Corrosion Fundamentals

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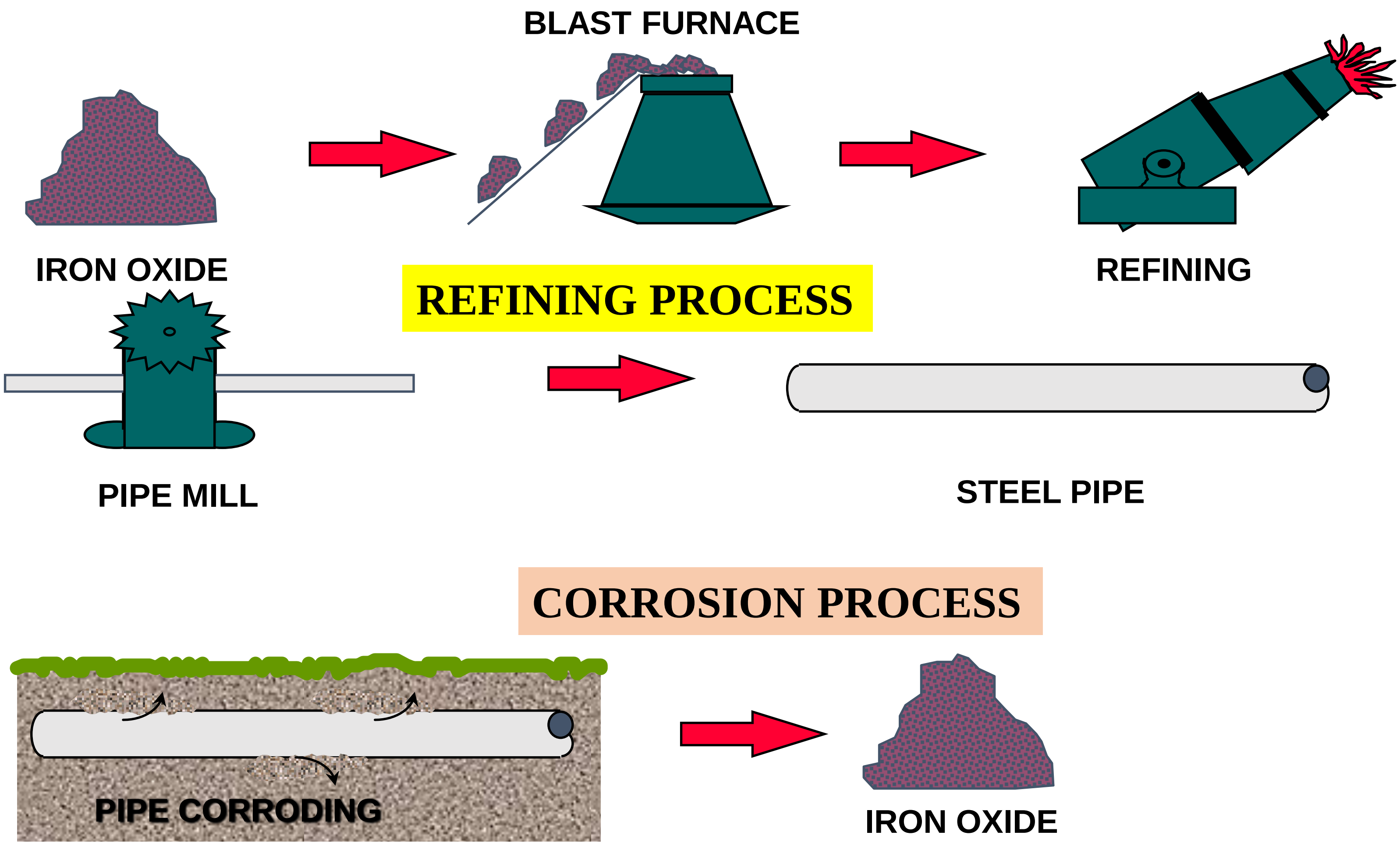
Appalachian Underground Corrosion Short Course

What Is Corrosion?

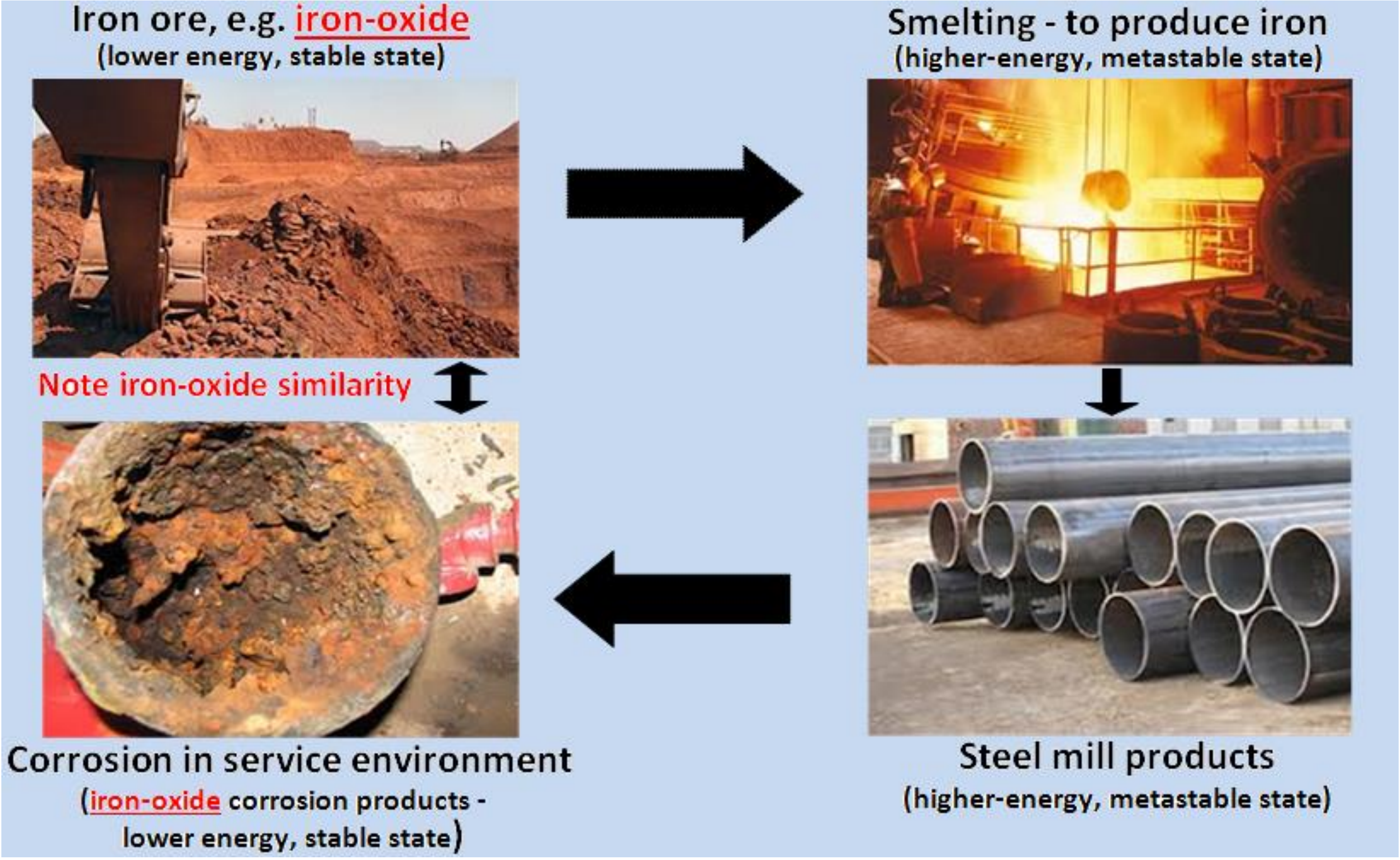
- Corrosion is the deterioration of a material by the reaction with its environment
  - Metals
  - Polymers
  - Concrete
  - Wood
- In this course we will be discussing metals in a pipeline environment

Energy Cycle of Steel



Corrosion of Steel

Natural process which returns metal to its native state

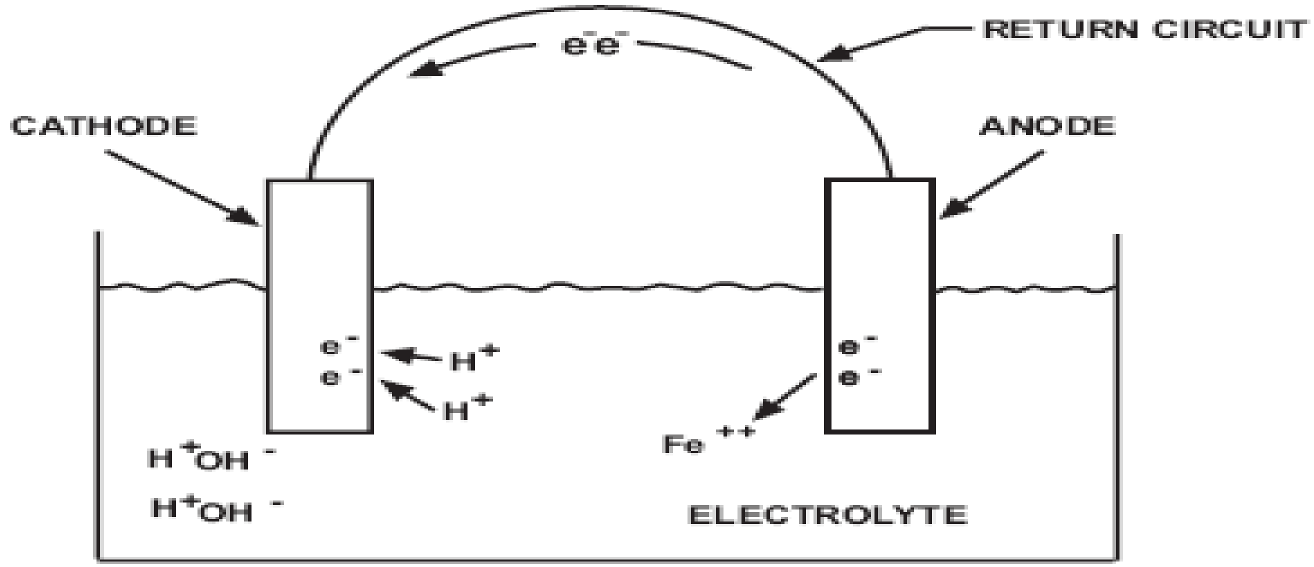


Corrosion Cell

Requirements of a Corrosion Cell

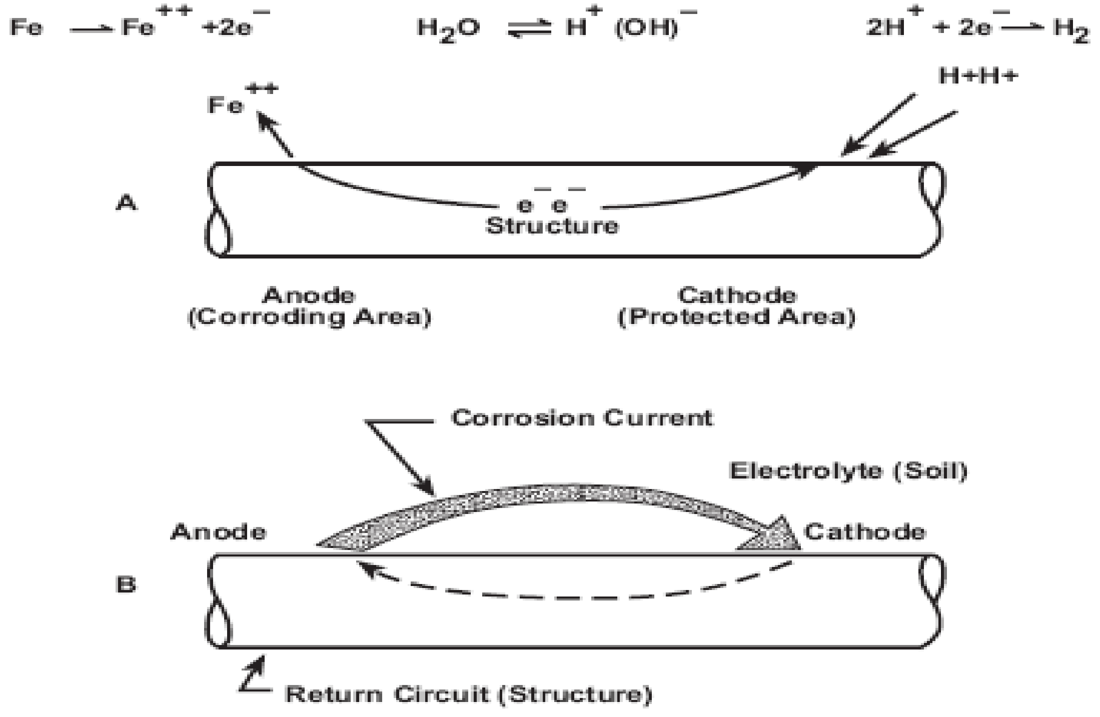
- **ANODE** – where corrosion (oxidation) occurs and metal ions and electrons are generated
- **CATHODE** – where reduction of certain species in the electrolyte occurs by consumption of electrons that were generated at the ANODE
- **ELECTROLYTE** – which allows passage of ionic current – (Earth or Water capable of carrying an electric current)
- **METALLIC PATH** – which allows passage of electrons from ANODE to CATHODE

Basic Corrosion Cell



FUNDAMENTAL CORROSION CELL

Basic Corrosion Cell



FUNDAMENTAL CORROSION CELL
AS IT APPLIES TO A PIPELINE
A Electrochemical cell
B Conventional current cell

Corrosion Reactions

- **ANODE**:
  - **More Active (i.e. more electronegative) potential**
  - **Metal atoms lose electrons and become ions**
- Electrons flow in the metallic path from Anode to Cathode
- **CATHODE**:
  - **More Noble (i.e. more electropositive) potential**
  - **Certain species in the electrolyte accept those electrons**

