# Table of Contents

Introduction .................................................................................................................................................. 3  
  Target Audience ........................................................................................................................................ 3  
  Requirements .......................................................................................................................................... 4  
Exam Blueprint .......................................................................................................................................... 5  
Types of Questions ..................................................................................................................................... 7  
  Description of Questions .......................................................................................................................... 7  
  Sample Questions ..................................................................................................................................... 8  
  Questions .................................................................................................................................................. 8  
  Answer Key ............................................................................................................................................. 9  
Preparation .................................................................................................................................................. 9  
  Training—None Required ......................................................................................................................... 9  
  Recommended Study Material ................................................................................................................. 9  
  Books ......................................................................................................................................................... 9  
  Standards ............................................................................................................................................... 9  
  Calculators .............................................................................................................................................. 10  
  Reference Material Provided in the Exam .............................................................................................. 12
Introduction

The Cathodic Protection Specialist (CP 4) Theory Exam is designed to assess whether a candidate has the requisite knowledge and skills that a minimally qualified Cathodic Protection Specialist must possess. The exam consists of 60 multiple-choice, multiple-choice with more than one correct answer, and matching questions that require the application of knowledge based on the Cathodic Protection (CP) body of knowledge. A candidate should have theoretical concepts and practical application of CP with a strong focus on interpretation of CP data and troubleshooting.

<table>
<thead>
<tr>
<th>Exam Name</th>
<th>NACE-Cathodic Protection Specialist Theory Exam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exam Code</td>
<td>NACE-CP4-Theory</td>
</tr>
<tr>
<td>Time</td>
<td>4 hours*</td>
</tr>
<tr>
<td>Number of Questions</td>
<td>60</td>
</tr>
<tr>
<td>Format</td>
<td>Computer Based Testing- CBT</td>
</tr>
</tbody>
</table>

NOTE: A pass/fail grade is provided at the end of the exam. The Theory and Case-Based exams are scored separately, and candidates must pass both exams.

*Exam time includes 4 minutes for the non-disclosure agreement and 6 minutes for the system tutorial.

NOTE: The CP 4 course manual is NOT provided in the exam. Reference material is provided as a PDF for questions that require an equation, conversion chart, or other reference.

Target Audience

CP 4 certification is geared toward persons involved in the design, installation, and maintenance of CP systems. Prior to taking the exam or the NACE training course, students must have completed college or university-level courses in algebra, geometry, and trigonometry, and must have significant practical experience in cathodic protection.

NOTE: There is NOT a direct progression from Cathodic Protection Technologist (CP 3) to Cathodic Protection Specialist (CP 4). Substantial experience, beyond that of a CP 3, involving all aspects of CP, including design and formal education in math/science/engineering is critical to a candidate’s success on this exam. Attendance in the Cathodic Protection Technologist (CP 3) course is strongly recommended before attempting Cathodic Protection Specialist (CP 4). However, additional experience and education are also recommended.
## Requirements

### Cathodic Protection Specialist (CP 4)

**Requirements for Cathodic Protection Specialist (CP 4):**
1 Prerequisite + Work Experience + 2 Core Exams + Application

<table>
<thead>
<tr>
<th>The following prerequisite is required:</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Work Experience Requirements:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choose one of the following work experience options:</td>
</tr>
<tr>
<td>12 years verifiable CP work experience</td>
</tr>
<tr>
<td>6 years verifiable CP work experience</td>
</tr>
<tr>
<td>AND</td>
</tr>
<tr>
<td>4-year physical science or engineering degree</td>
</tr>
<tr>
<td>AND</td>
</tr>
<tr>
<td>Advanced physical science or engineering degree</td>
</tr>
<tr>
<td>OR</td>
</tr>
<tr>
<td>PE, PE Eng or equivalent</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Core Exam Requirements:</th>
</tr>
</thead>
<tbody>
<tr>
<td>The following exams are required: (2 core exams required)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Cathodic Protection Specialist Level 4 Exam (Theory)</td>
</tr>
<tr>
<td>Cathodic Protection Specialist Level 4 Exam (Case-Based)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Application Requirement:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approved Cathodic Protection Specialist (CP 4) application</td>
</tr>
</tbody>
</table>

NOTE: Completion of course does not entitle the candidate to the certification.

Submit Application – candidates must apply for this certification by submitting an [on-line application](#) which is subject to approval. Applications must be submitted within 3 years of successful completion of exam.

Upon successful completion of requirements, the candidate will be awarded a Cathodic Protection Specialist (CP 4) Certification.
## Exam Blueprint

### Basics
- Understand the relationship between voltage, current, and resistance as expressed by Ohm's Law.
- Understand basic AC and DC circuits, to include series, parallel, and series-parallel.
- Understand the composition of a basic galvanic cell and the electro-chemical reactions that allow corrosion to occur at the anode rather than the cathode.
- Understand the cause and effect of polarization in a galvanic cell.
- Understand the concept cathodic protection and the two primary methods of applying it to metal objects underground or otherwise immersed in an electrolyte.
- Understand how corrosion cells are formed on metal objects that are underground or otherwise immersed in an electrolyte.
- Understand the concept of shielding and how it can affect metallic objects that are cathodically protected.
- Understand the principles of magnetism and how it applies to transformers.
- Be able to identify different forms of corrosion.
- Understand the effect of polarization on environment.

