft-drawn copper over the temperature range $T_1$ to $T_2$
M = mass of copper in kg (lb)
$T_1$ and $T_2$ = initial and final temperatures respectively in °C (°F).

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[2] Insulated Cable Engineers Association (ICEA), P.O. Box 440, Carrollton, GA 30112.

Figure 1 was developed using C = 0.104 BTU/lb °F, T1 = 68°F, and T2 = 1,300°F  Typical resistance values are shown in Table 2.
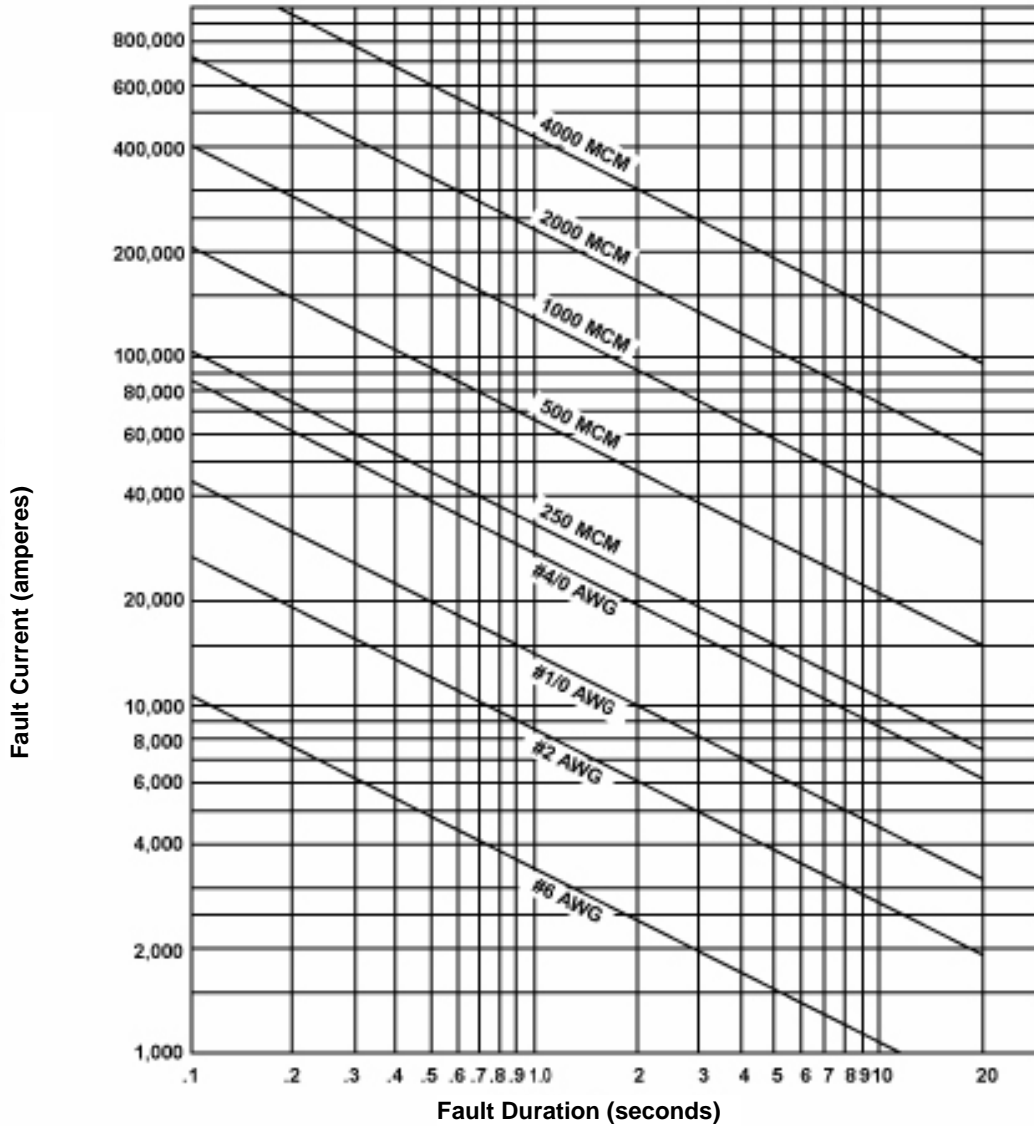


**FIGURE 1: Approximate Current Required to Raise the Temperature of Stranded Annealed Soft-Drawn Copper Cable 684⁰C (1,232⁰F) Above an Ambient Temperature of 20⁰C (68⁰F)[3]**

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[3] This figure was developed by Ebasco Services, Inc. (now Raytheon Company, 870 Winter St., Waltham, MA 02451), who graciously allowed its publication in the original standard.

**TABLE 2:  Average Impedance for Various Conductor Sizes[A]**

| Conductor[B] | Average 60-Hz Impedance (Ohms/1,000 ft) | Average 60-Hz Impedance (Ohms/km) |
|---|---|---|
| #6 AWG | 0.923 | 3.03 |
| #2 AWG | 0.366 | 1.20 |
| #1/0 AWG | 0.2295 | 0.753 |
| #4/0 AWG | 0.1097 | 0.360 |
| 250 MCM | 0.0968 | 0.318 |
| 500 MCM | 0.0492 | 0.161 |
| 1,000 MCM | 0.0259 | 0.0850 |
| 2,000 MCM | 0.0151 | 0.0495 |
| 4,000 MCM | 0.00972 | 0.0319 |

[A] Fusing current is 10% higher than current for 684°C (1,232°F) temperature rise.
[B] For cable sizes in metric units, see Appendix A (nonmandatory).
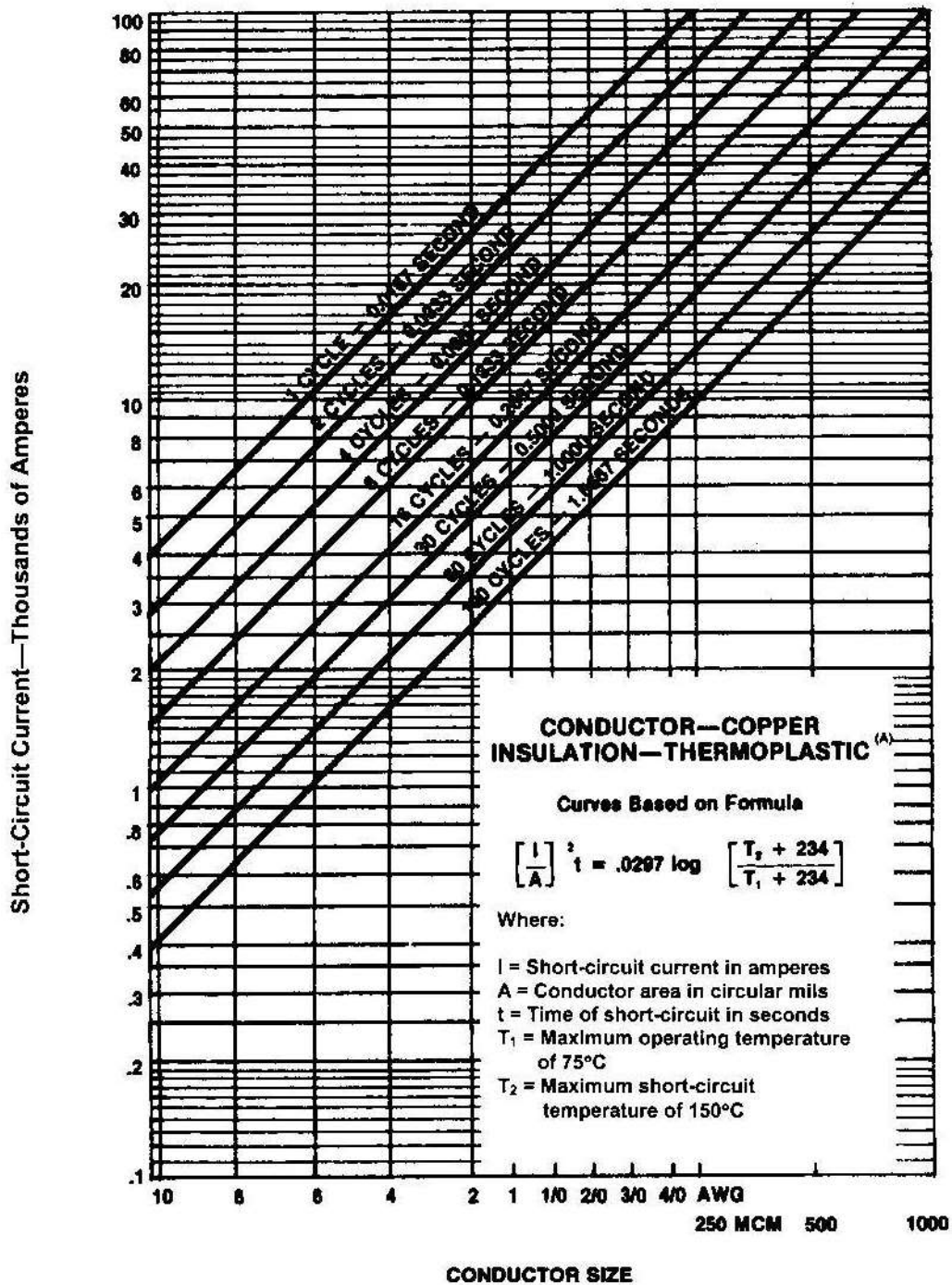
FIGURE 2: Allowable Short-Circuit Currents for Insulated Copper Conductors[7]

(A) To calculate this formula when the conductor sizes are in metric units, change metric values to circular mils for A as indicated in Table A1, Appendix A (nonmandatory).
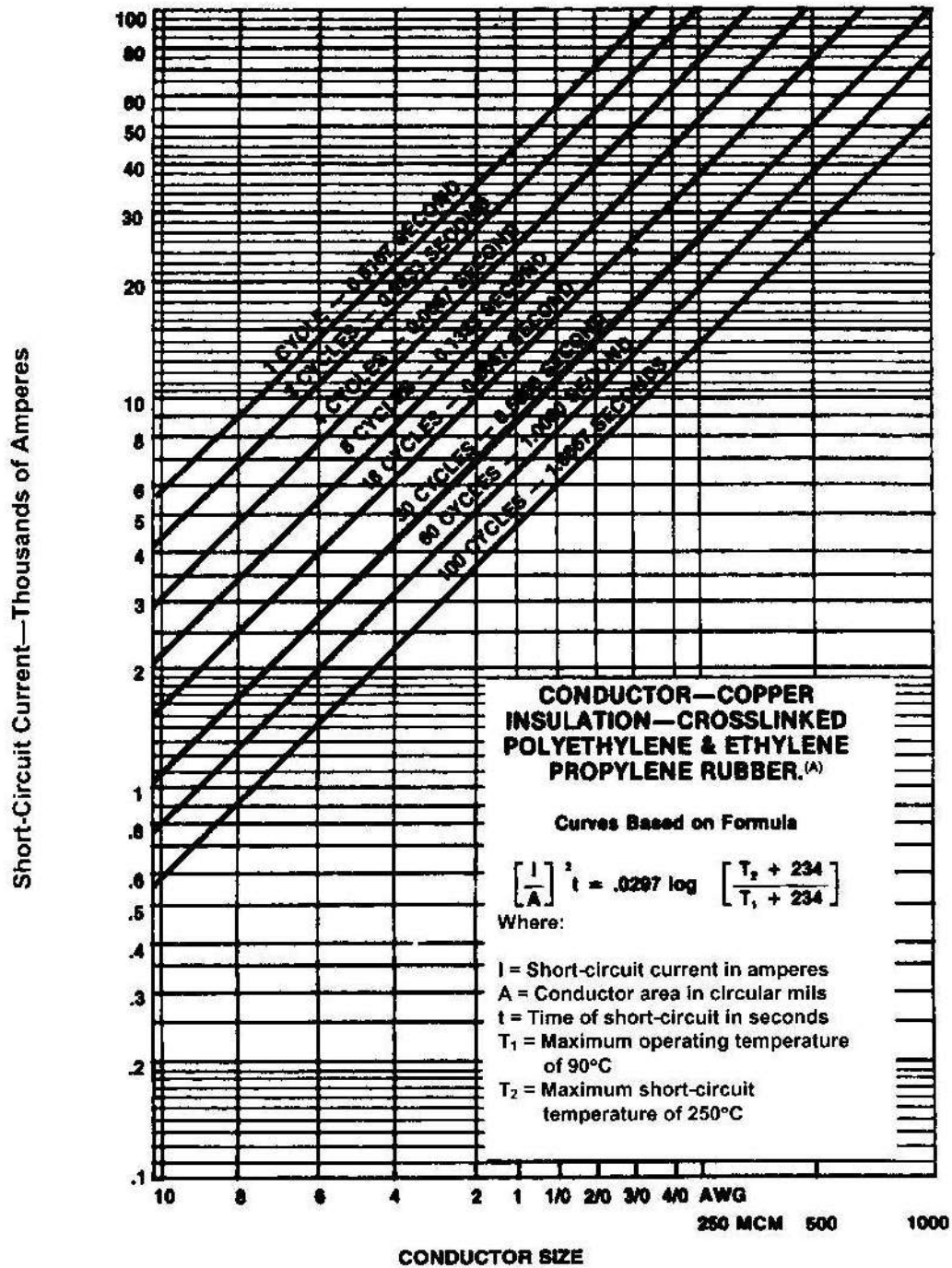
**FIGURE 3: Allowable Short-Circuit Currents for Insulated Copper Conductors[7]**

(A) To calculate this formula when the conductor sizes are in metric units, change metric values to circular mils for A as indicated in Table A1, Appendix A (nonmandatory).
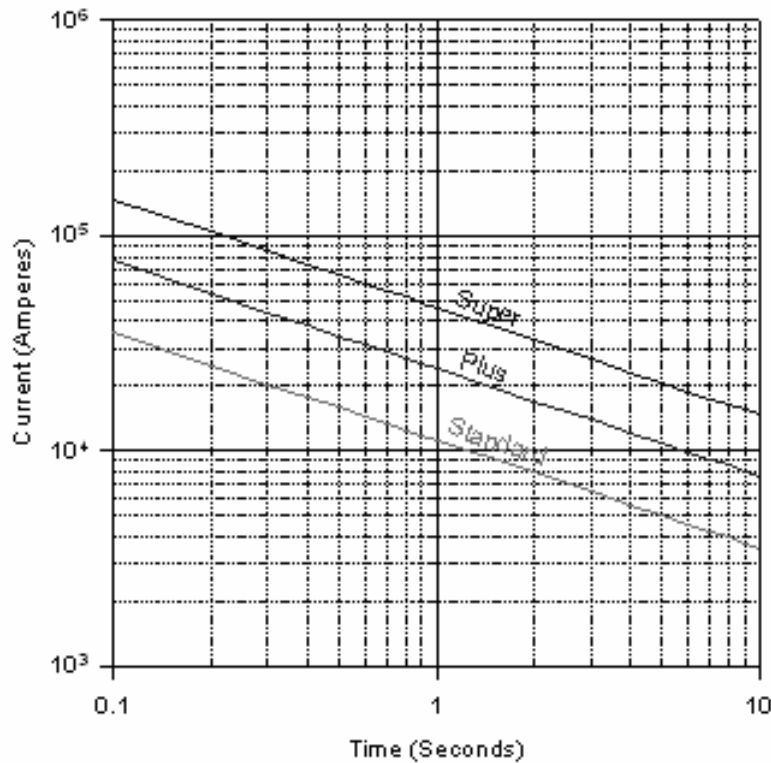
**FIGURE 4: Zinc Ribbon Ampacity**[4]

**Experimental results for 60-Hz current required to raise the temperature of three sizes of cast- and rolled-zinc ribbon anode from 20°C (68°F) to 250°C (482°F).**[8]

Super:  25.4 mm x 31.75 mm (1 in. x 1.25 in.)
Plus:  15.88 mm x 22.22 mm (0.625 in. x 0.875 in.)
Standard:  12.7 mm x 14.22 mm (0.50 in x 0.56 in.)

Note:  A design reduction factor should be determined by the user and applied in conjunction with the data in Figure 4, and connections to the ribbon steel core must be equivalent to the design ampacity requirement.

4.9  Isolation Joints

4.9.1  Although isolation joints (including flanges and fittings) can be installed to divide a structure into shorter electrical sections or to isolate a section adjacent to an AC power system from the remainder of the structure, this practice must be considered carefully for the specific application.  When used to reduce the length of pipeline exposed to AC at the entrance and exit of AC right-of-ways, the beneficial grounding effect from the remaining pipeline is lost, and AC potentials can increase on the isolated section.  The voltage will be reduced in proportion to the length of the sections if used in the joint corridor; however, a potential hazard may exist across the isolation joint (IJ), and it will as a minimum require fault protection.  Hazardous conditions may be transferred to the other side of isolating devices, where mitigation and protection measures may not be present during a fault even without protection devices.  Therefore, the AC interference study and mitigation design should not ignore pipe sections and appurtenances that are normally DC isolated.  DC decouplers or other devices that continuously pass AC should be utilized in most cases of steady-state AC interference.  In cases in which the steady-state concerns are low, but faults are a possibility, over-voltage protection devices that close during an electrical disturbance should be provided.  The breakdown voltage for a typical IJ is in the range of 3 kV; however, arcing can occur at much lower voltages without dielectric breakdown.  Arcing conditions must also be avoided in hazardous (classified) locations.

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[4] Courtesy of the Platt Bros. and Company, Inc., 2760 S. Main St., Waterbury, CT 06721.

4.10 Electrolytic Grounding Cells, Solid-State DC Decouplers, Polarization Cells, and Other Devices

4.10.1 The coordinated selection and installation of electrolytic grounding cells, solid-state DC decouplers, polarization cells (2.5-V DC maximum threshold), or other devices between the affected structure and suitable grounds should be considered where arcing and induced AC potentials could develop. These devices may eliminate or greatly reduce the induced potentials resulting during normal operation or surge conditions and also reduce the possibility of arcing and structure puncture. Polarization cells and solid-state DC decouplers should be considered for steady-state AC interference applications, as these devices pass AC continuously. The device and installation must be rated for the area classification, when installed in a hazardous location.