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Corrosion Reactions

- **Corrosion of the ANODE is Accelerated**
- **Corrosion of the CATHODE** is slowed down or stopped
  - **Species produced by reactions at the Anode and Cathode may react to form insoluble corrosion products, e.g.,**

$$M^{2+} + 2\,OH^{-} \longrightarrow M(OH)_2$$

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Corrosion Reactions

- At the ANODE:
  - $Al \longrightarrow Al^{3} + 3e^{-}$
- At the CATHODE:
  - $2\,H^{+} + 2e^{-} \longrightarrow H_2$

    (hydrogen ions reduced to gaseous hydrogen, e.g. in acids)
  - $3O_2 + 6H_2O + 12e^{-} \longrightarrow 12OH^{-}$

(dissolved oxygen reduced to hydroxyl ions, e.g. in neutral-pH waters)

Types of Natural Corrosion

- **Dissimilar Metals**
- **Dissimilar Surfaces**
- **Dissimilar Soils**
- **Differential Aeration**
- **Stress**

Dissimilar Metals

- There is a natural potential difference between different metals when immersed in a conducting electrolyte
- More “active” the more corrosive (anodic)
- Less “active” or more noble the less corrosive (cathodic)

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Galvanic Series

- **Ranking of Metals and Alloys according to their Electrode Potentials**
- **Potentials Measured in Bulk Electrolyte Environments,**
  - **e.g. Soil, Water**
- **Measured with respect to a Reference Electrode (half-cell)**

Practical Galvanic Series of Metals and Alloys in Neutral Soils and Water

Material	Potential (Volts) vs. $Cu/CuSO_4$
Pure Magnesium	- 1.75
Magnesium Alloy (Mg-6Al-3Zn-0.15Mn)	- 1.6
Zinc	- 1.1
Aluminum Alloy (5% Zn)	- 1.05
Commercially pure Aluminum	- 0.8
Low-carbon steel (clean and shiny)	- 0.5 to - 0.8
Low-carbon steel (rusty)	- 0.2 to - 0.5
Gray cast iron (not graphitized)	- 0.5
Lead	- 0.5
Low-carbon steel (in uncontaminated concrete)	- 0.2
Copper, Brass, Bronze	- 0.2
High-silicon cast iron	- 0.2
Mill-scale on steel	- 0.2
Carbon, Graphite, Coke	+ 0.3

More Anodic or Active end ↑

↓ **More Cathodic, Passive or Noble end**

Practical Galvanic Series of Metals and Alloys in Flowing Seawater (13 ft/s, 24^0C)

Material	Potential (Volts) vs. SCE
Magnesium	- 1.55
Zinc	- 1.03
Aluminum Alloy 3003-H	- 0.79
Ductile Cast iron	- 0.61
Carbon steel	- 0.61
Copper alloy (Naval brass)	- 0.40
Copper	- 0.36
Copper Alloy (Admiralty brass)	- 0.29
Type 316 SS (active)	- 0.18
Titanium	- 0.10
Ni-Cr-Mo Alloy C	- 0.08
Type 316 SS (passive)	-0.05
Platinum	+ 0.15
Graphite	+ 0.25

More Anodic or Active end

↑

↓

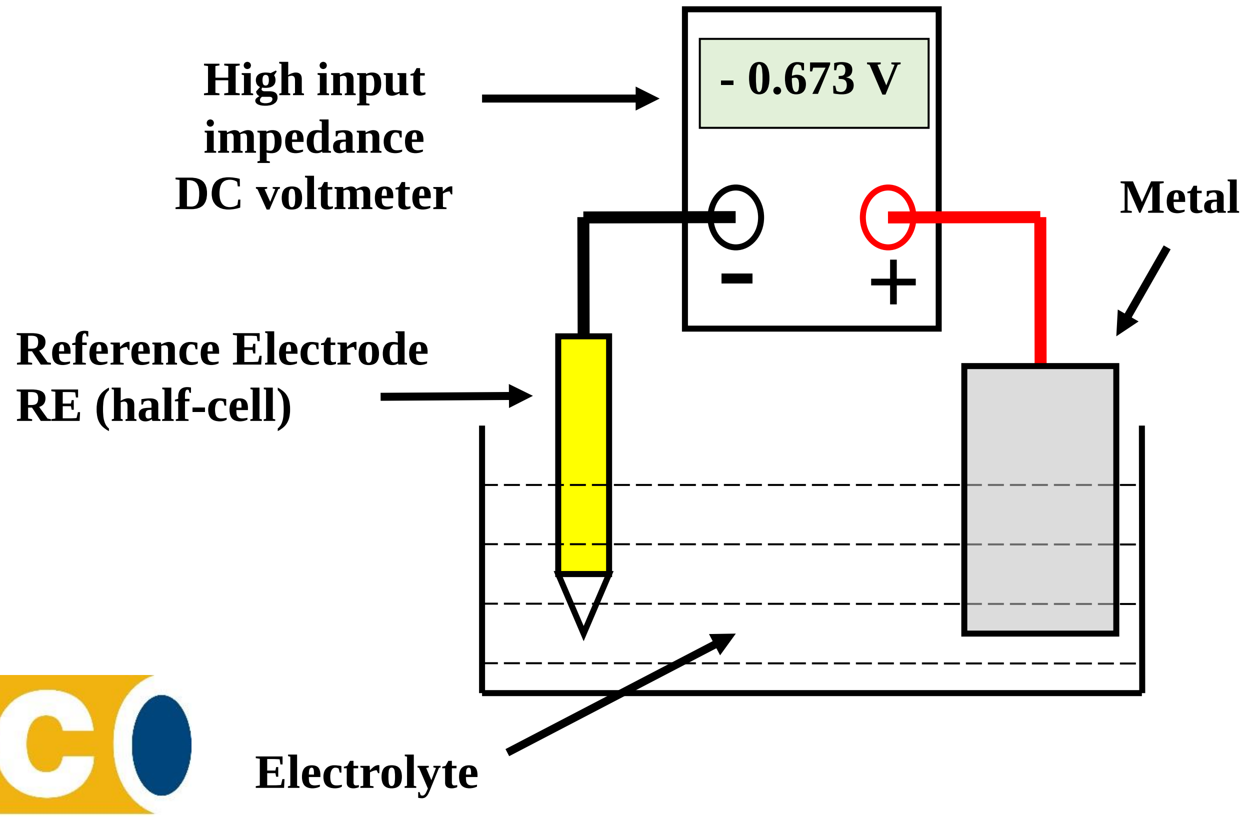
More Cathodic, Passive or Noble end

Dissimilar Metal Corrosion

- **Also called Galvanic Corrosion**
- **Different Metals have Different Electrode Potentials**
- **Potential of metal measured using a DC voltmeter and a reference electrode (half-cell) in electrolyte of interest**
- **Galvanic Corrosion Cell created when dissimilar metals are electrically coupled to each other in the same electrolyte**
- **ANODE – Metal with more Active or more Electronegative potential**
- **CATHODE – Metal with more Noble or more Electropositive potential**
- **Potential Difference between the two metals is the driving force of the corrosion cell**

Electrode Potential

- **Potential of Metal measured using a Reference Electrode (RE) and a DC Voltmeter**



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Reference Electrodes

- **Various types**
- **Examples:**
  - **Copper-Copper Sulfate (Cu/$CuSO_4$)**
  - **Silver-Silver Chloride (Ag/AgCl)**
  - **Saturated Calomel (SCE)**
  - **Standard Hydrogen (SHE)**
- **Measured values can be converted from one scale to another**

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Practical Reference Electrodes

- Examples:

Meters

Digital

Analog

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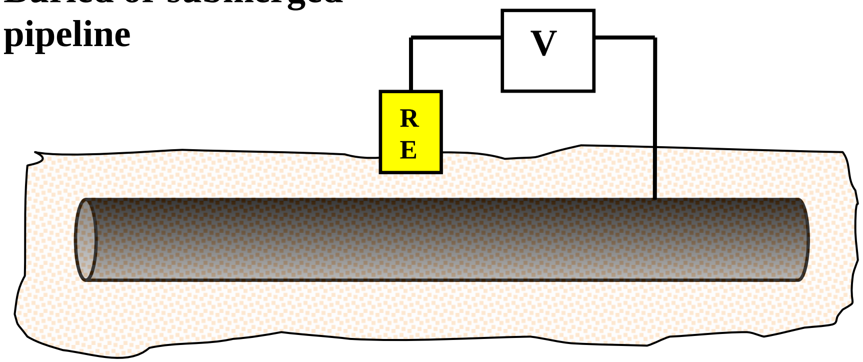
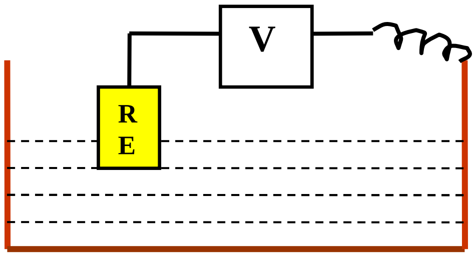
Examples of Potential Measurement

