HDR

Nebraska Section ASCE Geotechnical Short Course

Soil Corrosivity

Presented by: Lucy Jaramillo, EIT, CP2 &
Brien Clark, PE, NACE CP4
Prepared by: Mersedeh Akhoondan, PhD, PE
Marc E N Wegner, PE, CP3

February 2024

TRAINING
Session 1

Get comfortable, we have a lot of materials to cover today!

- 8:00 - Introductions and Course Objectives
- 8:20 - Introduction to Corrosion
- 9:15 - Driving Forces of Corrosion
- 10:45 - Soil Corrosivity
- 12:45 - Corrosion Prevention Techniques
- 1:30 - Basics of Cathodic Protection
- 2:45 – Corrosion Allowance for Piles
- 3:30 - Questions and Answers

LEARNING TOPICS :

- Who are your presenters
- What is the objective of this course

Introductions and Course Objectives

8:00 – 8:20 am

TODAY'S SPEAKERS

Lucy Jaramillo, EIT, NACE CP2

CORROSION FIELD SERVICES LEAD

Over 10 years of Corrosion Experience

AMPP NACE Cathodic Protection Technician

Brien Clark, PE, NACE CP4

SENIOR CORROSION TECHNICAL PM

Over 20 years of Corrosion Experience

Licensed Professional Engineer in CA, AZ, NM, ID, OR, HI

AMPP NACE Cathodic Protection Specialist

SHORT COURSE LEARNING OBJECTIVES

- Understanding of Electrochemical Corrosion Basics
- Identifying Common Environmental Elements that Drive Corrosion
- How to measure and define soil corrosivity
- Identify corrosion mitigation methods and understanding the pros and cons of each
- The types of cathodic protection and understanding how cathodic protection works
- Where to find associated industry standards and additional training
- What certification and qualifications does the industry recognize

LEARNING TOPICS:

- Why do we care?
- Cost of corrosion?
- Which industries care?
- What impacts on the water systems?
- What is corrosion
- Why does corrosion occur?
- What are the key components in the corrosion process?

INTRODUCTION TO CORROSION

8:20 - 9:15 am

DEFINITION OF CORROSION

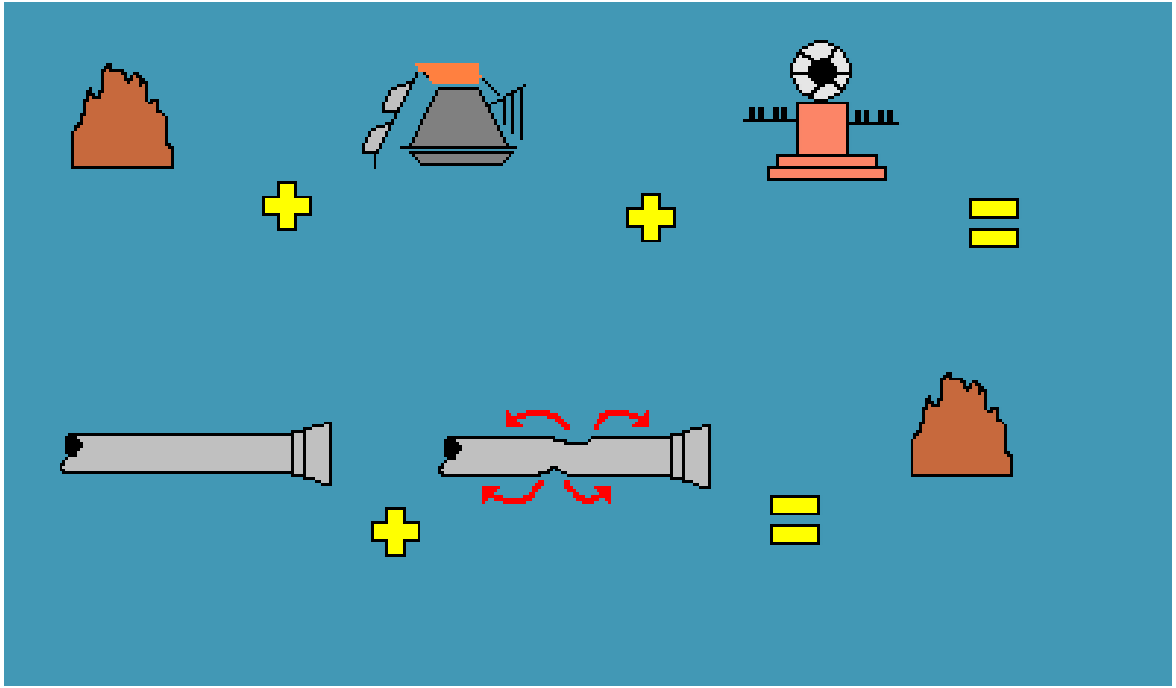
Corrosion is the deterioration of a substance or its properties as a result of an undesirable reaction with the environment.

- NACE International

It is irreversible and degenerative and related to the Second Law of Thermodynamics

$$\Delta S_{universe} \geq 0$$

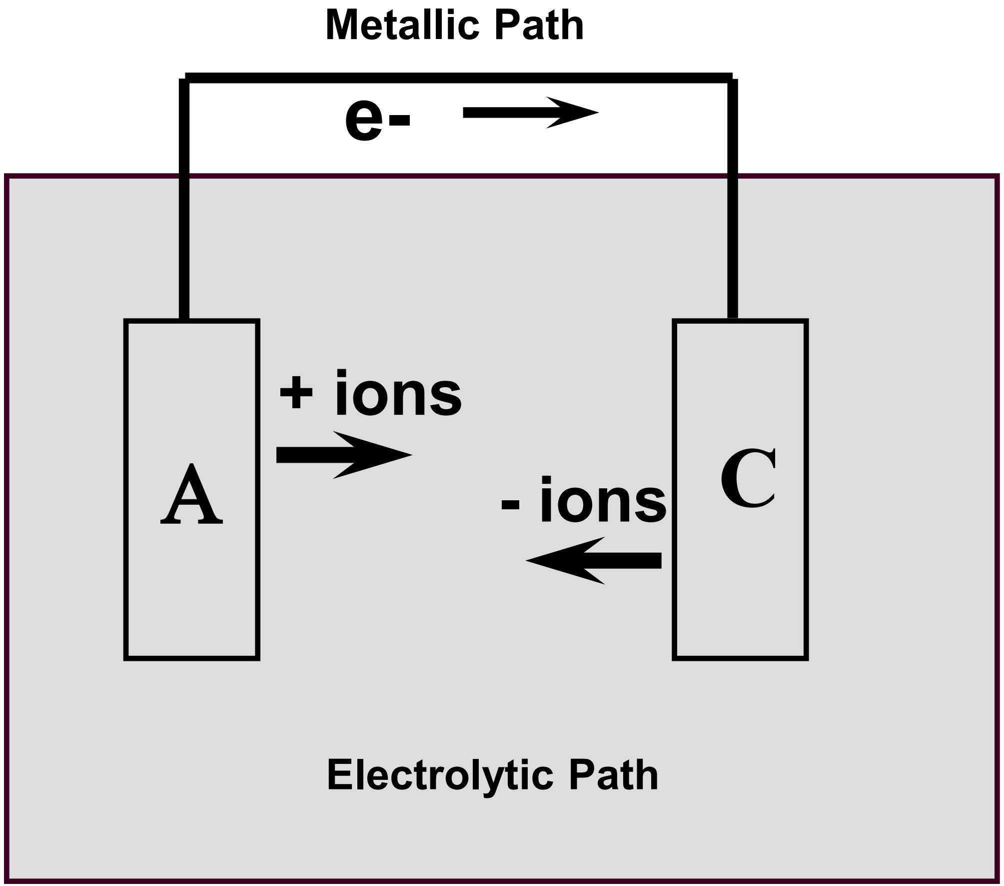
CORROSION IS INEVITABLE



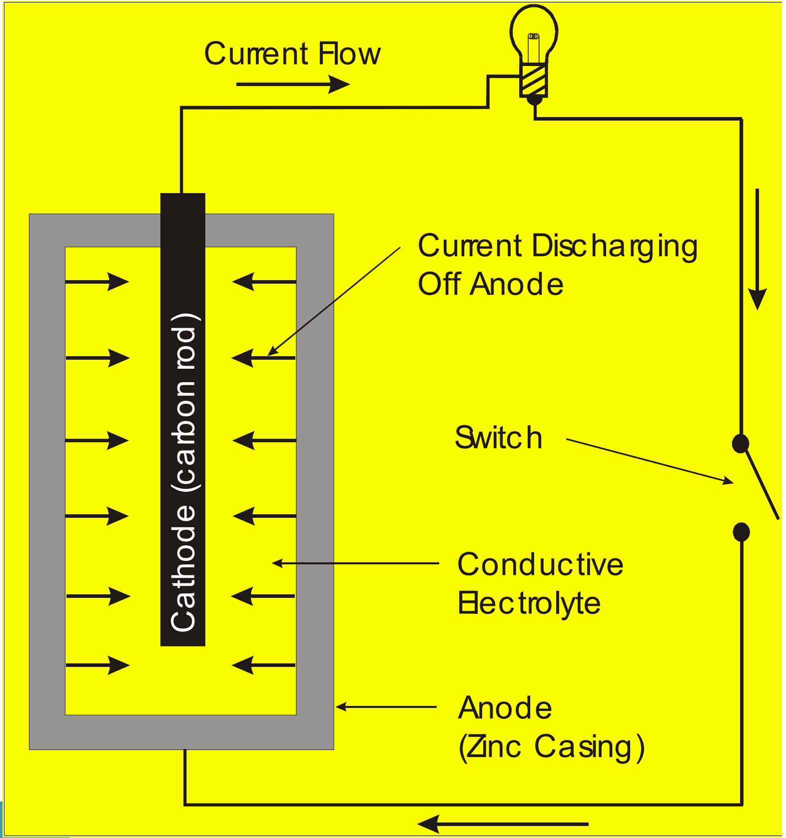
FORMS OF CORROSION

- ✓ Erosion
- ✓ Fretting
- ✓ Nuclear
- ✓ High Temperature
- ✓ Electrochemical
  - ➢ 97+% of corrosion is electrochemical

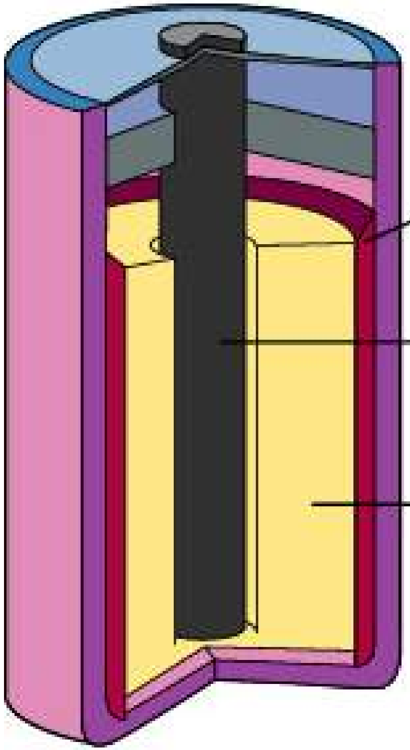
CORROSION CELL



Practical Use of Corrosion



GRAPHITE-ZINC BATTERY

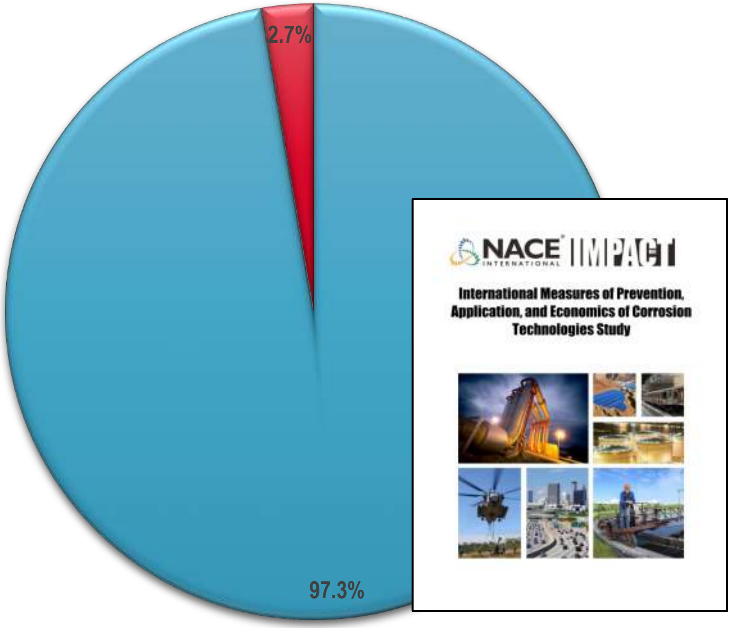


WHY DO WE CARE ABOUT CORROSION?

Direct Corrosion Costs $451 billion (2.7% U.S. GDP [2013])

- Few care about corrosion and mitigation (rectifiers, anodes, test stations, resistivity, chlorides, sulfates, etc.), but....
- Everybody cares about $$$

  - Direct Cost 2.7% of U.S GDP
  - Impact of corrosion on the U.S. economy: ~$1,400 / yr per each person in the U.S.
  - $451 billion does not include indirect costs



2013 U.S. GDP ($16.7 trillion)

Pub. No. OAPUS310GKOCH (2016)
more info: impact.nace.org

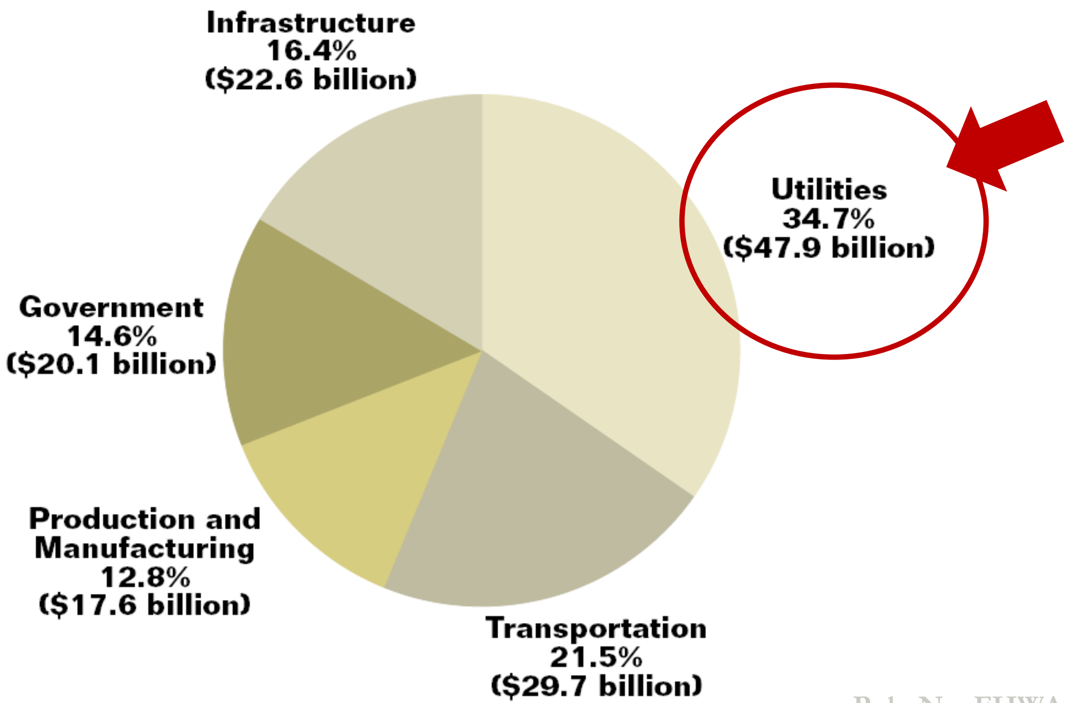
WHO CARES ABOUT CORROSION?

