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

NACE® INTERNATIONAL IMPACT

Corrosion Definition

- NACE International, National Association of Corrosion Engineers

- Corrosion is the degradation of any material buy chemical or electrochemical means.

Entropy & Thermodynamics 2nd Law

Any system will decay without maintenance.

Disorder is the natural process.

Corrosion of Metal

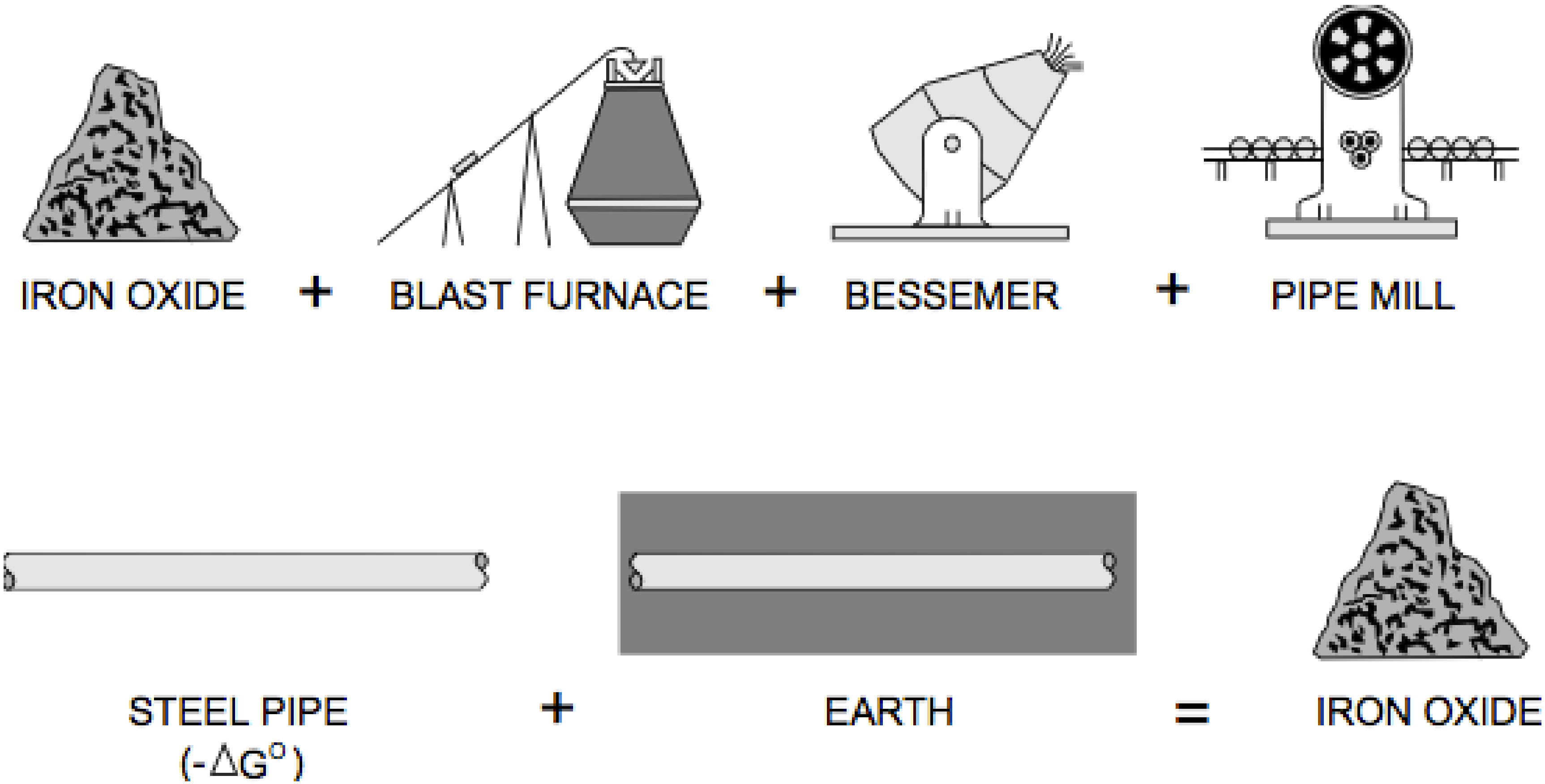
- All metals exist naturally in an ‘ore’ or combined state.
- Rocks basically ore metal in combination with silicates, minerals and other impurities.

Refining to Useable Metal

Refining Process

- MX_2O_3 + XX + Heat → M^o
- 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

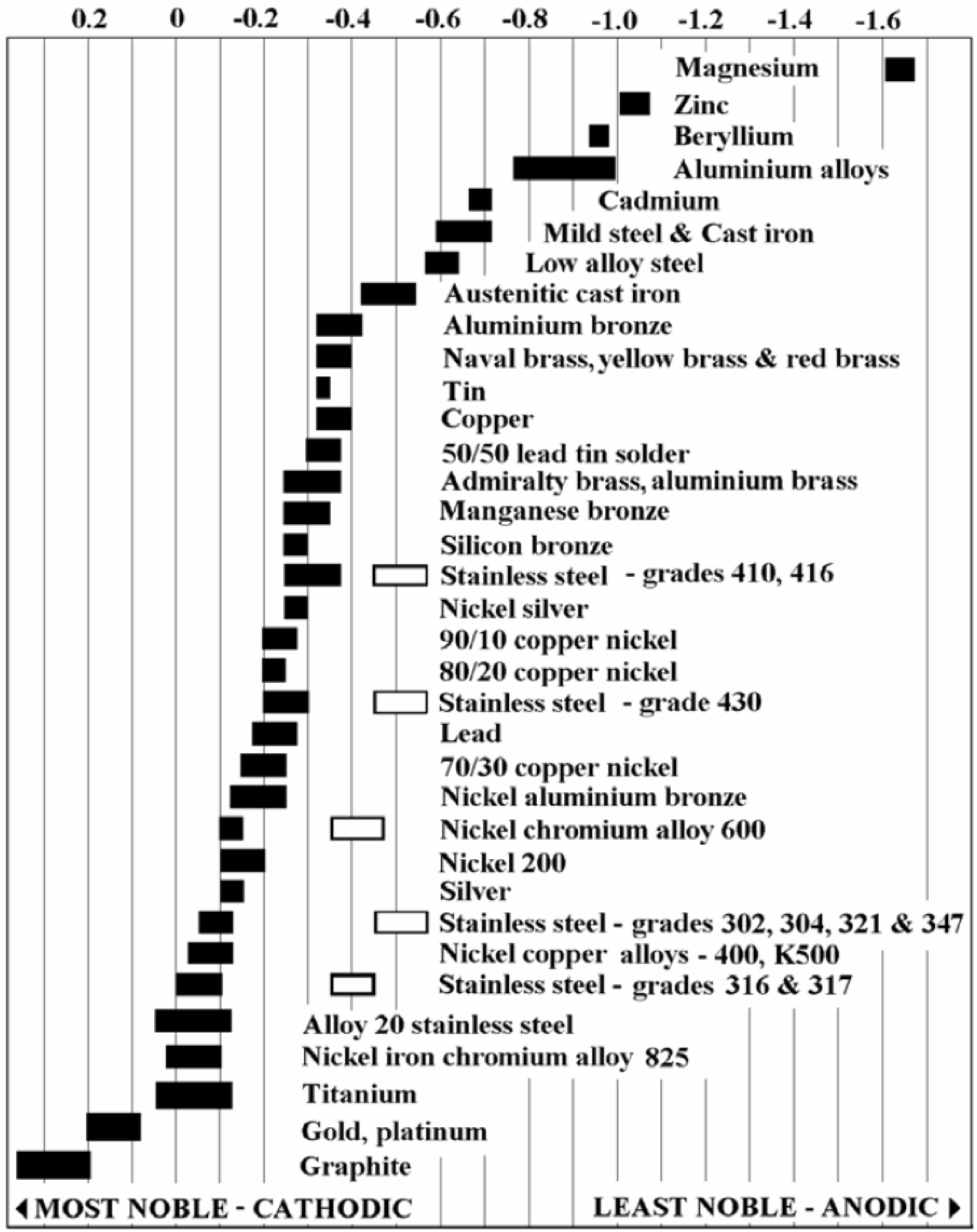

IRON OXIDE
+
BLAST FURNACE
+
BESSEMER
+
PIPE MILL
STEEL PIPE
(-ΔG°)
+
EARTH
=
IRON OXIDE

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.


0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
-1.6
Magnesium
Zinc
Beryllium
Aluminium alloys
Cadmium
Mild steel & Cast iron
Low alloy steel
Austenitic cast iron
Aluminium bronze
Naval brass, yellow brass & red brass
Tin
Copper
50/50 lead tin solder
Admiralty brass, aluminium brass
Manganese bronze
Silicon bronze
Stainless steel - grades 410, 416
Nickel silver
90/10 copper nickel
80/20 copper nickel
Stainless steel - grade 430
Lead
70/30 copper nickel
Nickel aluminium bronze
Nickel chromium alloy 600
Nickel 200
Silver
Stainless steel - grades 302, 304, 321 & 347
Nickel copper alloys - 400, K500
Stainless steel - grades 316 & 317
Alloy 20 stainless steel
Nickel iron chromium alloy 825
Titanium
Gold, platinum
Graphite
MOST NOBLE - CATHODIC
LEAST NOBLE - ANODIC

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

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

Iron (Fe)

- $Fe^{o} + O_2 \rightarrow Fe_2 O_3$

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

Rust is not a useable construction material!!

2^{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.