4.10.2 When electrolytic grounding cells, solid-state DC decouplers, polarization cells (2.5-V DC maximum threshold), or other devices are used, they must be properly sized, located, connected, and physically secured in a manner that safely conducts the maximum amount of anticipated surge current. Cables connecting these devices to the structures shall be properly sized, as described in Paragraph 4.8.1. Cables should be kept as short and straight as possible. An adequately sized bypass circuit should be provided prior to any electrical isolation of the grounding device during testing and maintenance.

4.11 Over-Voltage Protectors

4.11.1 Surge arresters are available in many different types and for many applications. These include lightning arresters, spark gaps, solid-state electronic devices, and metal oxide varistors (MOV). These devices may be used between structures and across pipeline electrical isolating devices, generally when steady-state interference is not a problem. However, one restriction to the use of arresters is that a potential difference has to develop before the arrester conducts. With certain types of arresters, this potential may be high enough to become hazardous to people coming in contact with the arrester. When arresters are used, they must be connected to the structure through adequately sized cables, as described in Paragraph 4.8.1. Arresters require a reliable, low-resistance ground connection. They should be located close to the structure being protected and have a short, straight ground path. Short lead length is especially important for lightning protection when the voltage build-up caused by lead induction can be significant. An adequately sized bypass circuit should be provided prior to any isolation of the grounding device during testing or maintenance.

4.11.2 Certain types of sealed, explosion-proof, enclosed, or repetitive transient arresters may be used in locations where a combustible atmosphere is anticipated, but only if it can be determined that the maximum possible power fault current does not exceed the design rating of the arrester. Open spark gaps shall not be used in these locations. The device and installation must be rated for the area classification, when installed in a hazardous location.

4.12 Stray Direct Current Areas

4.12.1 Galvanic anodes (including those in electrolytic grounding cells), grounding grids, or grounds directly connected to the structure may pick up stray DC in areas where stray direct currents are present. This current could possibly discharge directly to earth from the structure at other locations, resulting in corrosion of the structure at those points. Also, DC pickup by the structure could lead to DC discharge to earth through the galvanic anodes or grounding devices, resulting in increased consumption of the anode material or corrosion of grounding rods and an increase in their effective resistance to earth. The use of DC decoupling devices should be considered in these cases.

4.13 Coating Stress Voltage

4.13.1 External pipeline coatings can be subjected to stress voltages during a fault event on a nearby high-voltage power system. Both conductive and inductive components of a fault contribute to the stress voltage, with the conductive component acting on soil potentials and the inductive component acting on the pipeline steel potential. Typically, the pipeline steel potential tends to be of opposite polarity to that of the earth potential so that the total coating stress voltage is on the same order as the sum of the magnitudes of the inductive and conductive components. Properly designed mitigation (i.e., grounding) can reduce the coating stress voltage to protect the coating from disbondment or puncture. This, in effect, also protects the pipeline wall from arc burns and puncture, as the tolerable coating stress voltages are lower than the conditions reported to cause damage to steel.

4.13.2 Limiting the coating stress voltage should be a mitigation objective. Expected threshold values for coatings differ with type and are generally considered to be in the range of up to 2 kV for tape wraps and coal tar enamels and 3 to 5 kV for fusion-bonded epoxy (FBE) and polyethylene coatings for a short duration fault.

## Section 5: Personnel Protection

5.1 Introduction

5.1.1 This section recommends practices that contribute to the safety of people who, during construction, system operation, corrosion survey, or CP maintenance of metallic structures, may be exposed to the hazards of AC potentials on those structures. The possibility of hazards to personnel during construction and system operation because of contact with metallic structures exposed to AC electrical or lightning effects must be recognized and provisions made to alleviate such hazards. The severity of the personnel hazard is usually proportional to the magnitude of the potential difference between the structure and the earth or between separate structures. The severity also depends on the duration of the exposure. Before construction work is started, coordination with the appropriate utilities in the area must be made so that proper work procedures are established and the construction does not damage or interfere with other utilities' equipment or operations.[5]

5.1.2 Each utility should be aware of the others' facilities and cooperate in the mitigation of the electrical effects of one installation on the other. The mitigation required for a specific situation must be based on safety considerations with good engineering judgment.

5.1.3 Increasing the separation distance between facilities is generally effective in reducing the electrical effects of one installation on another.

5.2 Recognition of Shock Hazards to Personnel

5.2.1 AC potentials on structures must be reduced to and maintained at safe levels to prevent shock hazards to personnel. The degree of shock hazard and the threshold levels of current that can be tolerated by human beings depend on many factors. The possibility of shock from lower voltages is the most difficult to assess. The degree of shock hazard depends on factors such as the voltage level and duration of human exposure, human body and skin conditions, and the path and magnitude of any current conducted by the human body. The magnitude of current conducted by the human body is a function of the internal impedance of the voltage source, the voltage impressed across the human body, and the electrical resistance of the body path. This resistance also depends on the contact resistance (e.g., wet or dry skin, standing on dry land or in water), and on the current path through the body (e.g., hand-to-foot, hand-to-hand, etc.). Tables 3 and 4 indicate the probable human resistance to electrical current and current values affecting human beings.

**TABLE 3:  Human Resistance to Electrical Current[9]**

| | |
|---|---|
| Dry skin | 100,000 to 600,000 ohms |
| Wet skin | 1,000 ohms |
| Internal body—hand to foot | 400 to 600 ohms |
| Ear to ear | about 100 ohms |

**TABLE 4:  Approximate 60-Hz Alternating Current Values Affecting Human Beings**

| Current | Effects |
|---|---|
| 1 mA or less | No sensation—not felt. |
| 1 to 8 mA | Sensation of shock—not painful; individual can let go at will; muscular control not lost. |
| 8 to 15 mA | Painful shock—individual can let go at will; muscular control not lost. |
| 15 to 20 mA | Painful shock—muscular control lost; cannot let go. |
| 20 to 50 mA | Painful shock—severe muscular contractions; breathing difficult. |
| 50 to 100 mA | Ventricular fibrillation—Death results if prompt cardiac massage not administered. |
| 100 to 200 mA | Defibrillator shock must be applied to restore normal heartbeat.  Breathing probably stopped. |
| 200 mA and over | Severe burns—severe muscular contractions; chest muscles clamp heart and stop it during shock.  Breathing stopped—heart may start following shock, or cardiac massage may be required. |

Source:  Typical industry values

5.2.1.1 The safe limits must be determined by qualified personnel based on anticipated exposure conditions.  For the purpose of this standard, a steady-state touch voltage of 15 V or more with respect to local earth at above-grade or exposed sections and appurtenances is considered to constitute a shock hazard.

5.2.1.2 It must be recognized that when touch voltages are below 15 V, the current may be dangerously high in the structure and continuity provisions and other procedures are mandatory prior to separating affected sections.    All precautions must be implemented to eliminate the possibility of a person being placed in series with this current.

5.2.1.3 During short-circuit conditions, the permissible touch-and-step voltages at above-grade portions of the structure and appurtenances should be determined in accordance with the methodology specified in IEEE Standard 80[4] or other analogous methodologies, such as the International Electrotechnical Commission (IEC).[6]

5.2.1.4 In areas (such as urban residential zones or school zones) in which a high probability exists that children (who are more sensitive to shock hazard than are adults) can come in contact with a structure under the influence of induced AC voltage, a lower touch voltage shall be considered.

5.2.1.5 The beginning sensation of shock, which may occur at 1 to 8 mA, may not be painful or harmful to a human being, but may lead to an accident by causing rapid involuntary movement of a person.

5.2.2 In areas of AC influence, measured AC voltages between a structure and either an adjacent structure, a ground or an electrolyte are considered an indication that further investigation is needed to determine whether AC mitigation is required.

5.2.3 When the touch voltage on a structure presents a shock hazard, the voltage must be reduced to safe levels by taking remedial measures.  In those cases in which the voltage level cannot be practically reduced to a safe level on aboveground appurtenances by fault shields, gradient control wires, lumped grounding, AC continuity, etc., other safety measures shall be implemented to prevent shock to operating and maintenance personnel and to the public (see Paragraph 4.3) to satisfy the requirements in Paragraph 5.2.1.  The use of dead-front construction may be utilized in lieu of gradient control mats for test stations and other CP equipment enclosures when approved by the owner; however, caution is advised, and it must be recognized that this does not reduce any hazardous voltage present.

5.3  Construction

5.3.1 Severe hazards may exist during construction of facilities adjacent to AC power systems.  A competent person shall be in charge of electrical safety.  This person shall be fully aware of proper grounding procedures and of the dangers associated with inductive and capacitive couplings, fault current, lightning, etc., on aboveground and underground structures.  The person must also know the hazards of the construction equipment being used as related to the "limit-of-the-approach" regulations governing them.[6] The person shall be furnished with the instrumentation, equipment, and authority required to implement and maintain safe working conditions.

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[6] International Electrotechnical Commission (IEC), 3, rue de Varembé, P.O. Box 131, CH –1211, Geneva, Switzerland.

5.3.2 The AC potential difference between a structure and the earth can be substantially reduced by appropriate grounding procedures. The AC potential difference between structures can be reduced by appropriate bonding procedures. The AC potential difference between separate points in the earth can be reduced through the use of appropriate grounding grids. The grounding or bonding procedure for safe construction activities depends upon the type, magnitude, and duration of the AC exposure. Each situation shall be analyzed by a competent person, and safe operating procedures shall be employed during the entire construction operation.

5.3.3 During the construction of metallic structures in areas of AC influence, the following minimum protective requirements are prescribed:

(a) On long metallic structures paralleling AC power systems, temporary electrical grounds shall be used at intervals not greater than 300 m (1,000 ft), with the first ground installed at the beginning of the section. Under certain conditions, a ground may be required on individual structure joints or sections before handling.

(b) All temporary grounding connections shall be left in place until immediately prior to backfilling. Sufficient temporary grounds shall be maintained on each portion of the structure until adequate permanent grounding connections have been made.

5.3.4 Temporary grounding connections may be made to ground rods, bare pipe casing, or other appropriate grounds. These temporary grounding facilities are intended to reduce AC potentials. Direct connections made to the electrical utility's grounding system during construction could increase the probability of a hazard during switching surges, lightning strikes, or fault conditions, and may intensify normal steady-state effects if the grounding system is carrying AC; such connections should be avoided when possible.

5.3.5 Cables used for bonding or for connections to grounding facilities shall have good mechanical strength and adequate conductivity. As a minimum, copper conductor 35-mm$^2$ (0.054-in.$^2$) (No. 2 AWG) stranded welding cable or equivalent is recommended. See Table 1 and Figures 1, 2, and 3 for cable sizes adequate to conduct the anticipated fault current safely.

5.3.6 Temporary cable connections to the affected structure and to the grounding facilities shall be securely made with clamps that apply firm pressure and have a current-carrying capacity equal to or greater than that of the grounding conductor. Clamps shall be installed so that they cannot be accidentally dislodged.

5.3.7 All permanent cable connections shall be thoroughly checked to ensure that they are mechanically and electrically sound and properly coated prior to backfilling.

5.3.8 The grounding cable shall first be attached to the grounding facilities and then securely attached to the affected structure. Removal shall be in reverse order. Properly insulated tools or electrical safety gloves shall also be used to minimize the shock hazards. THE END CONNECTED TO THE GROUND SHALL BE REMOVED LAST.

5.3.8.1 In those instances in which high power levels are anticipated in the grounding cable, the following procedure is recommended to prevent electrical arc burns or physical damage to the coating or metal on the structure.

(a) The grounding clamp shall be connected to the structure without the ground lead.

(b) The grounding cable shall first be connected to the grounding facility.

(c) Next, the grounding cable shall be connected to the grounding clamp on the structure.

5.3.9 All grounding attachments and removals shall be made by, or under the supervision of, the person in charge of electrical safety.

5.3.10 If hazardous AC potentials are measured across an isolating joint or flange, both sides of the joint or flange shall be grounded and/or bonded across. If required, a permanent bond shall be made before the temporary bond is removed.

5.3.11 Before the temporary grounding facilities are removed, provisions must be made to permanently control the effects of AC potentials on the affected structure. These provisions depend on the type of CP, the type of structure, and the anticipated magnitude of AC potentials.

5.3.12 Vehicles and other construction equipment are subject to existing electrical safety regulations, when operated in the vicinity of high-voltage AC lines.[6]

5.3.12.1 Metallic construction sheds or trailers, fences, or other temporary structures shall be grounded if subject to hazardous AC influence.

5.3.13 The person in charge of electrical safety shall communicate at least daily with the utility controlling the involved power lines to ascertain any switching that might be expected during each work period. This person may request that reclosing procedures be suspended during construction hours and may explore the possibility of taking the power line out of service. The person shall also keep informed of any electrical storm activity that might affect safety on the work site. The person shall order a discontinuation of construction during local electrical storms or when thunder is heard.

5.3.14 The use of electrically isolating materials for aboveground appurtenances such as vent pipes, conduits, and test boxes may reduce shock hazards in specific instances. However, electrical wires permanently attached to the pipeline, such as CP test wires, may have a high possibility of a shock hazard because they cannot be isolated from the pipe (see Paragraph 7.2.6).

5.4 Operations and Maintenance

5.4.1 Maintenance of structures and CP facilities under conditions that include AC potentials may require special precautions. Warning signs shall be used as a minimum precaution. All maintenance shall be performed by or under the supervision of a person familiar with the possible hazards involved. Personnel must be informed of these hazards and of the safety procedures to follow.

5.4.2 Testing of devices intended to limit AC potentials shall be in accordance with manufacturer's recommendations and performed under the supervision of a person familiar with the possible hazards involved. In those areas in which the presence of combustible vapors is suspected, tests must be conducted before connections are made or broken to determine that the combustible vapor level is within safe limits. No more than one device intended to limit the AC potential should be disconnected at any one time. When a single protective device is to be installed, a temporary shunt bond, with or without another decoupling device, must be established prior to removing the unit for service.

5.4.3 Testing of CP systems under the influence of AC potentials must be performed by or under the supervision of a qualified person. In all cases, tests to detect AC potentials shall be performed first, and the structure shall be treated as a live electrical conductor until proven otherwise. CP records should include the results of these tests.

5.4.4 Test stations for CP systems on structures that may be subject to AC potentials shall have dead-front construction to reduce the possibility of contacting energized test leads. Test stations employing metallic pipes for support must be of dead-front construction.

5.4.5 Safe work practices must include attaching all test leads to the instruments first and then to the structure to be tested. Leads must be removed from the structure first and from the instruments last.

5.4.6 When structures subject to AC influence are exposed for the purpose of cutting, tapping, or separating, tests shall be made to determine AC potentials or current to ground. In the event that potentials or currents greater than those permitted by Paragraph 5.2 are found, appropriate remedial measures shall be taken to reduce the AC effects to a safe level. In the event this cannot be achieved, the structure shall be regarded as a live electrical conductor and treated accordingly. Solid bonding across the point to be cut or the section to be removed shall be established prior to separation, using as a minimum the cable and clamps outlined in Paragraphs 5.3.5 and 5.3.6.

5.4.7 On facilities carrying combustible liquids or gases, safe operating procedures require that bonding across the sections to be separated precede structure separation, regardless of the presence of AC.

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## Section 6: AC and Corrosion Control Considerations

6.1 Introduction

6.1.1 This section recommends practices for determining the level of AC influence and lightning effects to which an existing metallic structure may be subjected. This section also outlines several points for consideration regarding the effects these potentials may have on corrosion control systems and associated equipment.

6.2 Determination of AC Influence and Lightning Effects

6.2.1 A CP system design should include an evaluation to estimate the level of AC potentials and currents under normal conditions, fault conditions, and lightning surges. Because significant AC potentials may be encountered during field surveys, all personnel shall follow proper electrical safety procedures and treat the structure as a live electrical conductor until proven otherwise.

6.2.2 Tests and investigations to estimate the extent of AC influence should include the following:

(a) Meeting with electric utility personnel to determine peak load conditions and maximum fault currents and to discuss test procedures to be used in the survey.

(b) Electrical measurement of induced AC potentials between the affected structure and ground.

(c) Electrical measurement of induced AC current on the structure.

(d) Calculations of the potentials and currents to which the structure may be subjected under normal and fault conditions.[10]

6.2.3 A survey should be conducted over those portions of the affected structure in which AC exposure has been noted or is suspected. The location and time that each measurement was taken should be recorded.

6.2.3.1 The potential survey should be conducted using a suitable AC voltmeter of proper range. Contact resistance of connections should be sufficiently low to preclude measurement errors because of the relationship between external circuit impedance and meter impedance. Suitable references for measurements are:

(a) A metal rod.[7]

(b) Bare pipeline casings, if adequately isolated from the carrier pipe.

(c) Tower legs or power system neutrals, if in close proximity to the affected structure. (Meter connections made to tower legs or power system neutrals may present a hazard during switching surges, lightning strikes, or fault conditions.)

6.2.3.2 The presence of AC on a structure may be determined using a suitable AC voltmeter to measure voltage (IR) drop at the line current test stations. This method, however, provides only an indication of current flow, and cannot be readily converted to amperes because of the AC impedance characteristics of ferromagnetic materials. A clamp-on AC ammeter may be used to measure current in temporary or permanent bond and ground connections. Instrumentation with sufficient resolution may be used to measure current at buried coupons that are connected to the structure to provide an indication of the local AC leakage current density.

6.2.3.3 Indications of AC power levels on affected structures may be obtained by temporarily bonding the structure to an adequate ground and measuring the resulting current flow with a clamp-on AC ammeter while measuring the AC potential. Suitable temporary grounds may be obtained by bonding to tower legs, power system neutral, bare pipeline casings, or across an isolating joint to a well grounded system. DC drainage bonds

existing on the structure under investigation should also be checked for AC power levels.