- Airspace
- Electrical Power Plants
- Chemical Process and Manufacturing Plants
- Transportation Agencies
- Water/wastewater Agencies
- Developers
- Etc.,

- Costly
- Risk to Human Life and Safety

COST

COST OF CORROSION IN INDUSTRY CATEGORIES ($137.9 BILLION)



Pub. No. FHWA-RD-01-156 (2002)
NACE Summary: www.nace.org

Percentage and dollar contribution to the total cost of corrosion for the five sector categories analyzed.

WALKING THROUGH THE MINEFIELD OF CORROSION

CORROSION IMPACT ON WATER SYSTEMS

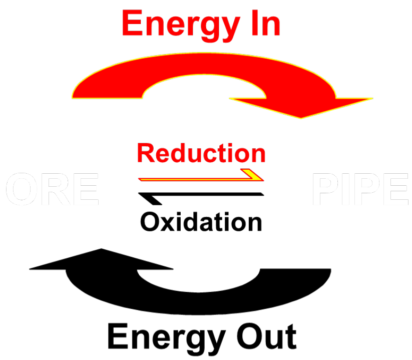
- Water loss
- Water quality concerns
- Water supply disruptions / unhappy customers
- Impediments to emergency response
- Damage to other structures
- Disruption to transportation and commerce

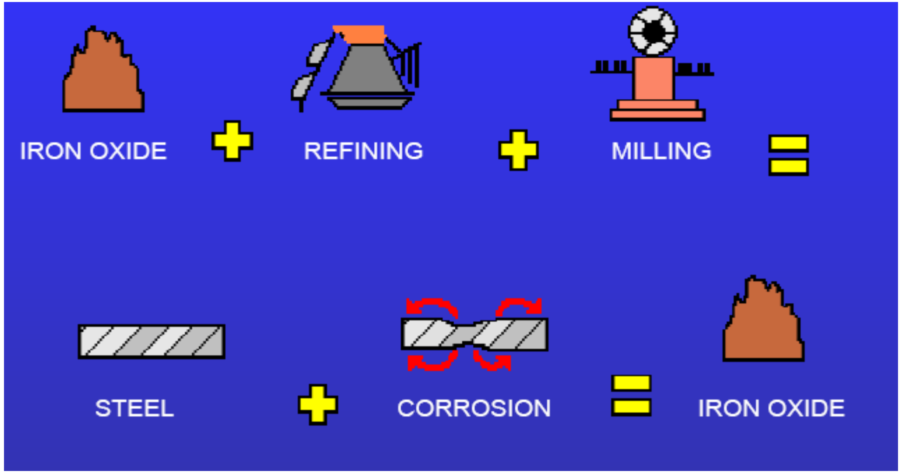
- ~ 170,000 public drinking water systems in US
- ~ 240,000 water main breaks/year most of which caused by corrosion
- Per AWWA 1.6 million km of pipes are to be replaced at $2.1 trillion (if all are replaced at once)

WHAT IS CORROSION?

(FOCUS ON METALLIC MATERIALS)

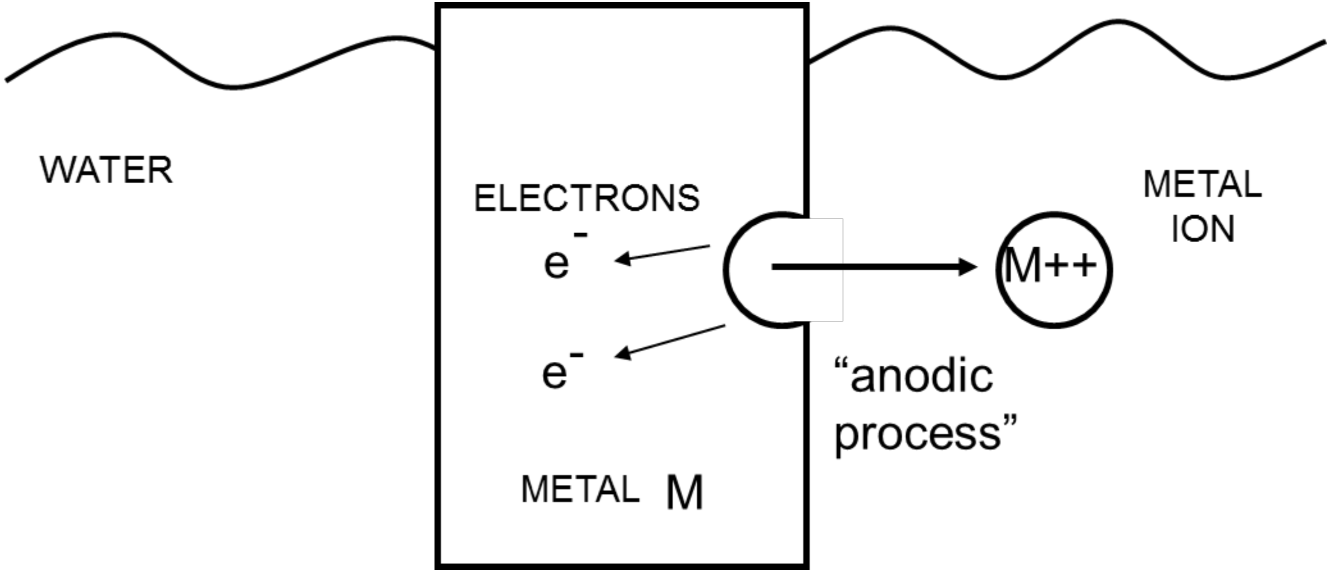
- "Attack (chemical) of a material by reaction with the environment with deterioration of properties".
- Different from mechanical/physical attack (e.g. erosion, abrasion, fatigue), or resulting from internal transformations (e.g. phase changes).
- A natural process !





CORROSION IS AN ELECTROCHEMICAL PROCESS

Most metals tend to spontaneously dissolve in water

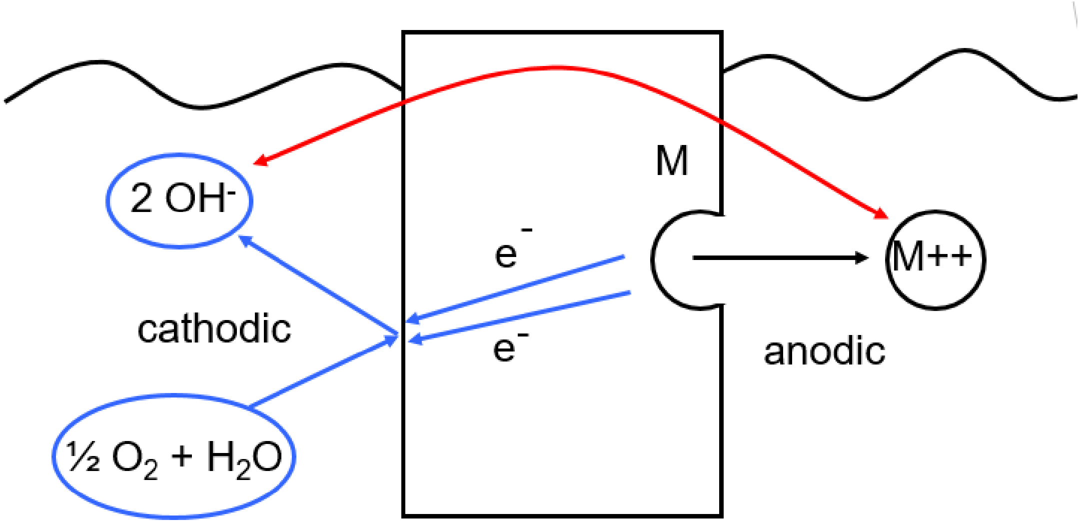


But process stops if electrons keep on building up

Source: A.A.SAGUES 2004

CORROSION IS AN ELECTROCHEMICAL PROCESS

Cathodic reaction removes electrons and lets anodic reaction continue



Metal ion combines later with hydroxide ions to form an ore-like compound:

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

- **"Return to nature" eventually is complete**

Source: A.A.SAGUES 2004

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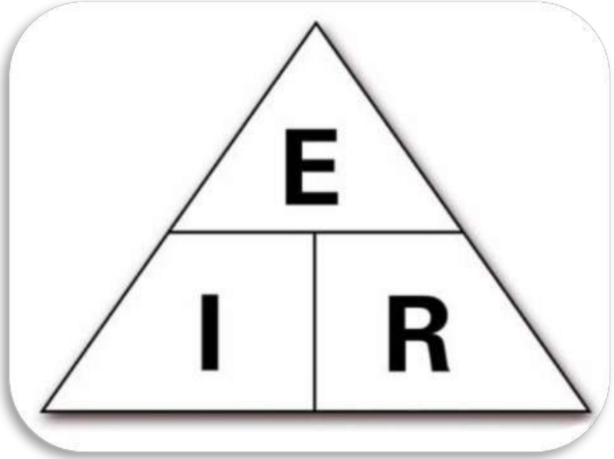
CORROSION IS AN ELECTROCHEMICAL PROCESS

Ohm's Law:

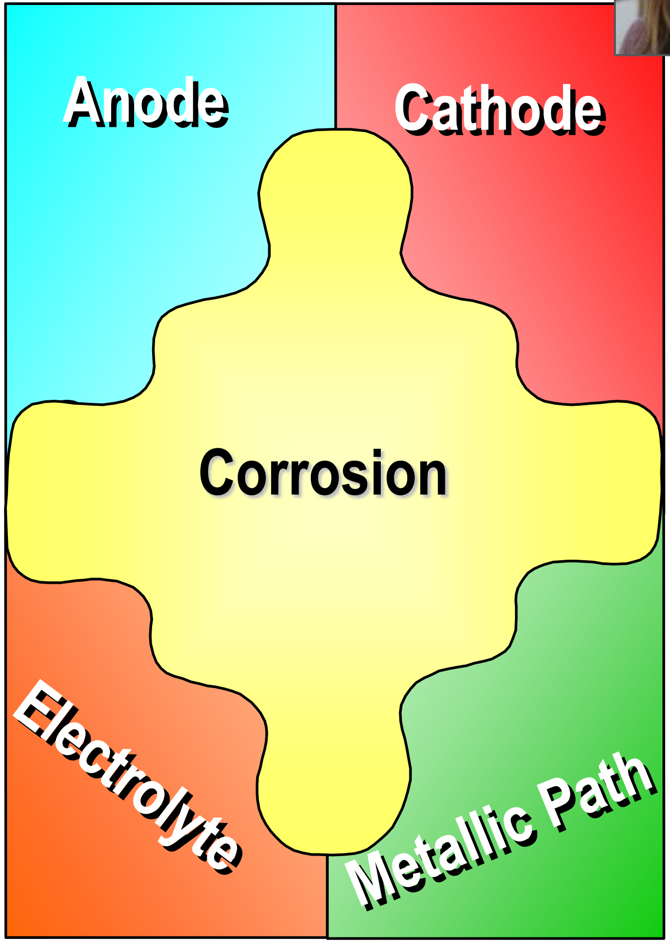
$$E = IR$$



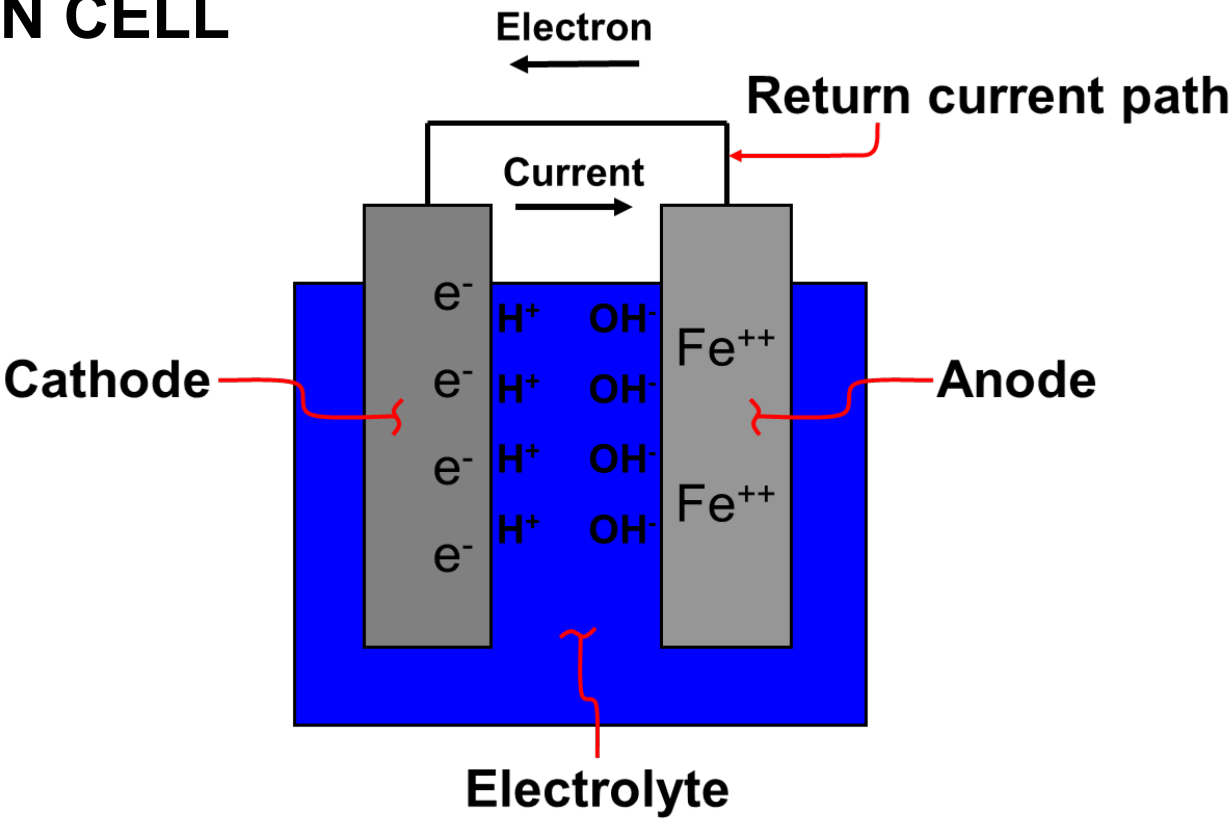
FOUR COMPONENTS NEEDED FOR CORROSION TO PROCEED