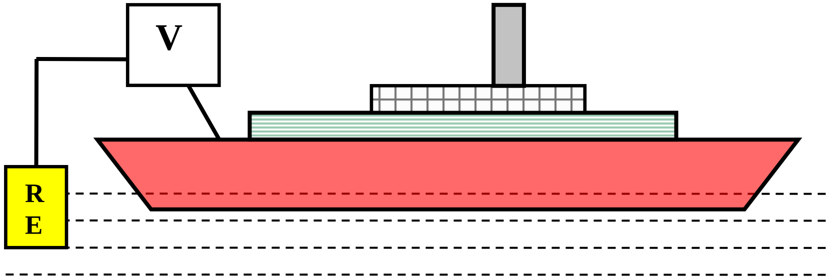
Buried or submerged pipeline



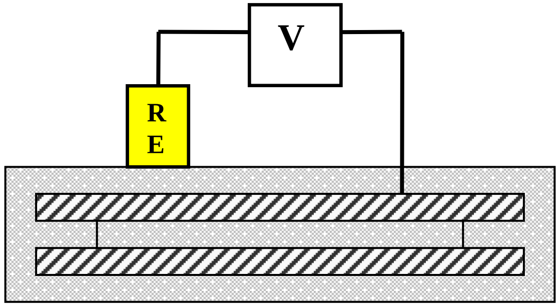
Storage tank interior



Ship or boat

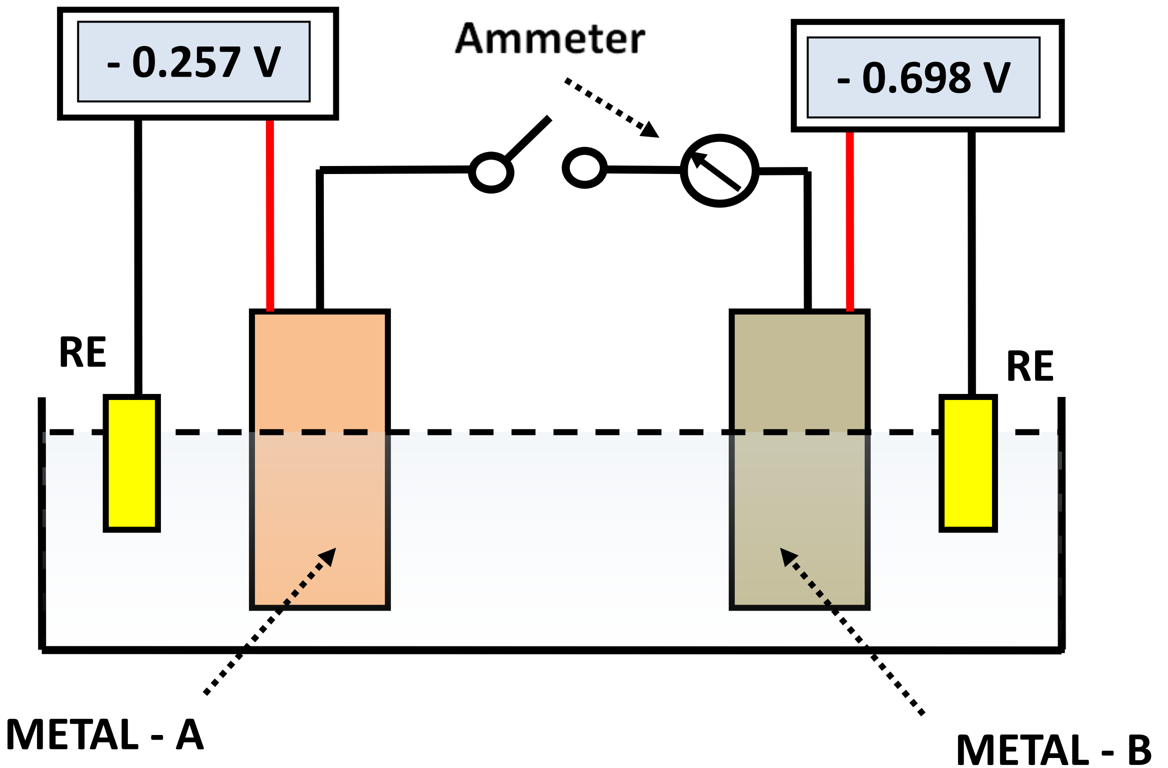


Rebar in concrete



Dissimilar Metal Potentials

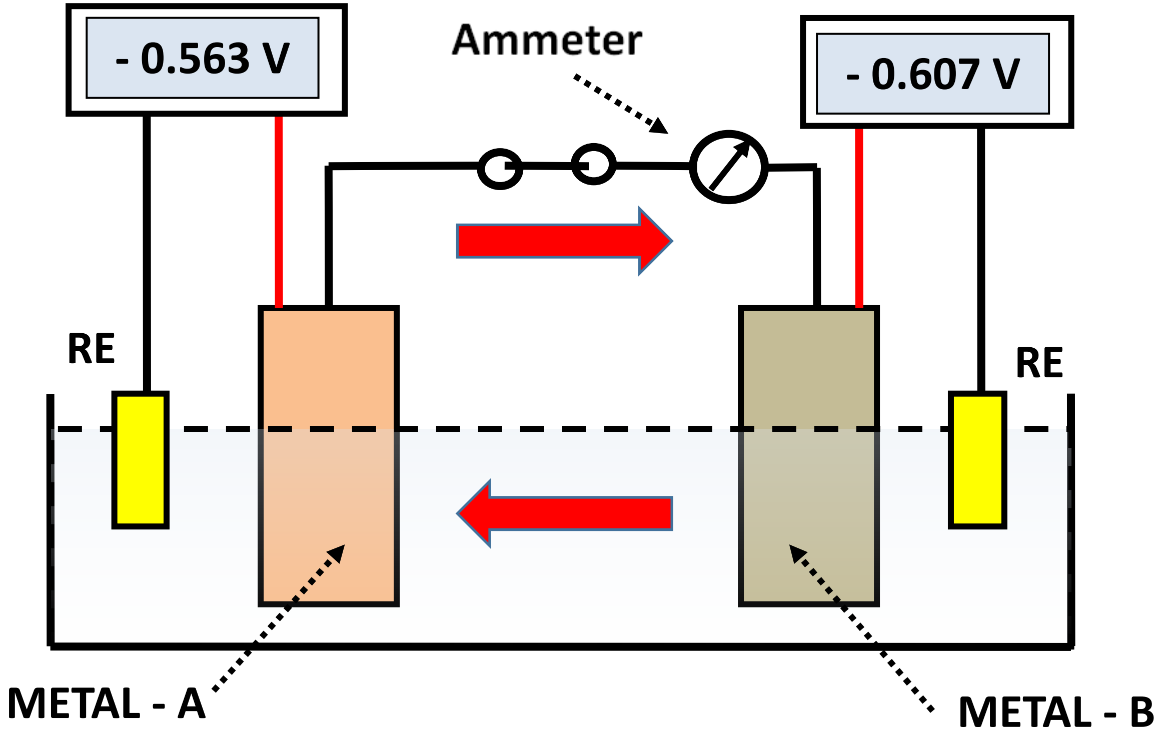
Open-Circuit Potential (OCP) or Corrosion Potential (native)