6.2.3.4 Locations indicating maximum AC potential and current flow values during the survey discussed in Paragraphs 6.2.3 through 6.2.3.2 should be surveyed with recording instruments for a period of 24 hours or until the variation with power line load levels has been established.[8]

6.2.4 To facilitate AC interference studies and to design mitigation measures, the following data are typically required:

(a) Power line cross-sectional dimensions, phasing, conductor types, and static wire bonding information;

(b) Power line structure grounding details (including footings) and substation ground resistances;

(c) Substation and power plant grounding system dimensions, if close to pipelines;

(d) Single line diagrams for power lines within interference corridor;

(e) Single phase-to-ground currents for representative faults on all power lines;

(f) Load current details for all power lines, including maximum load unbalance and system operating frequency;

(g) Maximum fault clearing time for each power line;

(h) Details on nearby power plants fed by any of the pipelines in the interference corridor;

(i) Alignment drawings of pipelines and appurtenances, power lines and structures, and power line installations (substations and power plants) throughout the common corridor and up to extremities of pipelines and power lines;

(j) Pipeline characteristics, dimensions, and design information;

(k) Soil resistivity measurements up to spacings of 100 m (328 ft) or more at representative locations throughout the common corridor;

(l) Drawings and locations of exposed appurtenances (scraper traps, valves, metering stations, etc.);

(m) Pipeline coating resistance and coating characteristics and thickness; and

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[7] Following meter hookup, the reference rod should be inserted deeper into the earth until no further potential increase is noted. This reduces the possibility of high-resistance contact errors in the measurement.
[8] Survey data gathered in accordance with Paragraphs 6.2.3 through 6.2.3.4 should be reviewed with electric utility personnel for the purpose of correlating with the power line operating conditions at the time of the survey.

(n) CP anode bed locations, dimensions, and design information.

6.3 Special Considerations in CP Design

6.3.1 AC influence on the affected structure and its associated CP system should be considered.

6.3.2 CP survey instruments should have sufficient AC rejection to provide accurate DC data.

6.3.3 The AC in the structure to be protected may flow to ground through CP equipment. Current flowing in the CP circuits under normal AC power system operating conditions may cause sufficient heating to damage or destroy the equipment. Heating may be significantly reduced by the use of properly designed series inductive reactances or shunt capacitive reactances in the CP circuits.

6.3.3.1 Rectifiers should be equipped with lightning and surge protection at the AC input and DC output connections.

6.3.3.2 Resistance bonds for the purpose of DC interference mitigation should be designed for the maximum normal AC and DC current flow in order to prevent damage to the bond. Installation of solid state DC decouplers, polarization cells, or other devices in parallel with DC resistance bonds may prevent damage to bonds. Installation of semiconductors in DC interference bonds between cathodically protected structures may result in undesirable rectification.

6.3.3.3 When bonds to other structures or grounds are used for AC considerations, the requirements as described in Paragraph 4.2.5 apply in order to maintain effective levels of CP.

6.3.3.4 Semiconductor drain switches (reverse current) for the mitigation of stray DC from transit systems should be provided with surge current protection devices.

6.3.4 In DC stray current areas, the grounding methods should be chosen to avoid creating interference problems.

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## Section 7: Special Considerations in Operation and Maintenance of Cathodic Protection and Safety Systems

7.1 Introduction

7.1.1 This section outlines safe maintenance and testing procedures for CP systems on structures subject to AC influence.

7.2 Safety Measures for Operation and Maintenance of CP Systems

7.2.1 CP rectifiers that are subject to damage by adjacent electric utility systems should be checked for proper operation at more frequent intervals than rectifiers not subject to electric system influence.

7.2.2 CP testing or work of similar nature must not be performed on a structure subject to influence by an adjacent electric utility system during a period of thunderstorm activity in the area.

7.2.3 Positive measures must be taken to maintain continuous rectifier operation when repeated outages can be attributed to adjacent electric utility system influences. One or more of the following mitigation measures may be employed:

(a) Repetitive transient lightning arresters across the AC input and DC output terminals.

(b) Heavy-duty choke coils installed in the AC and/or DC leads.

7.2.4 If galvanic anodes are used for CP in an area of AC influence, and if test stations are available, the following tests should be conducted during each structure survey using suitable instrumentation:

(a) Measure and record both the AC and DC from the anodes.

(b) Measure and record both the AC and DC structure-to-electrolyte potentials.

7.2.5 At all aboveground pipeline metallic appurtenances, devices used to keep the general public or livestock from coming into direct contact with the structure shall be examined for effectiveness. If the devices are found to be ineffective, they shall be replaced or repaired immediately.

7.2.6 In making test connections for electrical measurements, all test leads, clips, and terminals must be properly insulated. Leads shall be connected to the test instruments before making connections to the structure. When each test is completed, the connections shall be removed from the structure before removing the lead connection from the instrument. All test connections must be made on a step-by-step basis, one at a time.

7.2.7 When long test leads are laid out near a power line, significant potentials may be induced in these

leads. The hazards associated with this situation may be reduced by using the following procedures:

(a) Properly insulate all test lead clips, terminals, and wires.

(b) Avoid direct contact with bare test lead terminals.

(c) Place the reference electrode in position for measurement prior to making any test connections.

(d) Connect the lead to the reference electrode, and reel the wire back to the test location.

(e) Connect the other test lead to the instrument and then to the structure.

(f) Connect the reference electrode lead to the instrument.

(g) When the tests are complete, disconnect in reverse order.

NOTE: Close interval pipe-to-electrolyte surveys using long lead wires require special procedures and precautions.

7.2.8 Tools, instruments, or other implements shall not be handed at any time between a person standing over a ground mat or grounding grid and a person who is not over the mat or grid.

7.2.9 Grounding facilities for the purpose of mitigating AC effects should be carefully tested at regular intervals to ascertain the integrity of the grounding system.

7.2.9.1 No disconnection or reconnection shall be allowed when a flammable or explosive atmosphere is suspected without first testing to ensure a safe atmosphere.

7.2.9.2 No one shall make contact with the structure, either directly or through a test wire, while a grounding grid is disconnected for test purposes.

7.2.9.3 Measurement of the resistance to earth of disconnected grounds shall be made promptly to minimize personnel hazards.

7.2.10 All interference mitigation devices and test equipment should be maintained in accordance with the manufacturer's instructions.

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[9] The Institute of Radio Engineers (IRE) and the American Institute of Electrical Engineers (AIEE) merged in 1963 to form the Institute of Electrical and Electronics Engineers (IEEE).
[10] National Fire Protection Agency (NFPA), 1 Batterymarch Park, Quincy, MA 02169-9101.
[11] American National Standards Institute (ANSI), 1819 L St. NW, 6th Floor, Washington, DC 20036.
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## Appendix A: Wire Gauge Conversions
### (Nonmandatory)

Table A1 provides the nearest metric size for the conductor sizes mentioned in this standard.

**TABLE A1: Wire Gauge Conversions[11]**

| Conductor Size | Diameter in mils | Nearest metric size (mm$^2$) | Diameter in mm of nearest metric size |
|:---:|:---:|:---:|:---:|
| 4,000 MCM | 2,000 | 2,000 | 50.5 |
| 2,000 MCM | 1,410 | 1,000 | 35.7 |
| 1,000 MCM | 1,000 | 500 | 25.2 |
| 500 MCM | 707 | 240 | 17.5 |
| 250 MCM | 500 | 120 | 12.4 |
| 4/0 AWG | 460 | 120 | 12.4 |
| 3/0 AWG | 410 | 80 | 10.01 |
| 2/0 AWG | 365 | 70 | 9.44 |
| 1/0 AWG | 325 | 50 | 7.98 |
| 1 AWG | 290 | 50 | 7.98 |
| 2 AWG | 258 | 35 | 6.68 |
| 4 AWG | 204 | 25 | 5.64 |
| 6 AWG | 162 | 16 | 4.51 |
| 8 AWG | 128 | 10 | 3.57 |
| 10 AWG | 102 | 6 | 2.76 |

# Standard
# Test Method

# Measurement Techniques Related to Criteria for Cathodic Protection on Underground or Submerged Metallic Piping Systems

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## Foreword

This NACE International standard test method provides descriptions of the measurement techniques and cautionary measures most commonly used on underground piping to determine whether a specific criterion has been complied with at a test site. This test method includes only those measurement techniques that relate to the criteria or special conditions, such as a net protective current, contained in NACE Standard RP0169.[1] This test method is intended for use by corrosion control personnel concerned with the corrosion of buried underground or submerged piping systems, including oil, gas, water, and similar structures.

The measurement techniques described require that the measurements be made in the field. Because the measurements are obtained under widely varying circumstances of field conditions and pipeline design, this standard is not as prescriptive as those NACE standard test methods that use laboratory measurements. Instead, this standard gives the user latitude to make testing decisions in the field based on the technical facts available.

This standard contains instrumentation and general measurement guidelines. It includes methods for voltage drop considerations when making pipe-to-electrolyte potential measurements and provides guidance to prevent incorrect data from being collected and used.

The measurement techniques provided in this standard were compiled from information submitted by committee members and others with expertise on the subject. Variations or other techniques not included may be equally effective. The complexity and diversity of environmental conditions may require the use of other techniques.

Appendix A contains information on the common types, use, and maintenance of reference electrodes. Appendix B contains information for the net protective current technique, which, while not a criterion, is a useful technique to reduce corrosion. Appendix C contains information regarding the use of coupons to evaluate cathodic protection. While some engineers use these techniques, they are not universally accepted practices. However, there is ongoing research into their use.

The test methods in this standard were originally prepared by NACE Task Group T-10A-3 on Test Methods and Measurement Techniques Related to Cathodic Protection Criteria, a component of Unit Committee T-10A on Cathodic Protection. It was reviewed by Task Group 020 and reaffirmed in 2002 by Specific Technology Group (STG) 35 on Pipelines, Tanks, and Well Casings. This standard is issued by NACE under the auspices of STG 35.

In NACE standards, the terms *shall*, *must*, *should*, and *may* are used in accordance with the definitions of these terms in the *NACE Publications Style Manual*, 4th ed., Paragraph 7.4.1.9. *Shall* and *must* are used to state mandatory requirements. *Should* is used to state that which is considered good and is recommended but is not absolutely mandatory. *May* is used to state that which is considered optional.

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# NACE International
# Standard
# Test Method

# Measurement Techniques Related to Criteria
# for Cathodic Protection on Underground
# or Submerged Metallic Piping Systems

**Contents**

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## Section 1:  General

1.1 This standard provides testing procedures to comply with the requirements of a criterion at a test site on a buried or submerged steel, cast iron, copper, or aluminum pipeline.

1.2 The provisions of this standard shall be applied by personnel who have acquired by education and related practical experience the principles of cathodic protection of buried and submerged metallic piping systems.

1.3 Special conditions in which a given test technique is ineffective or only partially effective sometimes exist. Such conditions may include elevated temperatures, disbonded dielectric or thermally insulating coatings, shielding, bacterial attack, and unusual contaminants in the electrolyte. Deviation from this standard may be warranted in specific situations.  In such situations corrosion control personnel should be able to demonstrate that adequate cathodic protection has been achieved.

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## Section 2:  Definitions[1]

**Anode**:  The electrode of an electrochemical cell at which oxidation occurs.  Electrons flow away from the anode in the external circuit.  Corrosion usually occurs and metal ions enter the solution at the anode.

**Cable**:  A bound or sheathed group of insulated conductors.

**Cathode**:  The electrode of an electrochemical cell at which reduction is the principal reaction.  Electrons flow toward the cathode in the external circuit.

**Cathodic Disbondment**:  The destruction of adhesion between a coating and the coated surface caused by products of a cathodic reaction.

**Cathodic Polarization**:  The change of electrode potential in the active (negative) direction caused by current across the electrode/electrolyte interface.  See also *Polarization*.

**Cathodic Protection**:  A technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

**Cathodic Protection Coupon**:  A metal sample representing the pipeline at the test site, used for cathodic protection testing, and having a chemical composition approximating that of the pipe.  The coupon size should be small to avoid excessive current drain on the cathodic protection system.

**Coating**:  A liquid, liquefiable, or mastic composition that, after application to a surface, is converted into a solid protective, decorative, or functional adherent film.

**Conductor**:  A bare or insulated material suitable for carrying electric current.

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

**Corrosion Potential ($E_{corr}$)**:  The potential of a corroding surface in an electrolyte relative to a reference electrode under open-circuit conditions (also known as *rest potential*, *open-circuit potential*, or *freely corroding potential*).

**Criterion**:  A standard for assessment of the effectiveness of a cathodic protection system.

**Current Density**:  The current to or from a unit area of an electrode surface.

**Electrical Isolation**:  The condition of being electrically separated from other metallic structures or the environment.

**Electrode**:  A conductor used to establish contact with an electrolyte and through which current is transferred to or from an electrolyte.

**Electrode Potential**:  The potential of an electrode in an electrolyte as measured against a reference electrode.  (The electrode potential does not include any resistance losses in potential in either the electrolyte or the external circuit.  It represents the reversible work to move a unit charge from the electrode surface through the electrolyte to the reference electrode.)

**Electrolyte**:  A chemical substance containing ions that migrate in an electric field.  (For the purpose of this standard, *electrolyte* refers to the soil or liquid, including contained moisture and other chemicals, next to and in contact with a buried or submerged metallic piping system.)

**Foreign Structure**:  Any metallic structure that is not intended as part of a system under cathodic protection.

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[1] Definitions in this section reflect common usage among practicing corrosion control personnel and apply specifically to how terms are used in this standard.  As much as possible, these definitions are in accord with those in the "NACE Glossary of Corrosion-Related Terms" (Houston, TX: NACE).

**Free Corrosion Potential**: See *Corrosion Potential*.

**Galvanic Anode**: A metal that provides sacrificial protection to another metal that is more noble when electrically coupled in an electrolyte. This type of anode is the current source in one type of cathodic protection.

**Holiday**: A discontinuity in a protective coating that exposes unprotected surface to the environment.

**Impressed Current**: An electric current supplied by a device employing a power source that is external to the electrode system. (An example is direct current for cathodic protection.)

**"Instant Off" Potential**: A measurement of a pipe-to-electrolyte potential made without perceptible delay following the interruption of cathodic protection.

**Interference**: Any electrical disturbance on a metallic structure as a result of stray current.

**Isolation**: See *Electrical Isolation*.

**Long-Line Current**: Current through the earth between an anodic and a cathodic area that returns along an underground metallic structure.

**Long-Line Current Voltage Drop Error**: That voltage drop error in the "off" potential that is caused by current flow in the soil due to potential gradients along the pipe surface.

**"Off" or "On"**: A condition whereby cathodic protection current is either turned off or on.

**Pipe-to-Electrolyte Potential**: The potential difference between the pipe metallic surface and electrolyte that is measured with reference to an electrode in contact with the electrolyte. This measurement is commonly termed *pipe-to-soil (P/S)*.

**Pipe-to-Soil**: See *Pipe-to-Electrolyte Potential*.

**Polarization**: The change from the open-circuit potential as a result of current across the electrode/electrolyte interface.

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

**Potential Gradient**: A change in the potential with respect to distance, expressed in millivolts per unit of distance.

**Protection Potential**: A measured potential meeting the requirements of a cathodic protection criterion.

**Reference Electrode**: An electrode whose open-circuit potential is constant under similar conditions of measurement, which is used for measuring the relative potentials of other electrodes.

**Resistance to Electrolyte**: The resistance of a structure to the surrounding electrolyte.

**Reverse-Current Switch**: A device that prevents the reversal of direct current through a metallic conductor.

**Shielding**: Preventing or diverting the cathodic protection current from its intended path to the structure to be protected.

**Shorted Pipeline Casing**: A casing that is in metallic contact with the carrier pipe.

**Side Drain Potential**: A potential gradient measured between two reference electrodes, one located over the pipeline and the other located a specified distance lateral to the direction of the pipe.

**Sound Engineering Practices**: Reasoning exhibited or based on thorough knowledge and experience, logically valid, and having true premises showing good judgment or sense in the application of science.

**Stray Current**: Current through paths other than the intended circuit.

**Telluric Current**: Current in the earth that results from geomagnetic fluctuations.

**Test Lead**: A wire or cable attached to a structure for connection of a test instrument to make cathodic protection potential or current measurements.

**Voltage**: An electromotive force or a difference in electrode potentials expressed in volts.

**Voltage Drop**: The voltage across a resistance according to Ohm's Law.

**Voltage Spiking**: A momentary surging of potential that occurs on a pipeline when the protective current flow from an operating cathodic protection device is interrupted or applied. This phenomenon is the result of inductive and capacitive electrical characteristics of the system and may be incorrectly recorded as an "off" or "on" pipe-to-electrolyte potential measurement. This effect may last for several hundred milliseconds and is usually larger in magnitude near the connection of the cathodic protection device to the pipeline. An oscilloscope or similar instrument may be necessary to identify the magnitude and duration of the spiking.

**Wire**: A slender rod or filament of drawn metal. In practice, the term is also used for smaller gauge conductors (size 6 mm$^2$ [No. 10 AWG[2]] or smaller).

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[2] American Wire Gauge (AWG).

## Section 3:  Safety Considerations

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

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

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

3.1.3  Use caution when long test leads are extended near overhead high-voltage alternating current (HVAC) power lines, which can induce hazardous voltages onto the test leads.  High-voltage direct current (HVDC) power lines do not induce voltages under normal operation, but transient conditions may cause hazardous voltages.

3.1.3.1  Refer to NACE Standard RP01772 for additional information about electrical safety.

3.1.4  Use caution when making tests at electrical isolation devices.  Before proceeding with further tests, use appropriate voltage detection instruments or voltmeters with insulated test leads to determine whether hazardous voltages may exist.

3.1.5  Avoid testing when thunderstorms are in the area.  Remote lightning strikes can create hazardous voltage surges that travel along the pipe under test.

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

3.1.7  Before entering, inspect excavations and confined spaces to determine that they are safe.  Inspections may include shoring requirements for excavations and testing for hazardous atmospheres in confined spaces.

3.1.8  Observe appropriate electrical codes and applicable safety regulations.

## Section 4:  Instrumentation and Measurement Guidelines

4.1 Cathodic protection electrical measurements require proper selection and use of instruments.  Pipe-to-electrolyte potential, voltage drop, potential difference, and similar measurements require instruments that have appropriate voltage ranges.  The user should know the capabilities and limitations of the equipment, follow the manufacturer's instruction manual, and be skilled in the use of electrical instruments.  Failure to select and use instruments correctly causes errors in cathodic protection measurements.

4.1.1  Analog instruments are usually specified in terms of input resistance or internal resistance.  This is usually expressed as ohms per volt of full meter scale deflection.

4.1.2  Digital instruments are usually specified in terms of input impedance expressed as megaohms.

4.2  Factors that may influence instrument selection for field testing include:

(a)  Input impedance (digital instruments);
(b)  Input resistance or internal resistance (analog instruments);
(c)  Sensitivity;
(d)  Conversion speed of analog-to-digital converters used in digital or data logging instruments;
(e)  Accuracy;

(f)  Instrument resolution;
(g)  Ruggedness;
(h)  Alternating current (AC) and radio frequency (RF) signal rejection; and
(i)  Temperature and/or climate limitations.