- Anodic reaction
- Cathodic reaction
- Ionic path (Electrolyte)
- Electronic path

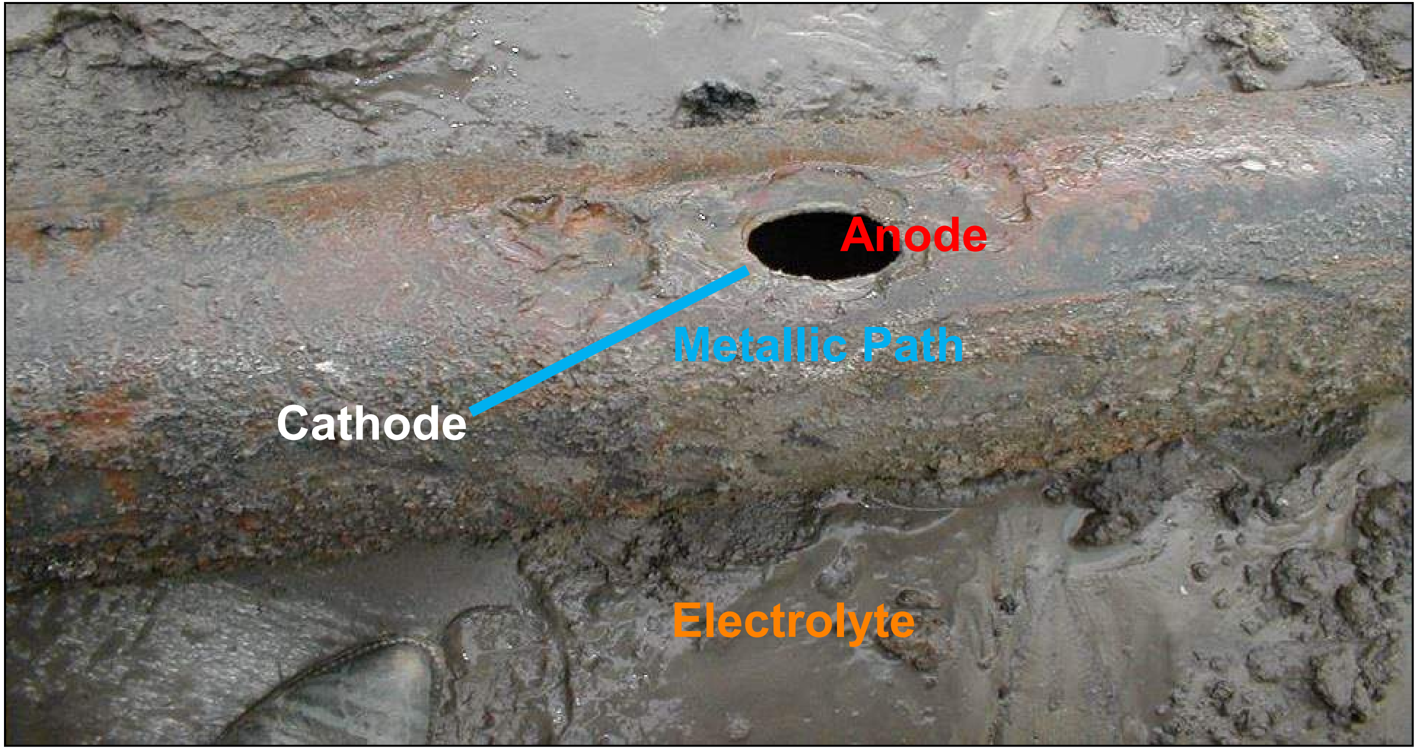
Corrosion can be stopped by controlling one or more of these components