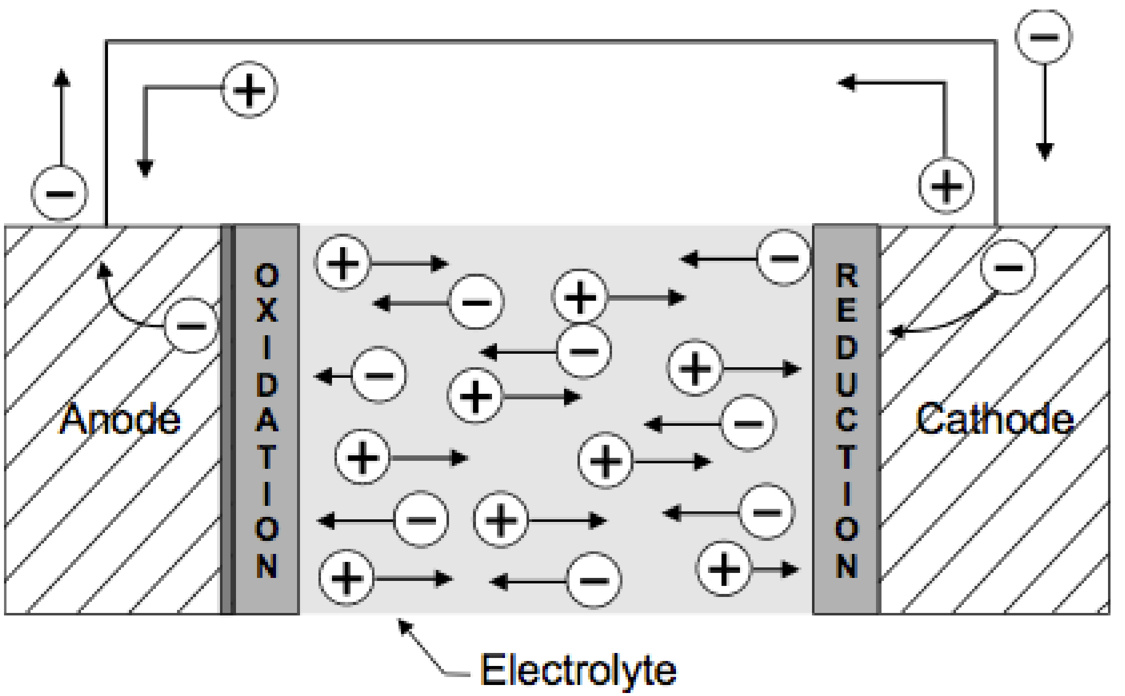
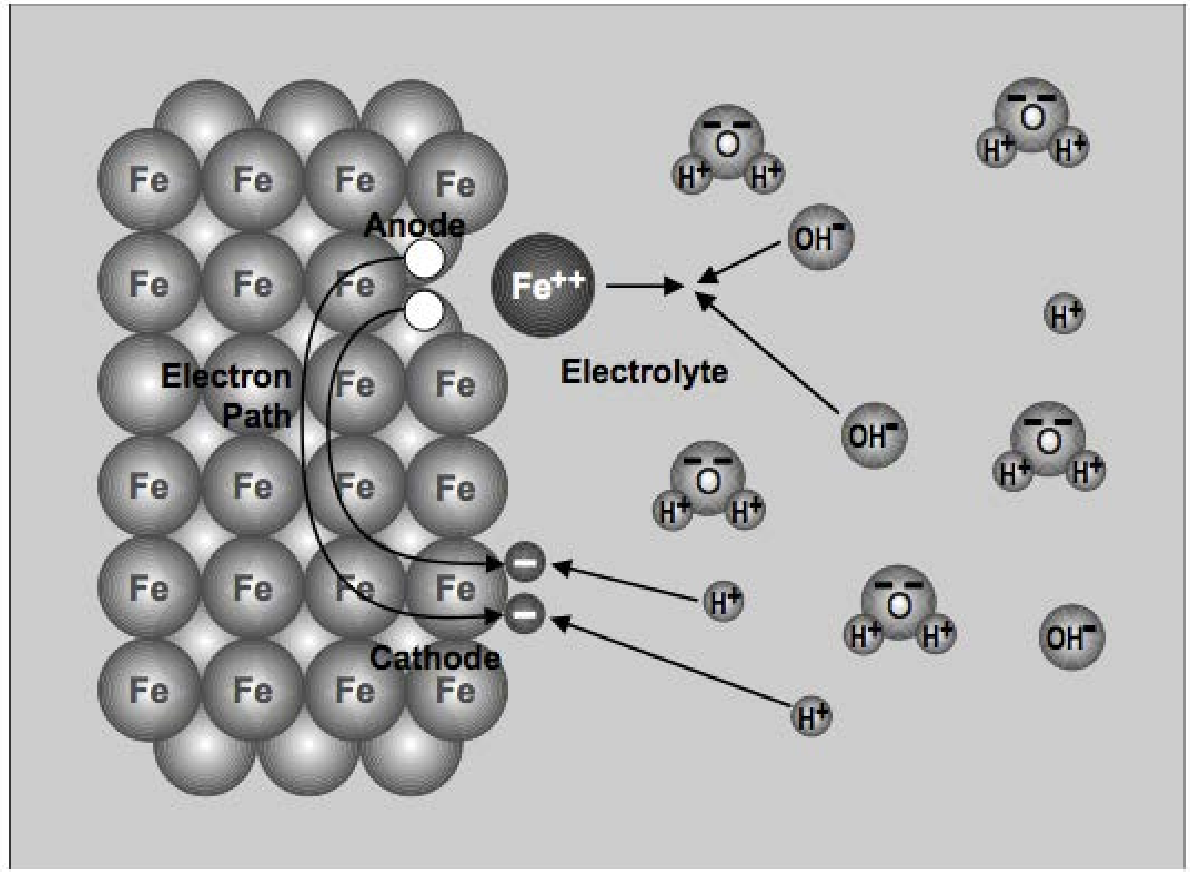


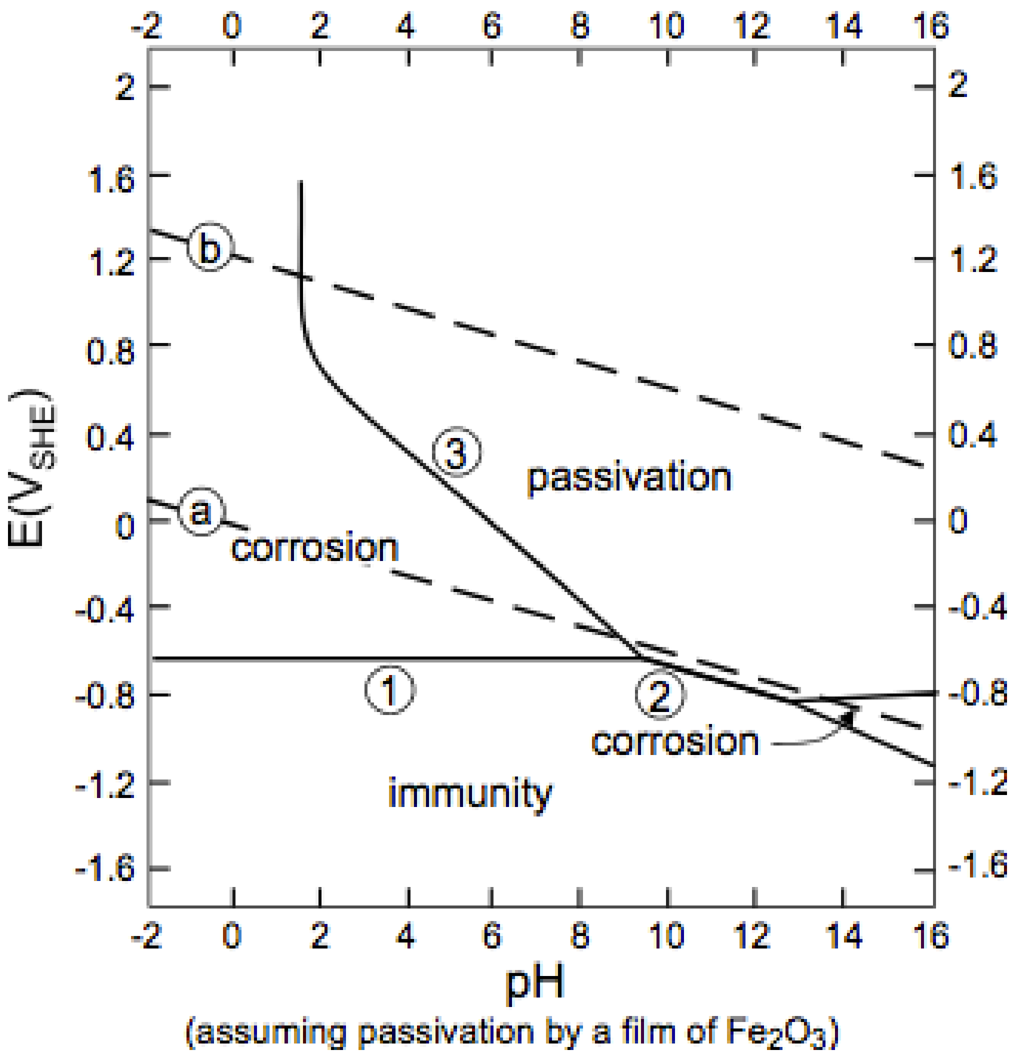
Figure 1-14: Charge Movement in a Corrosion Cell

Corrosion Process

- Electrical in that a transfer of electrons is involved.
- Chemical in that a physical and chemical change takes place.



Pourbaix Diagram



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

CP of Rebar

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
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-Cadmium
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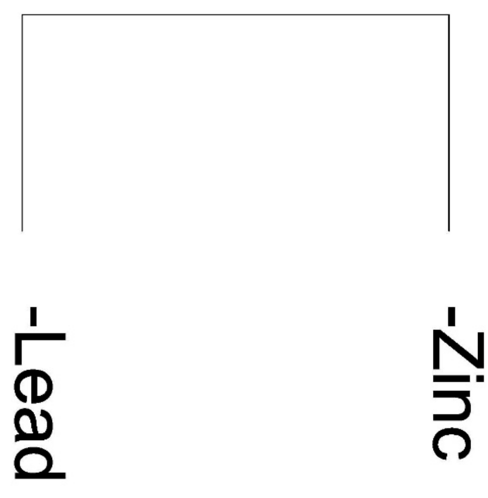
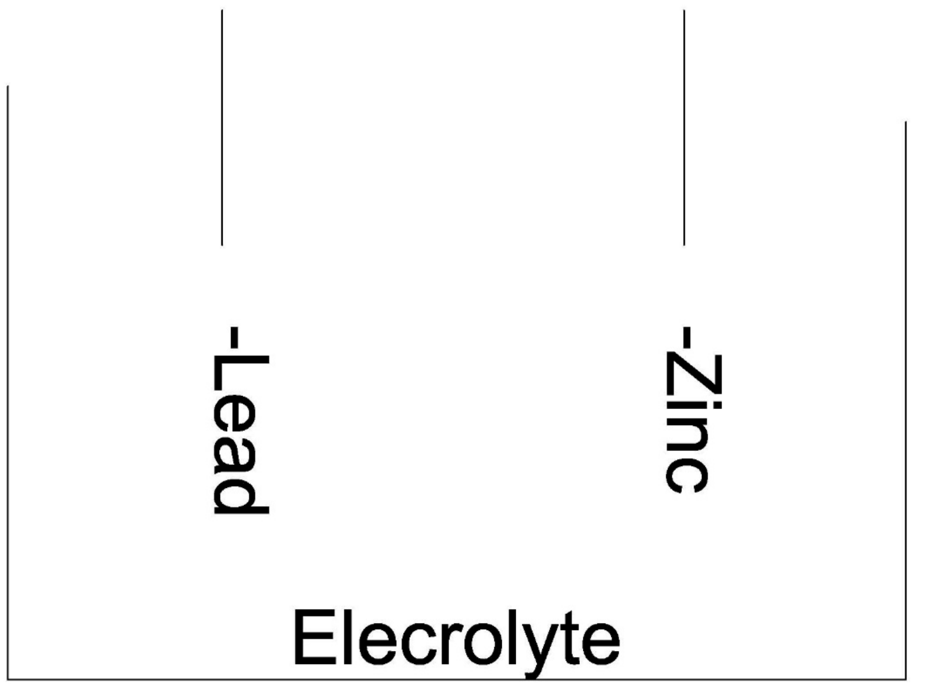
-Tin
-Copper
-Lead
-Gold Silver Platinum Titanium et. al.