4.2.1  Some instruments are capable of measuring and processing voltage readings many times per second.  Evaluation of the input wave-form processing may be required if an instrument does not give consistent results.

4.2.2  Measurement of pipe-to-electrolyte potentials on pipelines affected by dynamic stray currents may require the use of recording or analog instruments to improve measurement accuracy.  Dynamic stray currents include those from electric railway systems, HVDC transmission systems, mining equipment, and telluric currents.

4.3  Instrument Effects on Voltage Measurements

4.3.1  To measure pipe-to-electrolyte potentials accurately, a digital voltmeter must have a high input impedance (high internal resistance, for an analog instrument) compared with the total resistance of the measurement circuit.

4.3.1.1 An input impedance of 10 megaohms or more should be sufficient for a digital meter. An instrument with a lower input impedance may produce valid data if circuit contact errors are considered. One means of making accurate measurements is to use a potentiometer circuit in an analog meter.

4.3.1.2 A voltmeter measures the potential across its terminals within its design accuracy. However, current flowing through the instrument creates measurement errors due to voltage drops that occur in all resistive components of a measurement circuit.

4.3.2 Some analog-to-digital converters used in digital and data logging instruments operate so fast that the instrument may indicate only a portion of the input waveform and thus provide incorrect voltage indications.

4.3.3 Parallax errors on an analog instrument can be minimized by viewing the needle perpendicular to the face of the instrument on the centerline projected from the needle point.

4.3.4 The accuracy of potential measurements should be verified by using an instrument having two or more input impedances (internal resistance, for analog instruments) and comparing potential values measured using different input impedances. If the measured values are virtually the same, the accuracy is acceptable. Corrections need to be made if measured values are not virtually identical. Digital voltmeters that have a constant input impedance do not indicate a measurement error by changing voltage ranges. An alternative is to use a meter with a potentiometer circuit.

4.4 Instrument Accuracy

4.4.1 Instruments shall be checked for accuracy before use by comparing readings to a standard voltage cell, to another acceptable voltage source, or to another appropriate instrument known to be accurate.

## Section 5: Pipe-to-Electrolyte Potential Measurements

5.1 Instruments used to measure AC voltage, direct current (DC) voltage, or other electrical functions usually have one terminal designated "Common" (COM). This terminal either is black in color or has a negative (-) symbol. The positive terminal either is red in color or has a positive (+) symbol. The positive and negative symbols in the meter display indicate the current flow direction through the instrument (Figure 1a). For example, a positive symbol in the meter display indicates current flowing from the positive terminal through the meter to the negative terminal. One instrument test lead is usually black in color and the other red. The black test lead is connected to the negative terminal of the instrument and the red lead to the positive terminal.

5.2 Voltage measurements should be made using the lowest practicable range on the instrument. A voltage measurement is more accurate when it is measured in the upper two-thirds of a range selected for a particular instrument. Errors can occur, for example, when an instrument with a 2-V range is used to measure a voltage of 15 mV. Such a value might be a voltage drop caused by current flowing in a metal pipeline or through a calibrated shunt. A much more accurate measurement would be made using an instrument having a 20-mV range.

5.3 The usual technique to determine the DC voltage across battery terminals, pipeline metal/electrolyte interface, or other DC system is to connect the black test lead to the negative side of the circuit and the red test lead to the positive side of the circuit. When connected in this manner, an analog instrument needle moves in an upscale (clockwise) direction indicating a positive value with relation to the negative terminal. A digital instrument connected in the same manner displays a digital value, usually preceded by a positive symbol. In each situation the measured voltage is positive with respect to the instrument's negative terminal. (See instrument connections in Figure 1a.)

5.4 The voltage present between a reference electrode and a metal pipe can be measured with a voltmeter. The reference electrode potential is normally positive with respect to ferrous pipe; conversely the ferrous pipe is negative with respect to the reference electrode.

5.5 A pipe-to-electrolyte potential is measured using a DC voltmeter having an appropriate input impedance (or internal resistance, for an analog instrument), voltage range(s), test leads, and a stable reference electrode, such as a saturated copper/copper sulfate (CSE), silver/silver chloride (Ag/AgCl), or saturated potassium chloride (KCl) calomel reference electrode. The CSE is usually used for measurements when the electrolyte is soil or fresh water and less often for salt water. When a CSE is used in a high-chloride environment, the stability (lack of contamination) of the CSE must be determined before the readings may be considered valid. The Ag/AgCl reference electrode is usually used in seawater environments. The saturated KCl calomel electrode is used more often for laboratory work. However, more-rugged, polymer-body, gel-filled saturated KCl calomel electrodes are available, though modifications may be necessary to increase contact area with the environment.

5.6 Meter Polarity

5.6.1 Pipe-to-electrolyte potentials are usually measured by connecting the instrument negative terminal to the pipe and the positive terminal to the reference electrode, which is in contact with the pipe electrolyte. With this connection the instrument indicates that the reference electrode is positive with respect to the pipe. Because the reference electrode has a positive value with respect to the pipe, the pipe voltage is negative with respect to the reference electrode (see Figure 1a). This negative pipe-to-electrolyte potential is the value used for NACE criteria.

5.6.2 Pipe-to-electrolyte potential measurements are sometimes made with the reference electrode connected to the instrument negative terminal and the pipeline to the positive terminal. Figure 1b illustrates this connection.

5.6.2.1 If the instrument is a data logging device, the recorded data may be printed out with a negative symbol unless a polarity reversal occurs.

5.7 The pipe-to-electrolyte potential measurement of a buried pipe should be made with the reference electrode placed close to the metal/electrolyte interface of the pipe. The common practice, however, is to place the reference electrode as close to the pipe as practicable, which is usually at the surface of the earth above the centerline of the pipe. (See Figure 1a.) This measurement includes a combination of the voltage drops associated with the:

(a)  Voltmeter;
(b)  Test leads;
(c)  Reference electrode;
(d)  Electrolyte;
(e)  Coating, if applied;
(f)  Pipe; and
(g)  Pipe metal/electrolyte interface.

5.8 The pipe-to-electrolyte potential measurement as described above is a resultant of the:

(a)  Voltage drop created by current flowing through the electrical resistances of the items listed in Paragraph 5.7; and
(b)  For coated pipe, the influence of coating holidays, depending on their location, number, and size.

5.9 Pipe-to-electrolyte potential measurements made to determine the level of cathodic protection at the test site should consider the following:

(a)  Effectiveness of coatings, particularly those known or suspected to be deteriorated or damaged;
(b)  Bare sections of pipe;
(c)  Bonds to mitigate interference;
(d)  Parallel coated pipelines, electrically connected and polarized to different potentials;
(e)  Shielding;

(f)  Effects of other structures on the measurements;
(g)  History of corrosion leaks and repairs;
(h)  Location of impressed current anodes;
(i)  Unknown, inaccessible, or direct-connected galvanic anodes;
(j)  Location of isolation devices, including high-resistance pipe connections and compression couplings;
(k)  Presence of electrolytes, such as unusual corrosives, chemical spills, extreme soil resistivity changes, acidic waters, and contamination from sewer spills;
(l)  Location of shorted or isolated casings;
(m) DC interference currents, such as HVDC, telluric, welding equipment, foreign rectifier, mining equipment, and electric railway or transit systems;
(n)  Contacts with other metals or structures;
(o)  Locations where the pipe enters and leaves the electrolyte;
(p)  Areas of construction activity during the pipeline history;
(q)  Underground metallic structures close to or crossing the pipeline;
(r)  Valves and other appurtenances; and
(s)  HVAC overhead power lines.

5.10 Voltage drops other than those across the pipe metal/electrolyte interface shall be considered for valid interpretation of pipe-to-electrolyte voltage measurements made to satisfy a criterion. Measurement errors should be minimized to ensure reliable pipe-to-electrolyte potential measurements.

5.11 The effect of voltage drops on a pipe-to-electrolyte potential measurement can be determined by interrupting all significant current sources and then making the measurement. This measurement is referred to as an "instant-off" potential. The measurement must be made without perceptible delay after current interruption to avoid loss of polarization. The voltage value measured is considered to be the "polarized potential" of the pipe at that location. Because the current interruption may cause a voltage spike, recording the spike as the "instant-off potential" must be avoided. The magnitude and duration of the voltage spike can vary; however, the duration is usually within 0.5 second. The following are examples of when it may not be practical to interrupt all current sources to make the "instant-off potential" measurement.

5.11.1  Galvanic Anodes

5.11.1.1 Galvanic anodes connected directly to the pipe without benefit of aboveground test stations or connections. Interruption requires excavation of the connections.

5.11.2  Impressed Current Systems

5.11.2.1 Galvanic anodes directly connected to piping protected using an impressed current system;

5.11.2.2 Multiple impressed current sources;

Voltmeters

+0.850

DC

VOLT +

COM −

DC

Direction of meter current

Reference Electrode

Electrode potential does not vary

Pipe Test Lead →

Pipe potential is the variable

Pipe

Figure 1a
Instrument Connection

Voltmeter →

- 0.850

DC

VOLT +

COM

Direction of meter current

Reference Electrode

Electrode potential does not vary

Pipe Test Lead →

Pipe potential is the variable
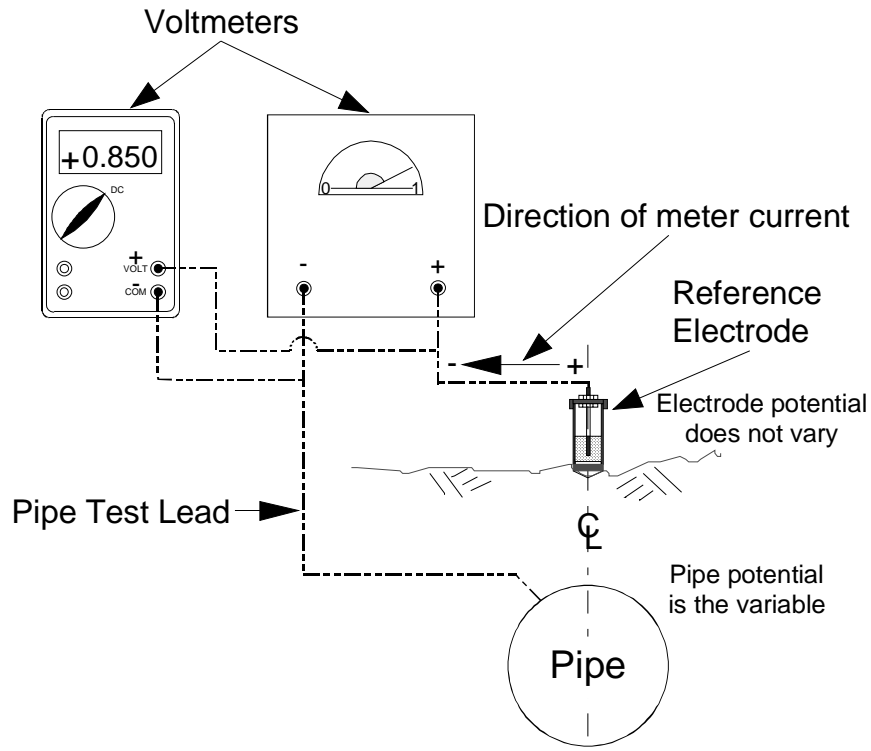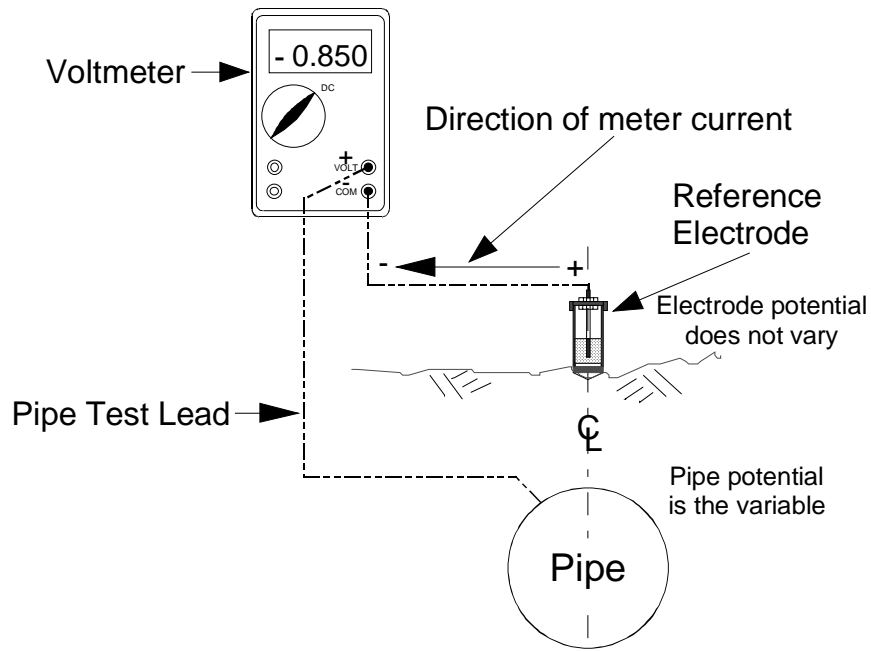
Pipe

Figure 1b
Alternative Instrument Connection

**FIGURE 1**
**Instrument Connections**

5.11.2.3 Impressed current devices on foreign piping; and

5.11.2.4 Numerous cross bonds to parallel pipelines.

5.11.3  Natural and Manmade Stray Currents

5.11.3.1 Telluric currents; and

5.11.3.2 Manmade DC stray currents, such as those from mass transit and mining operations.

5.12 When voltage drops have been evaluated at a test location and the pipe-to-electrolyte potential found to be satisfactory, the "on" pipe-to-electrolyte potential value may be used for monitoring until significant environmental, structural, or cathodic protection system parameters change.

5.12.1 Significant environmental, structural, or cathodic protection system parameter changes may include:

(a)  Replacement or addition of piping;
(b)  Addition, relocation, or deterioration of cathodic protection systems;
(c)  Failure of electrical isolating devices;
(d)  Effectiveness of coatings; and
(e)  Influence of foreign structures.

5.13 After a cathodic protection system is operating, time may be required for the pipe to polarize.  This should be considered when measuring the potential at a test site on a newly protected pipe or after reenergizing a cathodic protection device.

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## Section 6:  Causes of Measurement Errors

6.1 Factors that contribute to faulty potential measurements include:

6.1.1  Pipe and instrument test leads

(a)  Broken or frayed wire strands (may not be visible inside the insulation);
(b)  Damaged or defective test lead insulation that allows the conductor to contact wet vegetation, the electrolyte, or other objects;
(c)  Loose, broken, or faulty pipe or instrument connections; and
(d)  Dirty or corroded connection points.

6.1.2  Reference electrode condition and placement

(a)  Contaminated reference electrode solution or rod, and solutions of insufficient quantity or saturation (only laboratory-grade chemicals and distilled water, if water is required, should be used in a reference electrode);
(b)  Reference electrode plug not sufficiently porous to provide a conductive contact to the electrolyte;
(c)  Porous plug contaminated by asphalt, oil, or other foreign materials;
(d)  High-resistance contact between reference electrode and dry or frozen soil, rock, gravel, vegetation, or paving material;
(e)  Reference electrode placed in the potential gradient of an anode;
(f)  Reference electrode positioned in the potential gradient of a metallic structure other than the one with the potential being measured;
(g)  Electrolyte between pipe and disbonded coating causing error due to electrode placement in electrolyte on opposite side of coating;

(h)  Defective permanently installed reference electrode;
(i)  Temperature correction not applied when needed; and
(j)  Photo-sensitive measurement error (in CSE with a clear-view window) due to light striking the electrode electrolyte solution (photovoltaic effect).

6.1.3 Unknown isolating devices, such as unbonded tubing or pipe compression fittings, causing the pipe to be electrically discontinuous between the test connection and the reference electrode location.

6.1.4 Parallel path inadvertently established by test personnel contacting instrument terminals or metallic parts of the test lead circuit, such as test lead clips and reference electrodes, while a potential measurement is being made.

6.1.5 Defective or inappropriate instrument, incorrect voltage range selection, instrument not calibrated or zeroed, or a damp instrument sitting on wet earth.

6.1.6 Instrument having an analog-to-digital converter operating at such a fast speed that the voltage spikes produced by current interruption are indicated instead of the actual "on" and "off" values.

6.1.7 Polarity of the measured value incorrectly observed.

6.1.8 Cathodic protection current-carrying conductor used as a test lead for a pipe potential measurement.

6.1.9 Interference

6.1.9.1 Electromagnetic interference or induction resulting from AC power lines or radio frequency transmitters inducing test lead and/or instrument errors. This condition is often indicated by a fuzzy, fluctuating, or blurred pointer movement on an analog instrument or erratic displays on digital voltmeters. A DC voltmeter must have sufficient AC rejection capability, which can be determined by referring to the manufacturer's specification.

6.1.9.2 Telluric or stray DC currents flowing through the earth and piping.

6.2 Reference electrode contact resistance is reduced by:

6.2.1 Soil moisture—If the surface soil is so dry that the electrical contact of the reference electrode with the electrolyte is impaired, the soil around the electrode may be moistened with water until the contact is adequate.

6.2.2 Contact surface area—Contact resistance may be reduced by using a reference electrode with a larger contact surface area.

6.2.3 Frozen soil—Contact resistance may be reduced by removing the frozen soil to permit electrode contact with unfrozen soil.

6.2.4 Concrete or asphalt-paved areas—Contact resistance may be reduced by drilling through the paving to permit electrode contact with the soil.

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## Section 7:  Voltage Drops Other Than Across the Pipe Metal/Electrolyte Interface

7.1 Voltage drops that are present when pipe-to-electrolyte potential measurements are made occur in the following:

7.1.1 Measurement Circuit—The voltage drop other than across the pipe metal/electrolyte interface in the measurement circuit is the sum of the individual voltage drops caused by the meter current flow through individual resistances that include:

(a)    Instrument test lead and connection resistances;
(b)    Reference electrode internal resistance;
(c)    Reference electrode-to-electrolyte contact resistance;
(d)    Coating resistance;
(e)    Pipe metallic resistance;
(f)    Electrolyte resistance;
(g)    Analog meter internal resistance; and
(h)    Digital meter internal impedance.
A measurement error occurs if the analog meter internal resistance or the digital meter internal impedance is not several orders of magnitude higher than the sum of the other resistances in the measurement circuit.

