Corrosion and Cathodic Protection
Corrosion Engineering
Corrosion Basics

Corrosion 101
Cost of Corrosion

• Corrosion and it’s prevention costs more than any other natural process including fire, earthquakes, tsunamis and volcano eruption damage from termites and any other natural cause.
• $2.5 Trillion Annually / 3.4% of Global GDP
• 15-35% Improvement Possible
Corrosion Definition

• NACE International, National Association of Corrosion Engineers

• Corrosion is the degradation of any material by chemical or electrochemical means.
Entropy & Thermodynamics

2\textsuperscript{nd} Law

Any system will decay without maintenance.
Disorder is the natural process.
Corrosion of Metal

- All metals exist naturally in an ‘ore’ or combined state.
- Rocks basically ore metal in combination with silicates, minerals and other impurities.
Refining to Useable Metal
Refining Process

- $MX_2O_3 + XX + \text{Heat} \rightarrow M^0$
- Typical metal heating and driving off unwanted compounds and impurities to yield a useable material.
- Iron Ore + Heat = Pure Iron
- Malleable, workable, may be fabricated
- Stores the heat energy
Entropy

IRON OXIDE + BLAST FURNACE + BESSEMER + PIPE MILL

STEEL PIPE (-ΔG°) + EARTH = IRON OXIDE
Stability of Refined Metals

• Any metal in the refined state Contains energy
  – Magnesium Highest Stored Energy
  – Aluminum
  – Zinc
  – Cadmium
  – Iron, Mild Steel & Cast/Ductile Iron
  – Tin
  – Copper
  – Lead
  – Noble, Gold, silver, platinum, titanium et al.
    • Requires very little energy to refine.
Galvanic Series

- List of metals in the order in which they contain energy.
- Most heat required to refine and thus the most stored energy
- Down to least heat required to refine and thus the least stored energy.
All refined metals are unstable

Balanced/Equilibrium state for any refined metal is the ore state.

All metals corrode to get back to equilibrium state.

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

<table>
<thead>
<tr>
<th>Metal/Alloy</th>
<th>Element/Oxidation State</th>
<th>Density (g/cm³)</th>
<th>Equivalent Weight (gm)</th>
<th>Penetration Rate Equivalent to 1 μA/cm²</th>
<th>10⁻³ mm/y²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Metals</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>Fe/2</td>
<td>7.87</td>
<td>27.93</td>
<td>0.463</td>
<td>11.5</td>
</tr>
<tr>
<td>Nickel</td>
<td>Ni/2</td>
<td>8.90</td>
<td>29.36</td>
<td>0.431</td>
<td>10.8</td>
</tr>
<tr>
<td>Copper</td>
<td>Cu/2</td>
<td>8.96</td>
<td>31.77</td>
<td>0.463</td>
<td>11.6</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Al/3</td>
<td>2.70</td>
<td>8.99</td>
<td>0.435</td>
<td>10.87</td>
</tr>
<tr>
<td>Lead</td>
<td>Pb/2</td>
<td>11.3</td>
<td>103.6</td>
<td>1.20</td>
<td>29.9</td>
</tr>
<tr>
<td>Zinc</td>
<td>Zn/2</td>
<td>7.14</td>
<td>32.7</td>
<td>0.598</td>
<td>14.95</td>
</tr>
<tr>
<td>Tin</td>
<td>Sn/2</td>
<td>7.26</td>
<td>59.35</td>
<td>1.07</td>
<td>26.7</td>
</tr>
<tr>
<td>Titanium</td>
<td>Ti/2</td>
<td>4.51</td>
<td>23.93</td>
<td>0.69</td>
<td>17.3</td>
</tr>
<tr>
<td>Zirconium</td>
<td>Zr/4</td>
<td>6.52</td>
<td>22.81</td>
<td>0.457</td>
<td>11.4</td>
</tr>
</tbody>
</table>

Note: [1] A current density of 1 μA/cm² is approximately = 1 mA/ft²
[2] 1 mm = 40 mils
Iron (Fe)

- \( \text{Fe}^0 + \text{O}_2 \rightarrow \text{Fe}_2\text{O}_3 \)

This is the process of iron corroding and returning to its balanced state.