No Current Flow between the Metals

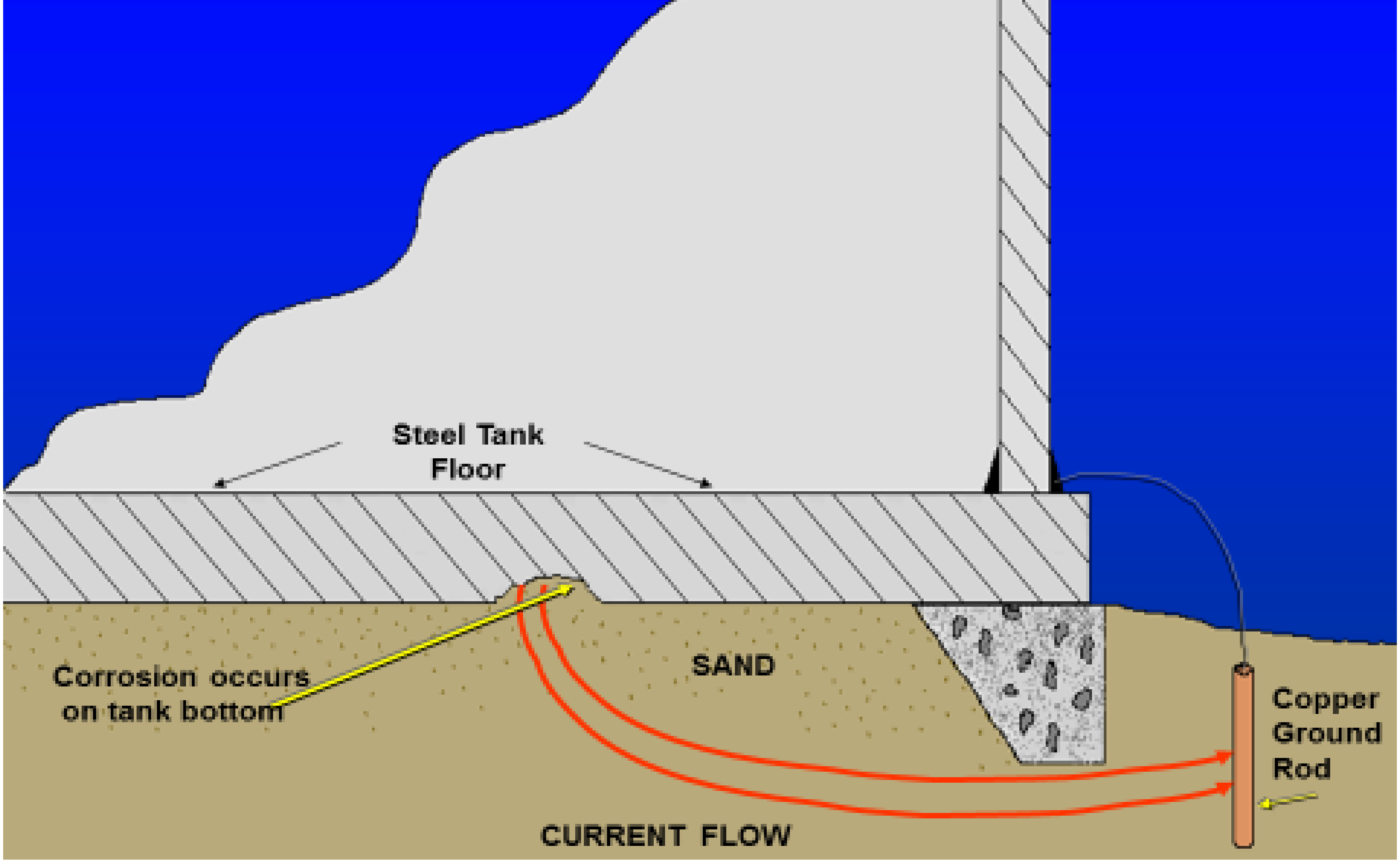
Dissimilar Metal (Galvanic) Corrosion

Metals Electrically Connected by Metallic Path

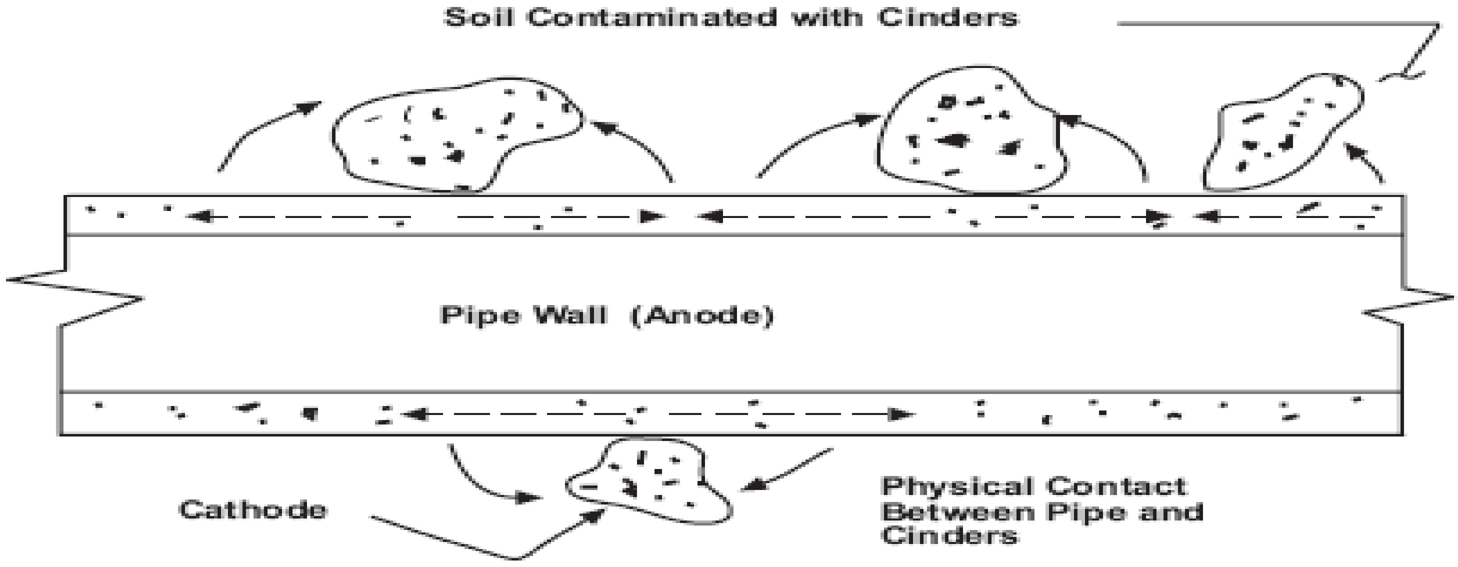


Current Flow between the Metals.
Metal-A is CATHODE and METAL-B is ANODE

Bimetallic Corrosion



Corrosion by Cinders

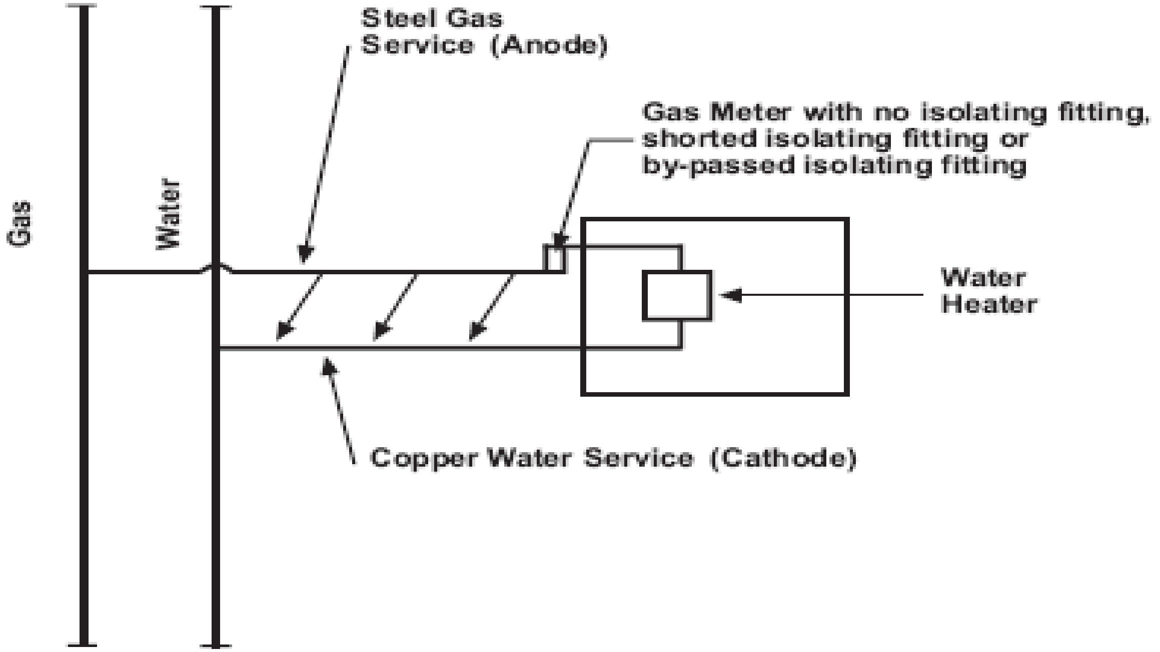


CORROSION DUE TO CINDERS

FIGURE 2-3

Corrosion by Cinders

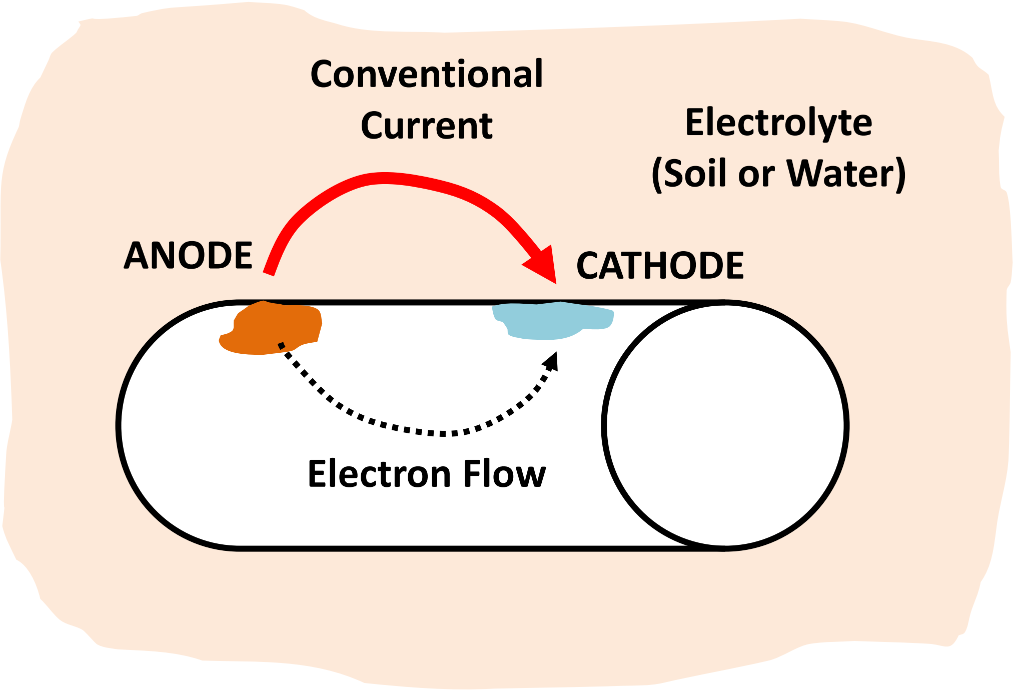
Galvanic Corrosion – Dissimilar Metal



DISSIMILAR METAL CORROSION
GAS AND WATER SERVICE LINES

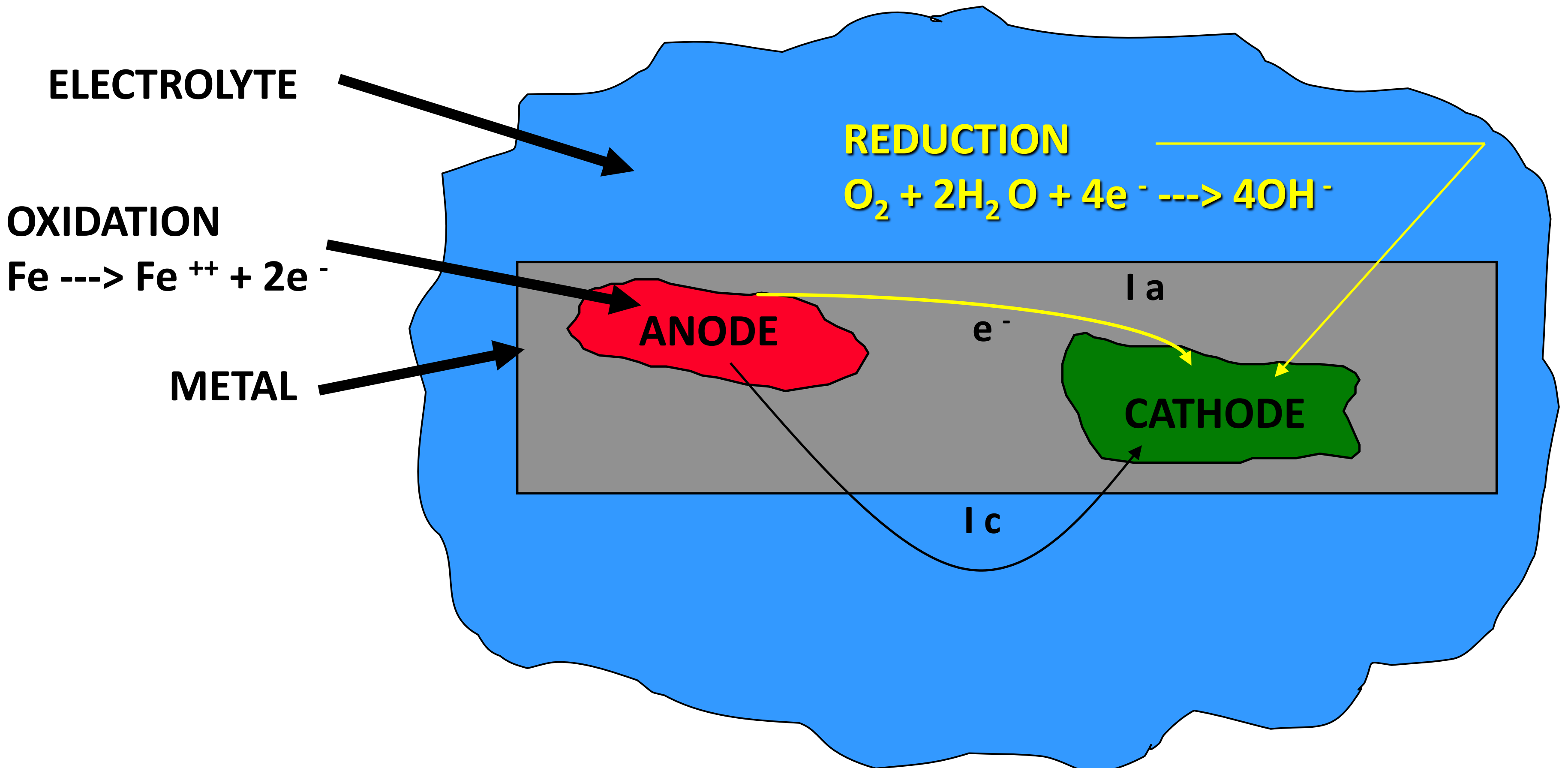
Dissimilar Surfaces

- Occurs on same metal
- E.g. due to local metallurgical differences, defects (bright metal scars), differences in stresses, etc.

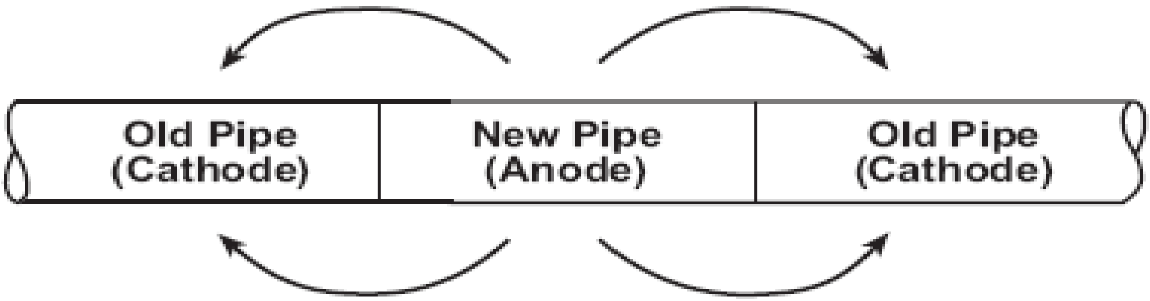


The Corrosion Process

- ANODE
- CATHODE
- ELECTROLYTE
- METALLIC PATH



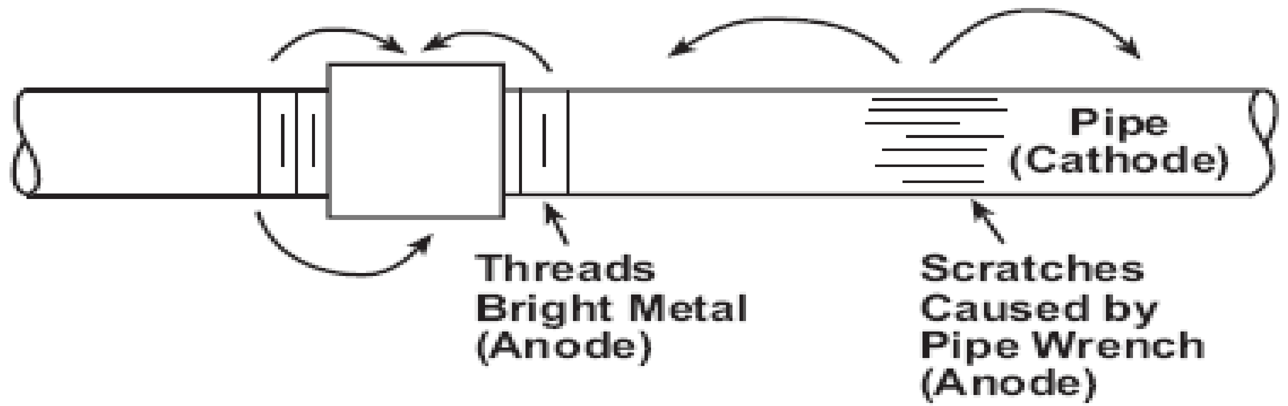
Galvanic Corrosion



NEW-OLD PIPE CELL

FIGURE 2-5

Surface Condition Variations

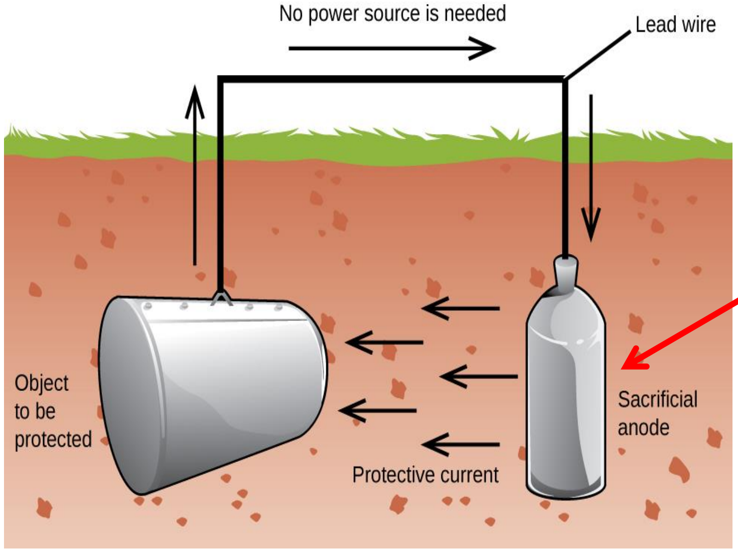


CORROSION CAUSED BY
DISSIMILARITY OF SURFACE CONDITIONS

FIGURE 2-6

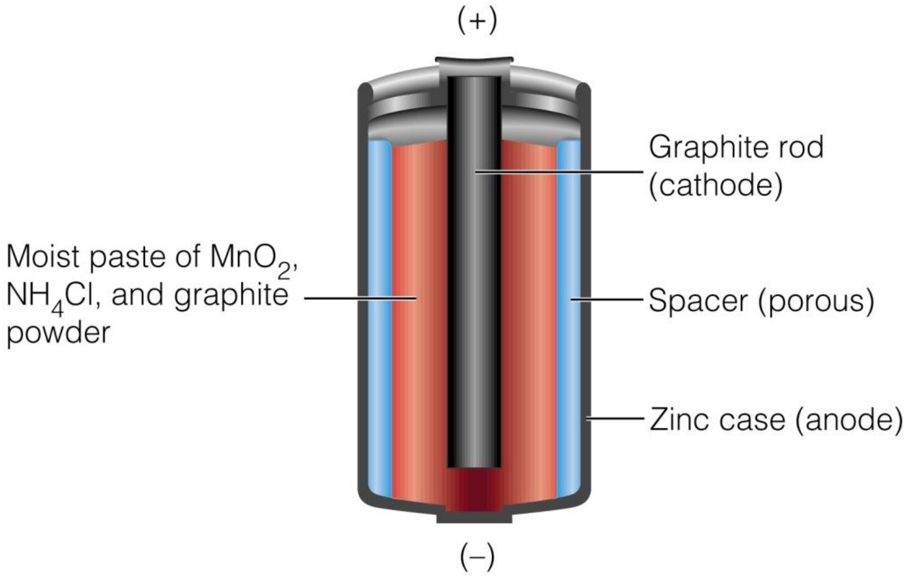
Galvanic Corrosion - Used to Advantage

- In Galvanic Cathodic Protection Systems



Mg or Zn anode

- In Batteries



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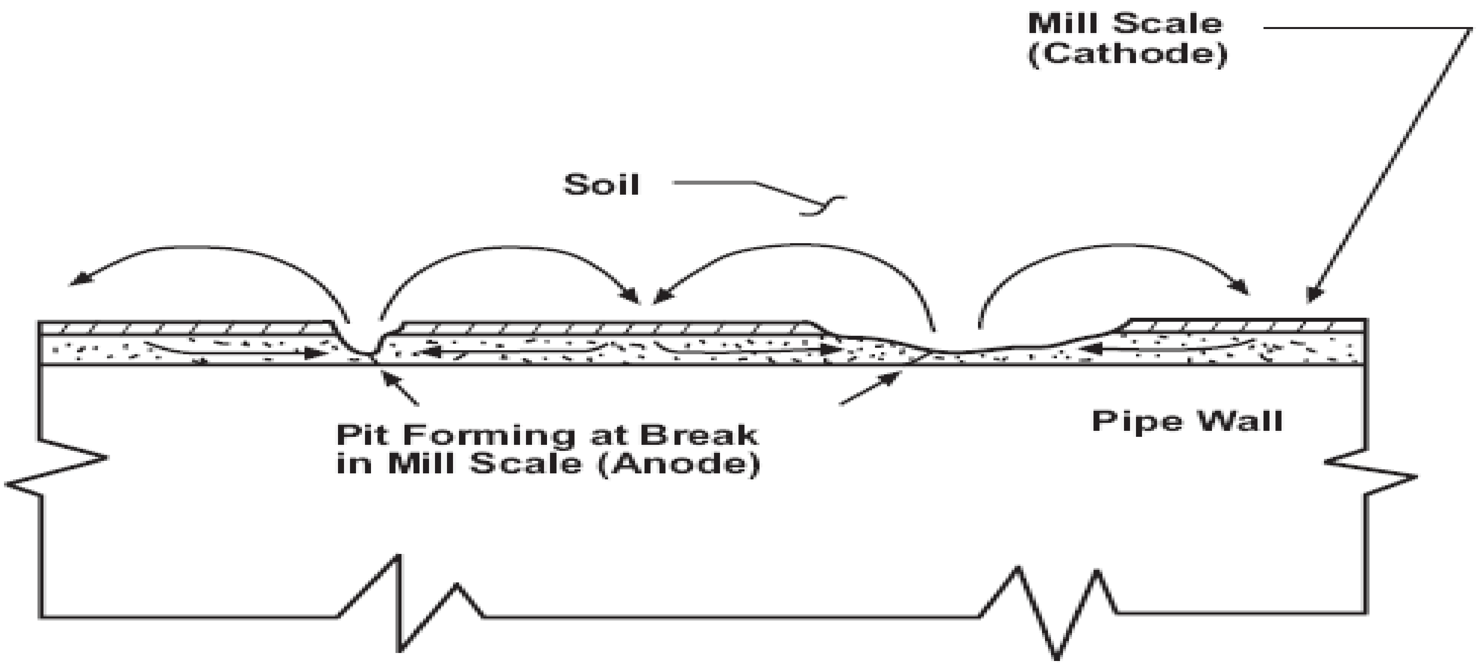
Dissimilar Surfaces

Mill scale – Thin, tightly adhered, surface oxide on steel that come from the mill.

- Electrically Conductive
- Potential of -0.2v - -0.5v

Which is the Anode and Cathode?