7.1.2 Pipe—Current flowing within the pipe wall creates a voltage drop. This voltage drop and the direction of the current shall be considered when the reference electrode is not near the pipe connection and significant current is conducted by the pipe. Consideration is needed because an error in the pipe-to-electrolyte potential measurement will occur if the pipe current causes a significant voltage drop. Current directed to the pipe connection from the reference electrode causes the measured potential to be more negative by the amount of the pipe current voltage drop (see Figure 2a). Conversely, the potential is less negative by that amount if the pipe current direction is from the pipe connection to the reference electrode (see Figure 2b).

7.1.3 Electrolyte—When a pipe-to-electrolyte potential is measured with cathodic protection current applied, the voltage drop in the electrolyte between the reference electrode and the metal/electrolyte interface shall be considered. Measurements taken close to sacrificial or impressed current anodes can contain a large voltage drop. Such a voltage drop can consist of, but is not limited to, the following:

(a)    A voltage drop caused by current flowing to coating holidays when the line is coated; and
(b)    A voltage drop caused by large voltage gradients in the electrolyte that occur near operating anodes (sometimes termed "raised earth effect").

7.1.3.1 Testing to locate galvanic anodes by moving the reference electrode along the centerline of the line may be necessary when the locations are not known.

7.1.4 Coatings—Most coatings provide protection to the pipe by reducing the pipe surface contact with the environment. Due to the relative ionic impermeability of coatings, they resist current flow. While the insulating ability of coatings reduces the current required for cathodic protection, coatings are not impervious to current flowing through them. Current flow through the coating causes a voltage drop that is greater than when the pipe is bare, under the same environmental conditions.

7.2 Specialized equipment that uses various techniques to measure the impressed current wave form and to calculate a pipe-to-electrolyte potential free of voltage drop is

available. This equipment may minimize problems resulting from spiking effects, drifting of interrupters, and current from other DC sources.

VOLTMETER

PIPE TEST
CONNECTION

REFERENCE
ELECTRODE

PIPE METAL VOLTAGE DROP
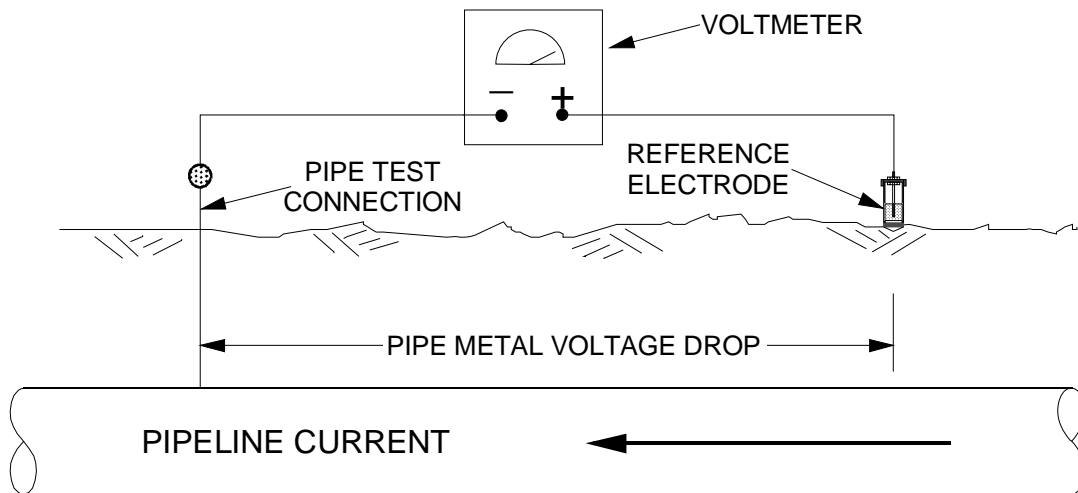
PIPELINE CURRENT

ADD PIPE METAL VOLTAGE DROP TO PIPE-TO-ELECTROLYTE
MEASUREMENT WHEN CURRENT IS TOWARD PIPE CONTACT

Figure 2a
Correction When Pipeline Current Flows Toward Pipe Test Connection

VOLTMETER

PIPE TEST
CONNECTION

REFERENCE
ELECTRODE

PIPE METAL VOLTAGE DROP
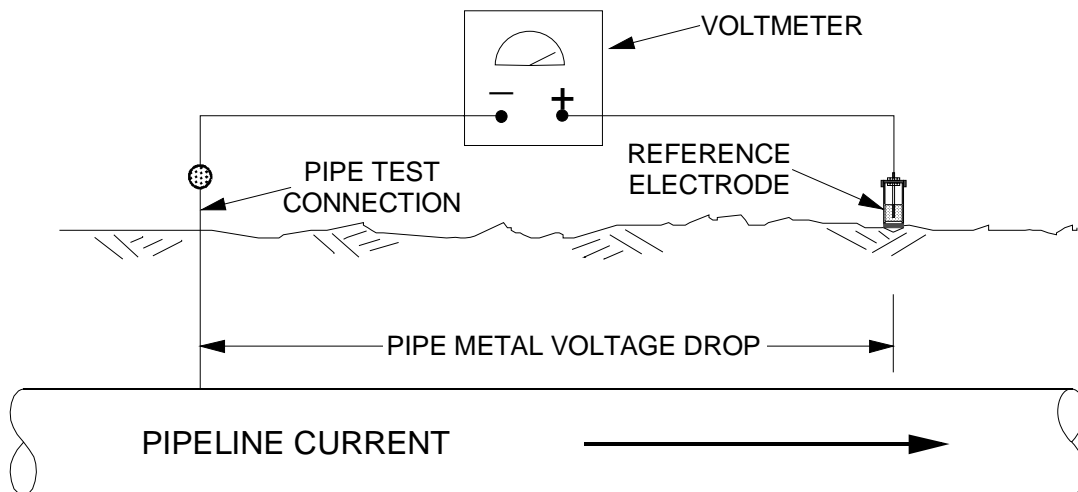
PIPELINE CURRENT

SUBTRACT PIPE METAL VOLTAGE DROP FROM PIPE-TO-ELECTROLYTE
MEASUREMENT WHEN CURRENT IS AWAY FROM PIPE CONTACT

Figure 2b
Correction When Pipeline Current Flows Away from Pipe Test Connection

**FIGURE 2**
**Pipe-to-Electrolyte Potential Corrections for Pipeline Current Flow**

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## Section 8:  Test Method 1—Negative 850 mV Pipe-to-Electrolyte Potential of Steel and Cast Iron Piping with Cathodic Protection Applied

8.1  Scope

Test Method 1 describes a procedure to assess the adequacy of cathodic protection on a steel or cast iron pipeline according to the criterion stated in NACE Standard RP0169,[1] Paragraph 6.2.2.1.1:

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

NOTE:  Consideration is understood to mean the application of sound engineering practice in determining the significance of voltage drops by methods such as:

(a)  Measuring or calculating the voltage drop(s);
(b)  Reviewing the historical performance of the cathodic protection system;
(c)  Evaluating the physical and electrical characteristics of the pipe and its environment; and
(d)  Determining whether there is physical evidence of corrosion.

8.2  General

8.2.1 Cathodic protection current shall remain "on" during the measurement process.  This potential is commonly referred to as the "on" potential.

8.2.2 Test Method 1 measures the pipe-to-electrolyte potential as the sum of the polarized potential and any voltage drops in the circuit.  These voltage drops include those through the electrolyte and pipeline coating from current sources such as impressed current, galvanic anodes, and telluric effects.

8.2.3 Because voltage drops other than those across the pipe metal/electrolyte interface may be included in this measurement, these drops shall be considered, as discussed in Paragraph 8.6.

8.3  Comparison with Other Methods

8.3.1  Advantages

(a)  Minimal equipment, personnel, and vehicles are required; and
(b)  Less time is required to make measurements.

8.3.2  Disadvantages

(a)  Potential measured includes voltage drops other than those across the pipe metal/electrolyte interface; and
(b)  Meeting the requirements for considering the significance of voltage drops (see Paragraph 8.6) can result in added time to assess adequacy of cathodic protection at the test site.

8.4  Basic Test Equipment

8.4.1 Voltmeter with adequate input impedance.  Commonly used digital instruments have a nominal impedance of 10 megaohms.  An analog instrument with an internal resistance of 100,000 ohms per volt may be adequate in certain circumstances in which the circuit resistance is low.  A potentiometer circuit may be necessary in other instances.

8.4.2 Two color-coded meter leads with clips for connection to the pipeline and reference electrode.

8.4.3  Reference Electrode

8.4.3.1  CSE.

8.4.3.2 Other standard reference electrodes may be substituted for the CSE.  These reference electrodes are described in Appendix A, Paragraph A2.

8.5  Procedure

8.5.1 Before the test, verify that cathodic protection equipment has been installed and is operating properly.  Time should be allowed for the pipeline potentials to reach polarized values.

8.5.2 Determine the location of the site to be tested.  Selection of a site may be based on:

(a)  Location accessible for future monitoring;
(b)  Other protection systems, structures, and anodes that may influence the pipe-to-electrolyte potential;
(c)  Electrical midpoints between protective devices;
(d)  Known location of an ineffective coating if the line is coated; and
(e)  Location of a known or suspected corrosive environment.

8.5.3 Make electrical contact between the reference electrode and the electrolyte at the test site, directly over the centerline of the pipeline or as close to it as is practicable.

8.5.4 Connect the voltmeter to the pipeline and reference electrode as described in Paragraph 5.6.

8.5.5 Record the pipe-to-electrolyte potential and its polarity with respect to the reference electrode.

8.6 Considering the Significance of Voltage Drops for Valid Interpretation of the Criterion

8.6.1 The significance of voltage drops can be considered by:

8.6.1.1 Comparing historical levels of cathodic protection with physical evidence from the pipeline to determine whether corrosion has occurred.

8.6.1.2 Comparing soil corrosiveness with physical evidence from the pipeline to determine whether corrosion has occurred.

8.6.2 Physical evidence of corrosion is determined by evaluating items such as:

(a)  Leak history data;

(b)  Buried pipeline inspection report data regarding locations of coating failures, localized conditions of more-corrosive electrolyte, or substandard cathodic protection levels have been experienced; and/or

(c)  Verification of in-line inspection-tool metal loss indications by follow-up excavation of anomalies and inspection of the pipe external surface.

8.6.3 Cathodic protection shall be judged adequate at the test site if:

(a)  The pipe-to-electrolyte potential measurement is negative 850 mV, or more negative, with respect to a CSE; and

(b)  The significance of voltage drops has been considered by applying the principles described in Paragraphs 8.6.1 or 8.6.2.

8.7 Monitoring

When the significance of a voltage drop has been considered at the test site, the measured potentials may be used for monitoring unless significant environmental, structural, coating integrity, or cathodic protection system parameters have changed.

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## Section 9:  Test Method 2—Negative 850 mV Polarized Pipe-to-Electrolyte Potential of Steel and Cast Iron Piping

9.1 Test Method 2 describes the most commonly used test method to satisfy this criterion (see Paragraph 9.2).  This method uses current interruption to determine whether cathodic protection is adequate at the test site according to the criterion.

9.2 Scope

This method uses an interrupter(s) to eliminate the cathodic protection system voltage drop from the pipe-to-electrolyte potential measurement for comparison with the criterion stated in NACE Standard RP0169,[1] Paragraph 6.2.2.1.2:

A negative polarized potential of at least 850 mV relative to a saturated copper/copper sulfate reference electrode (CSE).

9.3 General

9.3.1 Interrupting the known cathodic protection current source(s) eliminates voltage drops associated with the protective currents being interrupted.  However, significant voltage drops may also occur because of currents from other sources, as discussed in Section 7.

9.3.2 To avoid significant depolarization of the pipe, the "off" period should be limited to the time necessary

to make an accurate potential measurement.  The "off" period is typically less than 3 seconds.

9.3.3 The magnitude and duration of a voltage spike caused by current interruption can vary, but the duration is typically within 0.5 second.  After the current is interrupted, the time elapsed until the measurement is recorded should be long enough to avoid errors caused by voltage spiking.  On-site measurements with appropriate instruments may be necessary to determine the duration and magnitude of the spiking.

9.3.4 Current sources that can affect the accuracy of this test method include the following:

(a)  Unknown, inaccessible, or direct-connected galvanic anodes;

(b)  Cathodic protection systems on associated piping or foreign structures;

(c)  Electric railway systems;

(d)  HVDC electric power systems;

(e)  Telluric currents;

(f)  Galvanic, or bimetallic, cells;

(g)  DC mining equipment;

(h)  Parallel coated pipelines, electrically connected and polarized to different potentials;

(i)  Uninterrupted current sources;

(j)  Unintentional connections to other structures or bonds to mitigate interference; and

(k)  Long-line currents.

9.4  Comparison with Other Methods

   9.4.1  Advantages

   (a)  Voltage drops associated with the protective currents being interrupted are eliminated.

   9.4.2  Disadvantages

   (a)  Additional equipment is required;
   (b)  Additional time, personnel, and vehicles may be required to set up equipment and to make pipe-to-electrolyte potential measurements; and
   (c)  Test results are difficult or impossible to analyze when stray currents are present or direct-connected galvanic anodes or foreign impressed current devices are present and cannot be interrupted.

9.5  Basic Test Equipment

   9.5.1  Voltmeter with adequate input impedance. Commonly used digital instruments have a nominal impedance of 10 megaohms.  An analog instrument with an internal resistance of 100,000 ohms per volt may be adequate in certain circumstances in which the circuit resistance is low.  A potentiometer circuit may be necessary in other instances.

   9.5.2  Two color-coded meter leads with clips for connection to the pipeline and reference electrode.

   9.5.3  Sufficient current interrupters to interrupt influential cathodic protection current sources simultaneously.

   9.5.4  Reference electrode

      9.5.4.1  CSE.

      9.5.4.2  Other standard reference electrodes may be substituted for the CSE.  These reference electrodes are described in Appendix A, Paragraph A2.

9.6  Procedure

   9.6.1  Before the test, verify that cathodic protection equipment has been installed and is operating properly.  Time should be allowed for the pipeline potentials to reach polarized values.

   9.6.2  Install and place in operation necessary interrupter equipment in all significant DC sources protecting the pipe at the test site, and place in operation with a synchronized and/or known "off" and "on" cycle.  The "off" cycle should be kept as short as possible but still long enough to read a polarized pipe-to-electrolyte potential after any "spike" as shown in Figure 3a has collapsed.

   9.6.3  Determine the location of the site to be tested. Selection of a site may be based on:

   (a)  Location accessible for future monitoring;
   (b)  Other protection systems, structures, and anodes that may influence the pipe-to-electrolyte potential;
   (c)  Electrical midpoints between protection devices;
   (d)  Known location of an ineffective coating when the pipeline is coated; and
   (e)  Location of a known or suspected corrosive environment.

   9.6.4  Make electrical contact between the reference electrode and the electrolyte at the test site, directly over the centerline of the pipeline or as close to it as is practicable.

   9.6.5  Connect voltmeter to the pipeline and reference electrode as described in Paragraph 5.6.

      9.6.5.1  If spiking may be present, use an appropriate instrument, such as an oscilloscope or high-speed recording device, to verify that the measured values are not influenced by a voltage spike.

   9.6.6  Record the pipe-to-electrolyte "on" and "off" potentials and their polarities with respect to the reference electrode.

9.7  Evaluation of Data

Cathodic protection shall be judged adequate at the test site if the polarized pipe-to-electrolyte potential is negative 850 mV, or more negative, with respect to a CSE.

9.8  Monitoring

When the polarized pipe-to-electrolyte potential has been determined to equal or exceed a negative 850 mV, the pipeline "on" potential may be used for monitoring unless significant environmental, structural, coating integrity, or cathodic protection system parameters have changed.

## Section 10:  Test Method 3—100 mV Cathodic Polarization
## of Steel, Cast Iron, Aluminum, and Copper Piping

10.1 Test Method 3 describes the use of either pipeline polarization decay or pipeline polarization formation to determine whether cathodic protection is adequate at the test site according to the criterion.  Consequently, this test method consists of two mutually independent parts, Test Methods 3a and 3b, that describe the procedures for testing.  Cathodic polarization curves for Test Methods 3a and 3b are shown in Figure 3.  These are schematic drawings of generic polarization decay and formation.

10.2 Test Method 3a — Use of Pipeline Polarization Decay (Figure 3a)

10.2.1   Scope

This method uses pipeline polarization decay to assess the adequacy of cathodic protection on a steel, cast iron, aluminum, or copper pipeline according to the criterion stated in NACE Standard RP0169,[1] Paragraph 6.2.2.1.3, 6.2.3.1, or 6.2.4.1 (depending on the pipe metal).   The paragraph below states Paragraph 6.2.2.1.3:

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

10.2.2   General

10.2.2.1 Interrupting the known cathodic protection source(s) eliminates voltage drops associated with the protective current(s) being interrupted.

10.2.2.2 Other current sources that can affect the accuracy of this test method include the following:

(a)    Unknown, inaccessible, or direct-connected galvanic anodes;
(b)    Cathodic protection systems on associated piping or foreign structures;
(c)    Electric railway systems;
(d)    HVDC electric power systems;
(e)    Telluric currents;
(f)    Galvanic, or bimetallic, cells;
(g)    DC mining equipment;
(h)    Parallel coated pipelines, electrically connected and polarized to different potentials;
(i)    Uninterrupted current sources;
(j)    Unintentional connections to other structures or bonds to mitigate interference; and
(k)    Long-line currents.

10.2.2.3 The magnitude and duration of a voltage spike caused by current interruption can vary, but the duration is typically within 0.5 second.  After the current is interrupted, the time elapsed until the measurement is recorded should be long enough to avoid errors caused by voltage spiking.  On-site measurements with appropriate instruments may be necessary to determine the duration and magnitude of the spiking.

10.2.3   Comparison with Other Methods

10.2.3.1  Advantages

(a)    This method is especially useful for bare or ineffectively coated pipe; and
(b)    This method is advantageous when corrosion potentials may be low (for example, 500 mV or less negative) and/or the current required to meet a negative 850 mV polarized potential criterion would be considered excessive.