### Periodic Surveys
- Conduct annual pipe to soil surveys on all facilities.
- Conduct rectifier readings.
- Conduct surveys of bonds.
- Conduct surveys of diodes or current reversing switches.
- Conduct soil resistivity surveys.
- Collect data on external "coupon test stations."
- Conduct offshore platform and riser surveys.
- Utilize a current interrupter to determine IR Free readings during close interval or annual surveys.
- Understand how IR Free readings can be used to determine the true level of polarization on your pipeline.
- Conduct polarization decay test.

### Reference Cells
- Understand the construction and operation of reference cells and maintain them in a manner that will provide comparative readings.
- Install permanent reference cells and check them periodically to ensure that they are in good working order.
- Abide by the recommendations in the MSDS sheet pertaining to the handling and disposal of Copper Sulfate.
- Use an antimony half-cell in comparison to a copper/copper sulfate half cell for determining the pH of soils.

### Field Tests
- Perform current requirement test.
- Perform soil pH test.
- Perform IR Drop test.
- Run "shorted casing test" on casings that are suspected of being shorted and interpret the results of the test.
- Perform coating examinations on sections of pipeline that have been excavated.
- Perform soil resistivity test to evaluate the area for a conventional ground bed site.
- Conduct Pearson surveys to evaluate the coating condition of a section of pipeline.
- Conduct computerized close interval surveys where needed and evaluate the graphs produced from the data.
- Locate breaks in header cables with an "audio type" pipe and cable locator.
- Investigate shorts on a pipeline or other structure.
- Verify the results of shorted casing test.
- Understand the factors that affect cathodic protection system performance at the anode, at the structure performance, in the electrolyte, in the metallic path, at the power supply, because of anode arrangement, and interference.
Perform advanced cathodic protection testing using correct measurement techniques to monitor CP system performance and accurately interpret the data collected to ensure optimum CP system performance.

Based on data collected, determine if correction/modifications to system components are necessary.

Identify errors in data collection/CP measurements including contact resistance errors, voltage drop errors, and reference electrode errors.

Utilize the instruments required to accomplish advanced cathodic protection testing and collection of cathodic protection systems measurements.

Conduct cathodic protection surveys, including close interval surveys and DCVG, where needed or required and evaluate the graphs produced from the data collected during the surveys.

Troubleshoot rectifiers and make corrections/repair as necessary.

Perform efficiency test on rectifiers.

Install new rectifiers.

Understand the use of external CP coupons and be able to identify if the use of external coupons is needed for a CP system.

Understand in-line and direct inspection (understand and be able to implement ECDA).

**DC Stray Current Interference**

Conduct and document interference tests where stray currents are suspected.

Once interference tests have been run, suggest method of control that will mitigate the effects of the stray current.

Understand how IR Drop test stations can be used to evaluate stray current.

Understand how Coupon Test stations can be used to determine the presence of and the mitigation of stray current.

Calculate the resistance required to provide the amount of current drain desired at a resistance bond installation.

Understand the causes (sources) and the effects of interference.

Understand the methods available to mitigate interference.

**AC Mitigation**

Understand the safety requirements when installing test stations under high voltage power lines.

Take appropriate steps to mitigate the effects of excessive AC voltage induced on underground structures.

**Corrosion Theory**

Understand the composition of a basic galvanic cell and the electrochemical reactions that allow corrosion to occur at the anode rather than the cathode.

Describe the characteristics of anodic and cathodic reactions.

Understand and apply the principles of electricity and electrical circuits (series, parallel, and series-parallel circuits) (including the application of Ohm’s and Kirchhoff’s Laws to electrical circuits.)

**Polarization**

Understand the cause and effect of polarization in a galvanic cell.

Understand activation, concentration, and resistance polarization and the mathematical expressions of these concepts.

Understand the factors that affect polarization (area, temperature, relative movement, ion concentration, oxygen concentration).

Perform calculations using Ohm’s Law and calculations related to series and parallel circuits.

Understand how corrosion cells are formed on metal objects that are underground or otherwise immersed in an electrolyte.

Understand Faraday’s Law and perform calculations using Faraday’s law to determine required anode weight for cathodic protection.
### Cathodic Protection
- Understand the concept cathodic protection and be knowledgeable of the components required for both galvanic and impressed current systems.
- Be able to design and install simplistic forms of galvanic and impressed current cathodic protection facilities.
- Understand the relationship between cathodic protection and other methods of corrosion mitigation.
- Understand the factors that affect the amount of current required for a cathodic protection system.
- Understand the NACE criteria for Cathodic Protection and be able to apply the criteria and make adjustments as necessary to CP systems in order to comply with the criteria defined by the company where the specialist is employed.
- Understand IR drop and be able to determine the IR drop and apply correction techniques as needed.
- Understand and apply E Log I criteria and construct polarization curves.
- Understand the concept of current distribution and be able to determine ideal current distribution for a CP system taking into account the factors affecting current distribution (anode-to-cathode separation distance, electrolyte and structure resistivity variation, current attenuation).
- Understand the effects of current path geometry, protective coatings, and polarization on current distribution.

### Codes and Compliance
- Should have a good working knowledge of appropriate regulations that apply to the products, transportation or storage means being utilized by your company.
- Should know the reports and other documentation that is required by the agencies that inspect your facilities.
- Should have a good understanding of the National Electrical Code as it relates to cathodic protection facilities in all divisions and classes.
- Should have a good working knowledge of grounding practices and lightning protection and how it can affect a CP system.