Rust is not a useable construction material!!
2\textsuperscript{nd} Law of Thermodynamics

Any system when left without maintenance will decay.

Equipment
Relationships
Social Order
Steel Structures
Corrosion Process

- Corrosion is an electrical process.
- Corrosion is a chemical process.

![Diagram of Charge Movement in a Corrosion Cell](Image)
Corrosion Process

- Electrical in that a transfer of electrons is involved.

- Chemical in that a physical and chemical change takes place.
Theoretical Conditions of Corrosion, Immunity, and Passivation of Iron
- Simplified pH Pourbaix Diagram for Iron in Water at 25°C
Corrosion Process

Corrosion products and the process result
• Loss of structural integrity
• Destruction of property
• Leaks and spills
• Loss of life
• Contamination of environment
• ‘Spalling’ Concrete: Corrosion products generally occupy four times the volume of the elemental metal
Galvanic Series

- ANY TWO CONNECTED WILL FORM A CORROSION CELL
  - Magnesium Highest Stored Energy
  - Aluminum
  - Zinc
  - Cadmium
  - Iron, Mild Steel & Cast/Ductile Iron
  - Tin
  - Copper
  - Lead
  - Noble, Gold, silver, platinum, titanium et al. Least
    - Requires very little energy to refine.
Simple Electrolytic Cell

- Magnesium
- Aluminum
- Zinc
- Cadmium
- Iron, Mild Steel & Cast/Ductile Iron
- Tin
- Copper
- Lead
- Gold, Silver, Platinum, Titanium, et. Al.
Simple Electrolytic Cell

- Magnesium
- Aluminum
- Zinc
- Cadmium
- Iron, Mild Steel & Cast/Ductile Iron
- Tin
- Copper
- Lead
- Gold Silver Platinum Titanium et. al.
Simple Electrolytic Cell
Simple Electrolytic Cell

- Lead
- Zinc

Electrolyte
Simple Electrolytic Cell
MOST ASSEMBLIES DO NOT CONSIST OF DIFFERENT METALS

TYPICAL ASSEMBLY WILL CONSIST OF SLIGHTLY DIFFERENT ALLOYS OF THE SAME STEEL MATERIAL

- Steel Pipe or Tank Plate
- Flanges/Fittings
- Bolts & Fasteners
- Weld Metal
- Different Pipe or Plate Sections
- Inconsistencies in the Steel Plate (not homogenous)
- Dis-similar Metals in the construction
  - Cast Iron overflow pipe
  - Ladder Assembly
  - Grates & Hand Rails
- Motorized Equipment in the Tank
- Riser or Pipe Configuration
- Poor Grounding of Equipment
Classic Electrolytic Cell

Metallic Path

Anode

Cathode

Electrolyte

Anode Metallic Path

Cathode
Corrosion Types
to Plate

to Weld

to Bolt

to Accessory Plate
Boat Lift
Heavy Mobile Equipment
Typical Corrosion Cell on Metal Plate, Pipe, Tank Buried/Submerged (In Electrolyte)

Four Elements of Corrosion Cell
• Anode
• Cathode
• Electrolyte
• Metallic Path
• Steel Pipe
• Flanges/Fittings
• Weld Metal
• Different Pipe Sections
• Inconsistencies in the Steel Plate (homogenous)
• Dis-similar Metals in the construction
Bolt Corrosion on Valve Coated vs. Uncoated
Coated vs. Uncoated

• Coated is cathodic to uncoated
  – The uncoated structure will corrode selective to the coated structure.
  – New is Anodic to existing.
    • New will corrode when installed next to existing.
    • Leak repair results in providing a new anode (pipe)
Current Jumping DI Joints AC-DC
Corrosion Basics

- Corrosion can and will occur on any structure that remains uncoated or unprotected with corrosion prevention system.
- Maintenance of the system is paramount to the proper function of the cathodic protection system.
Corrosion Potential Measurement

Meter display shows a negative polarity sign. Record a negative structure potential.