Pitting at Breaks in Mill Scale



PITTING DUE TO MILL SCALE

FIGURE 2-7

Dissimilar Soils

- Changes in soil characteristics
- Difference in pipe to soil potentials in respect to a reference electrode
- Creates Cathodic & Anodic areas along the surface

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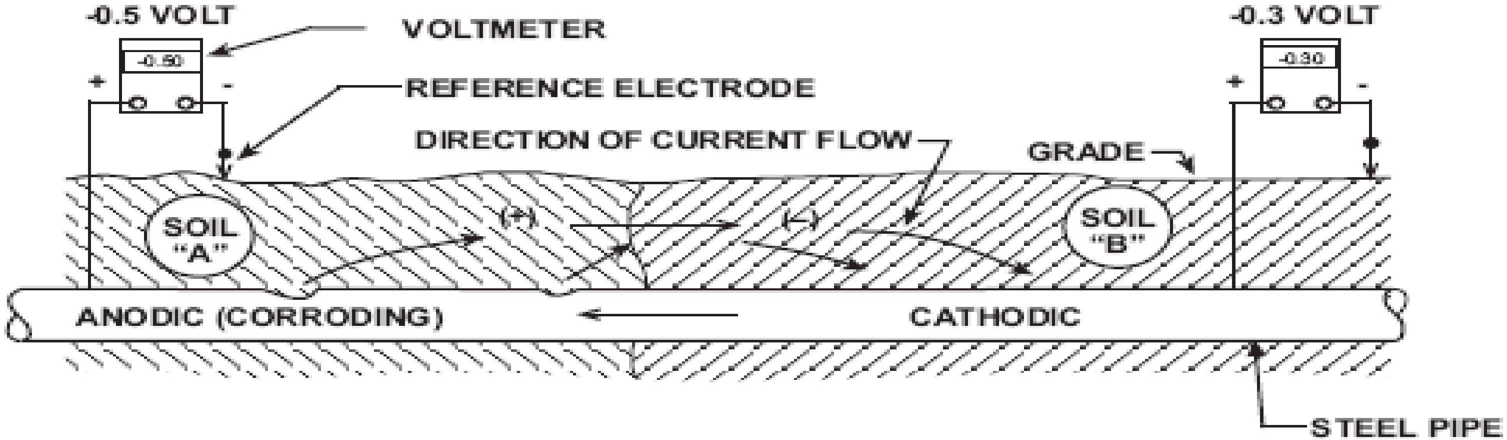
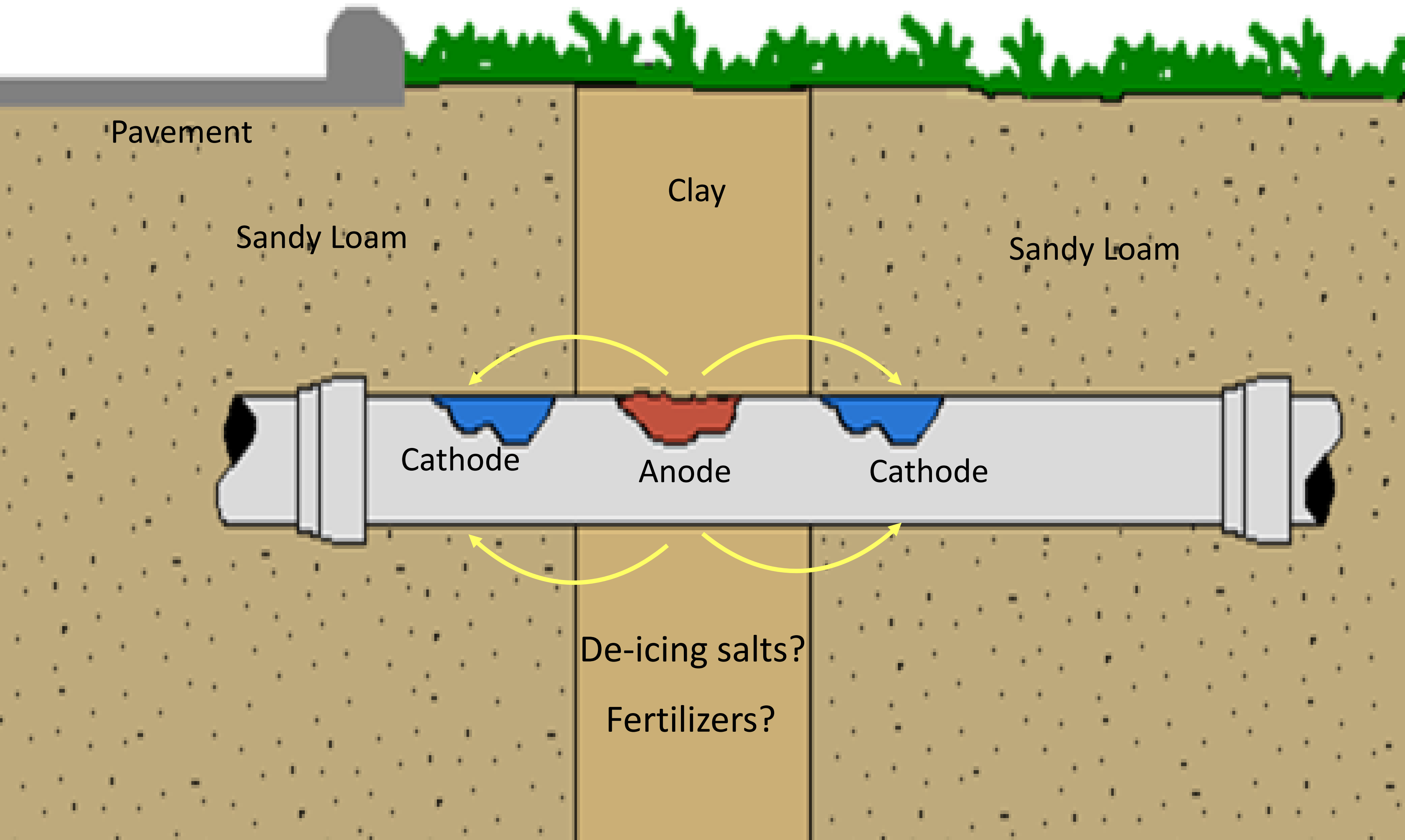
Variations in Soil Types