### Design
- Utilize field data to accomplish the calculations required to design cathodic protection current sources.
- Select site locations and implement the design of cathodic protection current sources for distribution or transmission pipeline systems.
- Design cathodic protection systems for the inside of water tanks.
- Design cathodic protection for the tank bottoms of aboveground storage tanks.
- Design cathodic protection for underground storage tanks.
- Work with engineering in the proper use of insulation for newly designed facilities.
- Provide information on underground coating performance for those selecting coatings for new facilities.

### Types of Questions

#### Description of Questions
This closed-book exam consists of multiple-choice questions which may have multiple answers and require selection of more than one answer choice, as well as matching items. The questions are based on the knowledge and skills required in the CP industry for a Cathodic Protection Specialist.
Sample Questions

The sample questions are included to illustrate the formats and types of questions that will be on the exam. Your performance on the sample questions should not be viewed as a predictor of your performance on the actual exam.

Questions

1. Which of the following statements describe the magnitude of geomagnetically induced voltage on a pipeline?

   **SELECT ALL THAT APPLY**

   A. Directly proportional to coating resistance  
   B. Inversely proportional to pipe length  
   C. Dependent on the pipeline’s location relative to the geomagnetic poles  
   D. Varies with the time of day

2. Which of the following electrical interference situations causes adverse effects?

   A. Stray DC current pick-up on a bare low carbon steel pipe  
   B. Stray AC current density of <2 mA / cm² on steel  
   C. Stray current discharge from a cast iron pipe  
   D. Polarized potential on steel shifted from $-1080 \text{ mV}_{\text{CSE}}$ to $-880 \text{ mV}_{\text{CSE}}$
Answer Key

1. A, C, and D

2. C

Preparation

Training—None Required

NACE Cathodic Protection Specialist—Course CP 4 (Available)
NACE Cathodic Protection Technologist—Course CP 3 (Available)
NACE Cathodic Protection Technician—Course CP 2 (Available)
NACE Cathodic Protection Tester—Course CP 1 (Available)

Recommended Study Material

Books

NACE Cathodic Protection Specialist—CP 4 course material

Standards


Calculators

Students will have access to either a TI Standard or TI Scientific calculator for use during the CBT Exam.

**Standard Calculator**

**Standard Mode Functions**

- **Add**: +
- **Subtract**: -
- **Multiply**: ×
- **Divide**: ÷
- **Negative**: (−)
- **Percentage**: %
- **Square Root**: √
  - Example: 4 √
- **Reciprocal (Inverse)**: x
  - Example: 1 ÷ 2
- **Store value to variable**: M±
  - Example: 3 5 M±
- **Access variable**: MRC
  - Example: 7 3 MRC
- **Clear variable**: M− MRC

**Scientific Calculator**

**Scientific Mode Functions**

- **Add**: +
- **Subtract**: −
- **Multiply**: ×
- **Divide**: ÷
- **Negative**: (−)
- **Percentage**: 2nd [%]
- **Square Root**: √
  - Example: 2nd √ 4 enter
- **Reciprocal (Inverse)**: x¹
  - Example: 2 x¹ enter
- **Store value to variable**: stô X^2
  - Example: 3 5 stô X^2
- **Access variable**: X^2 or 2nd [recall]
  - Example: 7 1 2nd [recall] enter enter

**Numeric Notation**

- **Standard** (Floating Decimal)
  - Notation (digits to the left and right of decimal)
  - mode menu options
    - NORM SCI ENG
    - e.g. 1234567.8
    - FLOAT 0 1 2 3 4 5 ...
    - e.g. 12345678

- **Scientific**
  - Notation (1 digit to the left of decimal and appropriate power of 10)
  - mode menu options
    - NORM SCI ENG
    - e.g. 1.2345678 × 10^5

- **Engineering**
  - Notation (number from 1 to 999 times 10 to an integer power that is a multiple of 3)
  - mode menu options
    - NORM SCI ENG
    - e.g. 123.45678 × 10^3
Fractions

<table>
<thead>
<tr>
<th>Simple fractions</th>
<th>( \frac{n}{d} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed numbers</td>
<td>2nd [Un/d]</td>
</tr>
<tr>
<td>Conversion b/w simple fraction and mixed number</td>
<td>2nd [n/d \quad \text{Un/d}]</td>
</tr>
<tr>
<td>Conversion b/w fraction and decimal</td>
<td>2nd [f \quad \text{d}]</td>
</tr>
</tbody>
</table>

Powers, roots, and inverses

<table>
<thead>
<tr>
<th>Square a value</th>
<th>( \sqrt{} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cube a value</td>
<td>( \sqrt[3]{\text{a}} )</td>
</tr>
<tr>
<td>Raise value to specified power</td>
<td>( \sqrt[n]{\text{a}} )</td>
</tr>
<tr>
<td>Square root</td>
<td>2nd [\sqrt{}]</td>
</tr>
<tr>
<td>Reciprocal</td>
<td>( x^{-1} )</td>
</tr>
</tbody>
</table>

Example (2^4): \( 2 \times 2 \times 2 \times 2 = 16 \)

Example (\( \sqrt{16} \)): 2nd \[\sqrt{}\] 16

Example (n^th root): 5\(^{th}\) root of 8: 5\[2nd \[\sqrt{}\]] 8

Pi

| \( \pi \) (\( \pi \)) | \( \pi \) |

Toggle

The scientific calculator might show the results of certain calculations as a fraction—possibly involving \( \pi \) or a square root. To convert this kind of result to a single number with a decimal point, you will need to use the “toggle answer” button circled in the picture below. Pressing this button will change the display from a fractional to a decimal format.