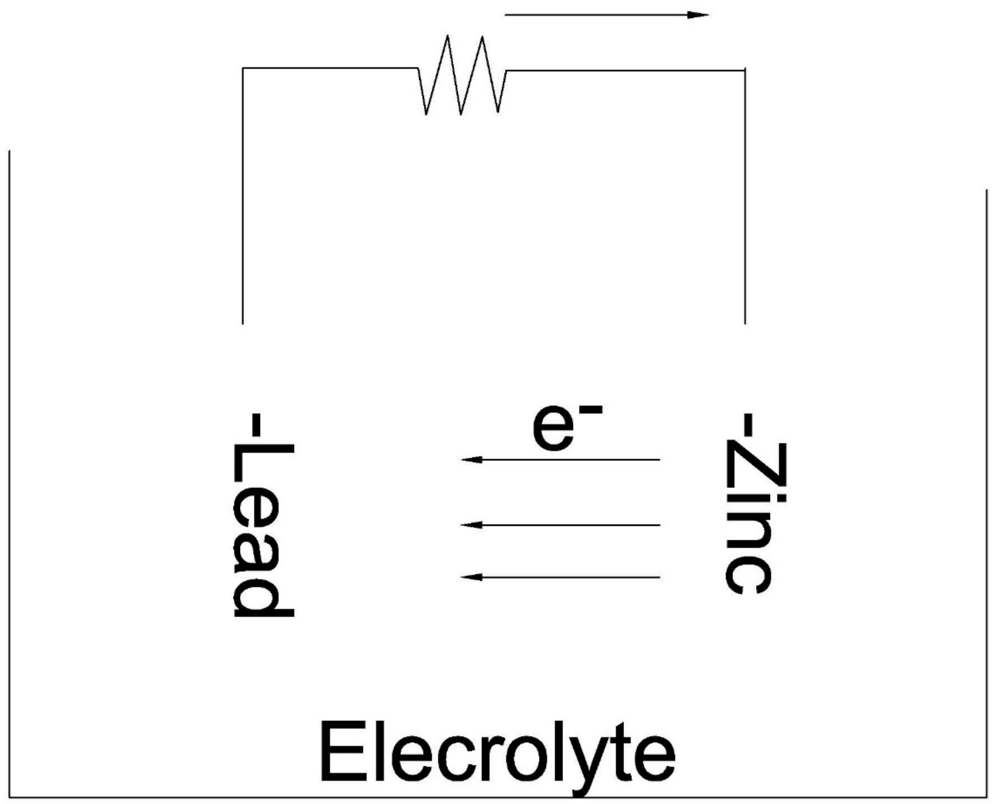
Simple Electrolytic Cell

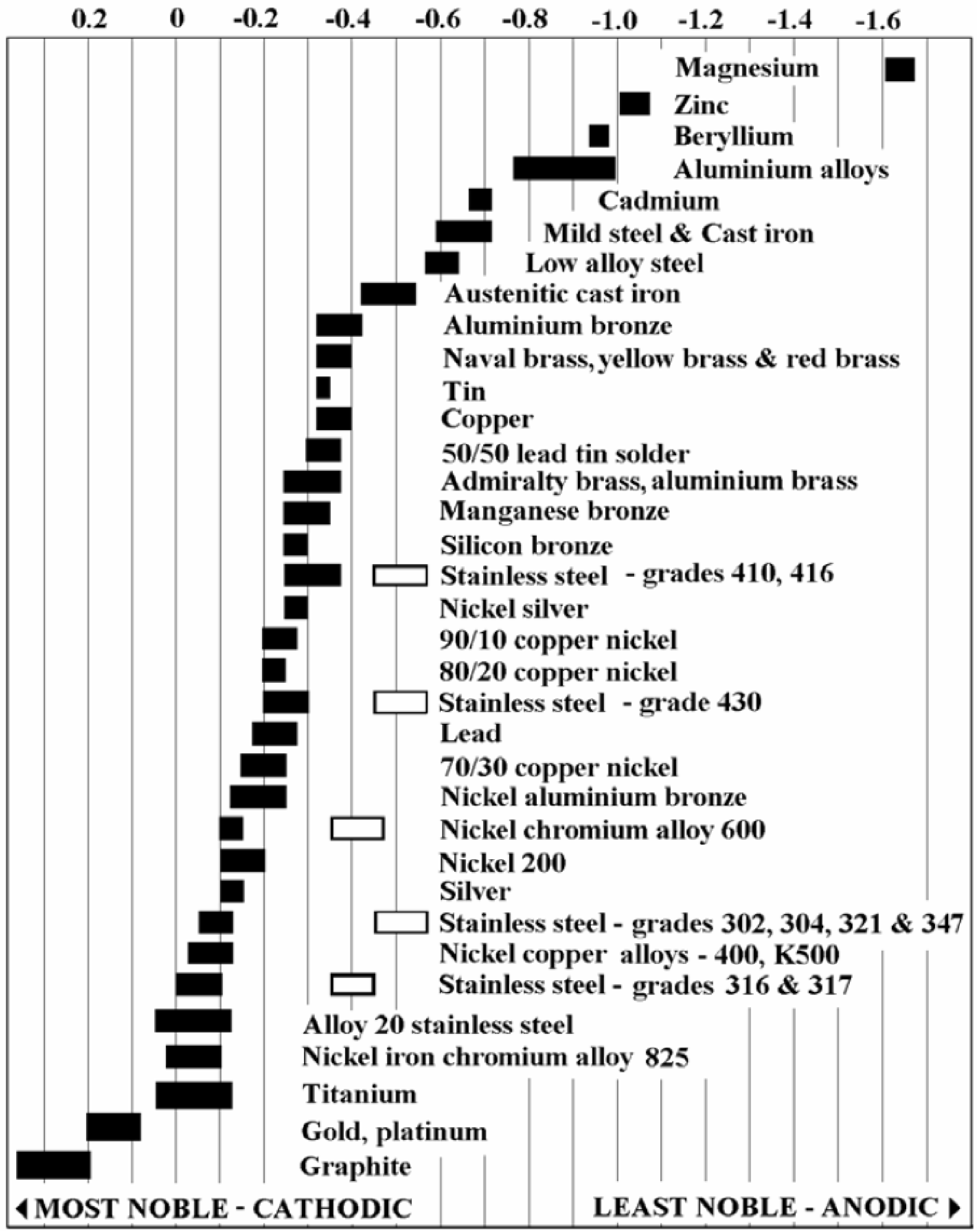


Simple Electrolytic Cell



Simple Electrolytic Cell

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Zinc
Beryllium
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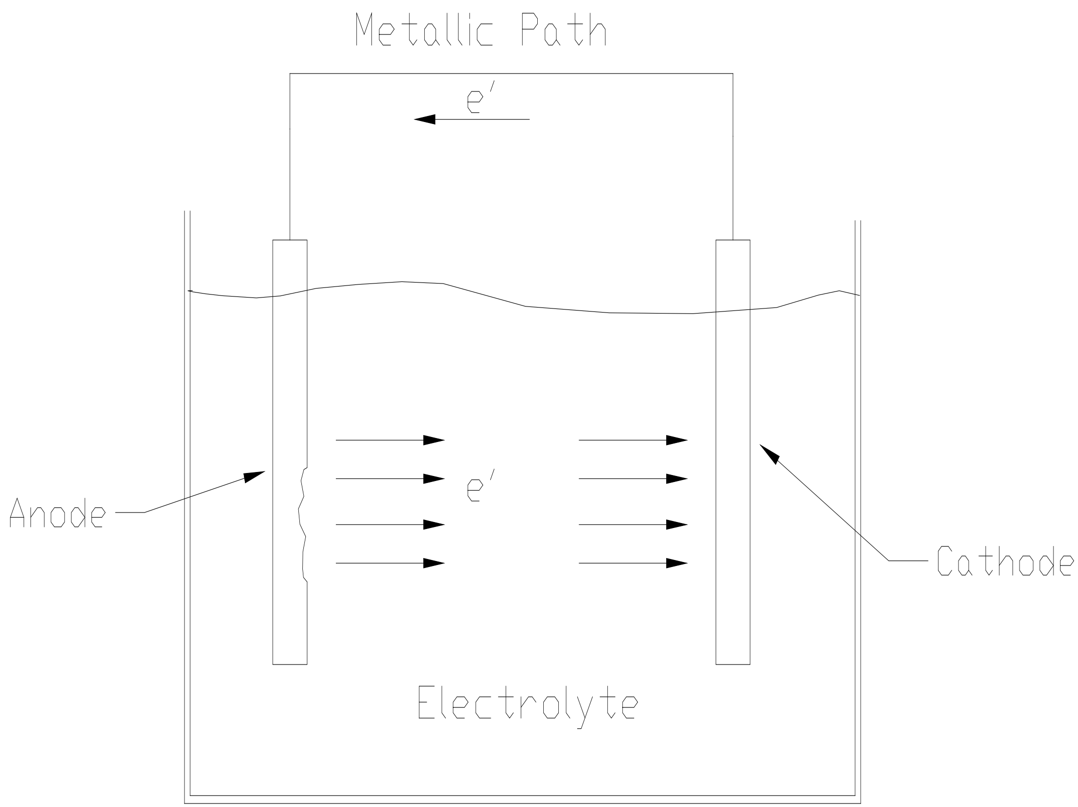
Mild steel & Cast iron
Low alloy steel
Austenitic cast iron
Aluminium bronze
Naval brass, yellow brass & red brass
Tin
Copper
50/50 lead tin solder
Admiralty brass, aluminium brass
Manganese bronze
Silicon bronze
Stainless steel - grades 410, 416
Nickel silver
90/10 copper nickel
80/20 copper nickel
Stainless steel - grade 430
Lead
70/30 copper nickel
Nickel aluminium bronze
Nickel chromium alloy 600
Nickel 200
Silver
Stainless steel - grades 302, 304, 321 & 347
Nickel copper alloys - 400, K500
Stainless steel - grades 316 & 317
Alloy 20 stainless steel
Nickel iron chromium alloy 825
Titanium
Gold, platinum
Graphite
MOST NOBLE - CATHODIC
LEAST NOBLE - ANODIC