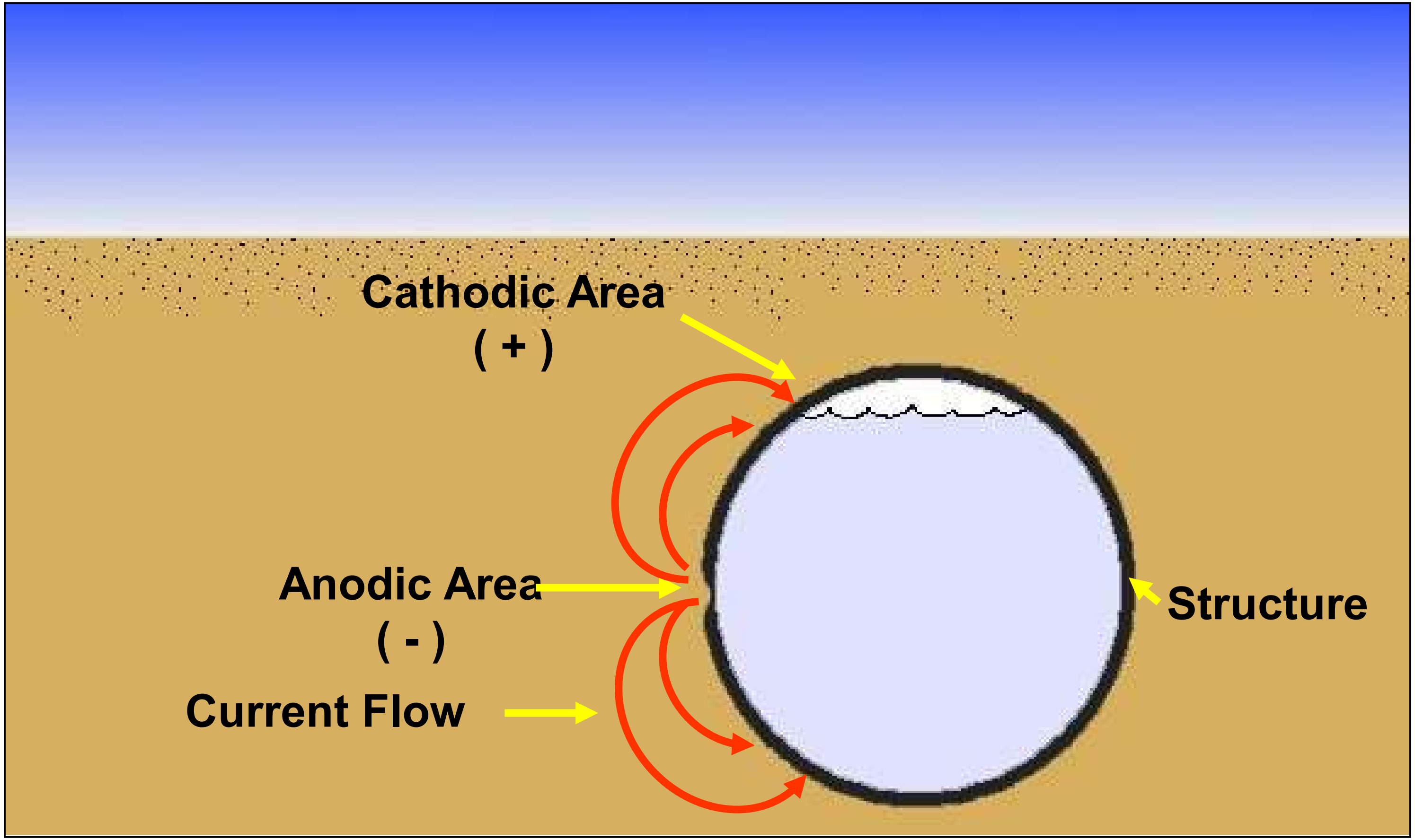
CORROSION CELL



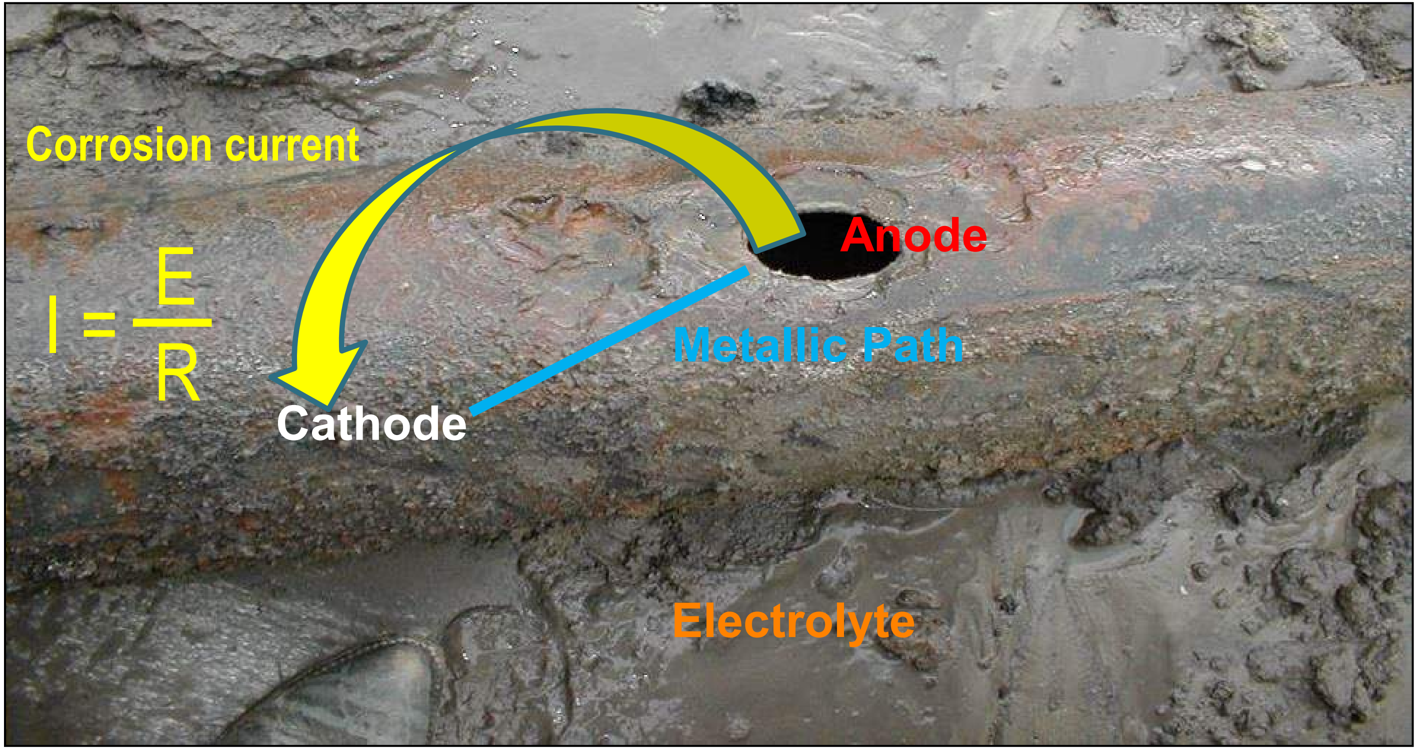
FOUR COMPONENTS OF CORROSION EXAMPLE



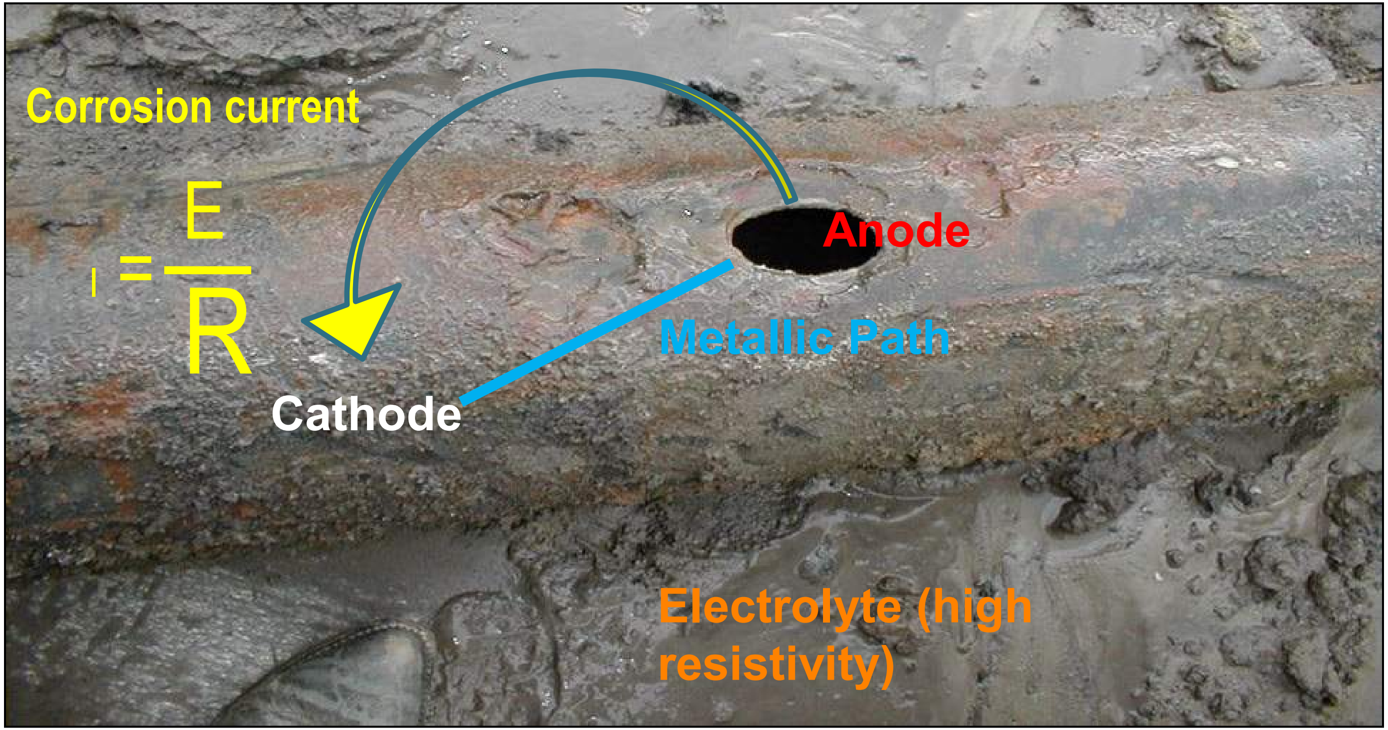
TYPICAL STEEL PIPELINE



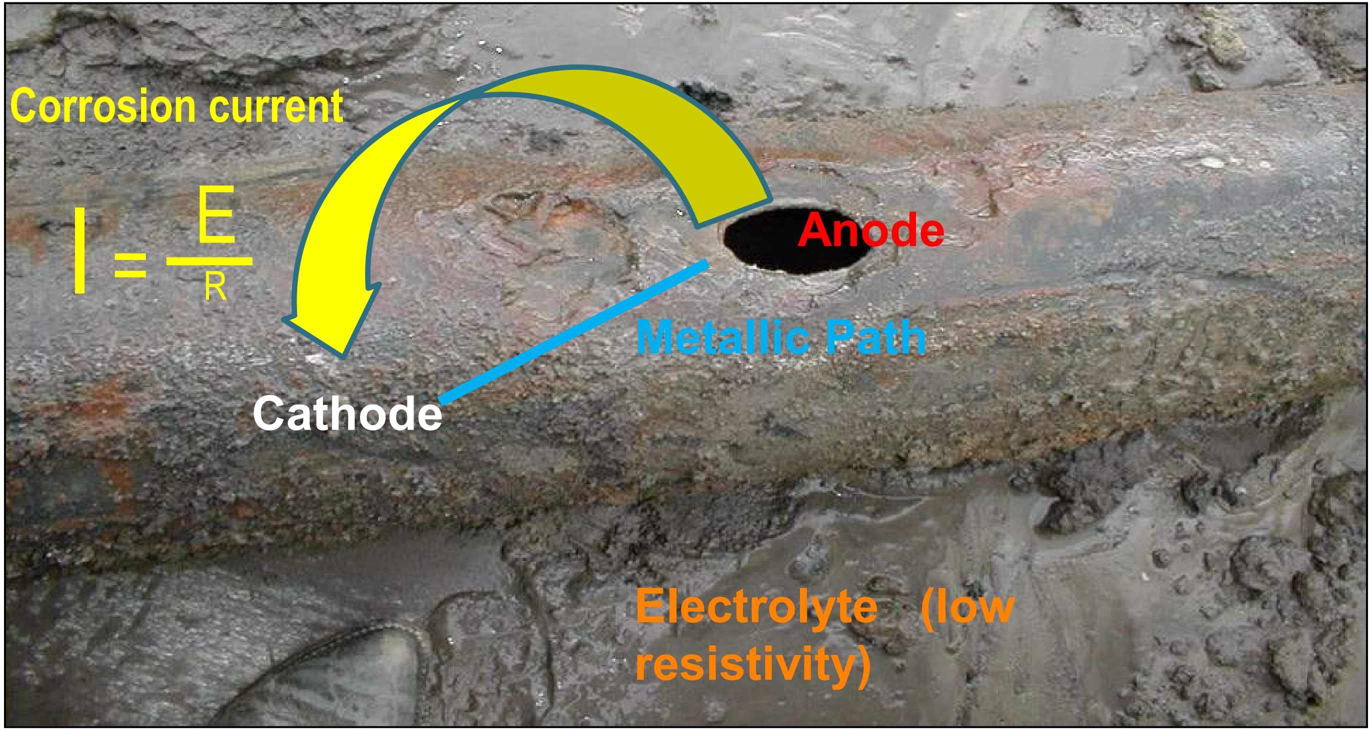
FOUR COMPONENTS OF CORROSION EXAMPLE



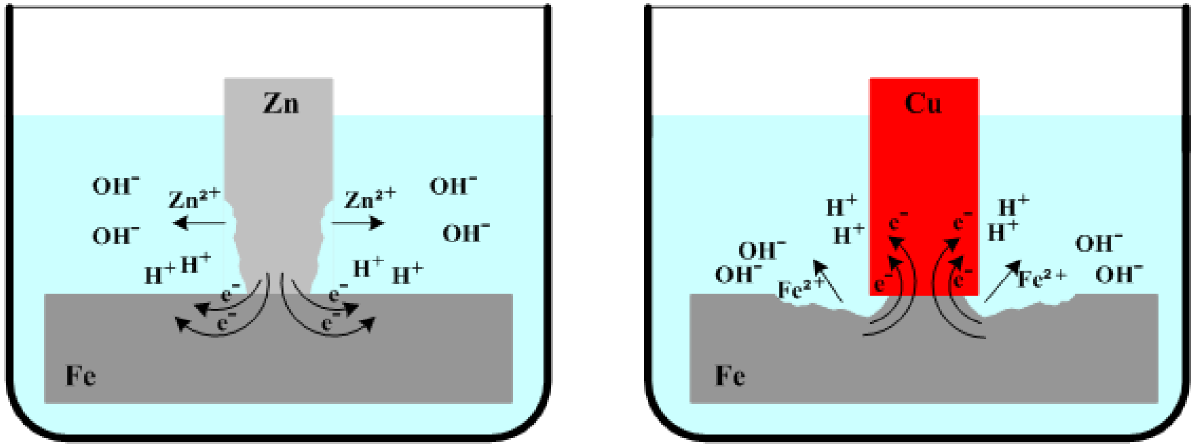
FOUR COMPONENTS OF CORROSION EXAMPLE



FOUR COMPONENTS OF CORROSION EXAMPLE

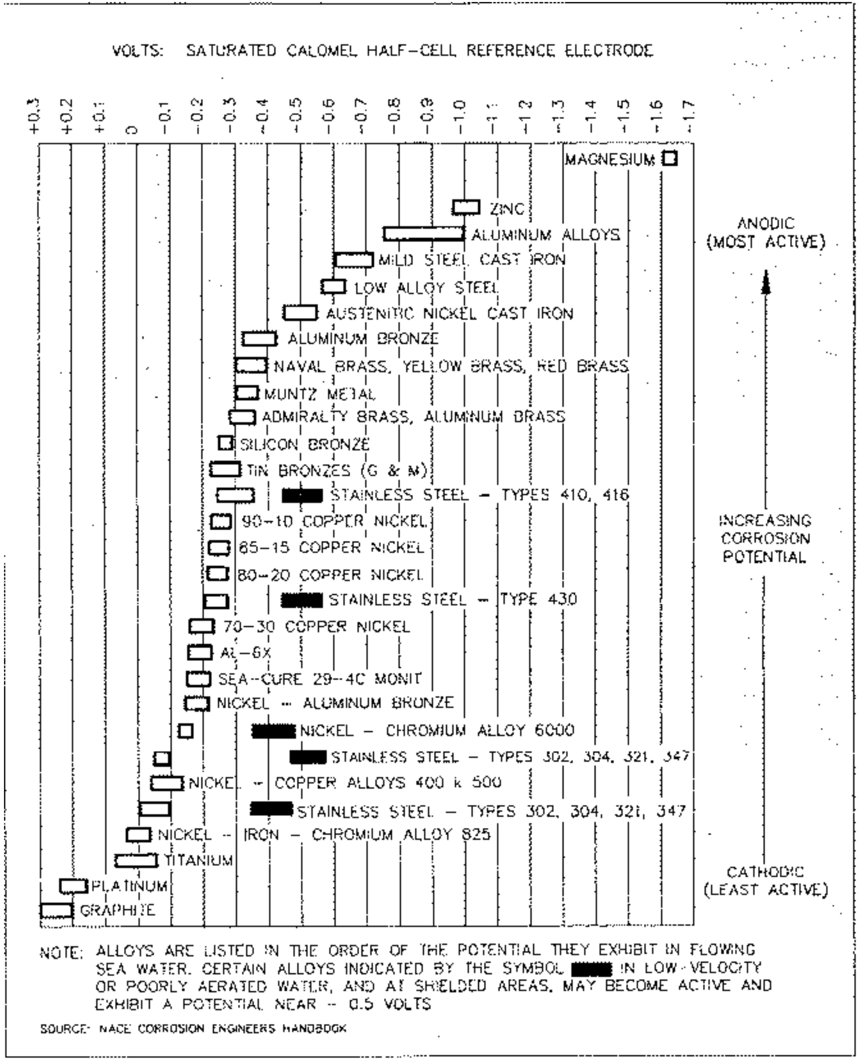


BIMETALLIC CORROSION



GALVANIC SERIES

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



THE TENDENCY TO CORRODE

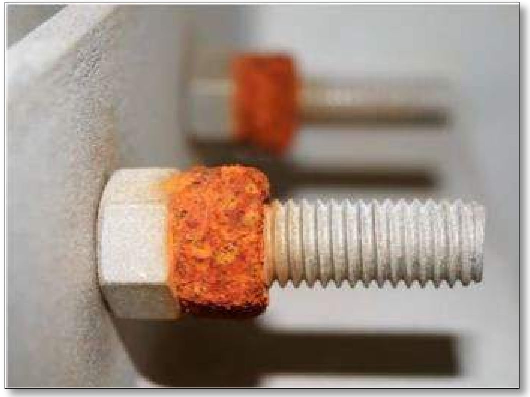
Directly Related to the Potential of the Material in the Environment

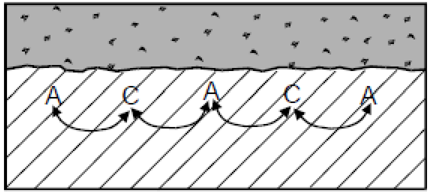
Metal	Potential (v) vs. CSE
Mg	-1.75
Zn	-1.1
Clean Mild Steel	**-0.5 to -0.8**
Rusty Mild Steel	-0.2 to -0.5
Cast or Ductile Iron	-0.5
Mild Steel in Concrete	**-0.2**
Copper	-0.2
Stainless Steel	-0.2
Graphite	+0.3

Table is for near neutral pH environment

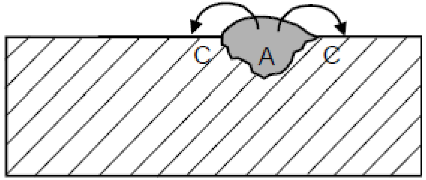
CAN YOU FIND THE ANODE?

TYPICAL FORMS OF CORROSION IN WATER SYSTEMS

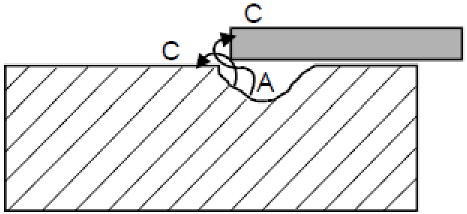




Uniform Corrosion – anodes and cathodes change locations resulting in general metal loss (e.g., atmospheric corrosion).



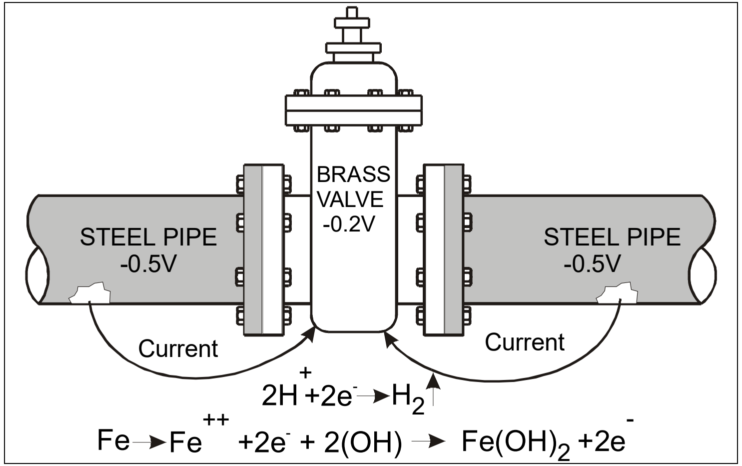
Pitting Corrosion – the anode site remains fixed and corrosion is localized (e.g., stainless steels in the presence of chlorides).



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).

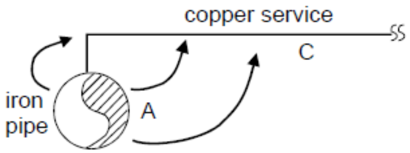
TYPICAL FORMS OF CORROSION

Dissimilar Metal Corrosion



Anodic	Metal	Volts[a]
↑	Commercially pure magnesium	-1.75
	Magnesium alloy (6% Al, 3% Zn, 0. 15% Mn)	-1.55
	Zinc	-1.15
	Aluminum alloy (5% zinc)	-1.05
	Mild steel (clean and shiny)	-0.5 to -0.7
	Mild steel (rusted)	-0.2 to -0.5
	Cast iron (not graphitized)	-0.5
	Dielectrically coated steel	-0.5
	Lead	-0.5
	Stainless steel, AISI 316	-0.25
	Mild steel in concrete	-0.2
	Copper, brass, bronze	-0.2
	Cast iron - high silicon	-0.2
↓	Mill scale on steel	-0.2
Cathodic	Stainless steel, AISI 304	-0.15

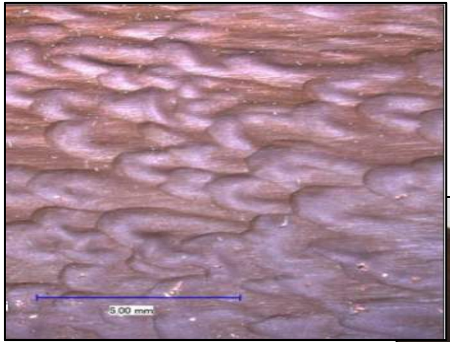
Note: (a) With respect to a copper-copper sulfate reference cell.

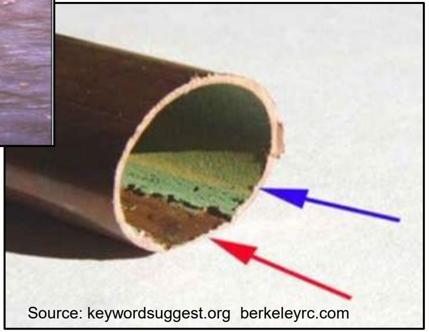


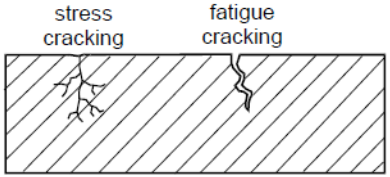
Galvanic Corrosion – dissimilar metals are interconnected and exposed to a common environment (e.g., cast iron water main with copper services).