10.2.3.2  Disadvantages

(a)    Additional equipment is required;
(b)    Additional time, personnel, and vehicles may be required to set up equipment and to make pipe-to-electrolyte potential measurements; and
(c)    Test results are difficult or impossible to analyze when direct-connected galvanic anodes or foreign impressed current devices are present and cannot be interrupted, or when stray currents are present.

10.2.4   Basic Test Equipment

10.2.4.1 Voltmeter with adequate input impedance.  Commonly used digital instruments have a nominal impedance of 10 megaohms.  An analog instrument with an internal resistance of 100,000 ohms per volt may be adequate in certain circumstances in which the circuit resistance is low.  A potentiometer circuit may be necessary in other instances.

10.2.4.1.1 Recording voltmeters can be useful to record polarization decay.

10.2.4.2 Two color-coded meter leads with clips for connection to the pipeline and reference electrode.

10.2.4.3 Sufficient current interrupters to interrupt influential cathodic protection current sources simultaneously.
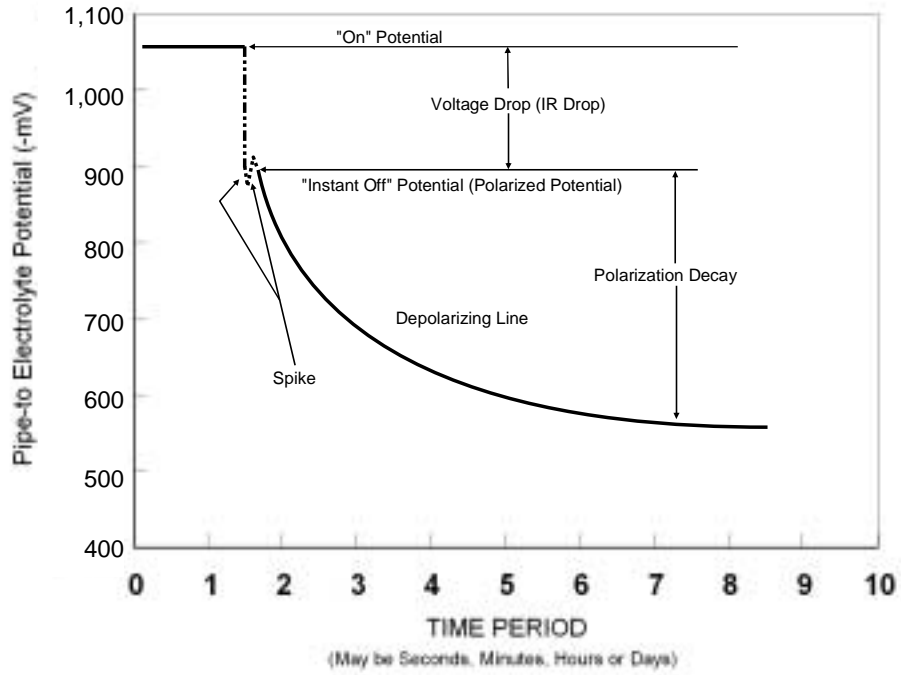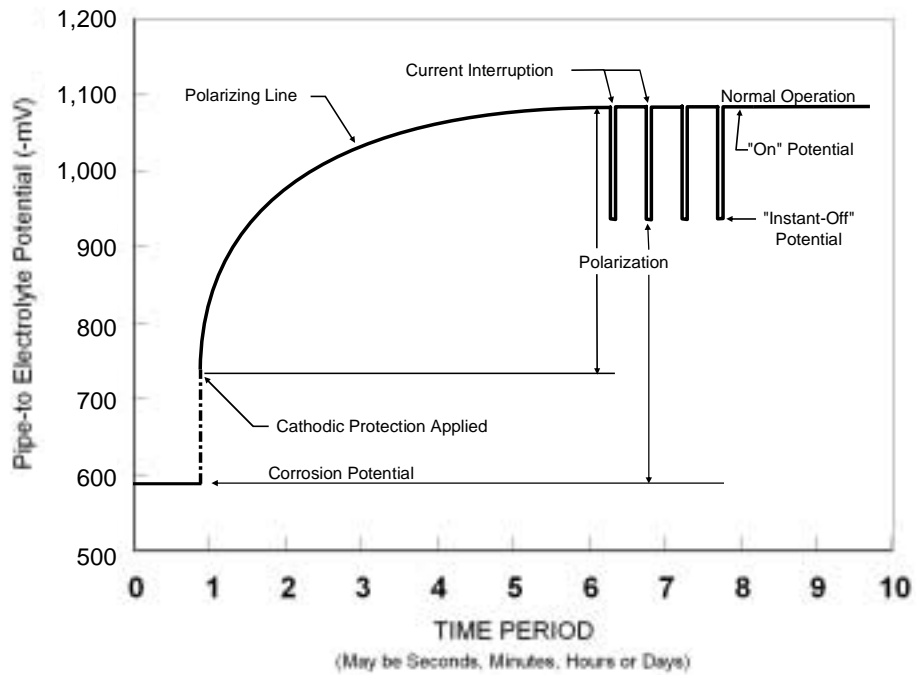
Figure 3a
Polarization Decay



Figure 3b
Polarization Formation

**FIGURE 3**
**Cathodic Polarization Curves**

10.2.4.4 Reference electrode

10.2.4.4.1 CSE.

10.2.4.4.2 Other standard reference electrodes may be substituted for the CSE. These reference electrodes are described in Appendix A, Paragraph A2.

10.2.5 Procedure

10.2.5.1 Before the test, verify that cathodic protection equipment has been installed and is operating properly. Time should be allowed for the pipeline potentials to reach polarized values.

10.2.5.2 Install and place in operation necessary interrupter equipment in all significant DC sources protecting the pipe at the test site, and place in operation with a synchronized and/or known "off" and "on" cycle. The "off" cycle should be kept as short as possible but still long enough to read a polarized pipe-to-electrolyte potential after any "spike" as shown in Figure 3a has collapsed.

10.2.5.3 Determine the location of the site to be tested. Selection of a site may be based on:

(a)     Location accessible for future monitoring;
(b)     Other protection systems, structures, and anodes that may influence the pipe-to-electrolyte potential;
(c)     Electrical midpoints between protection devices;
(d)     Known location of an ineffective coating if the pipeline is coated; and
(e)     Location of a known or suspected corrosive environment.

10.2.5.4 Make electrical contact between the reference electrode and the electrolyte at the test site, directly over the centerline of the pipeline or as close to it as is practicable.

10.2.5.4.1 Identify the location of the electrode to allow it to be returned to the same location for subsequent tests.

10.2.5.5 Connect the voltmeter to the pipeline and reference electrode as described in Paragraph 5.6.

10.2.5.5.1 If spiking may be present, use an appropriate instrument, such as an oscilloscope or high-speed recording device, to verify that the measured values are not influenced by a voltage spike.

10.2.5.6 Measure and record the pipe-to-electrolyte "on" and "instant off" potentials and their polarities with respect to the reference electrode.

10.2.5.6.1 The "instant off" pipe-to-electrolyte potential is the "baseline" potential from which the polarization decay is calculated.

10.2.5.7 Turn off sufficient cathodic protection current sources that influence the pipe at the test site until at least 100 mV cathodic polarization decay has been attained.

10.2.5.7.1 Continue to measure and record the pipe-to-electrolyte potential until it either:

(a)     Has become at least 100 mV less negative than the "off" potential; or
(b)     Has reached a stable depolarized level.

10.2.5.7.2 Measurements shall be made at sufficiently frequent intervals to avoid attaining and remaining at a corrosion potential for an unnecessarily extended period.

10.2.5.7.3 When extended polarization decay time periods are anticipated, it may be desirable to use recording voltmeters to determine when adequate polarization decay or a corrosion potential has been attained.

10.2.6 Evaluation of Data

Cathodic protection shall be judged adequate at the test site if 100 mV or more of polarization decay is measured with respect to a standard reference electrode.

10.2.7 Monitoring

When at least 100 mV or more of polarization decay has been measured, the pipeline "on" potential at the test site may be used for monitoring unless significant environmental, structural, coating integrity, or cathodic protection system parameters have changed.

10.3 Test Method 3b—Use of Pipeline Polarization Formation (Figure 3b)

10.3.1 Scope

This method provides a procedure using the formation of polarization to assess the adequacy of cathodic protection at a test site on steel, cast iron, aluminum, or copper piping according to the criteria stated in NACE Standard RP0169,[1] Paragraphs 6.2.2.1.3, 6.2.3.1, or 6.2.4.1 (depending on the pipe metal). The paragraph below states Paragraph 6.2.2.1.3:

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

10.3.2  General

Ferrous, aluminum, and copper pipelines may be adequately cathodically protected if applying cathodic protection causes a polarization change of 100 mV or more with respect to a reference potential.

10.3.2.1 Current sources that can affect the accuracy of this test method include the following:

(a)  Unknown, inaccessible, or direct-connected galvanic anodes;
(b)  Cathodic protection systems on associated piping or foreign structures;
(c)  Electric railway systems;
(d)  HVDC electric power systems;
(e)  Telluric currents;
(f)  Galvanic, or bimetallic, cells;
(g)  DC mining equipment;
(h)  Parallel coated pipelines, electrically connected and polarized to different potentials;
(i)  Uninterrupted current sources;
(j)  Unintentional connections to other structures or bonds to mitigate interference; and
(k)  Long-line currents.

10.3.3  Comparison with Other Methods

10.3.3.1  Advantages

(a)  This method is especially useful for bare or ineffectively coated pipe; and
(b)  This method is advantageous when corrosion potentials may be low (for example, 500 mV or less negative) and/or the current required to meet a negative 850 mV potential criterion would be considered excessive.

10.3.3.2  Disadvantages

(a)  Additional equipment is required;
(b)  Additional time, personnel, and vehicles may be required to set up equipment and to make the pipe-to-electrolyte potential measurements; and
(c)  Test results are difficult or impossible to analyze when stray currents are present or when direct-connected galvanic anodes or foreign impressed currents are present and cannot be interrupted.

10.3.4  Basic Test Equipment

10.3.4.1 Voltmeter with adequate input impedance.  Commonly used digital instruments have a nominal impedance of 10 megaohms.  An analog instrument with an internal resistance of 100,000 ohms per volt may be adequate in certain circumstances in which the circuit resistance is low.  A potentiometer circuit may be necessary in other instances.

10.3.4.2 Two color-coded meter leads with clips for connection to the pipeline and reference electrode.

10.3.4.3 Sufficient current interrupters to interrupt influential cathodic protection current sources simultaneously.

10.3.4.4 Reference electrode

10.3.4.4.1  CSE.

10.3.4.4.2 Other standard reference electrodes may be substituted for the CSE. These reference electrodes are described in Appendix A, Paragraph A2.

10.3.5  Procedure

10.3.5.1 Before the test, verify that cathodic protection equipment has been installed but is not operating.

10.3.5.2 Determine the location of the site to be tested.  Selection of a site may be based on:

(a)  Location accessible for future monitoring;
(b)  Other protection systems, structures, and anodes that may influence the pipe-to-electrolyte potential;
(c)  Electrical midpoints between protection devices;
(d)  Known location of an ineffective coating if the line is coated; and
(e)  Location of a known or suspected corrosive environment.

10.3.5.3 Make electrical contact between the reference electrode and the electrolyte at the test site, directly over the centerline of the pipeline or as close to it as is practicable.

10.3.5.3.1 Identify the location of the electrode to allow it to be returned to the same location for subsequent tests.

10.3.5.4 Connect the voltmeter to the pipeline and reference electrode as described in Paragraph 5.6.

10.3.5.5 Measure and record the pipe-to-electrolyte corrosion potential and its polarity with respect to the reference electrode.

10.3.5.5.1 This potential is the value from which the polarization formation is calculated.

10.3.5.6 Apply the cathodic protection current. Time should be allowed for the pipeline potentials to reach polarized values.

10.3.5.7 Install and place in operation necessary interrupter equipment in all significant DC sources protecting the pipe at the test site, and place in operation with a synchronized and/or known "off" and "on" cycle. The "off" cycle should be kept as short as possible but still long enough to read a polarized pipe-to-electrolyte potential after any "spike" as shown in Figure 3a has collapsed.

10.3.5.8 Measure and record the pipe-to-electrolyte "on" and "off" potentials and their polarities with respect to the reference electrode. The difference between the "off" potential and the corrosion potential is the amount of polarization formation.

10.3.5.8.1 If spiking may be present, use an appropriate instrument, such as an oscilloscope or high-speed recording device, to verify that the measured values are not influenced by a voltage spike.

10.3.6 Evaluation of Data

Cathodic protection shall be judged adequate if 100 mV or more of polarization formation is measured with respect to a standard reference electrode.

10.3.7 Monitoring

When at least 100 mV or more of polarization formation has been measured, the pipeline "on" potential may be used for monitoring unless significant environmental, structural, coating integrity, or cathodic protection system parameters have changed.

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2. NACE Standard RP0177 (latest revision), "Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems" (Houston, TX: NACE).

3. F.J. Ansuini, J.R. Dimond, "Factors Affecting the Accuracy of Reference Electrodes," MP 33, 11 (1994), p. 14.

4. NACE Publication 35201 (latest revision), "Technical Report on the Application and Interpretation of Data from External Coupons Used in the Evaluation of Cathodically Protected Metallic Structures" (Houston, TX: NACE).

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## Appendix A: Reference Electrodes

A1 Pipeline metals have unstable electrical potentials when placed in an electrolyte such as soil or water. However, a half-cell that has a stable, electrochemically reversible potential characterized by a single, identifiable half-cell reaction is a reference electrode. The stability of a reference electrode makes it useful as an electrical reference point or benchmark for measuring the potential of another metal in soil or water. When connected by a voltmeter to another metal in soil or water, the reference electrode becomes one half of a corrosion cell. The reference electrodes used for measuring potentials on buried or submerged pipelines have voltage values that are normally positive with respect to steel.

A2 Pipeline potentials are usually measured using either a saturated copper/copper sulfate (CSE), a silver/silver chloride (Ag/AgCl), or a saturated potassium chloride (KCl) calomel reference electrode. CSEs are usually used for measurements when the electrolyte is soil or fresh water, and less often for salt water. When a CSE is used in a high-chloride environment, the stability (i.e., lack of contamination) of the electrode must be determined before the readings may be considered valid. Ag/AgCl reference electrodes are usually used for seawater environments. The KCl calomel electrodes are more often used for laboratory work because they are generally less rugged, unless specially constructed, than the other two reference electrodes.

A2.1 The voltage equivalents (at 25°C [77°F]) to negative 850 mV referred to a CSE are:

A2.1.1 Ag/AgCl seawater reference electrode used in 25 ohm-cm seawater: -800 mV,[3] and

A2.1.2 Saturated KCl calomel reference electrode: -780 mV.

A2.2 A CSE is composed of a pure copper rod immersed in a saturated solution of distilled water and copper sulfate ($CuSO_4$). The pure copper rod extends from one end of the reference electrode, providing a means of connection to a voltmeter. The other end of the reference electrode has a porous plug that is used to make an electrical contact with the pipeline electrolyte. Undissolved $CuSO_4$ crystals in the reference electrode should always be visible to ensure the solution is saturated. The reference is reasonably accurate (within 5 mV when measured against a reference electrode known to be free of contamination). The advantages of this reference electrode are low cost and ruggedness.

A2.3 Ag/AgCl reference electrodes are used in marine and soil environments. The construction and the electrode potential vary with the application and with relation to the potential of a CSE reference electrode. The electrolytes involved may be natural seawater, saturated KCl, or other concentrations of KCl. The user shall utilize the manufacturer's recommendations and potential values for the type of Ag/AgCl cell used. The Ag/AgCl reference electrode has a high accuracy (typically less than 2 mV when handled and maintained correctly) and is very durable.

A2.4 A saturated KCl calomel reference electrode for laboratory use is composed of a platinum wire in contact with a mercury/mercurous chloride mixture contacting a saturated KCl solution enclosed in a glass container, a voltmeter connection on one end, and a porous plug on the other end for contact with the pipeline electrolyte. For field use a more-rugged, polymer-body, gel-filled KCl calomel electrode is available, though modifications may be necessary to increase contact area with the environment. The presence of mercury in this electrode makes it environmentally less desirable for field use.

A2.5 In addition to these standard reference electrodes, an alternative metallic material or structure may be used in place of the saturated CSE if the stability of its electrode potential is ensured and if its voltage equivalent referred to a CSE is established.

A2.6 A permanently installed reference electrode may be used; however, whether it is still accurate should be determined.

A3  It is good practice to verify the accuracy of reference electrodes used in the field by comparing them with a carefully prepared master reference electrode that, to avoid contamination, is never used for field measurements. The accuracy of a field reference electrode can be verified by placing it along with the master reference electrode in a common solution, such as fresh water, and measuring the voltage difference between the two electrodes. A maximum voltage difference of 5 mV between a master reference electrode and another reference electrode of the same type is usually satisfactory for pipeline potential measurements. When reference electrode-to-reference electrode potential measurements are made in the field, it is necessary that electrodes with matching potentials be used.

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## Appendix B:  Net Protective Current

B1  NACE Standard RP0169,[1] Paragraph 6.2.2.2.1, states that measuring the net protective current from the electrolyte to the pipe surface by an earth current technique at predetermined current discharge points may be sufficient on bare or ineffectively coated pipelines when long-line corrosion activity is of primary concern.

B1.1  This technique is a measure of the net protective current from the electrolyte onto the pipe surface and is most practicable for use on bare pipelines.

B1.2  The electrolyte current measurements often are not meaningful in multiple pipe rights-of-way, high-resistivity electrolyte, deeply buried pipe, large-diameter pipe, stray current areas, and pipe that is not electrically isolated from other underground structures. Using this technique does not confirm elimination of local corrosion cell action.

B2  Measurement Techniques for Net Protective Current

B2.1  The principal anodic areas along the pipeline should be located. Sufficient cathodic protection current should be applied to cause a net protective current from the electrolyte to the pipe surface. The pipe-to-electrolyte potential measurements for these techniques are performed on piping that is not cathodically protected.

B2.2  The two-reference-electrode potential survey or a pipe-to-electrolyte potential survey method is used to detect the probable current discharge (anodic) areas along a pipeline.