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



Anode
Cathode

Electrolyte
Metallic Path

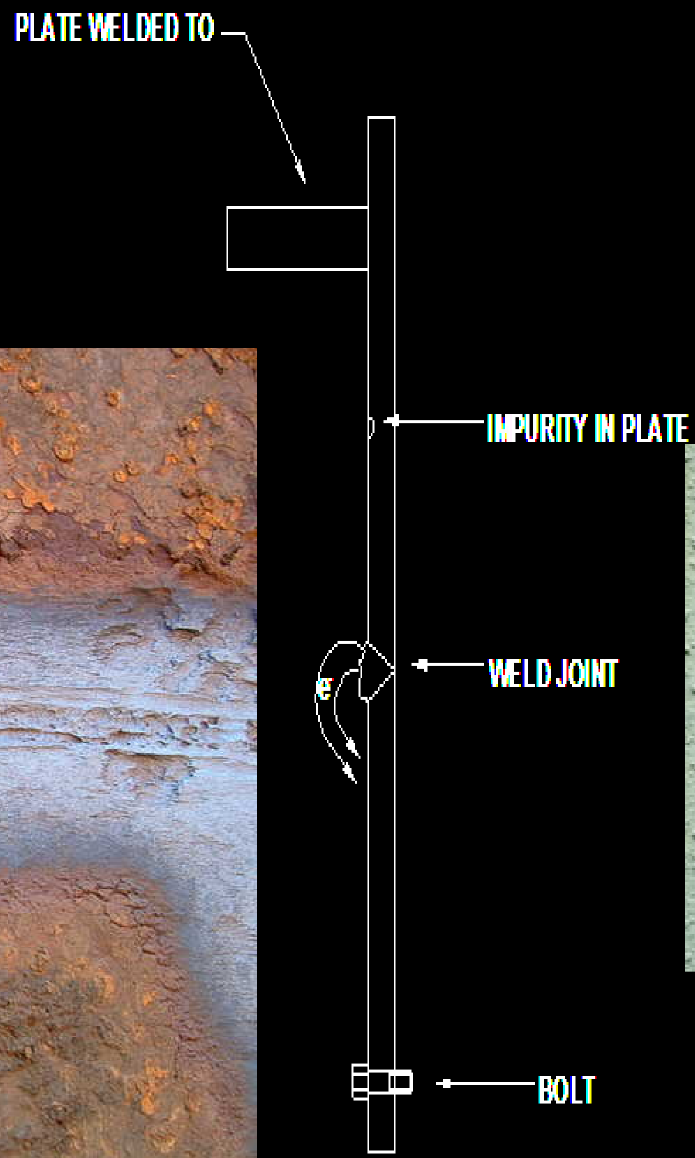
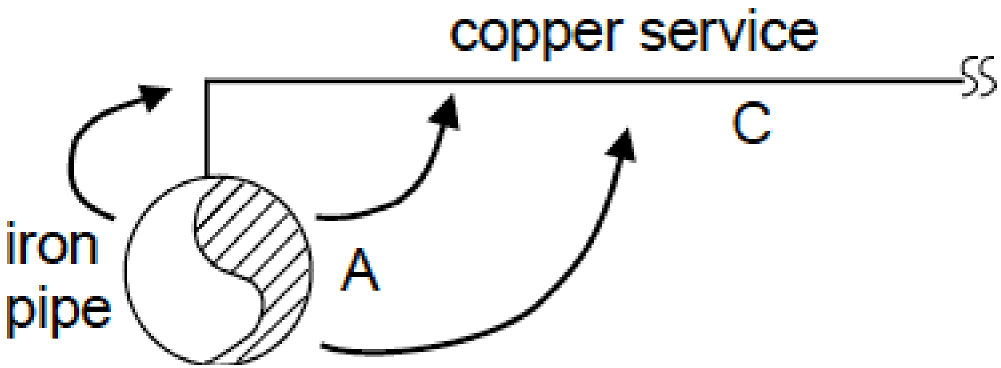
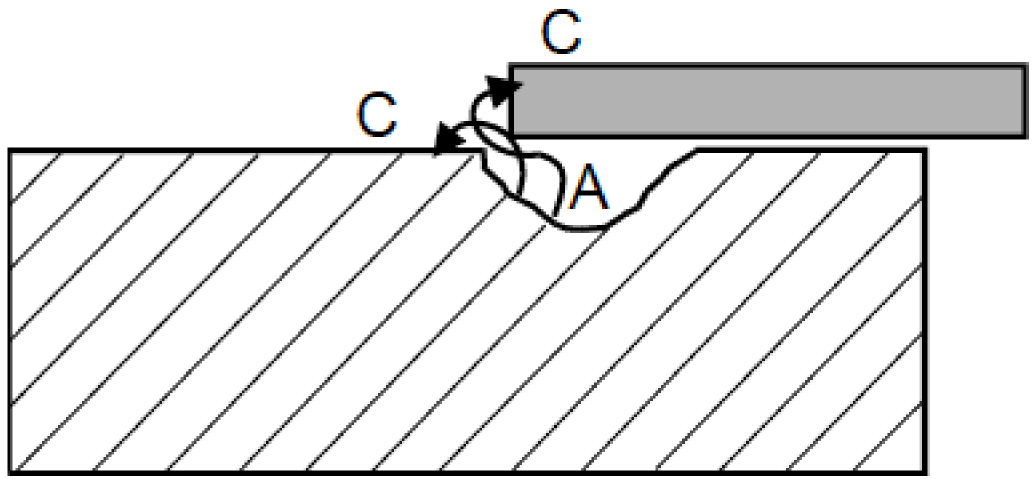
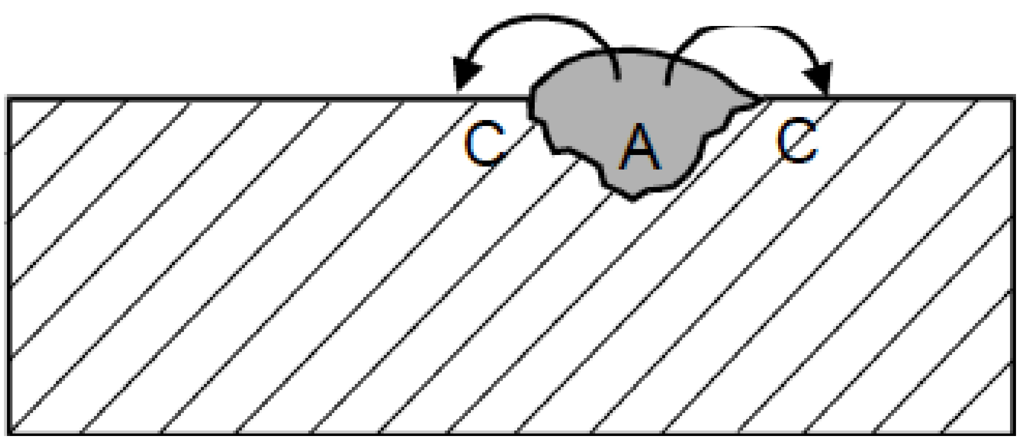