Answer Toggle

Press the \( \pi \) key to toggle the display result between fraction and decimal answers, exact square root and decimal, and exact \( \pi \) and decimal.

Example

<table>
<thead>
<tr>
<th>Answer toggle</th>
<th>2nd [\sqrt{}] 8 enter</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{\pi}{8} )</td>
<td>( \frac{\pi}{2} )</td>
</tr>
</tbody>
</table>

Note: If you find this onscreen calculator difficult to use, raise your hand and ask the Test Administrator to provide you with a hand-held calculator. If available, you will be provided with a scientific or non-scientific calculator. Candidates are not permitted to bring their own calculator into the testing room.
Reference Material Provided in the Exam

**NOTE:** All references, including equations, were taken from original sources and may differ from those used in course manuals and presentations

**EQUATIONS**

**RESISTANCE TO EARTH OF SINGLE VERTICAL ANODE**

\[
R_v = \left[ \frac{0.00521 \rho}{L} \right] \ln \left[ \frac{8L}{d} \right] - 1
\]

Where
- \( R_v \) = resistance in ohms
- \( \rho \) = resistivity in ohm-cm
- \( L \) = anode length in feet
- \( d \) = anode diameter in feet

OR

\[
R_v = \left[ \frac{\rho}{2 \pi L} \right] \ln \left[ \frac{8L}{d} \right] - 1
\]

Where
- \( R_v \) = resistance in ohms
- \( \rho \) = resistivity in ohm-m
- \( L \) = anode length in m
- \( d \) = anode diameter in m

**RESISTANCE TO EARTH OF MULTIPLE VERTICAL ANODES**

\[
R_v = \left[ \frac{0.00521 \rho}{NL} \right] \ln \left[ \frac{8L}{d} \right] - 1 + \left[ \frac{2L}{S} \right] \ln(0.66N)
\]

Where
- \( R_v \) = resistance in ohms
- \( \rho \) = resistivity in ohm-cm
- \( L \) = anode length in feet
- \( N \) = number of anodes
- \( S \) = anode spacing center-to-center in feet
- \( d \) = anode diameter in feet

OR

\[
R_v = \left[ \frac{\rho}{2 \pi NL} \right] \ln \left[ \frac{8L}{d} \right] - 1 + \left[ \frac{2L}{S} \right] \ln(0.66N)
\]

Where
- \( R_v \) = resistance in ohms
- \( \rho \) = resistivity in ohm-m
- \( L \) = anode length in m
- \( N \) = number of anodes
- \( S \) = anode spacing center-to-center in m
- \( d \) = anode diameter in m

**NOTE:** Use the units specified.
RESISTANCE TO EARTH OF SINGLE HORIZONTAL ANODE

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

Where

\( R_H = \) resistance in ohms  \\
\( \rho = \) resistivity in ohm-cm  \\
\( L = \) anode length in feet  \\
\( S = \) twice the anode depth in feet  \\
\( d = \) anode diameter in feet

OR

\[ R_H = \left[ \frac{\rho}{2\pi L} \right] \left[ \ln \left( \frac{4L^2 + 4L \sqrt{S^2 + L^2}}{dS} \right) + \frac{S}{L} - \frac{\sqrt{S^2 + L^2}}{L} - 1 \right] \]

Where

\( R_H = \) resistance in ohms  \\
\( \rho = \) resistivity in ohm-m  \\
\( L = \) anode length in m  \\
\( S = \) twice the anode depth in m  \\
\( d = \) anode diameter in m

RESISTANCE TO EARTH OF MULTIPLE HORIZONTAL ANODES

\[ R_T = \frac{R_H F}{N} \]

Where

\( R_T = \) resistance of multiple horizontal anodes in ohms  \\
\( F = \) Anode Interference or Crowding Factor  \\
\( R_H = \) resistance of single horizontal anode in ohms  \\
\( N = \) number of anodes

COUPLING FACTOR

\[ R = \frac{\Delta V}{\Delta I} \]

Where

\( R = \) coupling factor in mV / A  \\
\( \Delta V = \) pipe-to-soil potential shift in mV  \\
\( \Delta I = \) applied current A

ANODE INTERFERENCE BETWEEN ANODES (Crowding Factor)

\[ F = 1 + \frac{\rho}{\pi SR_H} \ln 0.66N \]

Where

\( F = \) Anode Interference or Crowding Factor  \\
\( \rho = \) resistivity in ohm-m  \\
\( R_H = \) resistance of single horizontal anode in ohms  \\
\( N = \) number of anodes  \\
\( S = \) distance between anodes in m
CALCULATE PIPE OR CABLE RESISTANCE FROM RESISTIVITY
(Pouillet’s Law)

\[ R = \frac{\rho L}{A} \]

Where
- \( R \) = resistance in ohms
- \( \rho \) = resistivity in ohm-cm
- \( A \) = cross-sectional area in cm²
- \( L \) = length in cm