B2.2.1  The two-reference-electrode method measures the direction of the potential gradient along the earth's surface. Measurements should be made at 3-m (10-ft) intervals directly over the centerline of the pipe. The instrument positive terminal is connected to the lead (front) reference electrode in the direction of survey travel. A suspected anodic condition is indicated by a change of the instrument polarity indication. Suspected anodic conditions and their magnitudes can be confirmed by making two-reference-electrode tests laterally to the pipeline. One reference electrode is placed over the line and the other spaced laterally the same distance as for the transverse measurements over the line. These tests should be made on both sides of the pipe to verify that current is leaving the line.

B2.3  The pipe-to-electrolyte potential survey, when used as a tool for locating probable anodic conditions on unprotected pipe, should be conducted by making individual readings at 3-m (10-ft) intervals along the route of the pipe. Probable anodic conditions are indicated at survey points where the most negative readings are determined. It may be desirable to confirm these suspected anodic conditions by making the two-reference-electrode test lateral to the pipe as described for the two-reference-electrode method.

B3  Two-Reference-Electrode Surface Survey

B3.1  Two-reference-electrode surface measurements consist of measuring the potential difference between two matched CSEs in contact with the earth. This type of test, when made directly over the route of the pipe, is useful in locating suspected anodic conditions on the pipe. The two-reference-electrode survey is particularly suited for bare pipe surveys to locate anodic areas for applying a "hot spot" type of protection. The technique is not usually used on coated pipe.

B3.2  For this survey technique to be effective, special attention shall be given to the reference electrodes used. Because potential values to be measured can be expected to be as low as 1 mV, the reference electrodes shall be balanced to within 3 mV of each other. The potential difference between reference electrodes can be measured by:

(a)  Placing about 2.5 cm (1 in.) depth of tap water in a small plastic or glass container;
(b)  Placing the two reference electrodes in the water; and
(c)  Measuring the potential difference between them.

B3.2.1  If the potential difference between the two reference electrodes is not satisfactory, they can be corrected by servicing both reference electrodes. This may be accomplished by thoroughly cleaning the inside of the plastic body, rinsing it with distilled water, soaking the porous plug in distilled water or simply replacing the old plug with a new one, cleaning the copper rod

inside the reference electrode, and replacing the solution with new, clean saturated copper sulfate solution. If the first cleaning does not achieve the desired results, the process should be repeated. The copper rod should never be cleaned with emery cloth or any other material with metallic abrasive. Only nonmetallic sandpaper should be used.

NOTE: Reference electrode potential values may change during the survey. Therefore, it is desirable to check reference electrodes periodically for balance and to have matched or balanced spares available for replacement if needed.

B3.3 A voltmeter with sufficiently high input impedance, at least 10 megaohms, and sufficiently low ranges should be used to make the two-reference-electrode surface survey. Measured values are usually less than 50 mV. The required equipment for this survey includes an appropriate voltmeter, two balanced CSEs, and related test leads. The front reference electrode in the direction of travel shall be connected to the positive terminal of the instrument. (See Figure B1.)

B3.4 Careful placement of reference electrodes is essential when using the two-reference-electrode surface survey. Minor measurement errors due to incorrect placement of the reference electrodes can result in misinterpretation of the data. Before the survey is conducted, the pipe should be accurately located and marked, using a dependable locating device. Special care shall be exercised in situations in which multiple pipelines are on the same right-of-way.

B3.5 Reference electrode spacing should be uniform. A spacing of 3 m (10 ft) is acceptable. When a ground gradient reversal (anodic condition) has been located, the spacing may be reduced by one half and the area reexamined to locate the anodic area more closely.

B3.6 The survey is made by placing two reference electrodes in the earth at the selected spacing directly over the pipeline. The front test lead in the direction of travel is connected to the positive terminal of the instrument. Because the voltage values between the reference electrodes arel normally low, it is desirable that the reference electrode contact with the earth be free of leaves, grass, rocks, and other debris.

B3.7 Results of the measurement are recorded on an appropriate form. Special attention shall be given to recording the polarity of each voltage measurement correctly. With the reference electrodes placed and the instrument connected as described, a possibly anodic condition is indicated when a polarity change occurs. (When the polarity of the measured value changes again, a possibly cathodic condition is indicated.) (See Figure B1.)

B3.8 The severity and extent of an anodic condition may be further determined by making two-reference-electrode surface measurements lateral to the direction of the pipe. This is accomplished by relocating the rear reference electrode to the side of the pipe. A positive value measured from this side reference electrode indicates current flowing from the pipe into the electrolyte, which is an anodic condition. A negative value measured from this side reference electrode toward the reference electrode over the pipe indicates current flowing from the electrolyte toward the pipe, which is a cathodic condition. Measurements should be taken on both sides of the pipe. Enough measurements along the pipe and on both sides of the pipe should be taken to define the limits of the anodic condition.

B3.9 The presence of a galvanic anode connected to the pipe affects two-reference-electrode surface measurements and generally appears as an anodic condition. Close observation of measured values quite often suggests the presence of galvanic anodes. As an anode is approached, its presence is usually indicated by earth gradients that are somewhat higher than normal for the area being surveyed. The two-reference-electrode lateral test may provide higher measured values on the side of the pipe where the anode is buried and lower values on the side of the pipe opposite the anode. Service taps, side connections, other components of the pipe (such as mechanical couplings or screw collars with a higher metallic resistance than the pipe), or other close buried metallic structures may provide measured values that indicate an anodic condition. The lateral test is useful to evaluate the data. Any situation not determined to be caused by some other factor shall be considered as an anodic condition. Adequate marking of anodic conditions is necessary so they can be located for future attention.

B3.10 Soil resistivity tests should be made at anodic areas discovered by using the two-reference-electrode surface survey. These tests are helpful in evaluating the severity of ongoing corrosion, anode current, and anode life.

B3.11 The two-reference-electrode surface potential survey data may be used to generate a pipe-to-electrolyte potential gradient curve using closely spaced measurements. This curve appears as any other pipe-to-electrolyte potential curve and is generated by the following procedure:

B3.11.1 The pipe-to-electrolyte potential is measured at a test point, such as a test station. This value is recorded and becomes the reference value to which all other two-reference-electrode measurements are referenced.

B3.11.2 The reference electrode is left in the same location and is connected to the negative terminal of the voltmeter. A second reference electrode is

placed over the pipe centerline in clean, moist earth a selected distance from the first reference electrode and is connected to the positive side of the instrument.

B3.11.3 The potential between the two reference electrodes is then measured and recorded. Special attention shall be given to the polarity of the measurement between the two reference electrodes.

B3.11.4 The measured value is then algebraically added to the pipe-to-electrolyte potential measured in the first step of this procedure. The sum obtained from the algebraic addition is the pipe-to-electrolyte potential at the location of the second reference electrode.

B3.11.5 The rear reference electrode (connected to the instrument negative terminal) is moved forward and placed in the same spot previously occupied by the front reference electrode.

B3.11.6 The front reference electrode is moved ahead over the line to the previously selected distance.

B3.11.7 The potential between the two reference electrodes is again measured with special attention to reference electrode polarity. This value is algebraically added to the calculated value for the previous test. This calculated pipe-to-electrolyte potential is the pipe-to-electrolyte potential at the location of the front reference electrode.

B3.11.8 This process is repeated until the next test station is met. At this time the last calculated pipe-to-electrolyte potential is compared with the pipe-to-electrolyte potential measured using the test station. If the survey is carefully performed, upon comparison these two values should be nearly identical.

B3.11.9 These potential data can then be plotted as a typical pipe-to-electrolyte potential curve.

B3.12 Errors in observing instrument polarities, incorrect algebraic calculations, unbalanced reference electrodes, and poor earth/reference electrode contacts cause the calculated values to be incorrect.

B3.13 To use the data collected effectively, a form having a suitable format should be developed. The specific needs of each user should be considered when a data form is being developed. The form should have space for each measured numerical value, the polarity of each value, calculated values, and comments. It is also useful to provide space for a sketch of the area surveyed.

B4 Data Interpretation:

B4.1 Interpretation of survey data is complex but should consider the following:

(a) Polarity change of a measured value;
(b) Magnitude of the value measured;
(c) Magnitude of the lateral two-reference-electrode value;
(d) Soil resistivity;
(e) Unknown pipe resistances;
(f) Physical location of the pipe with respect to other structures; and
(g) Known corrosion leak history.

B5 Pipe-to-Electrolyte Potential Survey

B5.1 Pipe-to-electrolyte potential measurements measure the potential difference between a CSE in contact with the earth and a connection to the pipeline. When taken and recorded at measurement intervals of 3 m (10 ft) directly over a pipeline, these measurements are useful in locating suspected anodic conditions of an unprotected pipeline. The interval of measurement may be shortened when anodic conditions are indicated or other unusual conditions occur (see Figures B2a and B2b).

B5.2 Individual users may find it appropriate to modify the above suggested spacing based on the following conditions.

(a) Pipeline length;
(b) Availability of test leads to the pipe;
(c) Terrain characteristics;
(d) Accessibility;
(e) Presence of foreign pipelines and cathodic protection systems;
(f) Coating condition or lack of coating;
(g) Corrosion history of the pipeline;
(h) Results of previous surveys; and
(i) Pipe depth.

B5.3 The survey consists of measuring and recording voltages along an unprotected pipeline at specific intervals as shown in Figures B2a and B2b. To interpret the survey data correctly and to ensure meaningful results, the pipeline must be electrically continuous, or the location of insulating or high-resistance joints must be known. The "peaks," or areas of highest negative potential, usually indicate anodic conditions. Pipe-to-electrolyte potential measurements should be plotted or tabulated (see Figure B2c).

B5.4 The presence of an unknown galvanic anode affects measurements, causing a location to appear to be an anodic condition. If records or measurements do not indicate that a galvanic anode has been installed, all "peaks" shall be considered as anodic conditions. If records regarding galvanic anodes in the area are not available or are believed to be inaccurate, a few additional measurements can help to determine the source of the peaks. Pipe-to-electrolyte (or electrode-to-electrode) potential measurements should be made

in 0.3-m (1-ft) increments for about 1.5 to 3.0 m (5 to 10 ft) laterally to the pipe and through the "peak." The maximum potential will occur a few feet to the side of the pipe if the peak is due to a galvanic anode. Moreover, if the pipe location is known with certainty and a galvanic anode is present, the potentials will be a minimum over or to the side of the pipe opposite where the maximum occurs. The closer the transverse measurements are to the anode, the more the location of the minimum will be shifted away from the side of the pipe opposite the location of the maximum.

B5.5  Stray current flowing to a pipe from sources such as foreign rectifiers and electrified railroads cause the pipe at that location to have more-negative potential and may be misinterpreted as an anodic condition. Stray current discharging from a pipe can cause a less-negative potential and be misinterpreted as a cathodic condition.

B6  Cathodic Protection Using the Net Protective Current Technique

B6.1  Cathodic protection should be applied to the anodic area(s).

B6.2  It is necessary to wait until polarization has stabilized before making a detailed evaluation of the net current protective level. Polarization of bare pipe may require a relatively long time ranging up to several months.

B6.3  When an impressed current source is used, the side drain potential (potential gradient lateral to the pipe longitudinal direction) should be measured at the predetermined anodic condition with the protective current applied. Relative to the reading directly over the pipe, a higher (more-negative) reading with the reference electrode lateral to the pipe indicates that current is being conducted to the pipe at this point. The amount of current flow indicated by this method may not be enough to control small local corrosion cells.

B6.4  Galvanic anodes are usually installed at or near the location of the anodic areas. Caution shall be used when interpreting the results of pipe-to-electrolyte potential measurements made close to an anode.
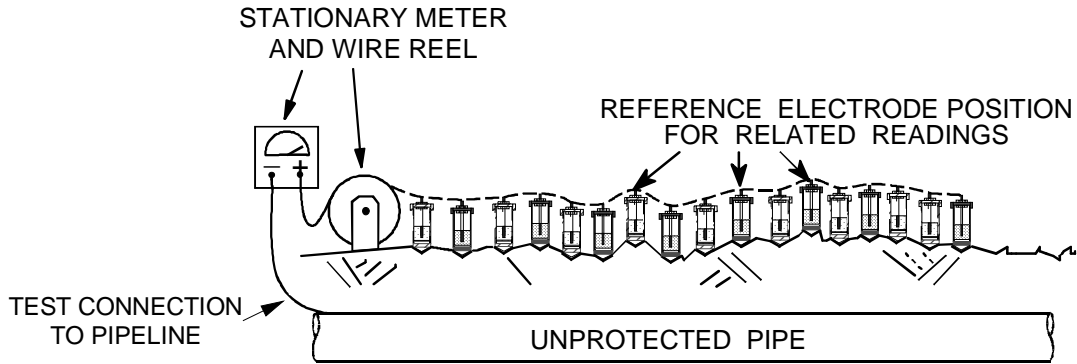
B6.5  Monitoring of cathodic protection can be simplified by establishing test points and recording the pipe-to-electrolyte potential exhibited when the side drain measurements indicate a net current flow to the pipe. These potentials may then be used to monitor the level of cathodic protection.
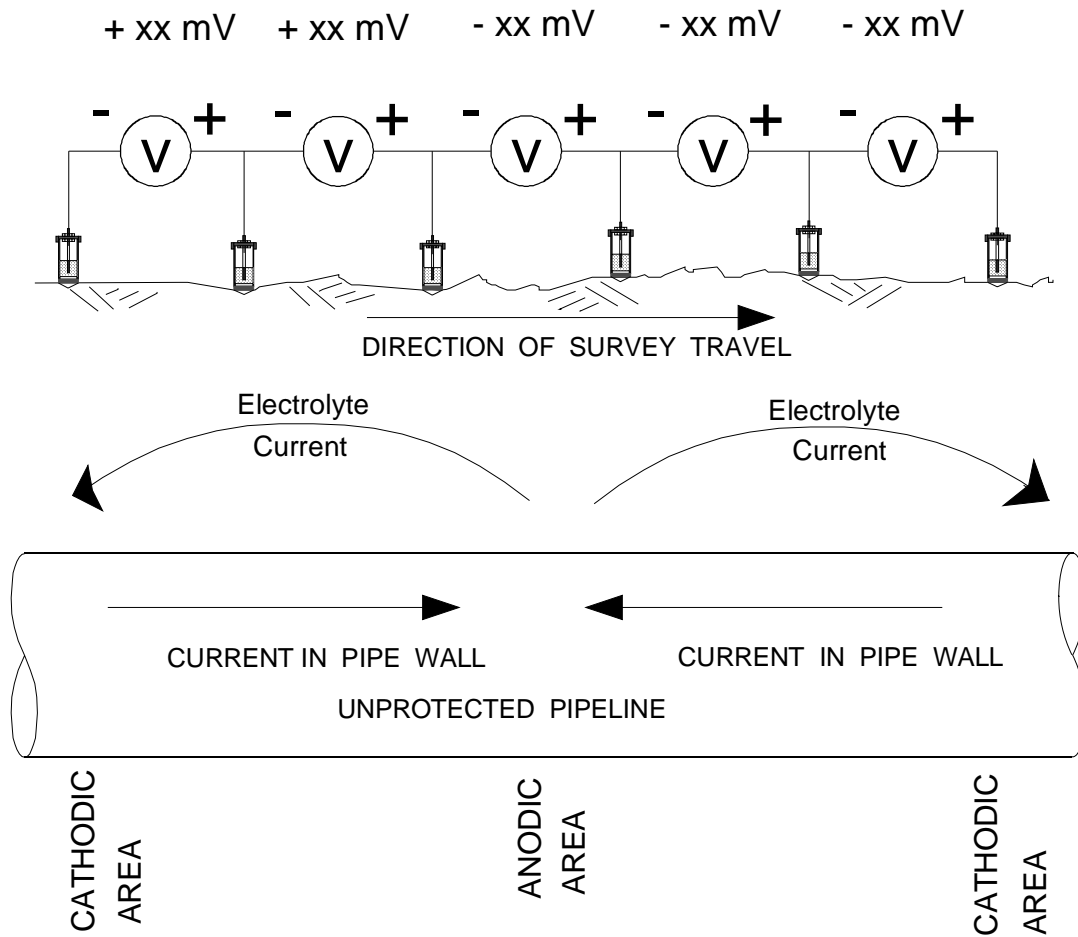
NOTE: Actual readings are usually 50 mV or less.

As the anodic condition in the center of the figure is passed (traveling left to right), the indicated polarity switches from positive to negative. This polarity reversal indicates an anodic condition.

**FIGURE B1**
**Surface Potential Survey**

STATIONARY METER
AND WIRE REEL

REFERENCE ELECTRODE POSITION
FOR RELATED READINGS

TEST CONNECTION
TO PIPELINE

UNPROTECTED PIPE

Significant errors in the potential measurements can occur when surveys are undertaken as shown if there is a break in the lead wire insulation or if leakage occurs through the insulation.

Figure B2a
Reference Electrode Intervals for Potential Survey Using Stationary Meter and Wire Reel.
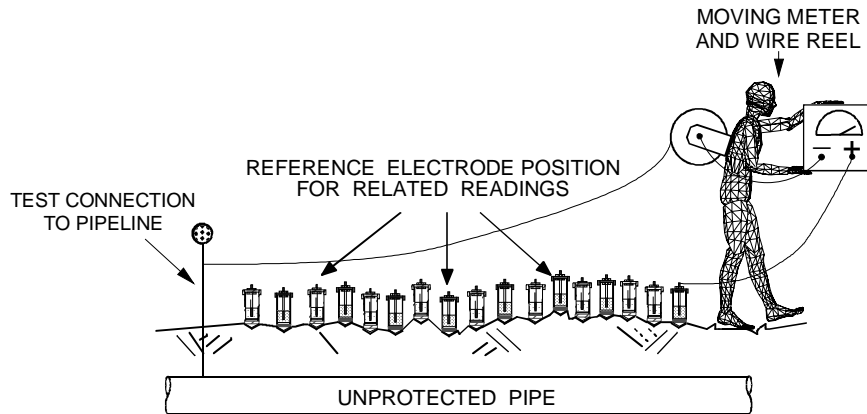
MOVING METER
AND WIRE REEL

REFERENCE ELECTRODE POSITION
FOR RELATED READINGS

TEST CONNECTION
TO PIPELINE

UNPROTECTED PIPE

Figure B2b
Reference Electrode Intervals for Potential Survey Using Moving Meter and Wire Reel.