(LESS) TYPICAL FORMS OF CORROSION

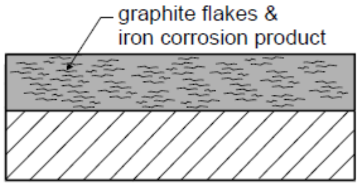

Source: integratedglobal.com



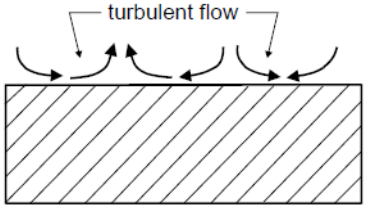

Source: keywordsuggest.org berkeleyrc.com



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).

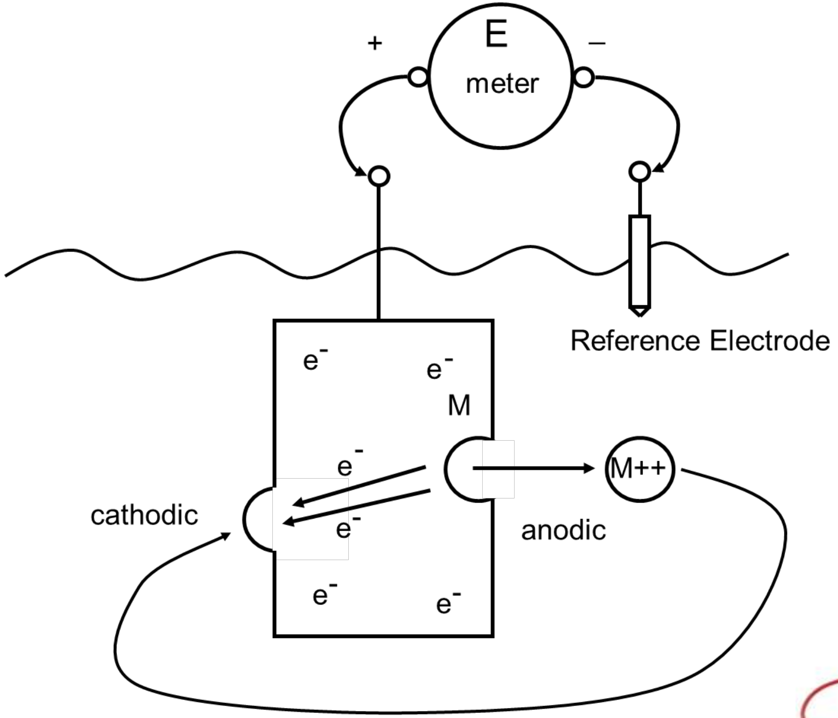


Dealloying and Dezincification – one of the alloying elements is more active than another resulting in the selective corrosion (sometimes called leaching) of the more active element (e.g., graphitic corrosion of gray cast iron).



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).

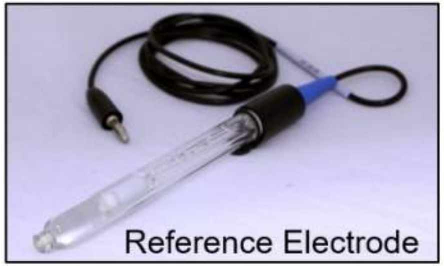
HOW TO MEASURE CORROSION?



A metal in equilibrium with its own ions develops a difference of potential “E” against the surrounding water.

“E” can be measured using a reference electrode and voltmeter.

Voltmeter



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Source: A.A.SAGUES 2004

HOW TO MEASURE CORROSION?

Potentials	Corrosion Probability
0.0 mV to - 200 mV	90% Probability of No Corrosion
-200 mV to -350 mV	Probability of Corrosion is Uncertain
More electronegative than -350 mV	90% Probability of Corrosion Occurring

ASTM C876 Potentials versus Corrosion Probability

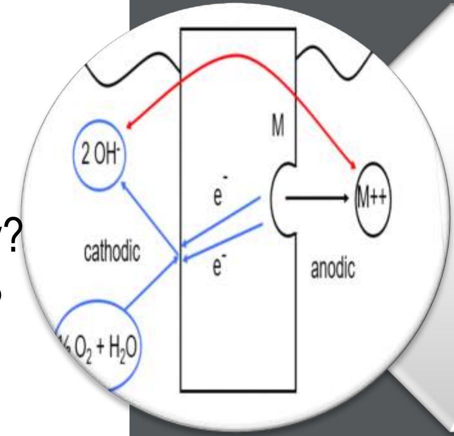
SECTION HIGHLIGHTS

Corrosion Fundamentals

- Corrosion is a natural process by which metals “return to nature.” It manifests itself in different forms (uniform, pitting, etc.)
- Four components are needed for corrosion to take place: anodic reaction, cathode reaction, electron path, and electrolyte
- Different metals develop different electrical potentials in electrolyte that can be measured by a voltmeter and a reference electrode.

TOPICS

- What are the driving forces of corrosion?
- What are the effects of environments on common pipe materials?
- How to measure soil/water corrosivity?
- How to detect stray current and MIC?



Driving Forces of Corrosion

9:15 - 10:30 am

TYPICAL CAUSES OF CORROSION IN WATER SYSTEMS

- Corrosion cells
- Aggressive Environments
- System Assembly
- Bacteria
- Stray Current

TYPICAL CAUSES OF CORROSION IN WATER SYSTEMS

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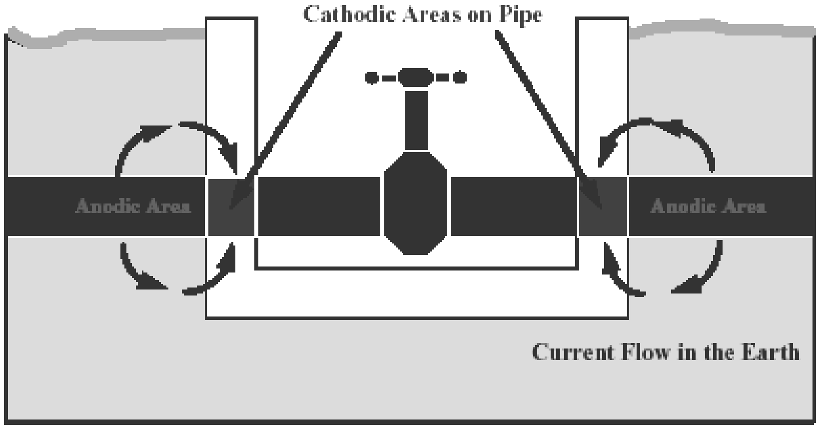
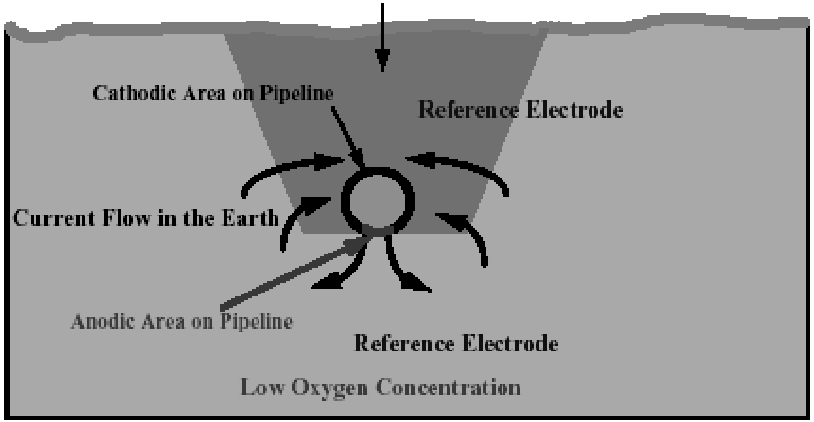
CORROSION CELLS
PH DIFFERENTIAL

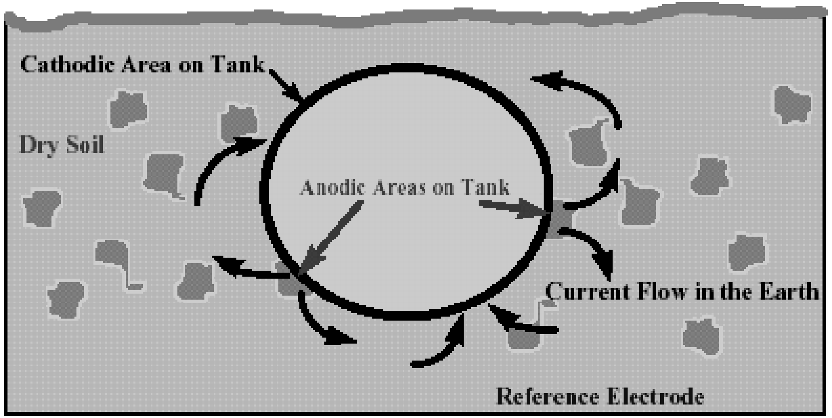


CORROSION CELLS
DIFFERENTIAL AERATION



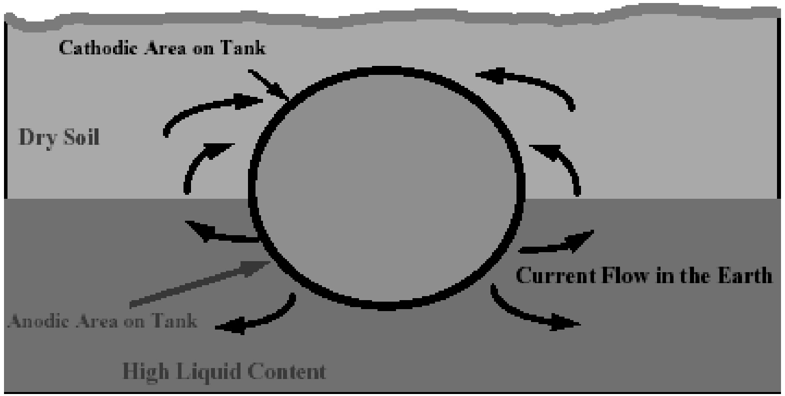
- Different oxygen concentration

CORROSION CELLS
NON-HOMOGENEOUS SOILS



- Dissimilar soil
- Mix of corrosive and non-corrosive

CORROSION CELLS
GROUNDWATER TABLE



- Anodic area in high liquid content

TYPICAL CAUSES OF CORROSION IN WATER SYSTEMS

- Corrosion cells
- Aggressive Environments
- System Assembly
- Bacteria
- Stray Current

AGGRESSIVE ENVIRONMENTS

Corrosive Soils:

- High concentration of aggressive ions
- High groundwater
- Low electrical resistivity
- Expansive soils
- Low pH, acidic soils

We will discuss this in more detail later!

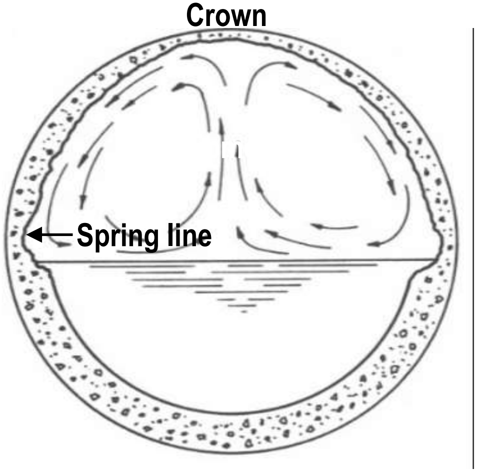
AGGRESSIVE ENVIRONMENT WATER VS. WASTEWATER

External Corrosion

- Virtually identical

Internal Corrosion

- Not the same at all
- Corrosion rates for wastewater can be extremely high
- This is one reason why external corrosion is often ignored



AGGRESSIVE ENVIRONMENT WASTEWATER

- Hydrogen sulfide
- Particularly in enclosed headspace

AGGRESSIVE ENVIRONMENTS

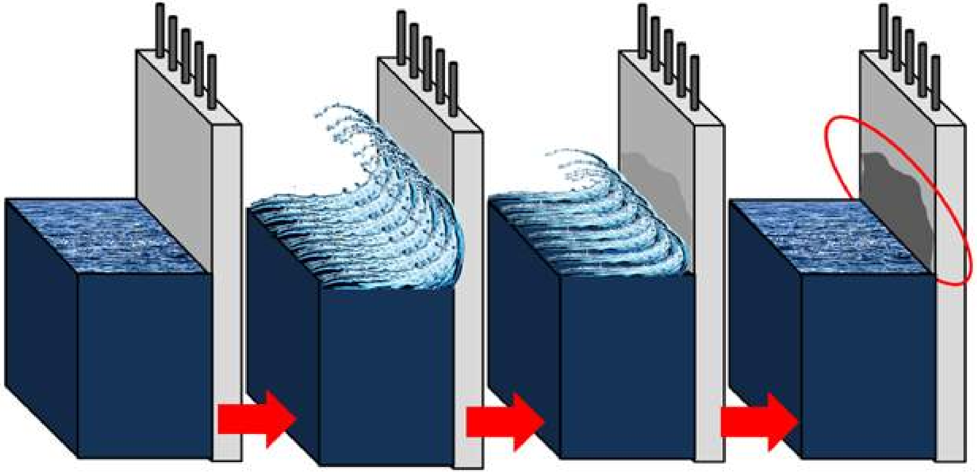
Corrosive Waters:

- High concentration of aggressive ions and low pH
- Splash zones
- Soft waters

AGGRESSIVE ENVIRONMENTS

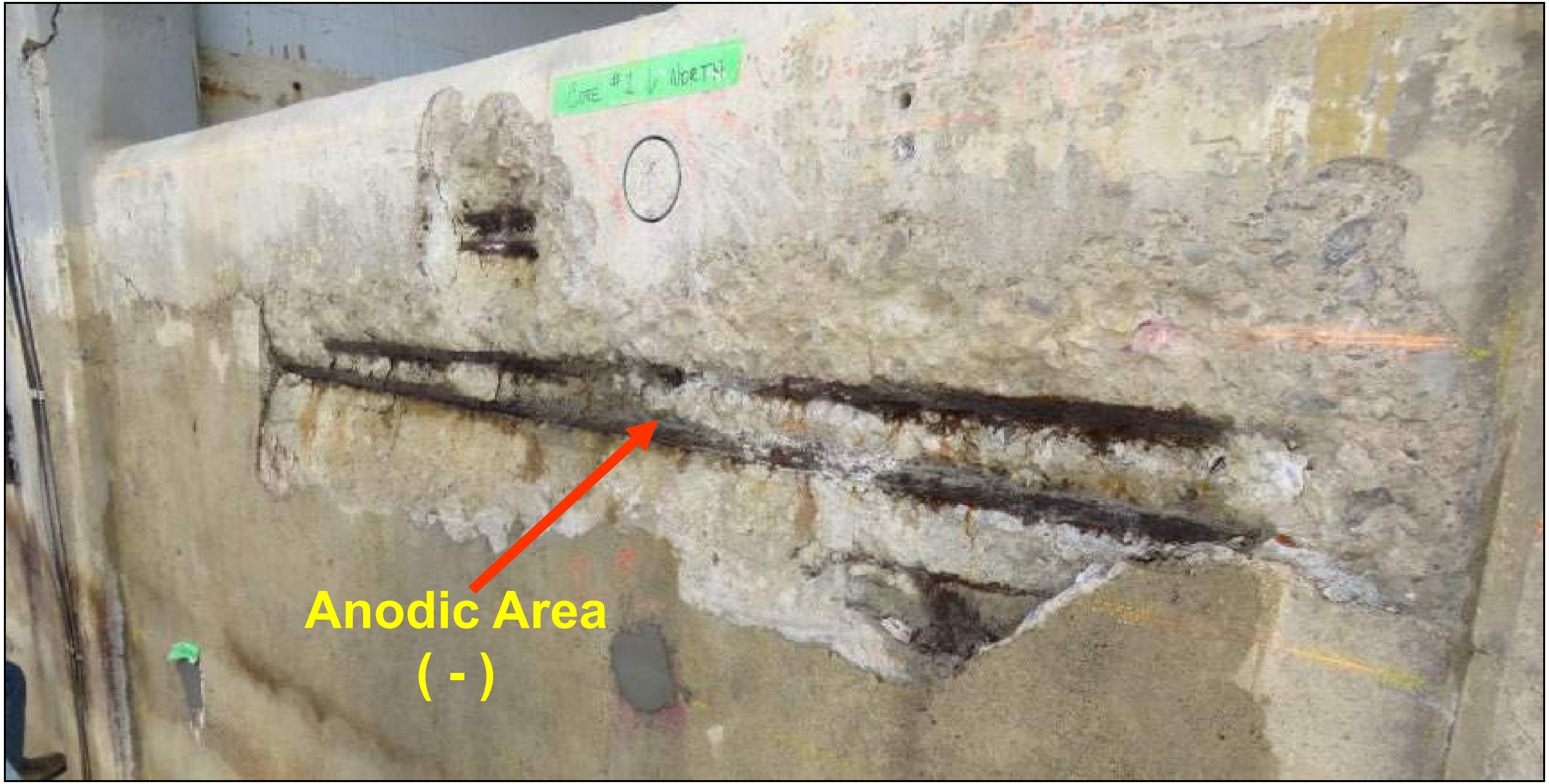
Corrosive Waters:

- Splash zones, and Cyclic wetting and drying
- Sources:
    - Intermittent rain events
    - Fluctuating groundwater
    - Tidal influence



We will discuss this in more detail later!

AGGRESSIVE ENVIRONMENTS
REINFORCED CONCRETE



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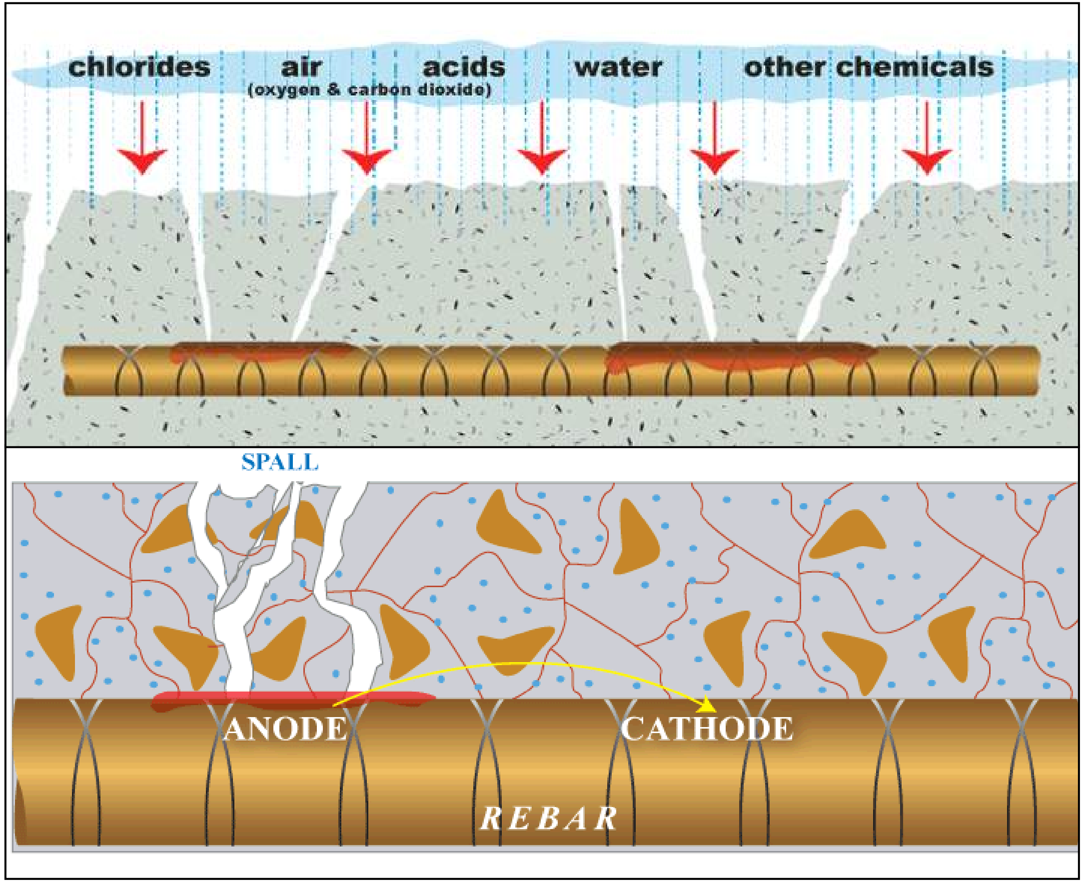
AGGRESSIVE ENVIRONMENTS
REINFORCED CONCRETE



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AGGRESSIVE ENVIRONMENTS IRON PIPE

- Gray-Iron and Ductile-Iron Pipe
- AWWA Manual 41, Ductile-Iron Pipe and Fittings

Table 3-1 Soil-test evaluation for ductile-iron pipe (10-point system)

Soil Characteristics Based on Samples Taken Down to Pipe Depth	Points*	Soil Characteristics Based on Samples Taken Down to Pipe Depth	Points*
Resistivity—ohm-*cm*†		Redox potential	
<1,500	10	> +100 mV	0
≥1,500–1,800	8	+50 to +100 mV	3.5
>1,800–2,100	5	0 to +50 mV	4
>2,100–2,500	2	Negative	5
>2,500–3,000	1	Sulfides	
>3,000	0	Positive	3.5
pH		Trace	2
0–2	5	Negative	0
2–4	3	Moisture	
4–6.5	0	Poor drainage, continuously wet	2
6.5–7.5	0‡	Fair drainage, generally moist	1
7.5–8.5	0	Good drainage, generally dry	0
>8.5	3		

Source: Based on Appendix A in AWWA/ANSI C105.

Appendix A of ANSI/AWWA C105/A21.5, Standard for Polyethylene Encasement

AGGRESSIVE ENVIRONMENTS
STEEL PIPE

- Steel pipe (AWWA Manual M11, Steel Pipe—A Guide for Design and Installation)

Table 3-2 Soils grouped in order of corrosive action on steel

Soil Group	Aeration and Drainage	Characterization	Soil Types
I—Lightly Corrosive	Good	Uniform color and no mottling anywhere in soil profile; very low water table.	• Sands or sandy loams • Light, textured silt loams • Porous loams or clay loams thoroughly oxidized to great depths
II—Moderately Corrosive	Fair	Slight mottling (yellowish brown and yellowish gray) in lower part of profile (depth 18-24 in.); low water table. Soils would be considered well drained in an agricultural sense, as no artificial drainage is necessary for crop raising.	• Sandy loams • Silt loams • Clay loams
III—Severely Corrosive	Poor	Heavy texture and moderate mottling close to surface (depth 6-8 in.); water table 2-3 ft below surface. Soils usually occupy flat areas and would require artificial drainage for crop raising.	• Clay loams • Clays
IV—Unusually Corrosive	Very poor	Bluish-gray mottling at depths of 6-8 in.; water table at surface or extreme impermeability because of colloidal material contained.	• Muck • Peat • Tidal marsh • Clays and organic soils • Adobe clay

Table 3-3 Relationship of soil corrosion to soil resistivity

Soil group	Description	Resistivity, *ohm-cm*
I	Excellent	10,000-6,000
II	Good	6,000-4,500
III	Fair	4,500-2,000
IV	Bad	2,000-0

AGGRESSIVE ENVIRONMENTS CONCRETE COATED PIPE

- Concrete Pressure Pipe, Steel Cylinder Type, with Bar or Wire Wrap
  - Chlorides
  - Sulfate soils
  - Acidic soils

AGGRESSIVE ENVIRONMENTS
COPPER PIPE

- Copper Pipe
  - Poor aeration
  - Sulfate-reducing bacteria activity
  - Ammonium and nitrates (animal waste, fertilizer)

AGGRESSIVE ENVIRONMENTS
ASBESTOS-CEMENT PIPE

AWWA C400, Standard for Asbestos

- Asbestos–Cement Pipe
  - pH
  - Sulfate

AGGRESSIVE ENVIRONMENTS
ALUMINUM

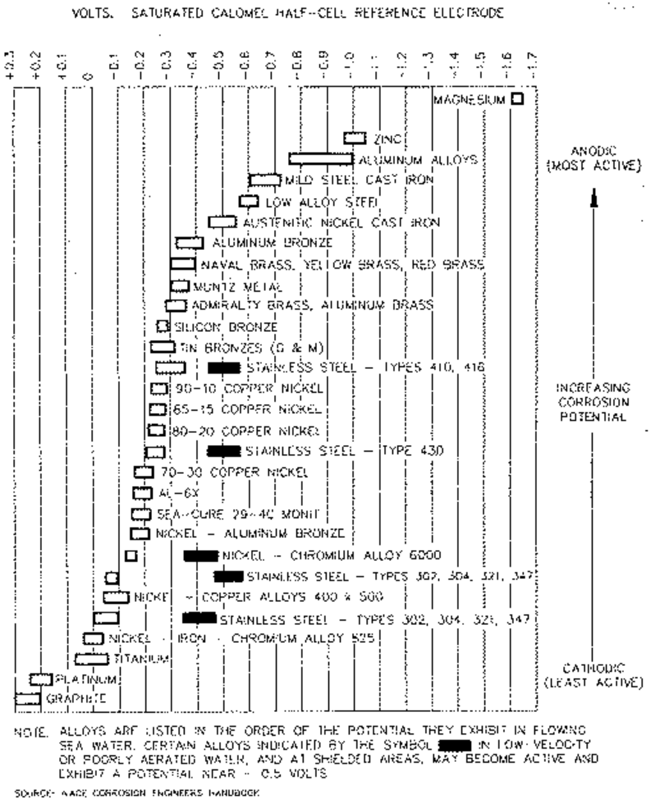
- Aluminum is an amphoteric material
- Concrete exposure is aggressive

TYPICAL CAUSES OF CORROSION IN WATER SYSTEMS

- Corrosion cells
- Aggressive Environments
- System Assembly
- Bacteria
- Stray Current

SYSTEM ASSEMBLY DISSIMILAR METALS (GALVANIC SERIES)

- Preferential corrosion of most active (anodic) metal in the galvanic series



SYSTEM ASSEMBLY THERMOGALVANIC

- Surface potential driven by temperature
- Electrically continuous piping with temperature differential
- Galvanic coupling

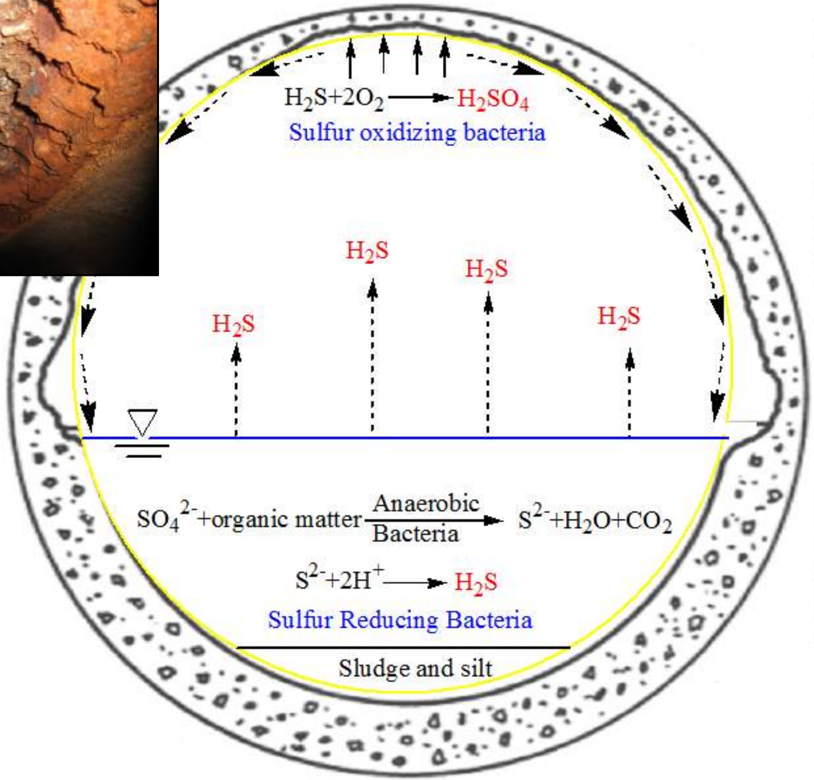
Hot water Cold water

TYPICAL CAUSES OF CORROSION IN WATER SYSTEMS

- Corrosion cells
- Aggressive Environments
- System Assembly
- Bacteria
- Stray Current

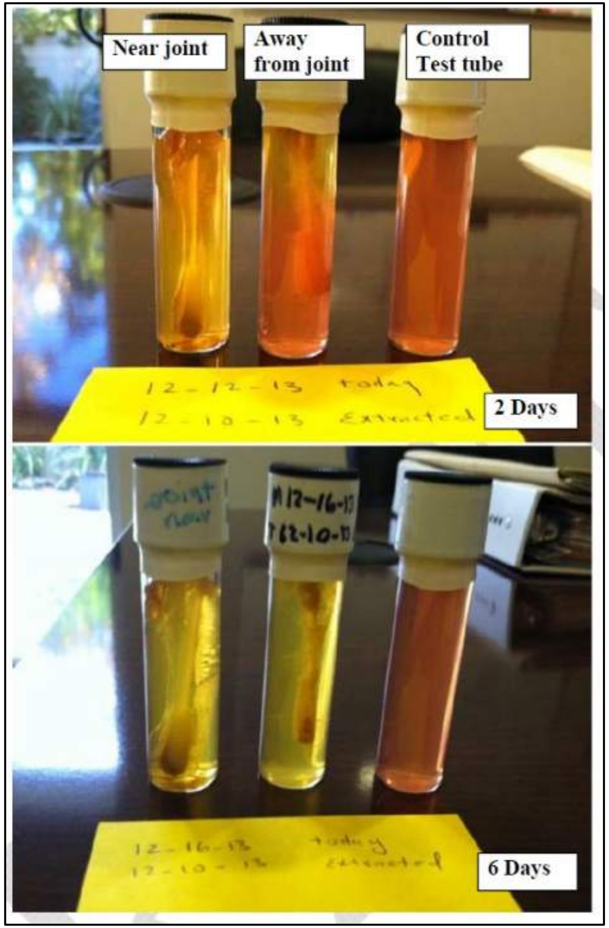
BACTERIA

Microbiological Induced Corrosion (MIC)



BACTERIA
HOW TO DETECT MIC?