PLATE WELDED TO
IMPURITY IN PLATE
WELD JOINT
BOLT

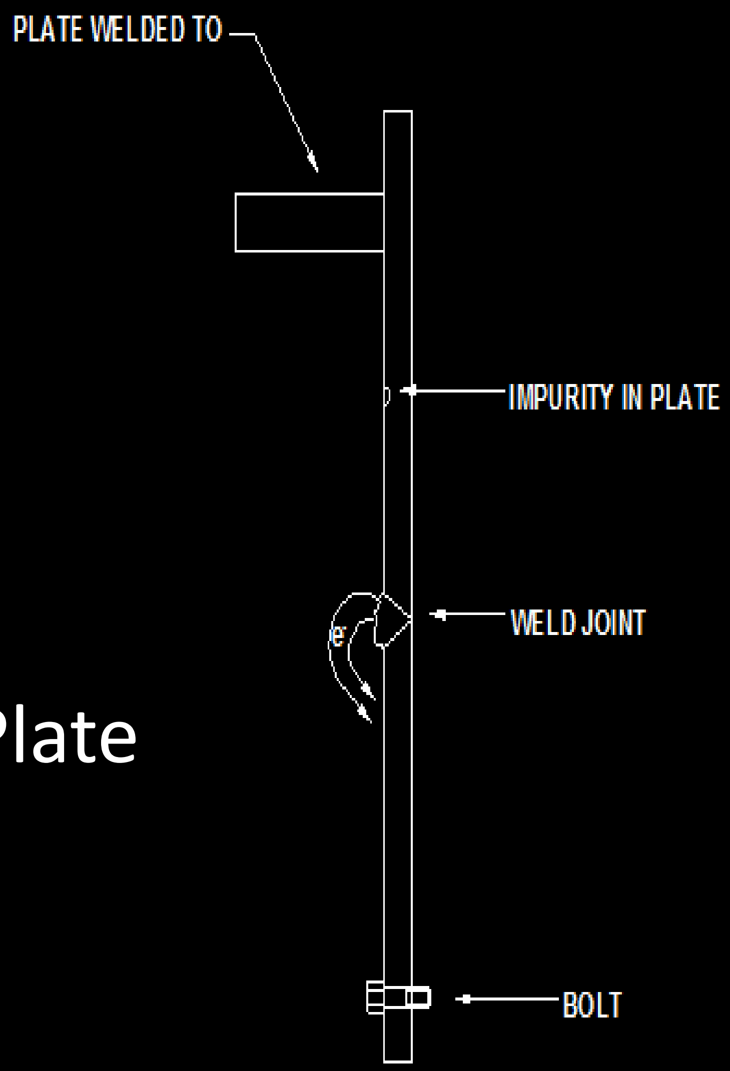
Corrosion Types







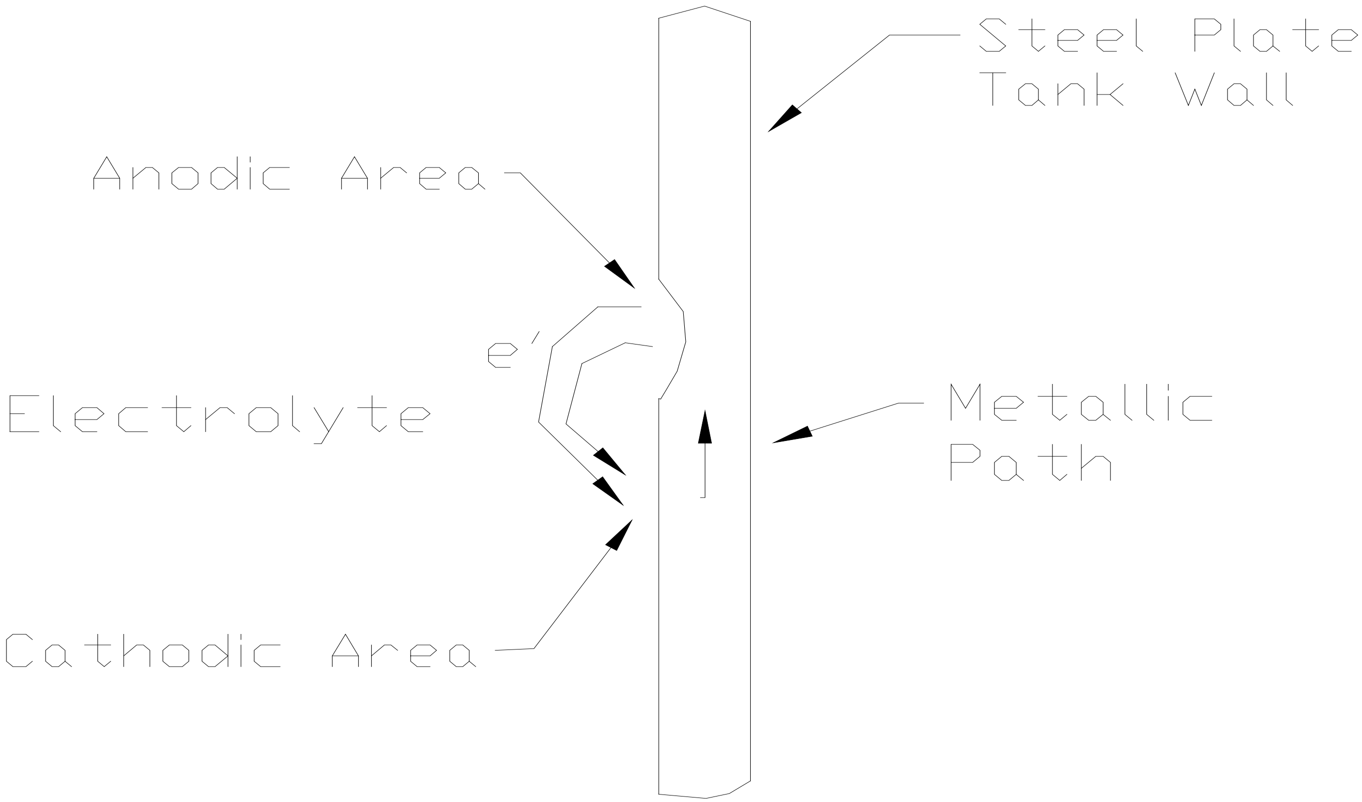
to Plate
to Weld
to Bolt
to Accessory Plate



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

Practical Galvanic Series

- Steel Pipe
- Flanges/Fittings
- Weld Metal
- Different Pipe Sections
- Inconsistencies in the Steel Plate (homogenous)
- Dis-similar Metals in the construction

Valve Bolt Corrosion

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)

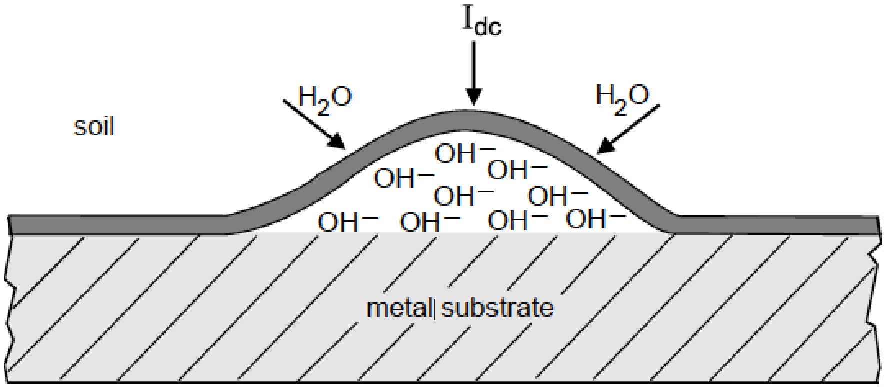
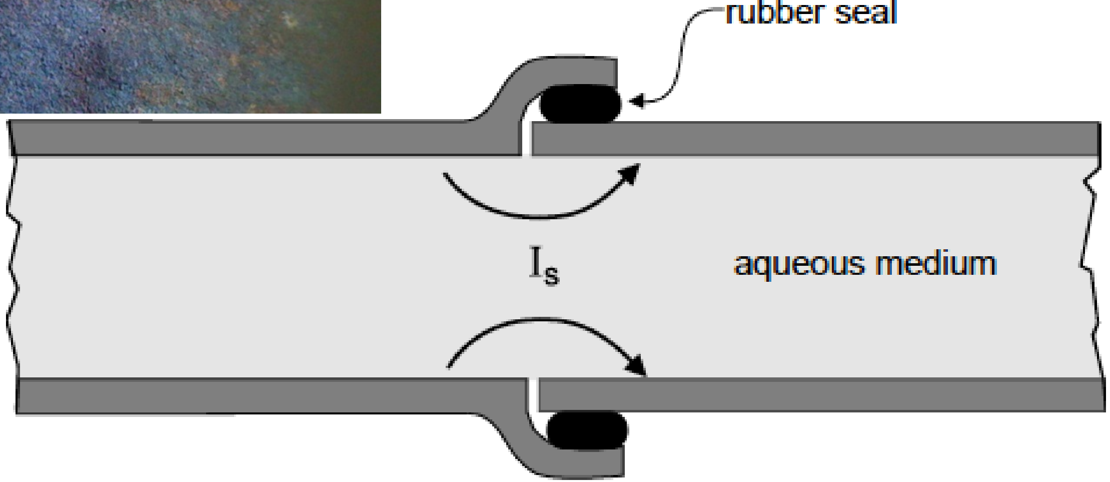