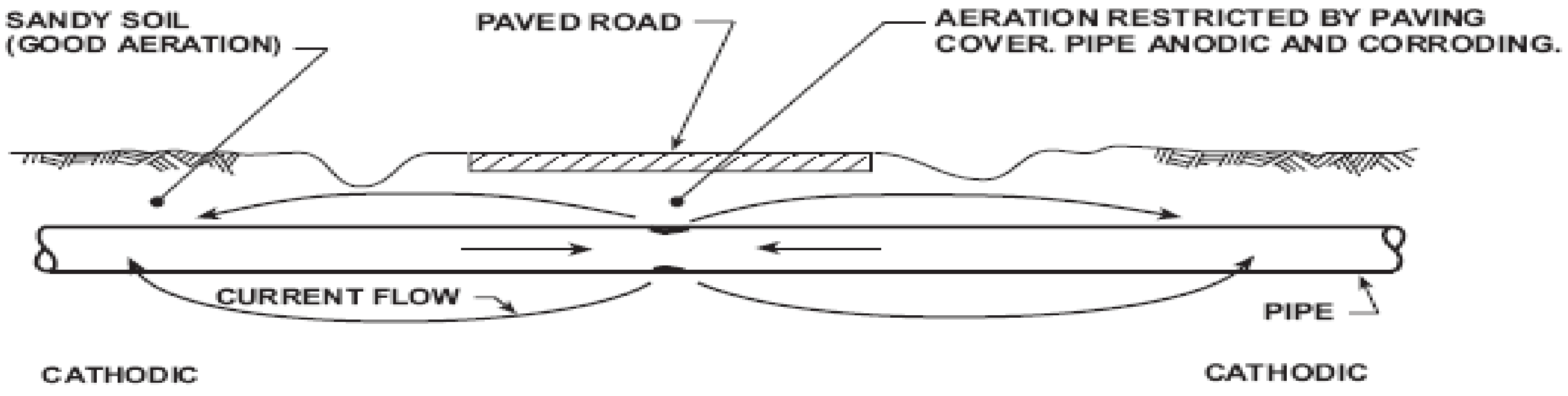
DISSIMILAR SOILS AS SOURCE
OF CORROSION CELL POTENTIAL

FIGURE 2-8

Differential Aeration



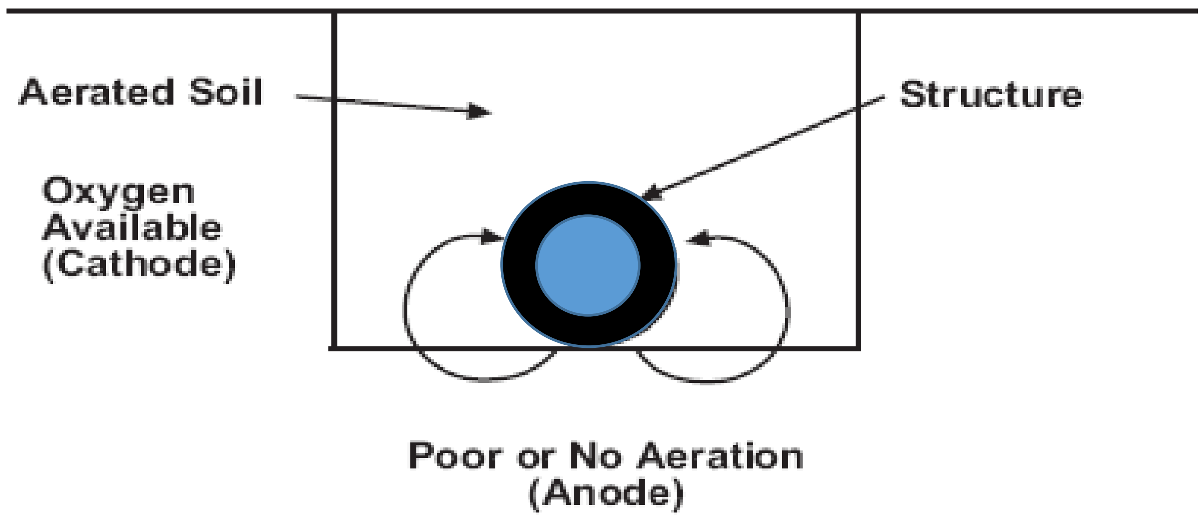
Corrosion Due to Differential Aeration



DIFFERENTIAL AERATION AS A
SOURCE OF CORROSION CELL POTENTIAL

FIGURE 2-10

Differential Aeration Corrosion

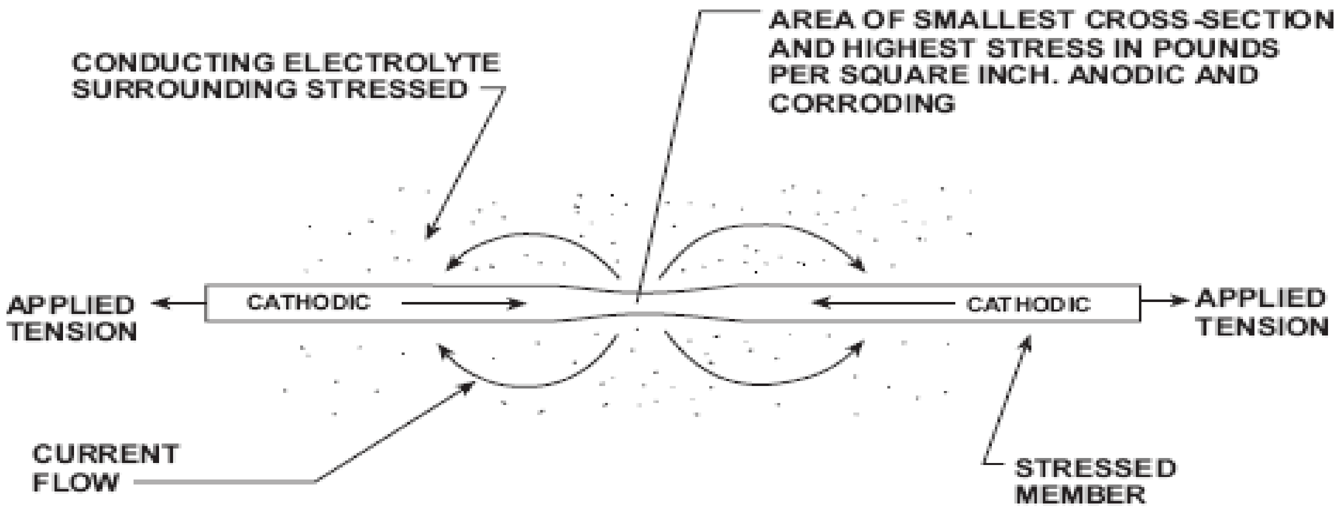


CORROSION CAUSED BY
DIFFERENTIAL AERATION OF SOIL

FIGURE 2-11

Pipe Leak

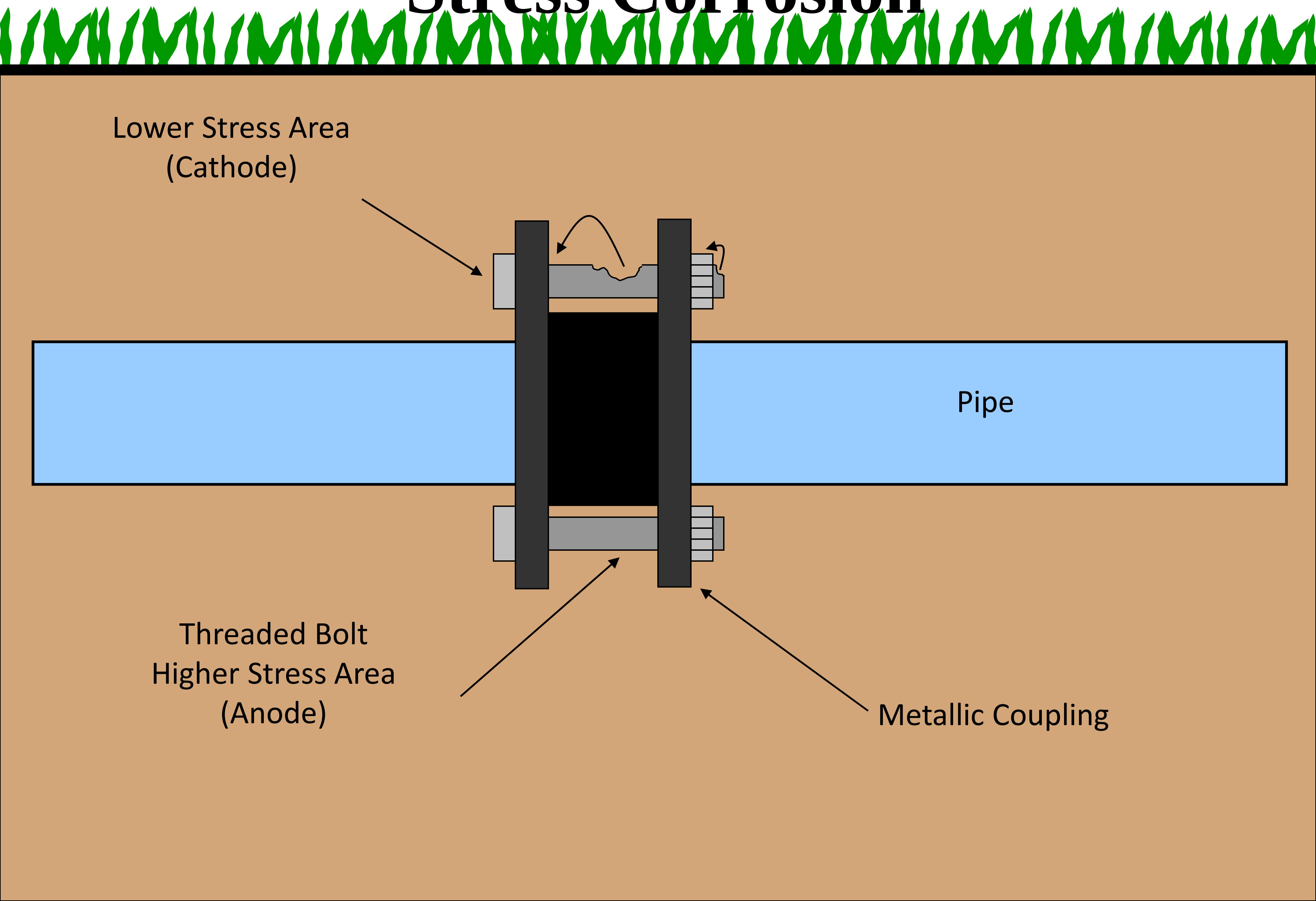
Stress-Cell Corrosion



DIFFERENTIAL STRESS AS A SOURCE OF CORROSION CELL POTENTIAL

FIGURE 2-12

Stress Corrosion



Microbiologically Influenced Corrosion (MIC)

- **Many different types of Bacteria**
- **Sulfate-Reducing Bacteria (SRB) -** Usually most problematic
  - **Require sulfate (SO_4^{2-})**
  - **Require anaerobic conditions**
  - **Require Organic carbon food source**
  - **SRB activity produces hydrogen sulfide (H_2S) which is corrosive to many metals. On steel corrosion product is iron sulfide**
- **Certain aerobic bacteria can also be problematic**

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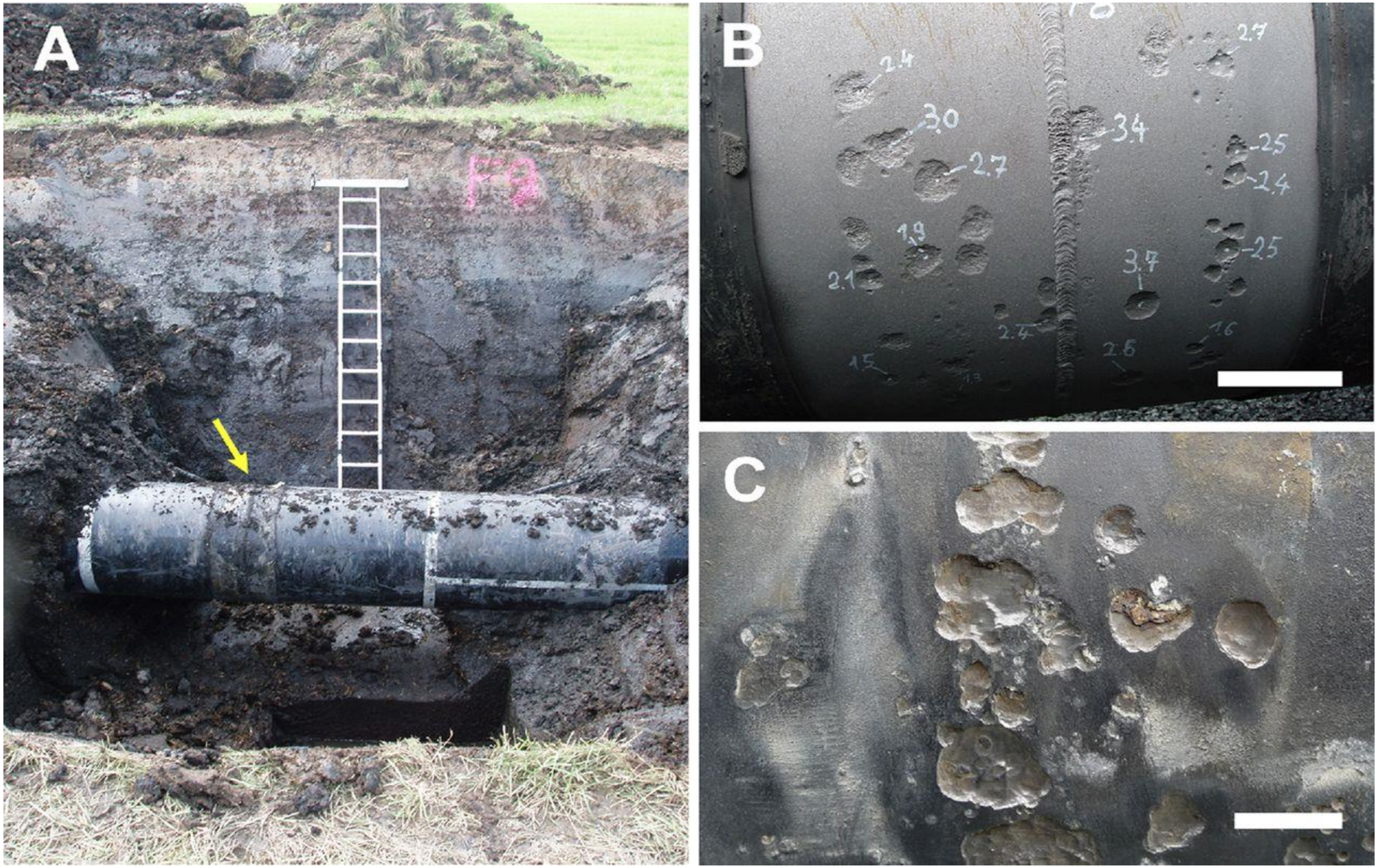
Corrosion of Steel by SRB



Examples of Corrosion Attack by SRB

Corrosion by Aerobic Bacteria


WARNING
PIPELINE

Amphoteric Metals

- **Metals that corrode in acidic as well as alkaline environments**
- **E.g. Aluminum, Zinc, Tin, Lead**
- **Possibly corrode under cathodic conditions**

Stray Current Corrosion

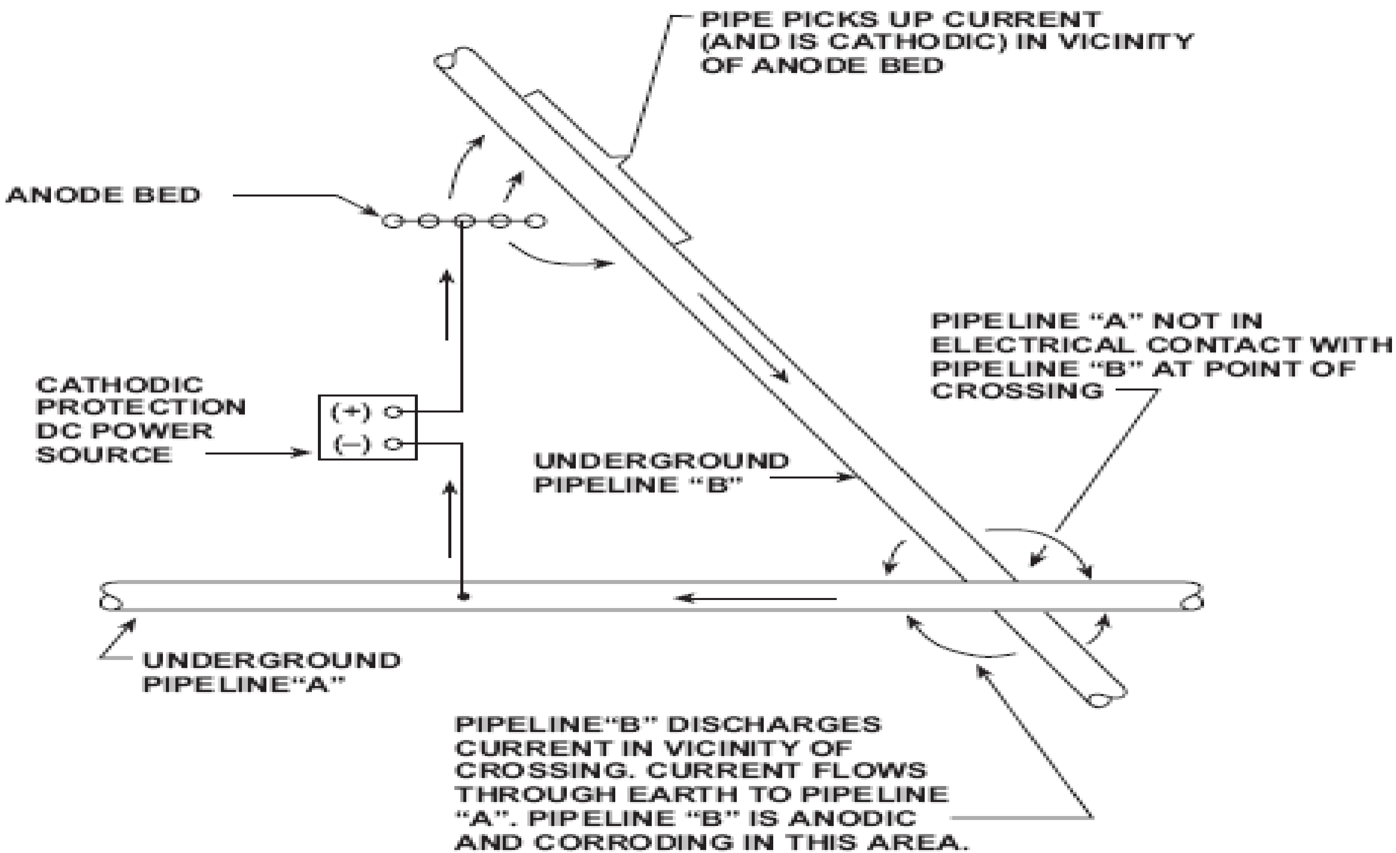
- **Corrosion caused by current that deviates (strays) from its intended path**

Sources of Stray Currents

- **Dynamic**
  - DC (Electric) Transit Systems
  - Mining Operations
  - Welding Operations
- **Static**
  - Impressed Current Cathodic Protection Systems (ICCP)
  - High Voltage Power Transmission