Voltmeter

Reference Cell

Electrolyte

Structure
Figure 5-2: Copper-Copper Sulfate Reference Electrode
Reference Cells
How Do We Stop it From Corroding

- Material Selection
- Coating
- Cathodic Protection
- Inhibitors
- Anodic Protection
Coating and Painting

- Isolates the metal surface from the environment thus stops corrosion
- Ascetic Value, makes it look better, cleaner
  - Any structure that looks good is structurally sound....right??
  - Contains a consumable substance and if it is rusty on the outside it is bad on the inside...right?
Coatings must be selected and applied to provide proper corrosion resistance:

- Environment in which they are located
  - Marine
  - Standard Atmospheric
  - Temperature Service
  - Application Considerations and Limitations
  - Buried/Submerged
Atmospheric Corrosion Prevention by Coating

• Most cases accessible and can be maintained.
• Not in an electrolyte like water or soil.
• Easy to inspect visually.
• Easy to test if accessible.
• Coating system and maintenance a consideration when selecting a coating system.
• Structure should be designed for coating maintenance access.
Coating must be selected and applied so that it will cover 100% of the surface area for 100% of the expected life of the coating system.

Possible?

No
Coating Buried or Submerged Structures

• Cannot coat and maintain the coating for 100% of the coating service life.

• Cannot coat and maintain the coating for the design life of the structure.

• At least a small percentage of the surface area will be exposed to the electrolyte.
• Cathodic protection works in conjunction with a well selected and applied coating system.

• Cathodic Protection protects the 1-2% or more bare surface area that the coating on any structure exhibits.

Coating and Cathodic Protection are not exclusive but work together to protect a surface.
Coating protects the area it covers 98%-99% on newly coated undamaged structures.

Cathodic Protection protects the other 1%-2% or more of the holidays in the coating after installation.
Cathodic Protection for Buried or Submerged Structures

• Coating will degrade over time.
  – Mechanical Damage
  – Vibration Damage
  – Poor environmental resistance from unexpected exposure
  – Peeling, Cracking or other Coating Defect
  – Temperature Service Not Anticipated
Coating degradation will produce more bare surface over the structure life thus more bare surface area exposed.

Current Capacity or Current Requirement of the cathodic protection system is directly proportional to the structure’s bare surface area.

Generally determines type of CP system
# Coating Quality

<table>
<thead>
<tr>
<th>Gas or Water Distribution with Many Fittings</th>
<th>Average Specific Coating Conductance</th>
<th>Average Specific Coating Resistance $r'_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality of Work</td>
<td>$g'_{Siemans/ft^2}$</td>
<td>$g'_{Siemans/m^2}$</td>
</tr>
<tr>
<td>Excellent</td>
<td>$&lt;5 \times 10^{-5}$</td>
<td>$&lt;5 \times 10^{-4}$</td>
</tr>
<tr>
<td>Good</td>
<td>$5 \times 10^{-5}$ to $1 \times 10^{-4}$</td>
<td>$5 \times 10^{-4}$ to $1 \times 10^{-3}$</td>
</tr>
<tr>
<td>Fair</td>
<td>$1 \times 10^{-4}$ to $5 \times 10^{-4}$</td>
<td>$1 \times 10^{-3}$ to $5 \times 10^{-3}$</td>
</tr>
<tr>
<td>Poor</td>
<td>$&gt;5 \times 10^{-4}$</td>
<td>$&gt;5 \times 10^{-3}$</td>
</tr>
<tr>
<td>Bare Pipe (2 to 12&quot;)</td>
<td>$4 \times 10^{-3}$ to $2 \times 10^{-2}$</td>
<td>$4 \times 10^{-2}$ to $2 \times 10^{-1}$</td>
</tr>
<tr>
<td>Bare Pipe (5 to 30 cm)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 4-1: Approximate Current Requirements for Cathodic Protection of Steel