BACTERIA
HOW TO DETECT MIC?



TYPICAL CAUSES OF CORROSION IN WATER SYSTEMS

- Corrosion cells
- Aggressive Environments
- System Assembly
- Bacteria
- Stray Current

STRAY CURRENT

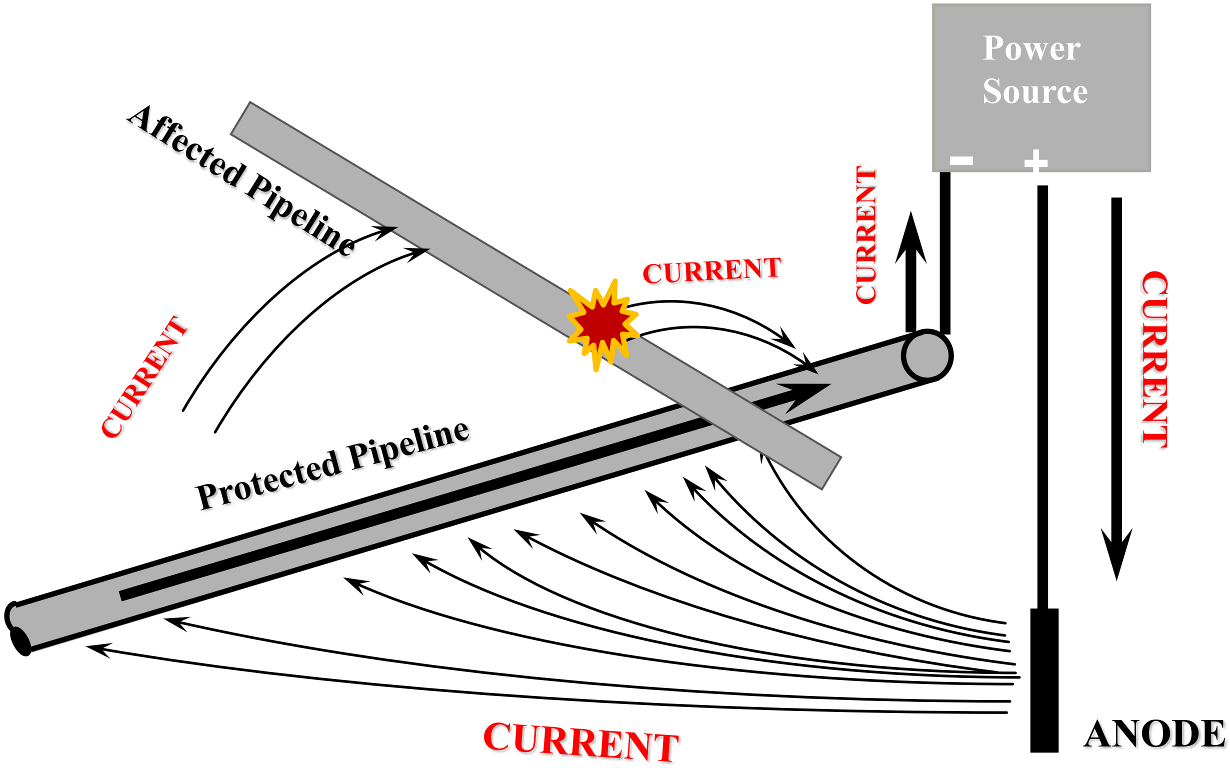
Stray Current - current in a structure that is not part of the intended circuit.

Corrosion occurs where the current **leaves** the structure

Sources:

- CP systems on other structures
- Electric-powered mass transit systems
- Arc welding, esp. where ground is distant from the welding electrodes
- Electric transmission lines
- High voltage DC transmission systems
- Telluric currents

DC STRAY CURRENT



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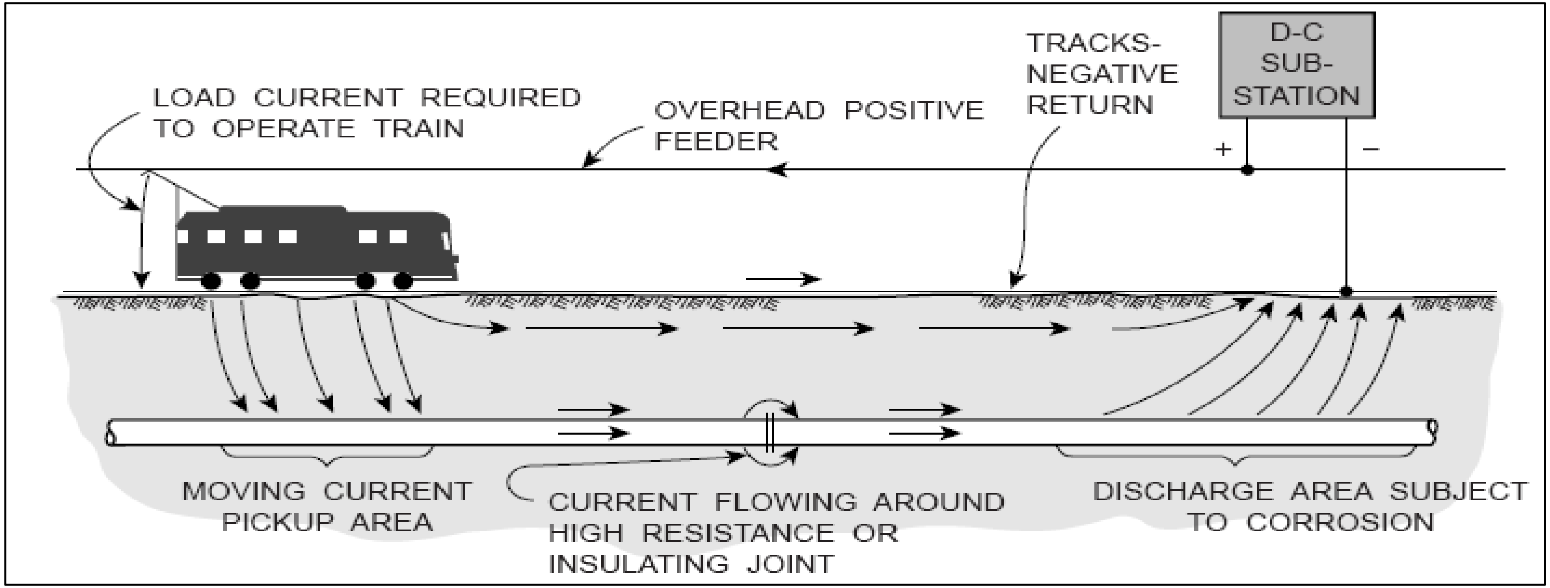
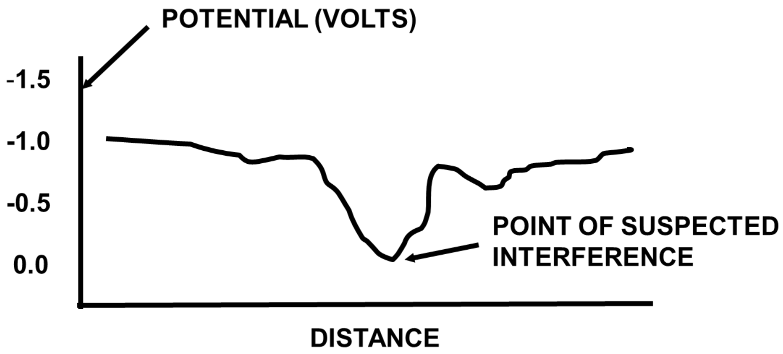
ELECTRIC-POWERED MASS TRANSIT SYSTEMS



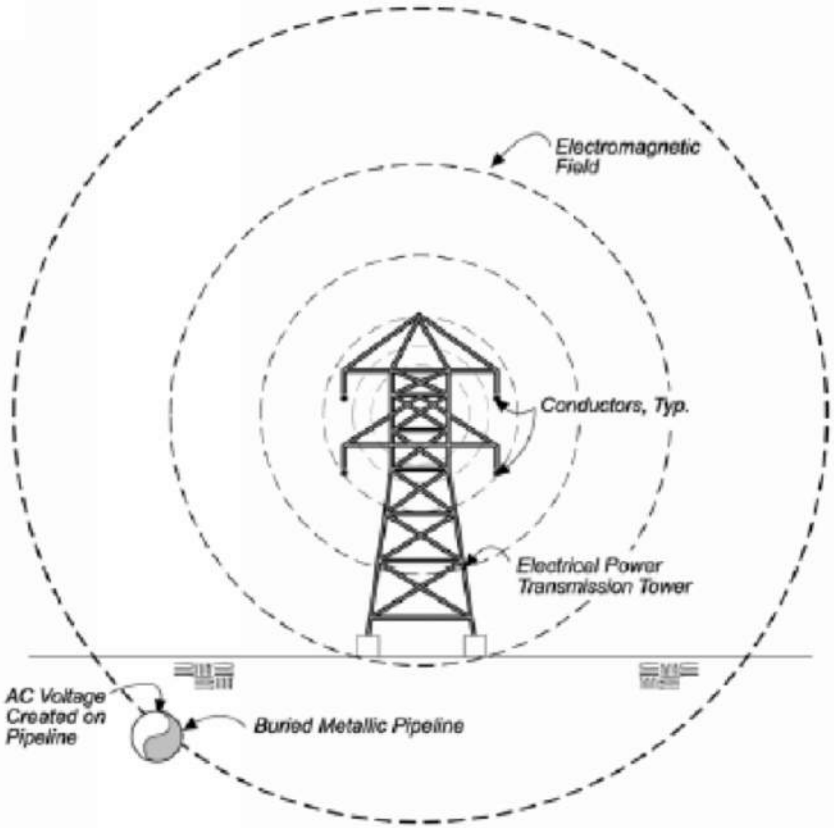
HOW TO DETECT STRAY CURRENT?

- Potential/current surveys
- SCM
- Line current test stations



AC STRAY CURRENT (AKA INDUCED AC OR AC INTERFERENCE)

- Dielectrically coated steel pipe
- Paralleling high voltage
- Corrosion and safety ($15V_{AC}$)



SECTION HIGHLIGHTS

Driving Forces of Corrosion

- Aggressive environment, improper design and system assembly, formation of corrosion cells, bacteria and stray current are known driving forces of corrosion.
- There are various field and laboratory methods to detect or/and measure sources of corrosion.

QUESTIONS?

- For additional information, please contact:

- Brien Clark, PE
- Brien.Clark@hdrinc.com

GOOD TIME TO TAKE A BREAK?

LEARNING TOPICS:

- What defines soil corrosivity?
- How to measure soil/water corrosivity?

SOIL CORROSIVITY

10:45 - 11:45 am

WHAT IS SOIL?

- Defined as the unconsolidated mineral material on the immediate surface of the earth that serves as a natural medium for the growth of land plants
- Caveats galore
  - Peaty “soils” almost no minerals – lots of plants
  - Nothing grows on salt flats

MORE ABOUT SOIL

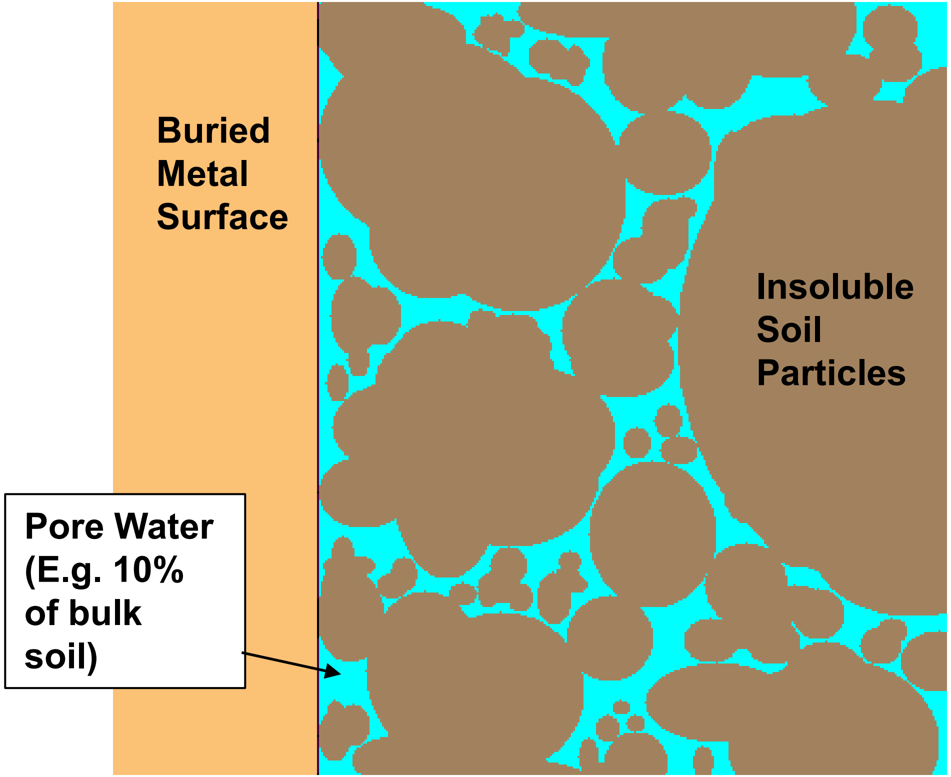
- May be shallow (a few cm) to deep (several meters)
- Develop from deposits of weathered & transported particles
  - Weathered rocks
  - Volcanic ash
  - Accumulated plant material
  - Accumulated salts
- Particles get deposited in "landforms"

SOIL IS HETEROGENEOUS!!!!