Figure 3-18: Cathodic Blistering/Disbondment of Protective Coating

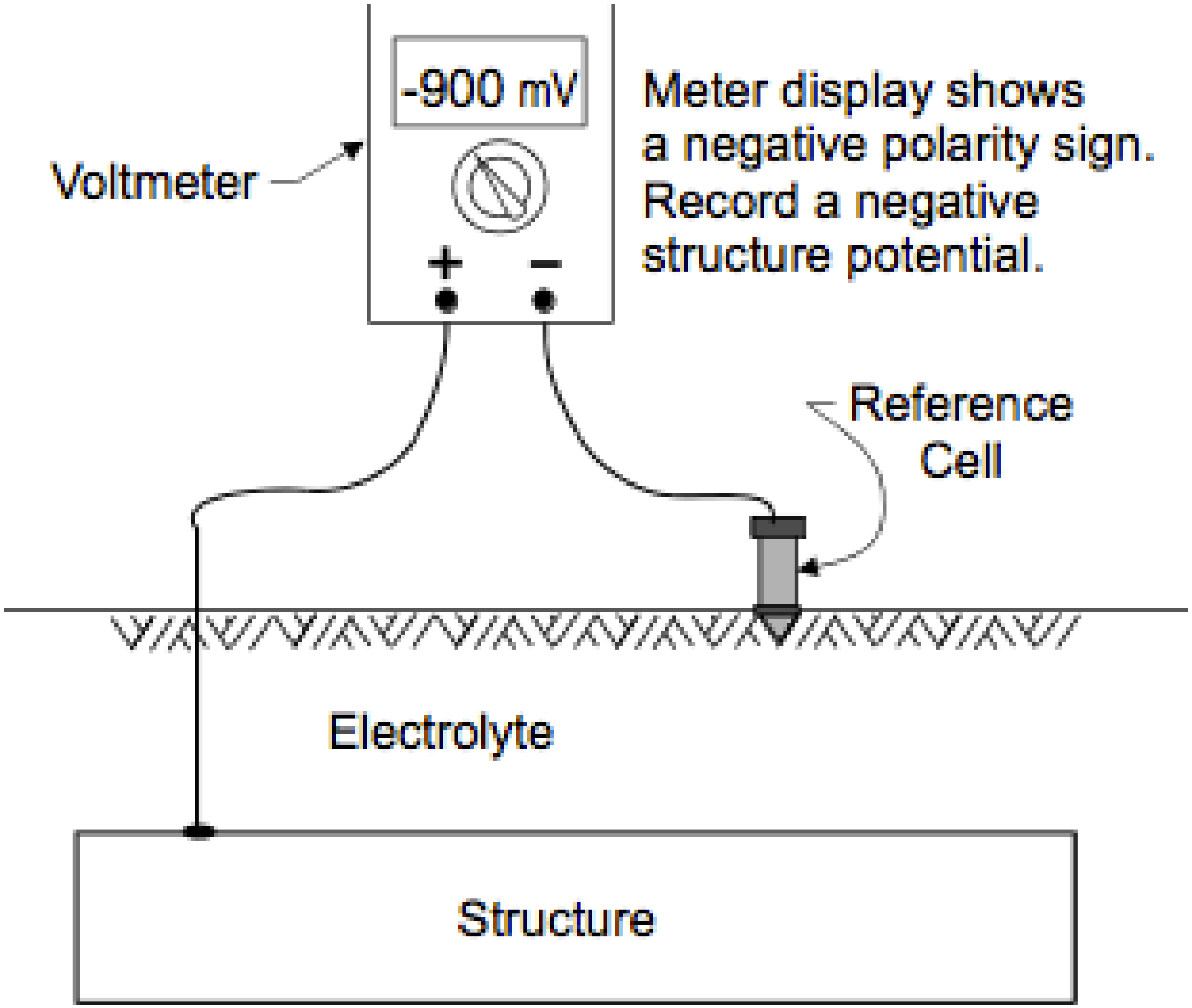
Current Jumping DI Joints AC-DC



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



CSE Reference Cell

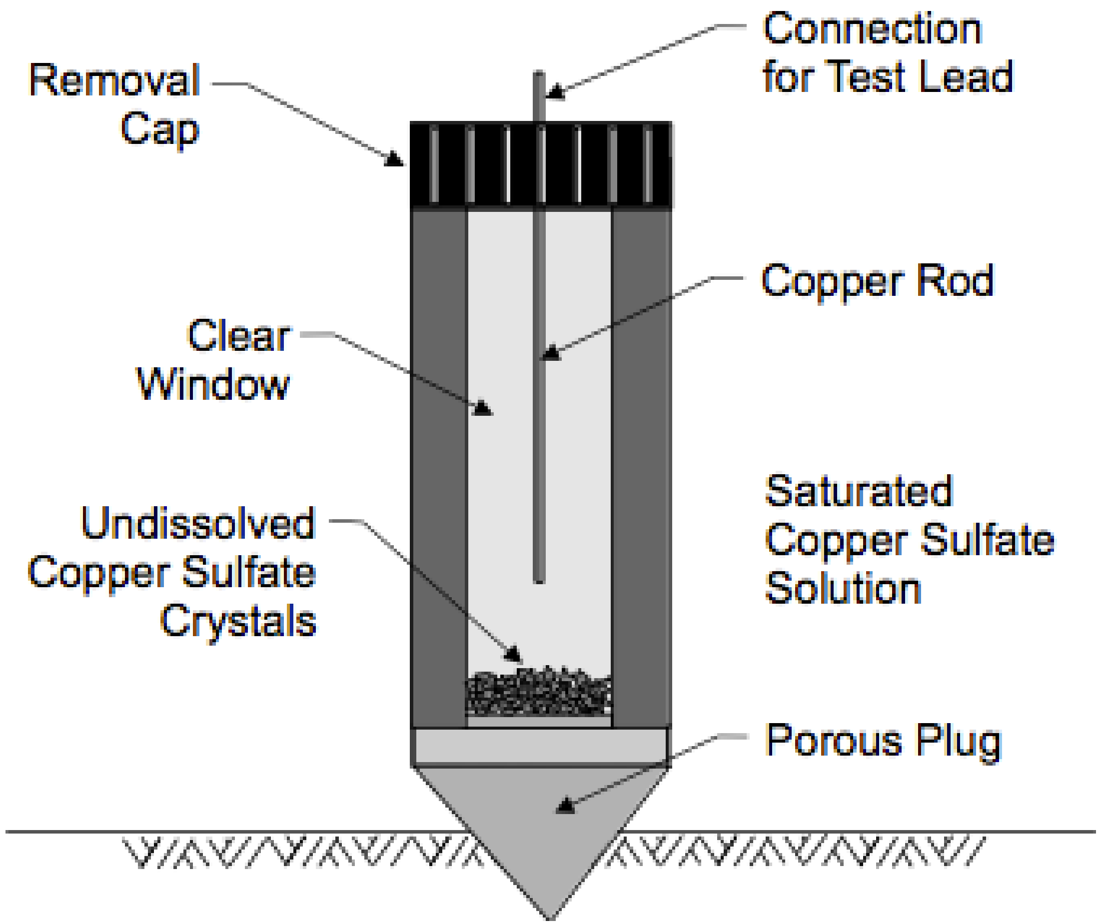


Figure 5-2: Copper-Copper Sulfate Reference Electrode

Reference Cells

Pipeline Close Interval Survey

How Do We Stop it From Corroding

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

How Do We Stop it from Corroding?

- 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?

Coating The Surface

- 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 any Surface

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.

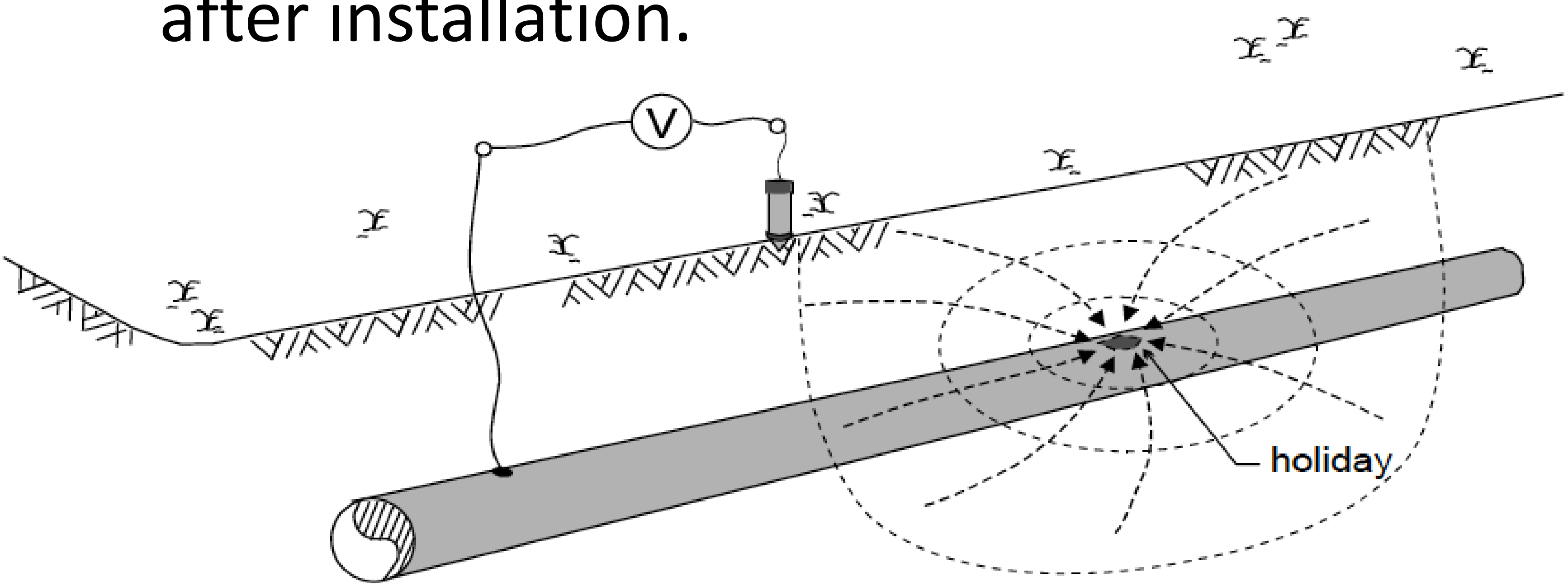
Cathodic Protection for Buried or Submerged Structures

- 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

Cathodic Protection for Buried or Submerged Structures

- 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

Cathodic Protection for Buried or Submerged Structures

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

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	5×10^{-5} to 1×10^{-4}	5×10^{-4} to 1×10^{-3}	10^{4} to 2×10^{4}	10^{3} to 2×10^{3}
Fair	1×10^{-4} to 5×10^{-4}	1×10^{-3} to 5×10^{-3}	2×10^{3} to 10^{4}	2×10^{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)	4×10^{-3} to 2×10^{-2}	4×10^{-2} to 2×10^{-1}	50 to 250	5 to 25

Design Criteria

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

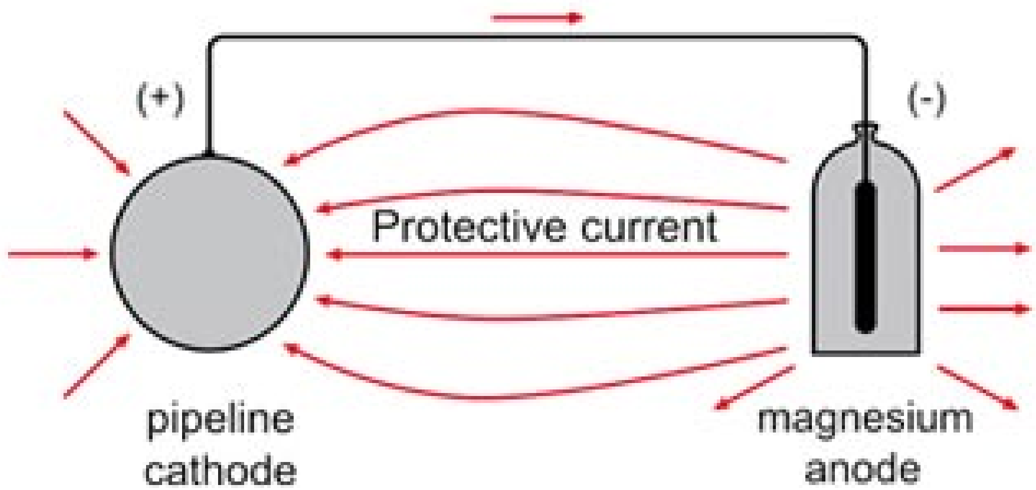
[a]Structures or vessels [d]Turbulent flow