LENGTH OF BARE STRUCTURE RECEIVING PROTECTION

\[ L = 2d \tan 60° \]

Where
- \( d \) = perpendicular distance between anode and structure
- \( L \) = length of structure receiving protection

TEMPERATURE CONVERSION

\[ ^°C = \frac{5}{9} (°F - 32°) \]
\[ ^°F = \frac{9}{5} (°C) + 32° \]

WENNER SOIL RESISTIVITY

\[ \rho = 2\pi AR \]

Where
- \( \rho \) = soil resistivity in ohm-cm
- \( A \) = distance between probes in cm
- \( R \) = soil resistance in ohms {instrument reading}

OR

\[ \rho = 191.5 AR \]

Where
- \( \rho \) = soil resistivity in ohm-cm
- \( A \) = distance between probes in feet
- \( R \) = soil resistance in ohms {instrument reading}

INPUT IMPEDANCE MEASUREMENT CORRECTION

\[ E_{true} = \frac{V_h(1 - K)}{1 - K \frac{V_h}{V_l}} \]

Where
- \( E_{true} \) = true potential in V
- \( K \) = input resistance ratio \( \frac{R_l}{R_h} \)
- \( R_l \) = lowest input resistance in ohms
- \( R_h \) = highest input resistance in ohms
- \( V_l \) = voltage measured with lowest input resistance in V
- \( V_h \) = voltage measured with highest input resistance in V
ATTENUATION

Where

\[ I_s = \text{current at sending end in Amps} \]
\[ E_s = \text{potential at sending end in mV} \]
\[ y = \text{number of unit lengths from sending end} \]
\[ x = \text{number of unit lengths from receiving end} \]
\[ I_r = \text{current at receiving end in Amps} \]
\[ E_r = \text{potential at receiving end in mV} \]

\[ E = E_r \cosh(\alpha x) + R_G I_r \sinh(\alpha x) \]
\[ E = E_s \cosh(\alpha y) - R_G I_s \sinh(\alpha y) \]
\[ I = I_r \cosh(\alpha x) + \frac{E_r}{R_G} \sinh(\alpha x) \]
\[ I = I_s \cosh(\alpha y) - \frac{E_s}{R_G} \sinh(\alpha y) \]

\[ \alpha = \sqrt{r g} \]

Where
\[ \alpha = \text{attenuation constant} \]
\[ r = \text{longitudinal resistance of structure in ohms} \]
\[ g = \text{conductance to earth in S} \]

\[ r' = R_L A_S \]

Where
\[ r' = \text{specific leakage resistance in ohm-m}^2 \text{ (ohm-ft}^2\text{)} \]
\[ R_L = \text{average total leakage resistance in ohms} \]
\[ A_S = \text{total surface area in m}^2 \text{ (ft}^2\text{)} \]

\[ R_G = \sqrt{\frac{r}{g}} \]

Where
\[ R_G = \text{characteristic resistance} \]
\[ r = \text{longitudinal resistance of structure in ohms} \]
\[ g = \text{conductance to earth in S} \]

\[ R_{SO} = R_G \coth(\alpha x) \]

Where
\[ R_{SO} = \text{Resistance looking into open line in ohms} \]

\[ R_G = \sqrt{R_{SO} R_{SS}} \]

Where
\[ R_{SS} = \text{Resistance looking into open line in ohms} \]
AC CURRENT DENSITY

\[ i_{AC} = \frac{8V_{AC}}{\rho \pi d} \]

Where
- \( i_{AC} \) = AC current density in A / m²
- \( V_{AC} \) = AC Volts in V
- \( \rho \) = soil resistivity in ohm-m
- \( d \) = holiday diameter in m

REFERENCE ELECTRODE TEMPERATURE CONVERSION

\[ E = E_{25\circ C/SHE}^0 + k_t(T - 25\circ C) \]

Where
- \( k_t \) = temperature coefficient in \( mV/(\circ C) \)
- \( E_t \) = reference potential at temperature \( T \) in °C (SHE)
- \( E_{25\circ C/SHE}^0 \) = reference potential at 25°C

KIRCHHOFF’S LAW

\[ V_m = \frac{R_m}{R_t} E_t \]

Where
- \( V_m \) = voltage drop across the voltmeter
- \( R_m \) = voltmeter input resistance
- \( R_t \) = total resistance
- \( E_t \) = true potential

FARADAY’S LAW

\[ \Delta m = \frac{MQ}{zF} \]

Where
- \( \Delta m \) = mass of dissolved metal
- \( M \) = atomic weight
- \( Q \) = transferred electric charge
- \( z \) = valance of the metal ions
- \( F \) = Faraday’s constant

MINIMUM WEIGHT OF ANY ANODE MATERIAL

\[ W = \frac{I_{cp} L C_r}{U E} \quad \text{or} \quad W = \frac{I_{cp} L}{C_a U E} \]

Where
- \( W \) = minimum weight of anode material in kg (lb)
- \( I_{cp} \) = cathodic protection in amps
- \( L \) = life of anode in years
- \( C_r \) = theoretical consumption rate of anode material in \( \frac{kg}{Amp-yr} \)
- \( C_a \) = theoretical capacity of anode material in \( \frac{Amp-yr}{kg} \)
- \( U \) = utilization factor
- \( E \) = electrochemical efficiency
BARNES LAYER

\[ R_{L2} = \frac{R_1R_2}{(R_1-R_2)} \]