<table>
<thead>
<tr>
<th>Environmental Conditions</th>
<th>Current Density (mA/m²)</th>
<th>Current Density (mA/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immersed in Seawater(^{(a)})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stationary</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well coated</td>
<td>1 to 2</td>
<td>0.1 to 0.2</td>
</tr>
<tr>
<td>Poor or old coating</td>
<td>2 to 20</td>
<td>0.2 to 2</td>
</tr>
<tr>
<td>Uncoated</td>
<td>20 to 30</td>
<td>2 to 3</td>
</tr>
<tr>
<td>Low Velocity(^{(b)})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well coated</td>
<td>2 to 5</td>
<td>0.2 to 0.5</td>
</tr>
<tr>
<td>Poor coating</td>
<td>5 to 20</td>
<td>0.5 to 2</td>
</tr>
<tr>
<td>Uncoated</td>
<td>50 to 150</td>
<td>5 to 15</td>
</tr>
<tr>
<td>Medium Velocity(^{(c)})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well coated</td>
<td>5 to 7</td>
<td>0.5 to 0.7</td>
</tr>
<tr>
<td>Poor coating</td>
<td>10 to 30</td>
<td>1 to 3</td>
</tr>
<tr>
<td>Uncoated</td>
<td>150 to 300</td>
<td>15 to 30</td>
</tr>
<tr>
<td>High Velocity(^{(d)})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poor coating or uncoated</td>
<td>250 to 1000</td>
<td>25 to 100</td>
</tr>
<tr>
<td>Buried Underground(^{(e)})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil Resistivity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 to 5 Ω-m</td>
<td>1 to 2</td>
<td>0.1 to 0.2</td>
</tr>
<tr>
<td>5 to 15 Ω-m</td>
<td>0.5 to 1</td>
<td>0.05 to 0.1</td>
</tr>
<tr>
<td>15 to 40 Ω-m</td>
<td>0.1 to 0.5</td>
<td>0.01 to 0.05</td>
</tr>
</tbody>
</table>

\(^{(a)}\) Structures or vessels
\(^{(b)}\) Turbulent flow
Cathodic Protection Systems Types

• Galvanic, Sacrificial Cathodic Protection
  – Smaller structures
  – Well coated structures
  – Interference issues
  – Maintenance Issues

Lower Current Requirement
Cathodic Protection System

Cathode Metallic Path Anode

Electrolyte

Cathodic protection with magnesium anodes
Bulkhead
Dam Outlet
Impressed Current

- Uses an outside power source
  - AC converted to DC
- Drives current to the structure
- Easily Adjustable
- Monitoring is by RMU or other type SCADA system
Rectifiers
AST Floor
Cathodic Protection System Design

- NACE International qualified personnel
  - [WWW.NACE.ORG](http://WWW.NACE.ORG) Coating and Cathodic Protection; Coating Inspection Training, Cathodic Protection Training; Certification of both.

- Steel Structures Painting Council SSPC
  - [www.sspc.org](http://www.sspc.org) Coating Inspection and Training

- DOD Facilities
  - UFC 3 570 01 Cathodic Protection Design Criteria
Thank You
Impressed Current Cathodic Protection

Anode
Lower Potential Metal
CI, Graphite, MMO

Electrolyte
Soil or Water

Cathode
Protected Structure

POWER
AC Corrosion
Corrosion Management By Sector

NACE IMPACT STUDY RESULTS

- Petroleum/Oil/Gas
- Pipelines
- Chemicals
- Metals, Mining, & Steel
- Aerospace & Automotive
- Machinery & Machinery
- Energy/Utility
- Water - Potable
- Government/Military
- Electronics & Instrumentation
- Environmental
- Construction
AST Floor