Cathodic Protection Systems Types

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

Lower Current Requirement

Cathodic Protection System



Cathodic protection with magnesium anodes

Cathode Metallic Path Anode

Electrolyte

Bulkhead

Dam Outlet

Cathodic Protection System Types

- 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

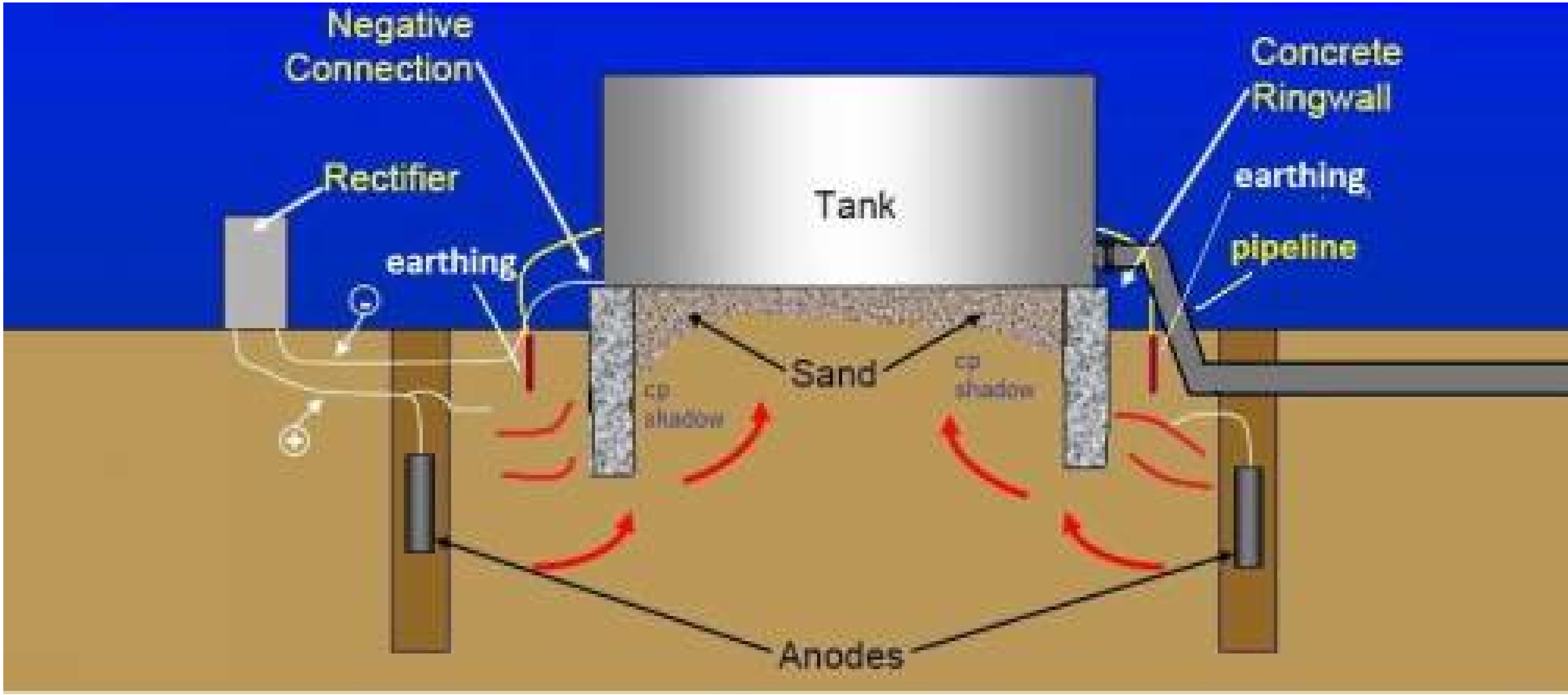
Rectifiers

FINE
AC FUSE
COARSE
WARNING
ACCESS SHOULD BE LIMITED TO QUALIFIED PERSONNEL. HIGH VOLTAGES ARE PRESENT.
POWER
D.C. AMPERES
SHUNT
1MV=.2AMPS
POS
NEG

WARNING
HIGH VOLTAGE
COARSE
FINE
J. A. ELECTRONICS
JA ELECTRONICS MANUFACTURING COMPANY
AC TO STACK
CAUTION
HIGH VOLTAGE
SECONDARY
PRESS
TO READ
50MV=25A
NEGATIVE
POSITIVE
MOBILTEX

AST Floor

AST Floor



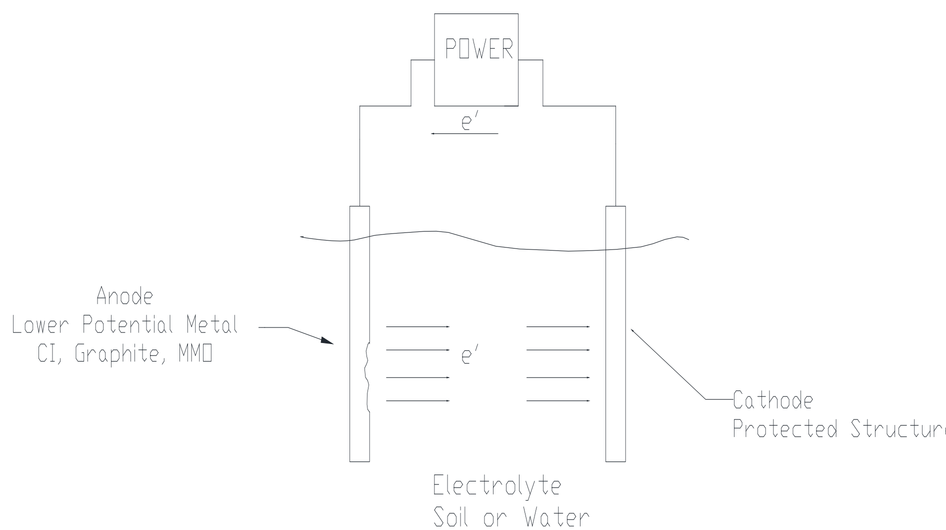
Negative Connection
Concrete Ringwall
Rectifier
Tank
earthing
earthing
pipeline
Sand
cp shadow
cp shadow
Anodes

Cathodic Protection System Design

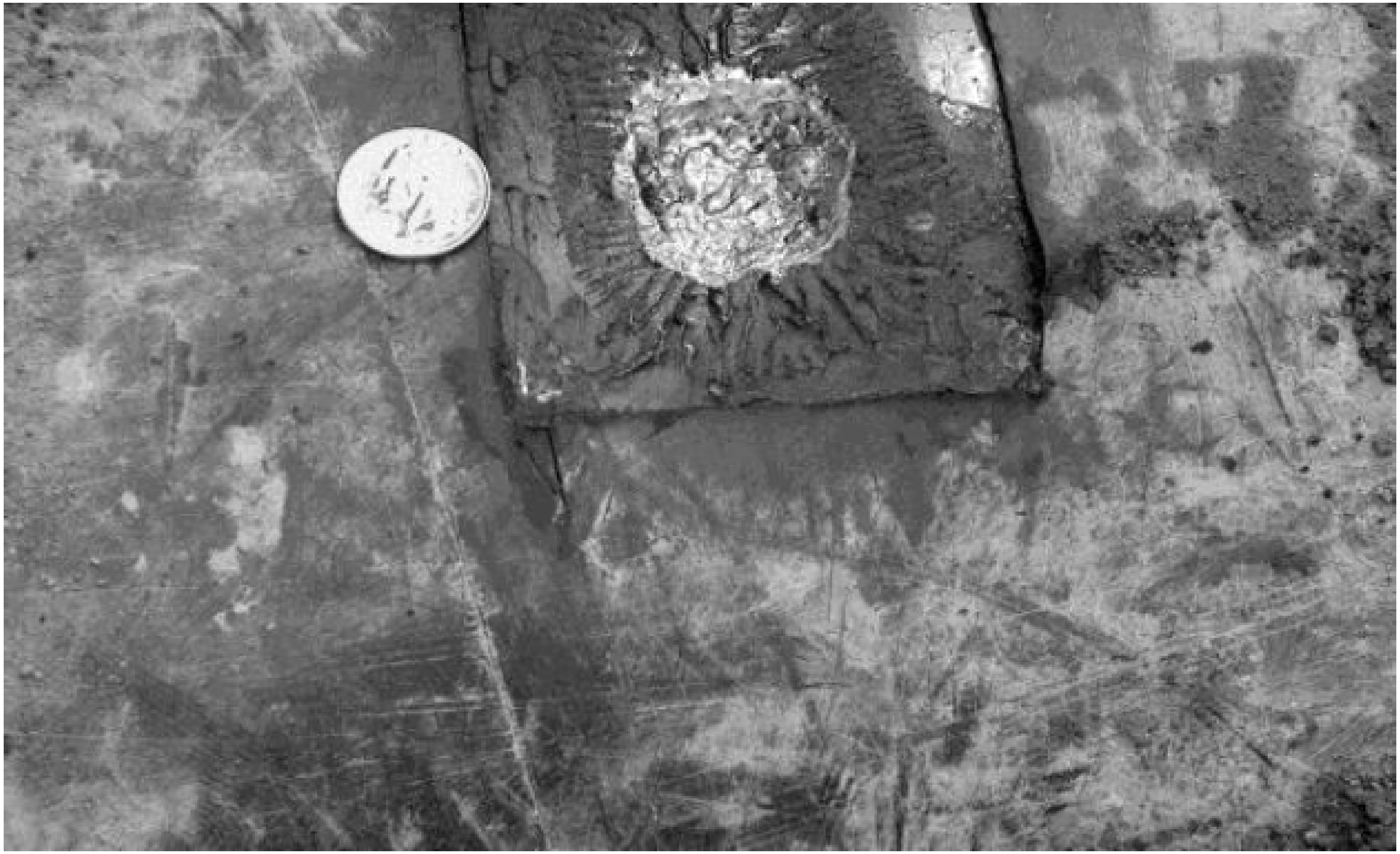
- NACE International qualified personnel
  - WWW.NACE.ORG Coating and Cathodic Protection; Coating Inspection Training, Cathodic Protection Training; Certification of both.
- Steel Structures Painting Council SSPC
  - www.sspc.org Coating Inspection and Training
- DOD Facilities
  - UFC 3 570 01 Cathodic Protection Design Criteria