Where
- \( R_{L2} \) = resistance of layer 2 in ohms
- \( R_1 \) = resistance measured to depth \( S_1 \) in ohms
- \( R_2 \) = resistance measured to depth \( S_2 \) in ohms
- \( L_2 = S_2 - S_1 \)

NERNST EQUATIONS

\[ E_M = E_M^\circ + \frac{RT}{nF} \ln \frac{\alpha^{M^{n+}}}{\alpha^{M^\circ}} \]

Where
- \( E_M \) = metal potential
- \( E_M^\circ \) = metal potential at standard conditions
- \( R \) = universal gas constant (J/mol•°K)
- \( T \) = absolute temperature in kelvin
- \( F \) = Faraday’s Constant (96,500 coulombs)
- \( \alpha^{M^{n+}} \) = metal ion activity
- \( \alpha^{M^\circ} \) = metal activity
- \( n \) = number of electrons transferred

CONVERSIONS

<table>
<thead>
<tr>
<th>Unit</th>
<th>Symbol</th>
<th>Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMF</td>
<td></td>
<td>electromotive force – any voltage unit</td>
</tr>
<tr>
<td>Electric Potential V</td>
<td>E or e</td>
<td>any voltage unit</td>
</tr>
<tr>
<td>Millivolt</td>
<td>mV</td>
<td>volts</td>
</tr>
<tr>
<td>Microvolt</td>
<td>( \mu )V</td>
<td>millivolts</td>
</tr>
<tr>
<td>Ampere</td>
<td>A</td>
<td>( \mu )A</td>
</tr>
<tr>
<td>Milliampere</td>
<td>mA</td>
<td>milliampere or millamps</td>
</tr>
<tr>
<td>Microampere</td>
<td>( \mu )A</td>
<td>microamperes or microamps</td>
</tr>
<tr>
<td>Resistance</td>
<td>R or ( \Omega )</td>
<td>Resistance</td>
</tr>
<tr>
<td>1,000,000 volts</td>
<td></td>
<td>1 megavolt</td>
</tr>
<tr>
<td>1,000 volts</td>
<td></td>
<td>1 kilovolt</td>
</tr>
<tr>
<td>1.0 volt</td>
<td></td>
<td>1000 millivolts</td>
</tr>
<tr>
<td>0.100 volt</td>
<td></td>
<td>100 millivolts</td>
</tr>
<tr>
<td>0.010 volt</td>
<td></td>
<td>10 millivolts</td>
</tr>
<tr>
<td>0.001 volt</td>
<td></td>
<td>1 millivolt</td>
</tr>
<tr>
<td>0.000001 volt</td>
<td></td>
<td>1 microvolt</td>
</tr>
<tr>
<td>1,000,000 amperes</td>
<td></td>
<td>1 mega-ampere</td>
</tr>
<tr>
<td>1,000 amperes</td>
<td></td>
<td>1 kiloampere</td>
</tr>
<tr>
<td>1.0 ampere</td>
<td></td>
<td>1000 milliampere</td>
</tr>
<tr>
<td>0.100 ampere</td>
<td></td>
<td>100 milliampere</td>
</tr>
<tr>
<td>0.010 ampere</td>
<td></td>
<td>10 milliampere</td>
</tr>
<tr>
<td>0.001 ampere</td>
<td></td>
<td>1 milliampere</td>
</tr>
<tr>
<td>0.000001 ampere</td>
<td></td>
<td>1 microampere</td>
</tr>
<tr>
<td>1,000,000 ohms</td>
<td></td>
<td>1 mega-ohm</td>
</tr>
<tr>
<td>1,000 ohms</td>
<td></td>
<td>1 kilo-ohm</td>
</tr>
<tr>
<td>1.0 ohms</td>
<td></td>
<td>1000 millionhs</td>
</tr>
<tr>
<td>0.100 ohm</td>
<td></td>
<td>100 millionhs</td>
</tr>
<tr>
<td>0.010 ohm</td>
<td></td>
<td>10 millionhs</td>
</tr>
<tr>
<td>0.001 ohm</td>
<td></td>
<td>1 millionhs</td>
</tr>
<tr>
<td>0.000001 ohm</td>
<td></td>
<td>1 micro-ohm</td>
</tr>
<tr>
<td>1 meter</td>
<td></td>
<td>100 cm</td>
</tr>
<tr>
<td>1 meter</td>
<td></td>
<td>1000 mm</td>
</tr>
<tr>
<td>1 inch</td>
<td></td>
<td>2.54 cm</td>
</tr>
<tr>
<td>1 foot</td>
<td></td>
<td>30.48 cm</td>
</tr>
</tbody>
</table>
### U.S. Customary/Metric Conversion for Units of Measure