Stray Current Corrosion

Source ICCP System

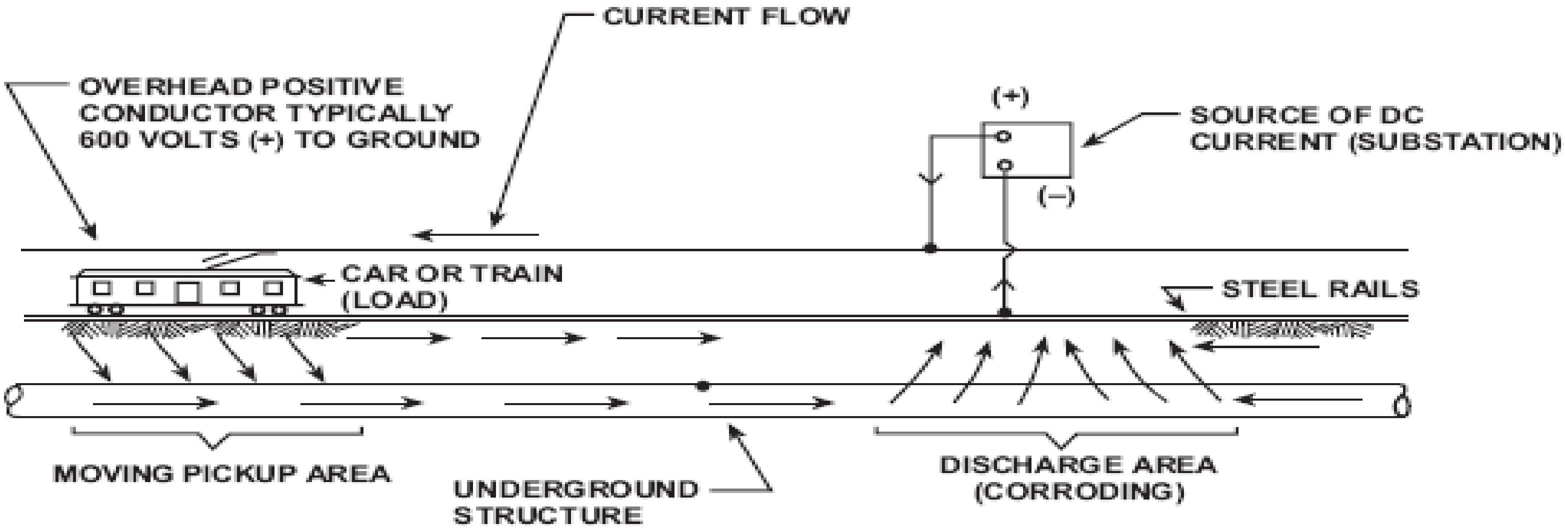


STRAY CURRENT CORROSION
FROM CATHODIC PROTECTION SYSTEM

FIGURE 2-15

Stray Current Corrosion

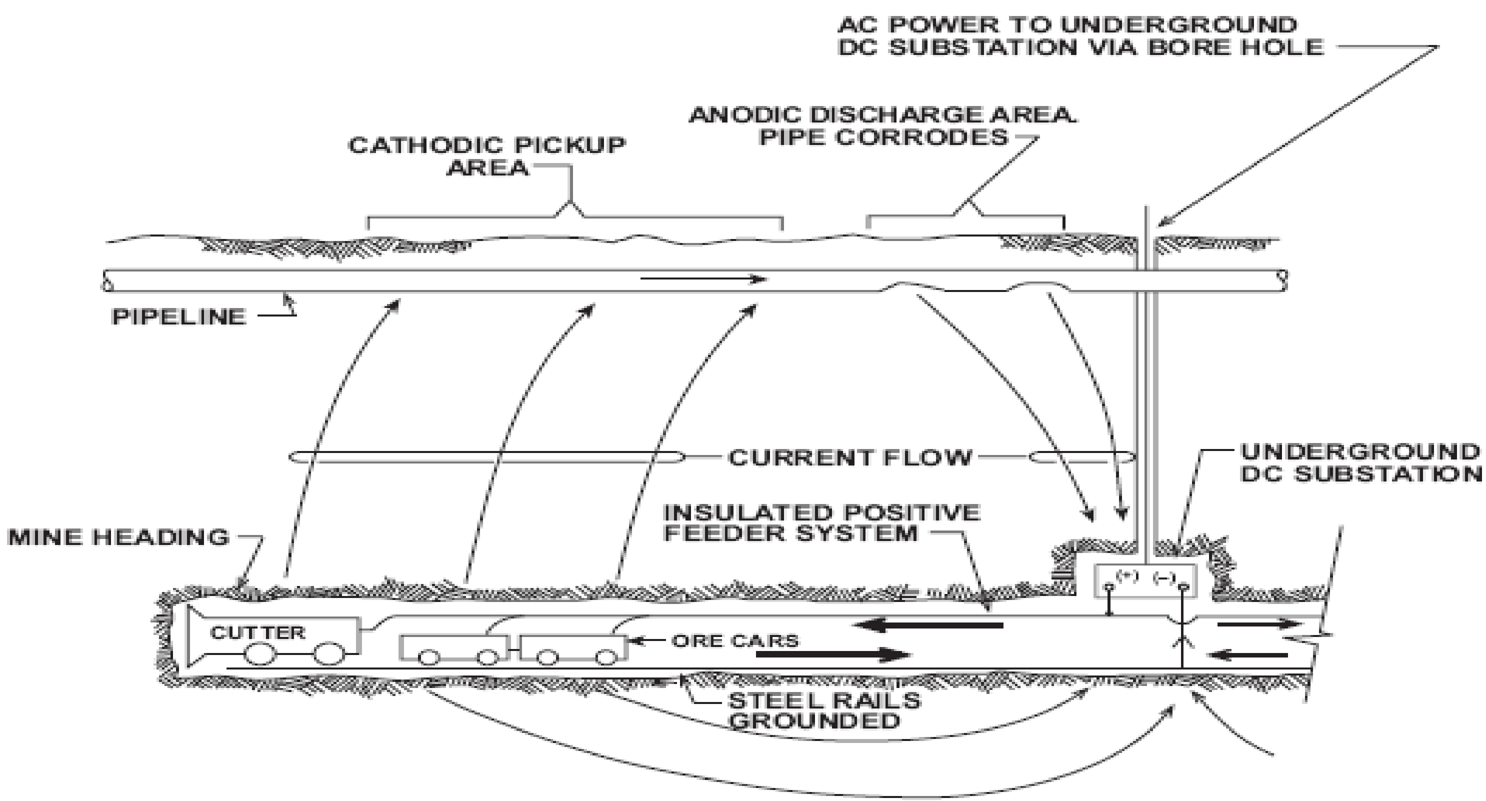
Source DC Transit System



DC TRANSIT SYSTEM AS A SOURCE OF STRAY CURRENT CORROSION

Stray Current Corrosion

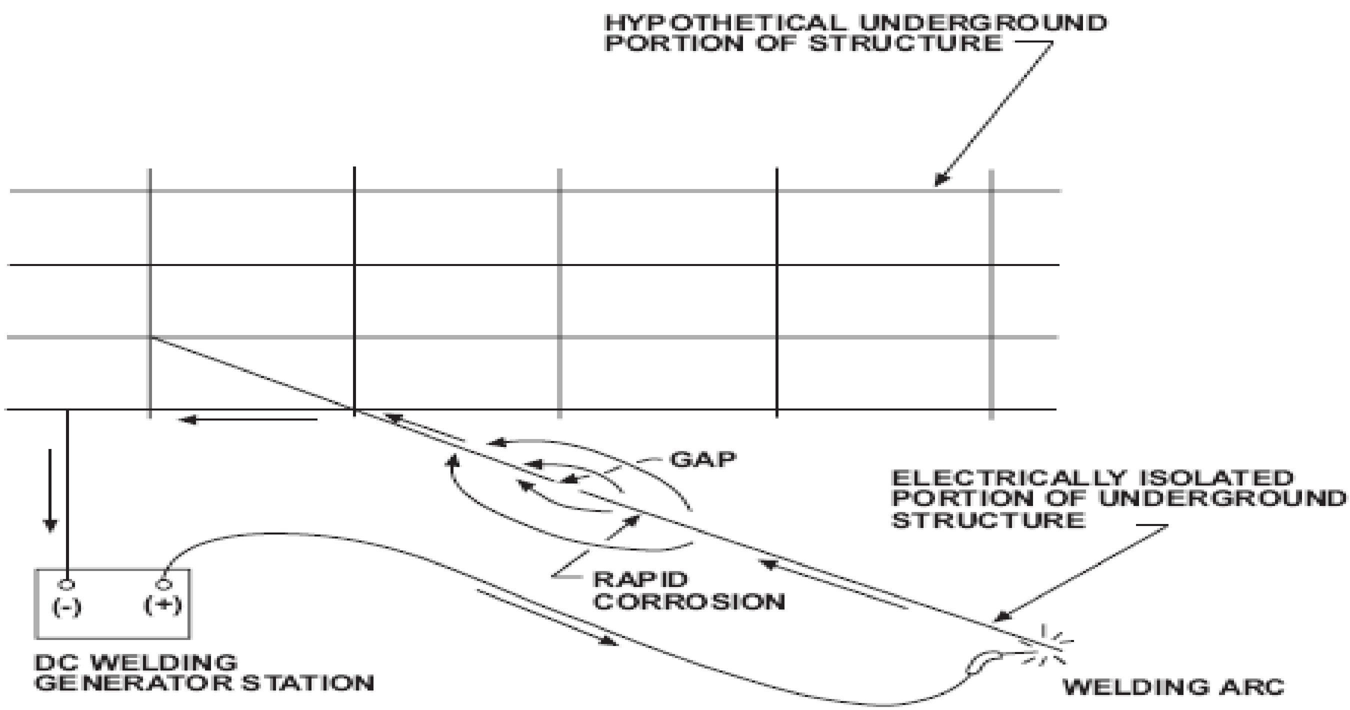
Source DC Mining Cars



CORROSION BY STRAY CURRENT
FROM DC MINING OPERATIONS

Stray Current Corrosion

Source DC Welding

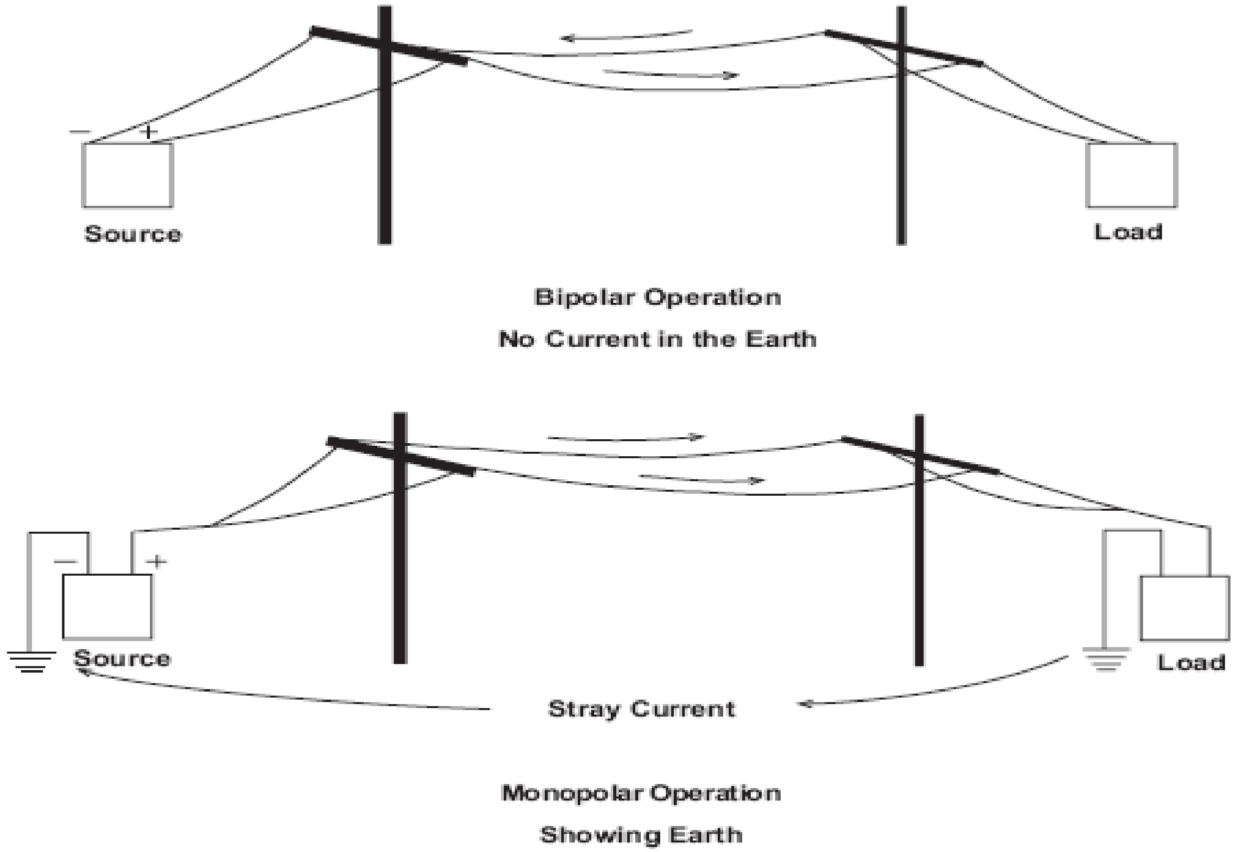


CORROSION BY STRAY CURRENT
FROM DC WELDING OPERATIONS

FIGURE 2-19


WARNING
GAS
WARNING
GAS

Stray Current Corrosion
HVDC System



HIGH VOLTAGE DC TRANSMISSION LINE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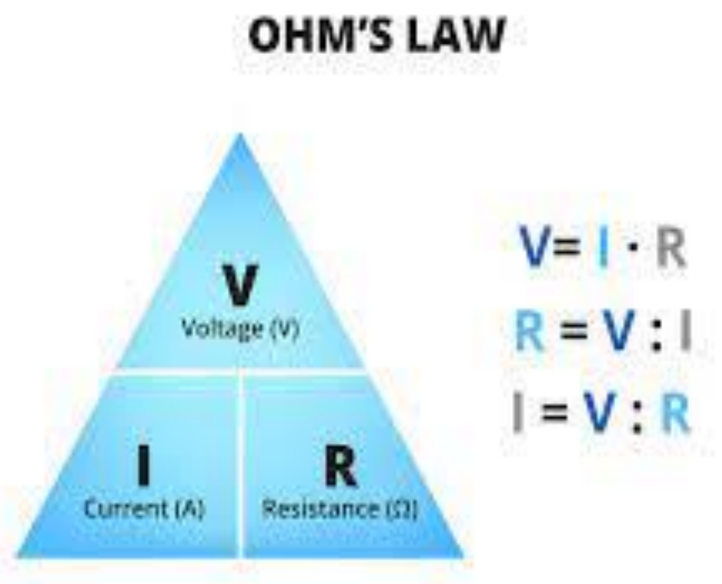
OHM'S LAW

$$I = \frac{E}{R}$$



I= Current (Amps)

E / V= Volts

R= Resistance (Ohms)