CATHODIC PROTECTION NOT APPLIED

AREAS EXPERIENCING CORROSION

Pipe-to-Electrolyte Potential (mV)

-700

-600

-500

-400

0   100   200   300   400   500   600   700   800
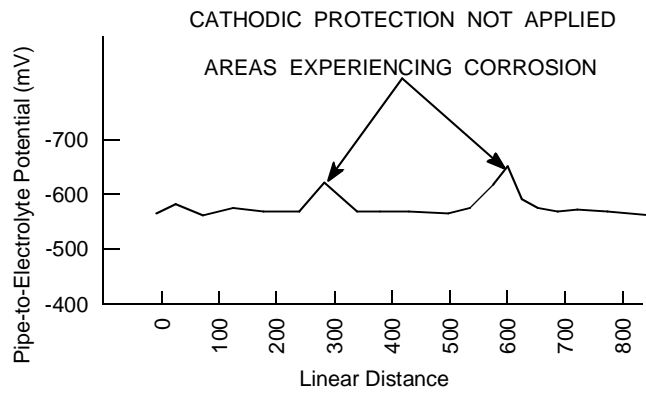
Linear Distance

Figure B2c
Variation of Pipe-to-Electrolyte Potential with Survey Distance

**FIGURE B2**
**Pipe-to-Electrolyte Potential Survey of a Noncathodically Protected Pipeline**

## Appendix C: Using Coupons to Determine Adequacy of Cathodic Protection

C1 Coupons have been used judiciously, particularly when accompanied by other engineering tools and data, to evaluate whether cathodic protection at a test site complies with a given criterion. See NACE Publication 35201[4] for more information on coupon use. The following test procedures are suggested as guides.

C2 Cathodic Protection Coupon Test Method 1—for Negative 850 mV Polarized Pipe-to-Electrolyte Potential of Steel and Cast Iron Piping

C2.1 Scope

This method uses a cathodic protection coupon to assess the adequacy of cathodic protection on a steel or cast iron pipeline according to the criterion stated in NACE Standard RP0169,[1] Paragraph 6.2.2.1.2:

A negative polarized potential of at least 850 mV relative to a saturated copper/copper sulfate reference electrode (CSE).

C2.2 General

C2.2.1 This method uses a coupon to assess the adequacy of cathodic protection applied to a selected test site. A cathodic protection coupon is a metal sample representing the pipeline at the test site and used for cathodic protection testing. The coupon should be:

(a) Nominally of the same metal and surface condition as the pipe;
(b) Small to avoid excessive current drain on the cathodic protection system;
(c) Placed at pipe depth in the same backfill as the pipe;
(d) Prepared with all mill scale and foreign materials removed from the surface; and
(e) Placed at a known location of an ineffective coating when the line is coated.

C2.2.2 A coupon has an insulated test lead brought above ground and, during normal operations, connected to a pipeline test lead. The coupon receives cathodic protection current and represents the pipeline at the test site. For testing purposes, this connection is opened, and the polarized potential of the coupon is measured. The time the connection is open to measure the coupon's "off" potential should be minimized to avoid significant depolarization of the coupon. The "off" period is typically less than 3 seconds. When possible, coupon current direction and magnitude should be verified, using a current clip gauge or resistor permanently placed in series with the coupon lead. Measurements showing discharge

of current from the coupon should be reason to question the validity of using a coupon at the test site.

C2.2.3 The significance of voltage drops due to currents from other sources may not be a problem when a coupon is used to represent the pipeline. The coupon's small size may reduce the effect of these voltage drops. The magnitude of these voltage drops can be quantified by interrupting cathodic protection current sources while the coupon is disconnected and noting whether there is a shift in the coupon-to-electrolyte potential.

C2.3 Comparison with Other Methods

C2.3.1 Advantages

(a) Can provide a polarized coupon-to-electrolyte potential, free of voltage drop, with a minimum of specialized equipment, personnel, and vehicles; and
(b) Can provide a more comprehensive evaluation of the polarization at the test site than conventional pipe-to-electrolyte potential measurements that may be influenced by the location, size, and number of coating holidays when the pipeline is coated.

C2.3.2 Disadvantage—Can have high initial costs to install coupons, especially for existing pipelines.

C2.4 Basic Test Equipment

C2.4.1 Voltmeter with adequate input impedance. Commonly used digital instruments have a nominal impedance of 10 megaohms. An analog instrument with an internal resistance of 100,000 ohms per volt may be adequate in certain circumstances in which the circuit resistance is low. A potentiometer circuit may be necessary in other instances.

C2.4.2 Two color-coded meter leads with clips for connection to the coupon and reference electrode.

C2.4.3 Reference electrode

C2.4.3.1 CSE

C2.4.3.2 Other standard reference electrodes may be substituted for the CSE. These reference electrodes are described in Appendix A, Paragraph A2.

C2.5 Procedure

C2.5.1 Before the test, verify that:

(a) Cathodic protection equipment has been installed and is operating properly; and
(b) Coupon is in place and connected to a pipeline test lead.

Time should be allowed for the pipeline and coupon potentials to reach polarized values.

C2.5.2 Determine the location of the site to be tested. Selection of a site may be based on:

(a) Location accessible for future monitoring;
(b) Other protection systems, structures, and anodes that may influence the pipe-to-electrolyte and coupon-to-electrolyte potentials;
(c) Electrical midpoints between protection devices;
(d) Known location of an ineffective coating when the line is coated; and
(e) Location of a known or suspected corrosive environment.

C2.5.3 Make electrical contact between the reference electrode and the electrolyte at the test site as close to the coupon as is practicable.

C2.5.4 Connect the voltmeter to the coupon test lead and reference electrode as described in Paragraph 5.6.

C2.5.5 Measure and record the pipeline and coupon "on" potentials.

C2.5.6 Momentarily disconnect the coupon test lead from the pipeline test lead and immediately measure and record the coupon-to-electrolyte "off" potential and its polarity with respect to the reference electrode. This should be performed quickly to avoid depolarization of the coupon.

C2.5.7 Reconnect the coupon test lead to the pipeline test lead for normal operations.

C2.6 Evaluation of Data

Cathodic protection may be judged adequate at the test site if the polarized coupon-to-electrolyte potential is negative 850 mV, or more negative, with respect to a CSE. The polarized potential of the coupon depends on the coupon surface condition, the soil in which the coupon is placed, its level of polarization, and its time polarized. Therefore, the polarized potential of the coupon may not be the same as that of the pipe and may not accurately reflect the polarization on the pipe at the coupon location. It must also be understood that the polarization measured on the pipeline is a "resultant" of the variations of polarization on the pipe at the test site. The causes of these variations include the pipe surface condition, soil strata variations, oxygen differentials, and length of time the pipe has been

polarized. Making precise comparisons may not be possible.

C2.7 Monitoring

When the polarized coupon-to-electrolyte potential has been determined to equal or to exceed a negative 850 mV, the pipeline "on" potential may be used for monitoring unless significant environmental, structural, coating integrity, or cathodic protection system parameters have changed.

C3 Cathodic Protection Coupon Test Method 2—for 100 mV Cathodic Polarization of Steel, Cast Iron, Aluminum, and Copper Piping

C3.1 Scope

This method uses cathodic protection coupon polarization decay to assess the adequacy of cathodic protection on a steel, cast iron, aluminum, or copper pipeline according to the criteria stated in NACE Standard RP0169,[1] Paragraphs 6.2.2.1.3, 6.2.3.1, or 6.2.4.1 (depending on the pipe metal). The paragraph below states Paragraph 6.2.2.1.3:

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

C3.2 General

Ferrous, aluminum, and copper pipelines may be adequately cathodically protected when applying cathodic protection causes a polarization change of 100 mV or more with respect to a reference potential.

C3.2.1 This method uses a coupon to assess the adequacy of cathodic protection applied at a test site. A cathodic protection coupon is a metal sample representing the pipeline at the test site and used for cathodic protection testing. The coupon should be:

(a) Nominally of the same metal and surface condition as the pipe;
(b) Small to avoid excessive current drain on the cathodic protection system;
(c) Placed at pipe depth in the same backfill as the pipe;
(d) Prepared with all mill scale and foreign materials removed from the surface; and
(e) Placed at a known location of an ineffective coating when the line is coated.

C3.2.2 The significance of voltage drops due to currents from other sources may be accounted for when a coupon is used to represent the pipeline. The magnitude of these voltage drops can be

quantified by interrupting cathodic protection sources while the coupon is disconnected and noting whether there is a shift in the coupon-to-electrolyte potential.

C3.2.3 A coupon has an insulated test lead brought above ground and, during normal operations, connected to a pipeline test lead. The coupon receives cathodic protection current and represents the pipeline at the test site. For testing purposes, this connection is opened, and the polarized "off" potential of the coupon is measured. The time the connection is open to measure the coupon's "off" potential should be minimized to avoid significant depolarization of the coupon. The "off" period is typically less than 3 seconds. The coupon is then allowed to depolarize. When possible, coupon current direction and magnitude should be verified, using a current clip gauge or resistor permanently placed in series with the coupon lead. Measurements showing discharge of current from the coupon should be reason to question the validity of using a coupon at the test site.

C3.3  Comparison with Other Methods

C3.3.1  Advantages

(a)  Can measure coupon-to-electrolyte polari-zation decay with a minimum of specialized equipment, personnel, and vehicles;
(b)  Can provide an indication of the amount of polarization present at the test site without interrupting the cathodic protection current supplied to the pipeline;
(c)  Can provide a better indication of cathodic protection levels due to eliminating the effects of "long-line" current flow when the pipeline "off" potentials are measured.

C3.3.2  Disadvantage—Can have high initial costs to install a coupon, especially for existing pipelines.

C3.4  Basic Test Equipment

C3.4.1  Voltmeter with adequate input impedance. Commonly used digital instruments have a nominal impedance of 10 megaohms. An analog instrument with an internal resistance of 100,000 ohms per volt may be adequate in certain circumstances where the circuit resistance is low. A potentiometer circuit may be necessary in other instances.

C3.4.2  Two color-coded meter leads with clips for connection to the coupon and reference electrode.

C3.4.3  Reference electrode

C3.4.3.1    CSE.

C3.4.3.2  Other standard reference electrodes may be substituted for the CSE. These reference electrodes are described in Appendix A, Paragraph A2.

C3.5  Procedure

C3.5.1  Before the test, verify that:

(a)  Cathodic protection equipment is installed
(b)  and operating properly; and
(c)  Coupon is in place and connected to a pipeline test lead.

Time shall be allowed for the pipeline and coupon potentials to reach polarized values.

C3.5.2  Determine the location of the site to be tested. Selection of a site may be based on:

(a)  Location accessible for future monitoring;
(b)  Other protection systems, structures, and anodes that may influence the pipe-to-electrolyte and coupon-to-electrolyte potentials;
(c)  Electrical midpoints between protection devices;
(d)  Known location of an ineffective coating when the line is coated; and
(e)  Location of a known or suspected corrosive environment.

C3.5.3  Make electrical contact between the reference electrode and the electrolyte at the test site as close to the coupon as is practicable.

C3.5.3.1  Identify the location of the electrode to allow it to be returned to the same location for subsequent tests.

C3.5.4  Connect the voltmeter to the coupon test lead and reference electrode as described in Paragraph 5.6.

C3.5.5  Measure and record the pipeline and coupon "on" potentials.

C3.5.6  Disconnect the coupon test lead from the pipeline test lead and immediately measure the coupon-to-electrolyte potential.

C3.5.6.1  The coupon-to-electrolyte potential becomes the "base line value" from which polarization decay is measured.

C3.5.7  Record the coupon-to-electrolyte "off" potential and its polarity with respect to the reference electrode.

C3.5.8  Leave the coupon test lead disconnected to allow the coupon to depolarize.

C3.5.9 Measure and record the coupon-to-electrolyte potential periodically. The difference between it and the "off" potential is the amount of polarization decay. Continue to measure and record the coupon-to-electrolyte potential until it either:

(a) Has become at least 100 mV less negative than the "off" potential; or
(b) Has reached a stable depolarized level.

C3.5.10 Reconnect the coupon test lead to the pipeline test lead for normal operations.

C3.6 Evaluation of Data

Cathodic protection may be judged adequate at the test site when 100 mV or more of polarization decay is measured with respect to a standard reference electrode. The depolarized potential of the coupon depends on the coupon surface condition, the soil in which the coupon is placed, its level of polarization, and its time polarized. Therefore, the depolarized potential of the coupon may not be the same as that of the pipe and may not accurately reflect the polarization on the pipe at the coupon location. It must also be understood that the polarization measured on the pipeline is a "resultant" of the variations of polarization on the pipe at the test site. These variations are caused by the pipe surface condition, soil strata variations, oxygen differentials, and time the pipe has been polarized. Making precise comparisons may not be possible.

C3.7 Monitoring

When at least 100 mV or more of polarization decay has been measured, the pipeline "on" potential at the test site may be used for monitoring unless significant environmental, structural, coating integrity, or cathodic protection system parameters have changed.

# NACE International Evaluation Survey

*NACE International takes the quality of instruction offered by its instructors seriously. NACE has a policy that requires that all instructors and courses be evaluated by their students, and that the evaluations be considered by the NACE Instructor/Peer and Course Quality Committee. The results of these evaluations are important to provide feedback to instructors on how their performance can be improved and to provide NACE with information to advance and revise it's training programs.*

Course Title: _____Date:_____

Location: _____ Course Code: _____

|  | Disagree (1) | (2) | (3) | (4) | Agree (5) |
|---|---|---|---|---|---|
| **Course Evaluation** | | | | | |
| I found the course to be generally interesting and informative. | ① | ② | ③ | ④ | ⑤ |
| Attending this course has improved my knowledge and understanding of the subject matter of this course. | ① | ② | ③ | ④ | ⑤ |
| I would recommend this course to others interested in improving their knowledge and understanding of the subject matter. | ① | ② | ③ | ④ | ⑤ |
| This course was what I expected from its description in NACE Literature. | ① | ② | ③ | ④ | ⑤ |
| This course was a worthwhile use of my time. | ① | ② | ③ | ④ | ⑤ |
| **Materials Evaluation** | | | | | |
| I was completely satisfied with the COURSE MANUAL used in this class. | ① | ② | ③ | ④ | ⑤ |
| I was completely satisfied with the REFERENCE MATERIALS (books, standards) used in this class. | ① | ② | ③ | ④ | ⑤ |
| I was completely satisfied with the GROUP EXERCISES used in this class. | ① | ② | ③ | ④ | ⑤ |
| I was completely satisfied with the DAILY QUIZZES used in this class. | ① | ② | ③ | ④ | ⑤ |
| I was completely satisfied with the SLIDES/VIDEOS used in this class. | ① | ② | ③ | ④ | ⑤ |
| I was completely satisfied with the CASE STUDIES used in this class. | ① | ② | ③ | ④ | ⑤ |
| I was completely satisfied with the CLASS DISCUSSION encountered in this class. | ① | ② | ③ | ④ | ⑤ |

**~MORE OVER~**

**My Company or division can best be described as:**
(Please choose one of the following)

| | |
|---|---|
| ❑ Aerospace | ❑ Original Equipment Manufacturer |
| ❑ Bridges & Highways | ❑ Oil & Gas Pipelines/Storage Tanks |
| ❑ Chemical Processing/Process Industries | ❑ Plastics/Nonmetals |
| ❑ Coating & Lining Application | ❑ Power Plant/Electric Utility |
| ❑ Coating & Lining Mfg/Distributor | ❑ Pulp & Paper |
| ❑ Construction | ❑ Railcar/Tank Trucks |
| ❑ Engineering/Architecture/Consulting Firms | ❑ Refining |
| ❑ Industrial Water Treatment | ❑ Research Services |
| ❑ Measuring Analyzing & Controlling | ❑ Ships/Marine Structures/Offshore Platforms |
| ❑ Metals/Mining | ❑ Testing Services |
| ❑ Municipal Water Distribution/Treatment | ❑ Other |

**What is your job function?**
(Please choose one of the following)

| | |
|---|---|
| ❑ Applicator | ❑ Manager |
| ❑ Chemist | ❑ Owner/Pres/VP |
| ❑ Consultant | ❑ Planner |
| ❑ Contractor | ❑ Sales/Marketing |
| ❑ Designer | ❑ Scientist/Researcher |
| ❑ Engineer | ❑ Supervisor |
| ❑ Foreman | ❑ Technician/Technologist |
| ❑ Inspector | ❑ Other |

**Comments:**

_____

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# Thank you for your participation!

# NACE International Instructor Evaluation Survey

*NACE International takes the quality of instruction offered by its instructors seriously.  NACE has a policy that requires that all instructors and courses be evaluated by their students, and that the evaluations be considered by the NACE Instructor/Peer and Course Quality Committees.  The results of these evaluations are important to provide feedback to instructors on how their performance can be improved and to provide NACE with information to advance and revise it's training programs.*

Course Title: _____Date: _____ Course Code: _____

Location: _____ Instructor:_____

## *Instructor Evaluation*

| | Disagree (1) | (2) | (3) | (4) | Agree (5) |
|---|:---:|:---:|:---:|:---:|:---:|
| The instructor demonstrated a thorough understanding of the subject matter and showed enthusiasm for the subject matter. | ○ | ○ | ○ | ○ | ○ |
| The instructor presented the material according to the course outline. | ○ | ○ | ○ | ○ | ○ |
| The instructor came to class well prepared and organized. | ○ | ○ | ○ | ○ | ○ |
| The instructor is a positive representative for NACE INTERNATIONAL. | ○ | ○ | ○ | ○ | ○ |
| The instructor generally was available to consult with and assist students. | ○ | ○ | ○ | ○ | ○ |
| The instructor encouraged student participation. | ○ | ○ | ○ | ○ | ○ |
| The instructor answered my questions to my satisfaction. | ○ | ○ | ○ | ○ | ○ |
| The instructor's presentation was interesting and kept my attention. | ○ | ○ | ○ | ○ | ○ |
| The instructor spoke audibly and clearly. | ○ | ○ | ○ | ○ | ○ |
| The instructor should continue to teach this course for NACE. | ○ | ○ | ○ | ○ | ○ |

**Comments:**

_____

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_____

ONLY COURSE ORGANIZERS AT NACE HEADQUARTERS SEE COMPLETED EVALUATION FORM.S