Commonly Used in Corrosion-Related Publications

<table>
<thead>
<tr>
<th>U.S. Unit</th>
<th>Metric Unit</th>
<th>Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 A/ft²</td>
<td>10.76 A/m²</td>
<td></td>
</tr>
<tr>
<td>1 acre</td>
<td>4,047 m²</td>
<td>0.4047 ha</td>
</tr>
<tr>
<td>1 Ah/lb</td>
<td>2.205 Ah/kg</td>
<td></td>
</tr>
<tr>
<td>1 bbl (oil, U.S.)</td>
<td>159 L = 0.159 m³</td>
<td></td>
</tr>
<tr>
<td>1 bpd (oil)</td>
<td>159 L/d = 0.159 m³/d</td>
<td></td>
</tr>
<tr>
<td>1 Btu</td>
<td>1,055 J</td>
<td></td>
</tr>
<tr>
<td>1 Btu/ft²</td>
<td>11,360 J/m²</td>
<td></td>
</tr>
<tr>
<td>1 Btu/h</td>
<td>0.2931 W</td>
<td></td>
</tr>
<tr>
<td>1 Btu/h-ft²</td>
<td>3.155 W/m² (K-factor)</td>
<td></td>
</tr>
<tr>
<td>1 Btu/h-ft²</td>
<td>5.678 W/m²K</td>
<td></td>
</tr>
<tr>
<td>1 Btu/in²</td>
<td>0.1442 W/m²K</td>
<td></td>
</tr>
<tr>
<td>1 cfm</td>
<td>28.32 L/min = 0.02832 m³/min</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40.78 m³/d</td>
<td></td>
</tr>
<tr>
<td>1 cup</td>
<td>236.6 mL = 0.2366 L</td>
<td></td>
</tr>
<tr>
<td>1 cycle/s</td>
<td>1 Hz</td>
<td></td>
</tr>
<tr>
<td>1 ft</td>
<td>0.3048 m</td>
<td></td>
</tr>
<tr>
<td>1 ft²</td>
<td>0.0929 m² = 929 cm²</td>
<td></td>
</tr>
<tr>
<td>1 ft³</td>
<td>0.02832 m³ = 28.32 L</td>
<td></td>
</tr>
<tr>
<td>1 ft³ (energy)</td>
<td>1.356 J</td>
<td></td>
</tr>
<tr>
<td>1 ft³ (torque)</td>
<td>1.356 Nm</td>
<td></td>
</tr>
<tr>
<td>1 ft/s</td>
<td>0.3048 m/s</td>
<td></td>
</tr>
<tr>
<td>1 gal (Imp.)</td>
<td>4.546 L = 0.004546 m³</td>
<td></td>
</tr>
<tr>
<td>1 gal (U.S.)</td>
<td>3.785 L = 0.003785 m³</td>
<td></td>
</tr>
<tr>
<td>1 gal (U.S.)/min (gpm)</td>
<td>3.785 L/min = 0.2271 m³/h</td>
<td></td>
</tr>
<tr>
<td>1 gal/bag (U.S.)</td>
<td>89 mL/kg (water/cement ratio)</td>
<td></td>
</tr>
<tr>
<td>1 grain</td>
<td>0.06480 g = 64.80 mg</td>
<td></td>
</tr>
<tr>
<td>1 grain/ft³</td>
<td>2.288 g/m³</td>
<td></td>
</tr>
<tr>
<td>1 grain/100 ft³</td>
<td>22.88 mg/m³</td>
<td></td>
</tr>
<tr>
<td>1 hp</td>
<td>0.7457 kW</td>
<td></td>
</tr>
<tr>
<td>1 microinch (µin)</td>
<td>0.0254 µm = 25.4 nm</td>
<td></td>
</tr>
<tr>
<td>1 in</td>
<td>0.0254 m = 2.54 cm = 25.4 mm</td>
<td></td>
</tr>
<tr>
<td>1 in²</td>
<td>6.452 cm² = 645.2 mm²</td>
<td></td>
</tr>
<tr>
<td>1 in³</td>
<td>16.387 cm³ = 0.01639 L</td>
<td></td>
</tr>
<tr>
<td>1 in lbf (torque)</td>
<td>0.113 Nm</td>
<td></td>
</tr>
<tr>
<td>1 in Hg</td>
<td>3.386 kPa</td>
<td></td>
</tr>
<tr>
<td>1 inH₂O</td>
<td>249.1 Pa</td>
<td></td>
</tr>
<tr>
<td>1 knot</td>
<td>0.5144 m/s</td>
<td></td>
</tr>
<tr>
<td>1 ksi</td>
<td>6.895 MPa</td>
<td></td>
</tr>
<tr>
<td>1 lb</td>
<td>453.6 g = 0.4536 kg</td>
<td></td>
</tr>
<tr>
<td>1 lbf/ft²</td>
<td>47.88 Pa</td>
<td></td>
</tr>
<tr>
<td>1 lbf/ft³</td>
<td>16.02 kg/m³</td>
<td></td>
</tr>
<tr>
<td>1 lb/100 gal (U.S.)</td>
<td>1.198 g/L</td>
<td></td>
</tr>
<tr>
<td>1 lb/1.000 bbl</td>
<td>2.853 mg/L</td>
<td></td>
</tr>
<tr>
<td>1 mA/in²</td>
<td>0.155 mA/cm²</td>
<td></td>
</tr>
<tr>
<td>1 mA/ft²</td>
<td>10.76 mA/m²</td>
<td></td>
</tr>
<tr>
<td>1 Mbd (oil)</td>
<td>159 kl/d = 159 m³/d</td>
<td></td>
</tr>
<tr>
<td>1 mile</td>
<td>1.609 km</td>
<td></td>
</tr>
<tr>
<td>1 square mile</td>
<td>2.590 km²</td>
<td></td>
</tr>
<tr>
<td>1 mile (nautical)</td>
<td>1.852 km</td>
<td></td>
</tr>
<tr>
<td>1 mil</td>
<td>0.0254 mm = 25.4 µm</td>
<td></td>
</tr>
<tr>
<td>1 Mscfd</td>
<td>2.832 x 10⁴ m³/d</td>
<td></td>
</tr>
<tr>
<td>1 mph</td>
<td>1.609 km/h</td>
<td></td>
</tr>
<tr>
<td>1 myd</td>
<td>0.0254 mm/y = 25.4 µm/y</td>
<td></td>
</tr>
<tr>
<td>1 oz</td>
<td>28.35 g</td>
<td></td>
</tr>
<tr>
<td>1 oz fluid (Imp.)</td>
<td>28.41 mL</td>
<td></td>
</tr>
<tr>
<td>1 oz fluid (U.S.)</td>
<td>29.57 mL</td>
<td></td>
</tr>
<tr>
<td>1 oz/t²</td>
<td>2.993 Pa</td>
<td></td>
</tr>
<tr>
<td>1 oz/gal (U.S.)</td>
<td>7.49 g/L</td>
<td></td>
</tr>
<tr>
<td>1 psi</td>
<td>0.006895 MPa = 6.895 kPa</td>
<td></td>
</tr>
<tr>
<td>1 qt (Imp.)</td>
<td>1.1365 L</td>
<td></td>
</tr>
<tr>
<td>1 qt (U.S.)</td>
<td>0.9464 L</td>
<td></td>
</tr>
<tr>
<td>1 tablespoon (tbs)</td>
<td>4.929 mL</td>
<td></td>
</tr>
<tr>
<td>1 teaspoon (tsp)</td>
<td>14.79 mL</td>
<td></td>
</tr>
<tr>
<td>1 ton (short)</td>
<td>907.2 kg</td>
<td></td>
</tr>
<tr>
<td>1 U.S. bag cement</td>
<td>42.63 kg (94 lb)</td>
<td></td>
</tr>
<tr>
<td>1 yd</td>
<td>0.9144 m</td>
<td></td>
</tr>
<tr>
<td>1 yd²</td>
<td>0.8361 m²</td>
<td></td>
</tr>
<tr>
<td>1 yd³</td>
<td>0.7646 m³</td>
<td></td>
</tr>
</tbody>
</table>