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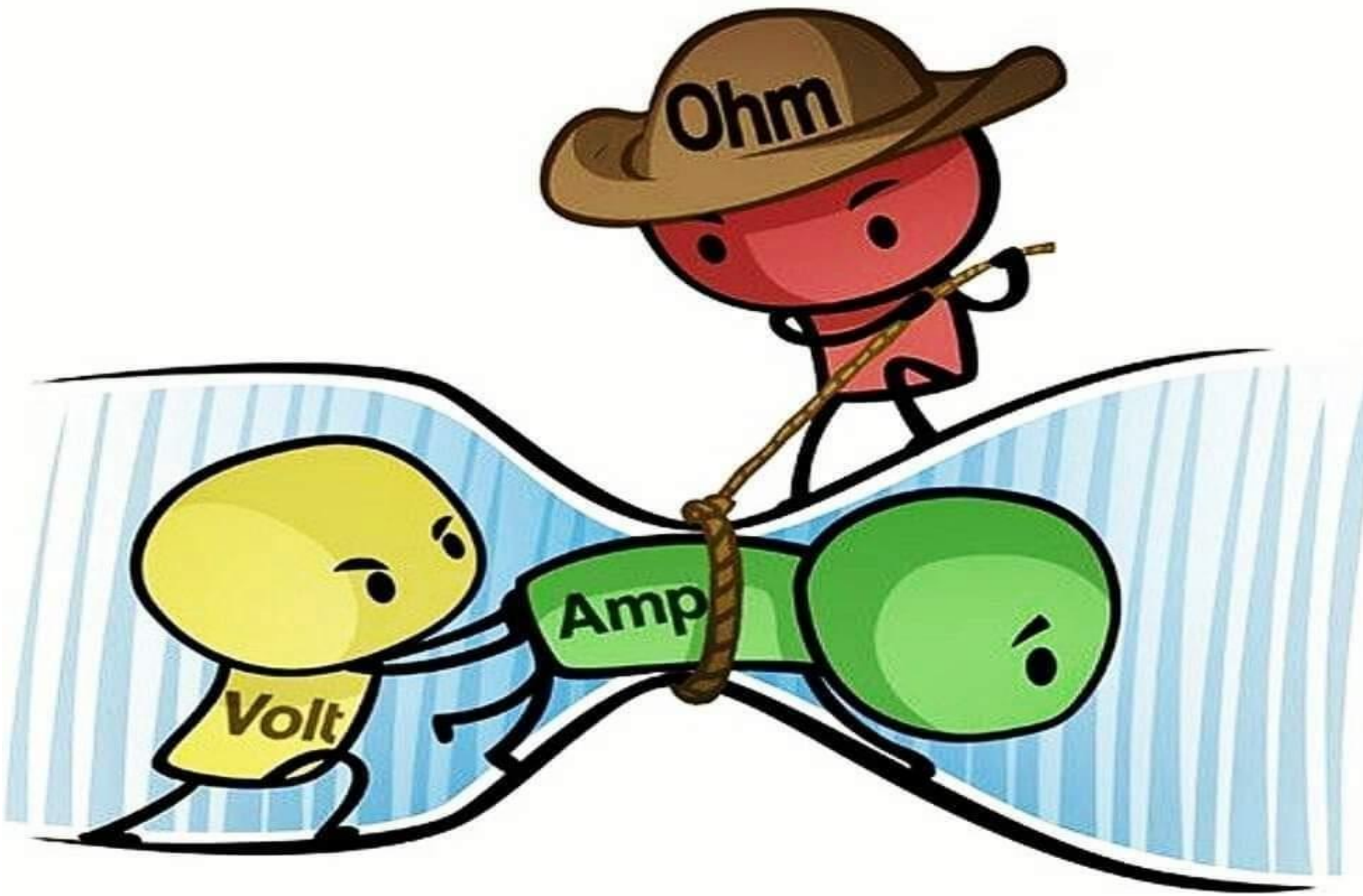
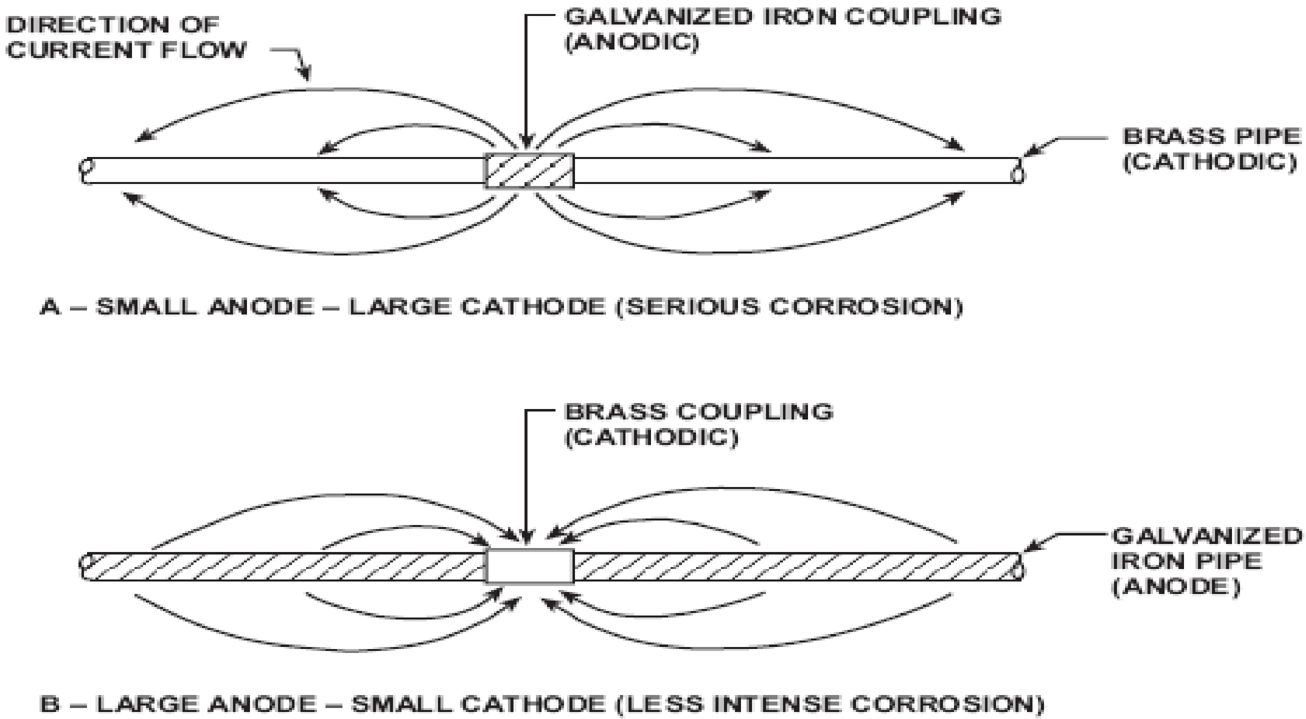
OHM'S LAW



Effect of Anode-to-Cathode Area Ratio

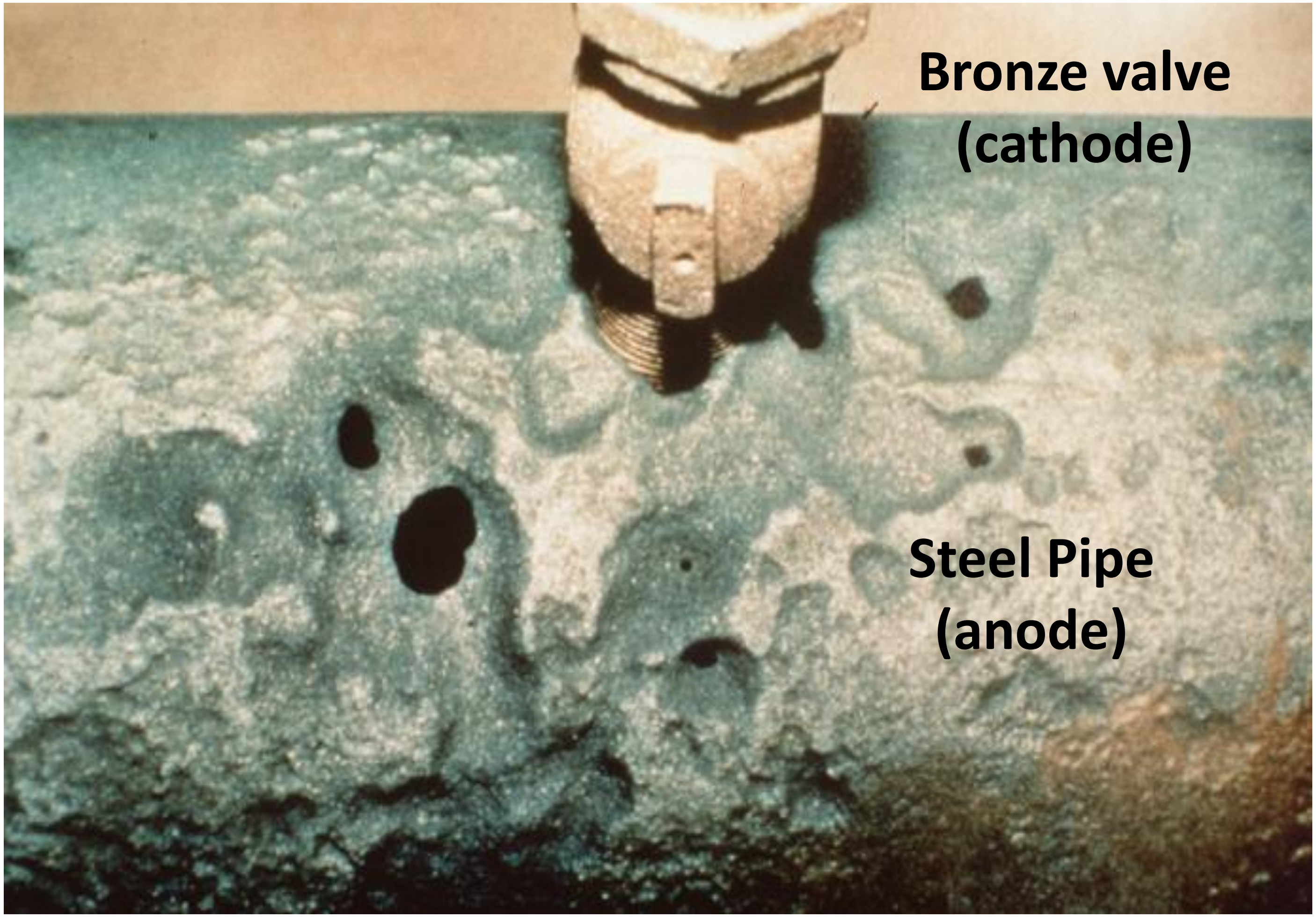
Galvanic Corrosion



ANODE-CATHODE SIZE RELATIONSHIP

FIGURE 2-20

Galvanic Corrosion



Faraday's Law

(Rate of Corrosion)

$W = K \times I \times T$

Where:

W = Weight Loss in One Year

K = Electrochemical Equivalent in Pounds Per Ampere Per Year

I = Corrosion Current in Amperes

T = Time in Years

Metal Corrosion Loss

TABLE 2-2

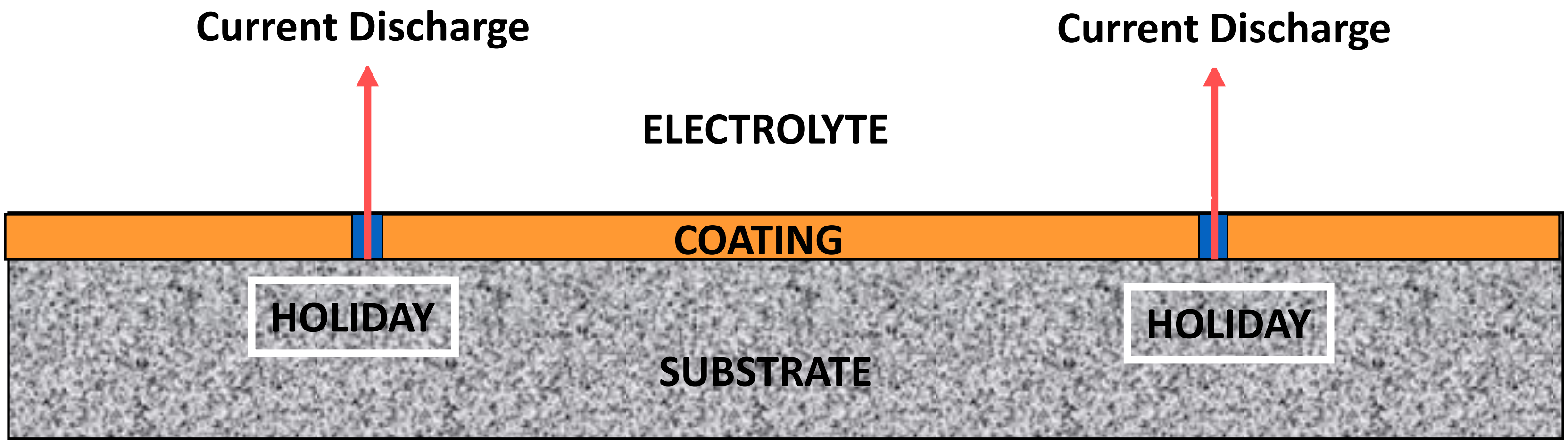
CONSUMPTION RATES OF TYPICAL METALS

Metal	Electrochemical Equivalent (Grams per coulomb)	Consumption Rate (Pounds per Ampere-year)	Volume of Metal Consumed (Cubic inches per Ampere-year)
Carbon* (C^{+++})**	0.4149×10^{-4}	2.89	36.99
Aluminum (Al^{+++})	0.9316×10^{-4}	6.48	69.99
Magnesium (Mg^{++})	1.2600×10^{-4}	8.76	141.47
Iron (Fe^{++})	2.8938×10^{-4}	20.12	70.81
Nickel (Ni^{++})	3.0409×10^{-4}	21.15	67.06
Copper (Cu^{++})	6.5875×10^{-4}	45.81	142.89
Zinc (Zn^{++})	3.3875×10^{-4}	23.56	90.87
Tin (Sn^{++})	6.1502×10^{-4}	42.77	162.43
Lead (Pb^{++})	10.736×10^{-4}	74.65	181.68

* Carbon is not strictly classified as a metal but as a metalloid -- but subject to consumption as a metal.

** Each metal is followed by its chemical symbol. The number of (+) signs following the symbol indicates the valence (a chemical term) for a typical anode reaction. The electrochemical equivalents are calculated on the valence shown. Other valences may apply under certain conditions for some metals.

Current Density at Coating Holidays



Anodic current density at coating holidays will be very high. According to Faraday's Law the metal penetration (corrosion) rate will also be proportionately high.

Corrosion Failure Consequences

Corrosion Failure Consequences

Corrosion Failure Consequences

Corrosion Failure Consequences