Thank You

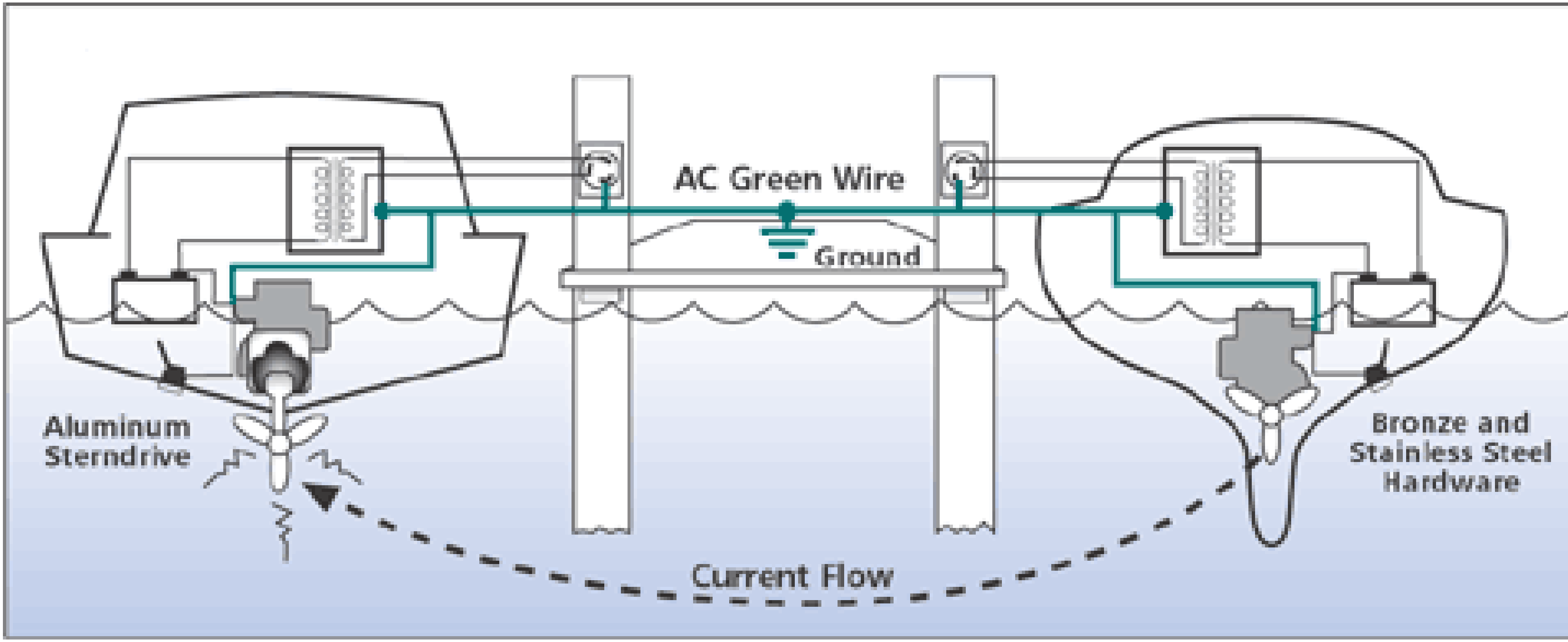
Impressed Current Cathodic Protection



AC Corrosion

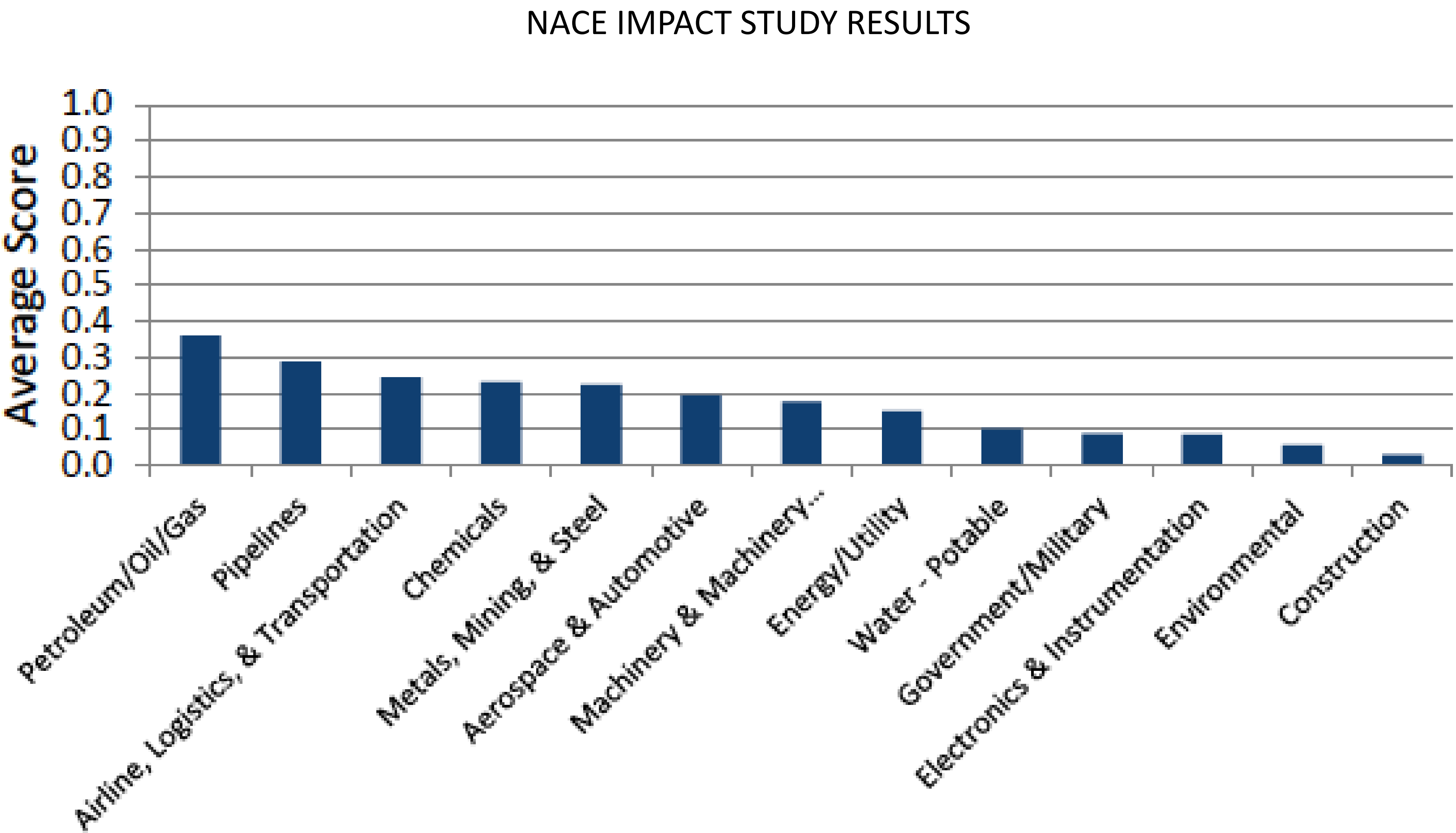


Marina

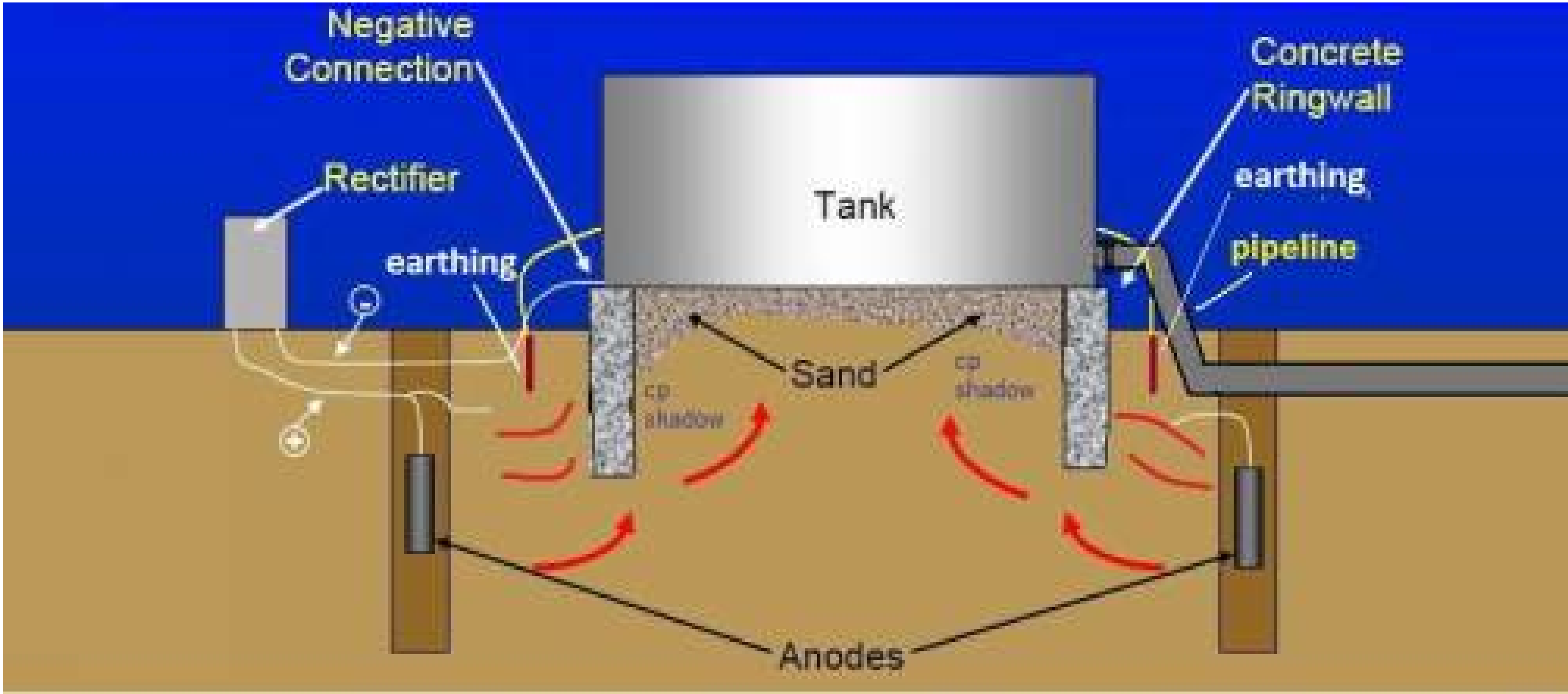


AC Green Wire
Ground
Aluminum
Sterndrive
Bronze and
Stainless Steel
Hardware
Current Flow

Corrosion Management By Sector



AST Floor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Tank
earthing
pipeline
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cp shadow
cp shadow
Anodes