Copyright © 2019 by NACE International Institute. All rights reserved.
### COMMON REFERENCE ELECTRODES AND THEIR POTENTIALS AT TEMPERATURE COEFFICIENTS

<table>
<thead>
<tr>
<th>Reference Electrode</th>
<th>Electrolyte Solution</th>
<th>Potential @ 25°C (V/SHE)</th>
<th>Temperature Co-efficient (mV/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu / CuSO₄ (CSE)</td>
<td>Sat. CuSO₄</td>
<td>+0.316</td>
<td>0.9</td>
</tr>
<tr>
<td>Ag / AgCl (SJ) (SSC)</td>
<td>0.6M NaCl (3½%)</td>
<td>+0.256</td>
<td>−0.33</td>
</tr>
<tr>
<td>Ag / AgCl (LJ) (SSC)</td>
<td>Sat. KCl</td>
<td>+0.222</td>
<td>−0.70</td>
</tr>
<tr>
<td>Ag / AgCl (LJ) (SSC)</td>
<td>0.1N KCl</td>
<td>+0.288</td>
<td>−0.43</td>
</tr>
<tr>
<td>Sat. Calomel (SCE)</td>
<td>Sat KCl</td>
<td>+0.244</td>
<td>−0.70</td>
</tr>
<tr>
<td>Zn (ZRE)</td>
<td>Saline Solution</td>
<td>−0.79</td>
<td>---</td>
</tr>
<tr>
<td>Zn (ZRE)</td>
<td>Soil</td>
<td>−0.80</td>
<td>---</td>
</tr>
</tbody>
</table>

SJ – solid junction   LJ – liquid junction
## Typical Consumption Rate and Capacities of Different Anode Materials in Soils or Fresh Waters

<table>
<thead>
<tr>
<th>Galvanic Anode Material</th>
<th>Theoretical Consumption Rate (kg / A-yr)</th>
<th>Theoretical Capacity (A-yr/kg)</th>
<th>Typical Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium</td>
<td>3.98</td>
<td>0.250</td>
<td>50</td>
</tr>
<tr>
<td>Zinc</td>
<td>10.76</td>
<td>0.093</td>
<td>90</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2.94</td>
<td>0.340</td>
<td>85 - 95</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Impressed Current Anode</th>
<th>Theoretical Consumption Rate (A-yr)</th>
<th>Typical Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite / Carbon</td>
<td>0.1 to 1.0</td>
<td></td>
</tr>
<tr>
<td>High Silicon Iron</td>
<td>0.25 to 1.0</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>9.1</td>
<td>90</td>
</tr>
</tbody>
</table>

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.
Typical Potential-pH (Pourbaix) Diagram Iron in Water at 25°C

Ionic species are at activities of 10^-4 and 10^-6.
REFERENCE ELECTRODE CONVERSION SCALE

(SJ) = only solid silver chloride (AgCl) over the silver wire.

(UJ) = a silver wire surrounded by a concentrated solution of KCl.
REFERENCES & STANDARDS USED TO DEVELOP THE REFERENCE MATERIAL