- Physical Properties
  - ✓ Particle Size
  - ✓ Compaction
  - ✓ Etc.
- Chemical Properties
  - ✓ Salt Content
  - ✓ Mineral grains that interact with ions (salt)
    - ✓ Quartz
    - ✓ "Silt"
    - ✓ Clay

SOIL PORE SPACE

- Corrosion occurring in 10% of bulk sample (moisture in pore space)
- Ions measured in terms of bulk sample but are concentrated in pore space
- Effective values underreported tenfold

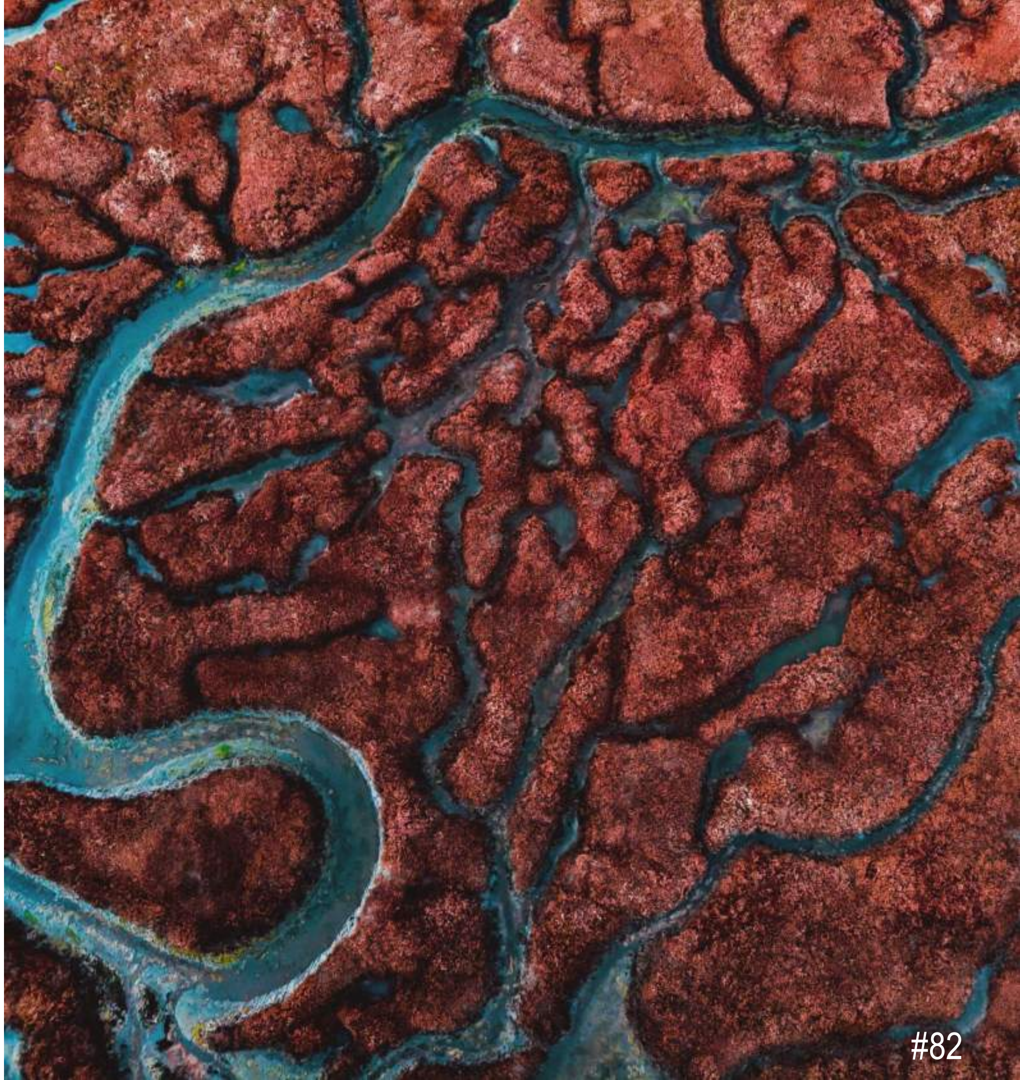


SOIL CORROSIVITY

- Is material dependent
  - ✓ Ferrous (pH and resistivity)
  - ✓ Copper (pH, nitrogen, sulfides, etc.)
  - ✓ Cementitious (pH, chlorides and sulfates)
- Testing is not standardized
  - ✓ One of the major issues with soil corrosivity testing

CORROSIVE SOILS

- Unequal moisture conditions along pipeline
- Acidic soils – natural & otherwise
- Mine tailings
- Organic matter
- Beach sand
- Road salts



FIELD AND LAB DATA ARE NEEDED TO DETERMINE CORROSIVITY – DO BOTH

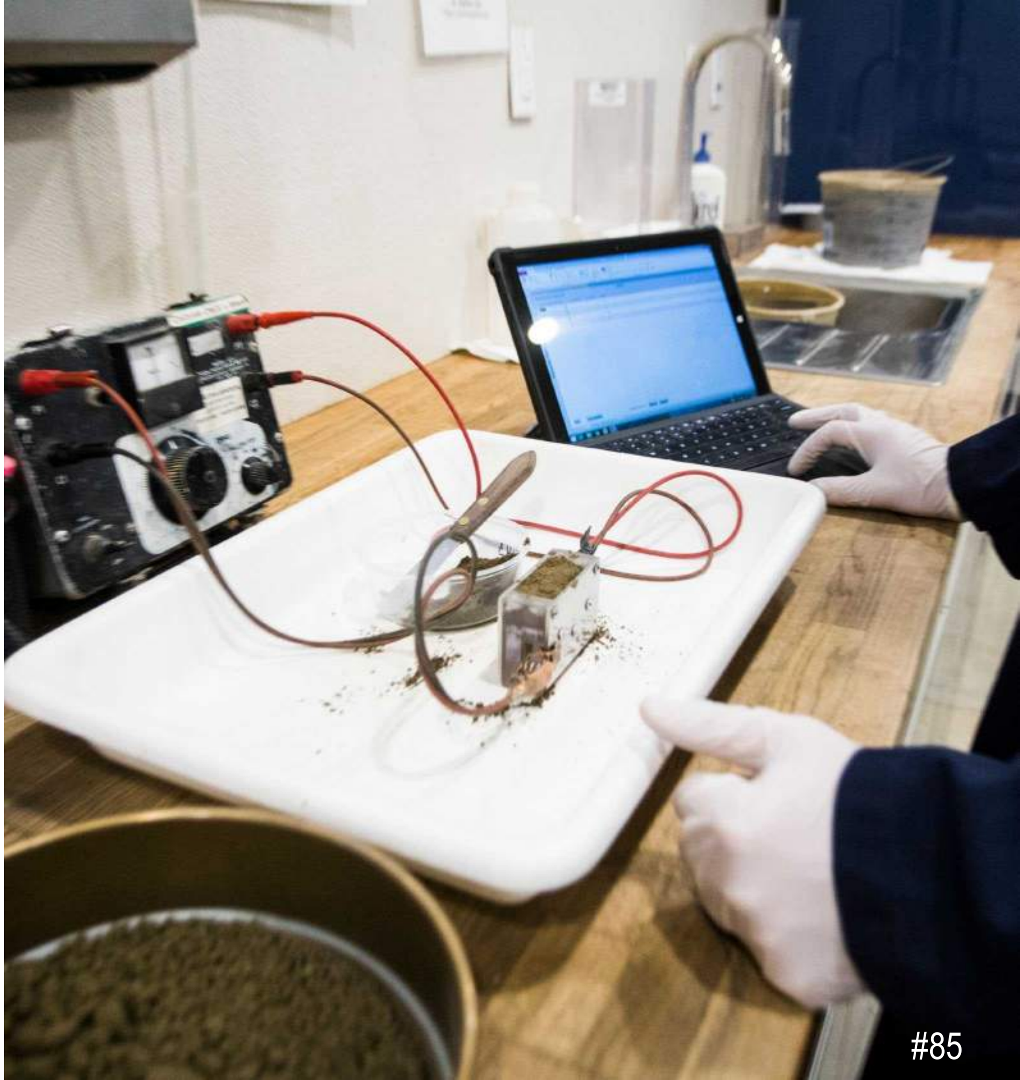
- Soil resistivity
- Chemical content
  - Relationships have been developed between the chemical content and resistivity.
  - Specific Anions (Cl^{1-} and SO_4^{2-}) require specific actions for each material considered.
- Soil pH
  - Total acidity gives more information on the resistance of the soil to changes in pH (buffering).

ELECTRICAL RESISTIVITY

- Traditional Indicator of Corrosivity
- Determining Factors
  - ✓ Soluble Salt Content
  - ✓ Solubilities
  - ✓ Moisture Content

RESISTIVITY RANGE

- >10,000 ohm-cm Mildly Corrosive
- 10,000 to 2,000 Moderately Corrosive
- 2,000 to 1,000 Corrosive
- <1,000 Severely Corrosive



pH

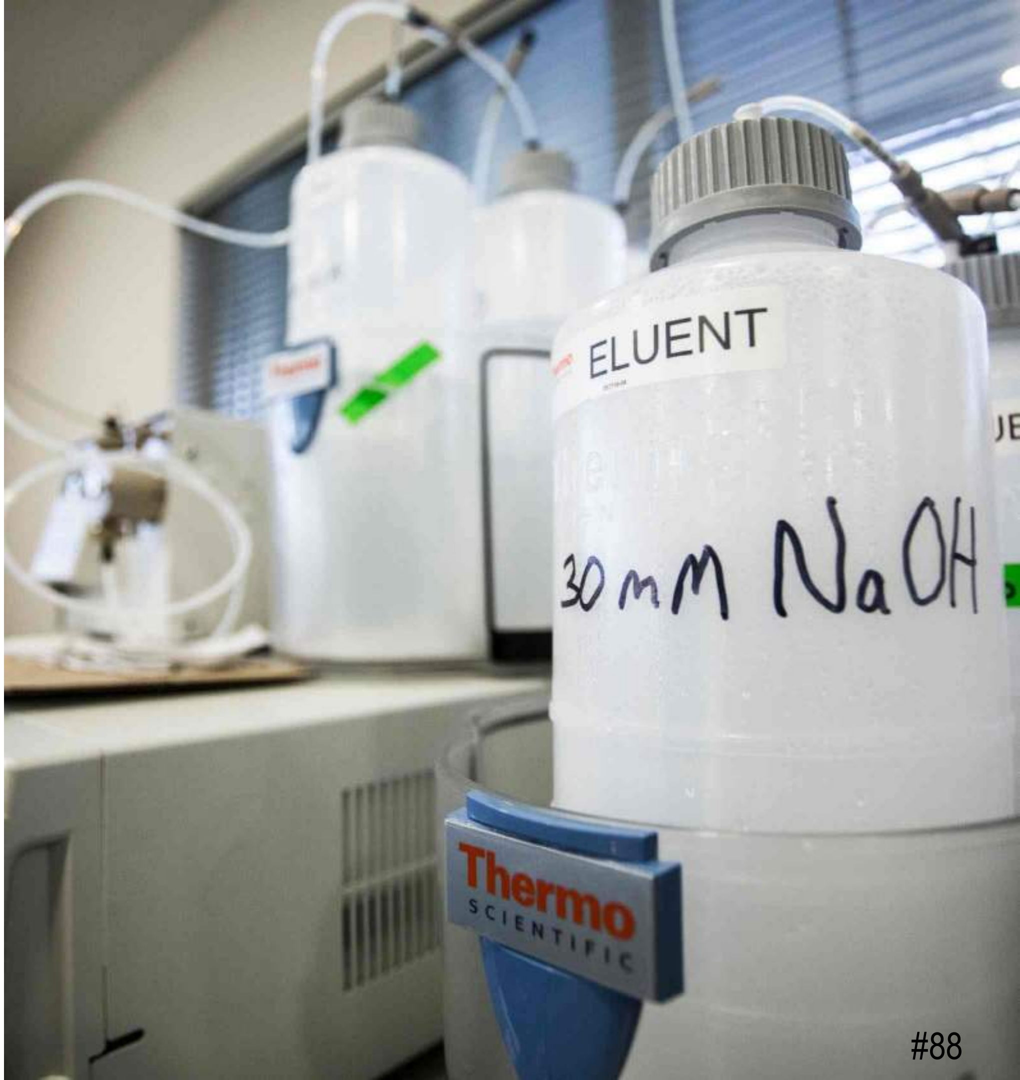
- Hydrogen ion concentration
- Not an indicator of buffering
- If less than 5.5, total acidity should be performed
- Elevated pH generally beneficial, but must be completely uniform. (Caution with lime treatment)

ELECTRICAL CONDUCTIVITY

- The inverse of resistivity
- Performed on 1:5 extract
- Primarily used for QA/QC
- Determining Factors:
  - Salts in solution
  - Soil particles in suspension
  - Ionic species
  - Temperature

CATIONS

- Ca^{2+}, Mg^{2+}, Na^{1+}, K^{1+}, and NH_4^+
- Provide QA/QC balance with anions
- Allow for inference of salts



ANIONS

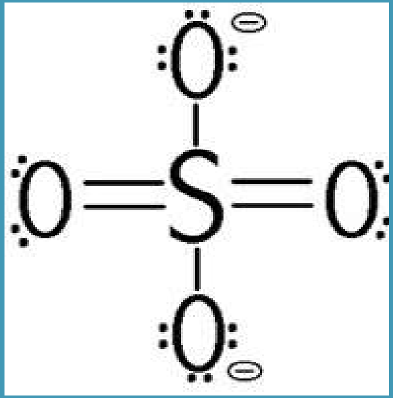
- CO_3^{2-}, HCO_3^{1-}, PO_4^{3-}, NO_3^{1-}, F^{1-}, Cl^{1-}, and SO_4^{2-}
- With cations comprise common soluble salts (QA/QC, resistivity)
- Cl^{1-} and SO_4^{2-} are infamous players in various corrosion reactions.
  - Ferrous metals, concrete, etc.

CHLORIDE

- Threat to reinforced concrete when greater than 350 ppm
- Permeates concrete and overcomes corrosion inhibiting effects of high pH on reinforcing steel, pipe walls, pre-stressing wires, etc.

SULFATE

- Sulfate attacks concrete directly
- 1,000 mg/kg to 2,000 mg/kg = Moderate
- 2,000 mg/kg to 20,000 mg/kg = Severe
- >20,000 mg/kg = Very Severe



STEEL CORROSION IS EXACERBATED UNDER THE FOLLOWING CONDITIONS:

- Moderately low soil resistivity
  (< 2,000 ohm-cm)
- pH <5.5
- Sulfides, Redox Potential, neutral pH (SRB)
- High groundwater

CAST AND DUCTILE IRON ARE SIMILAR TO STEEL

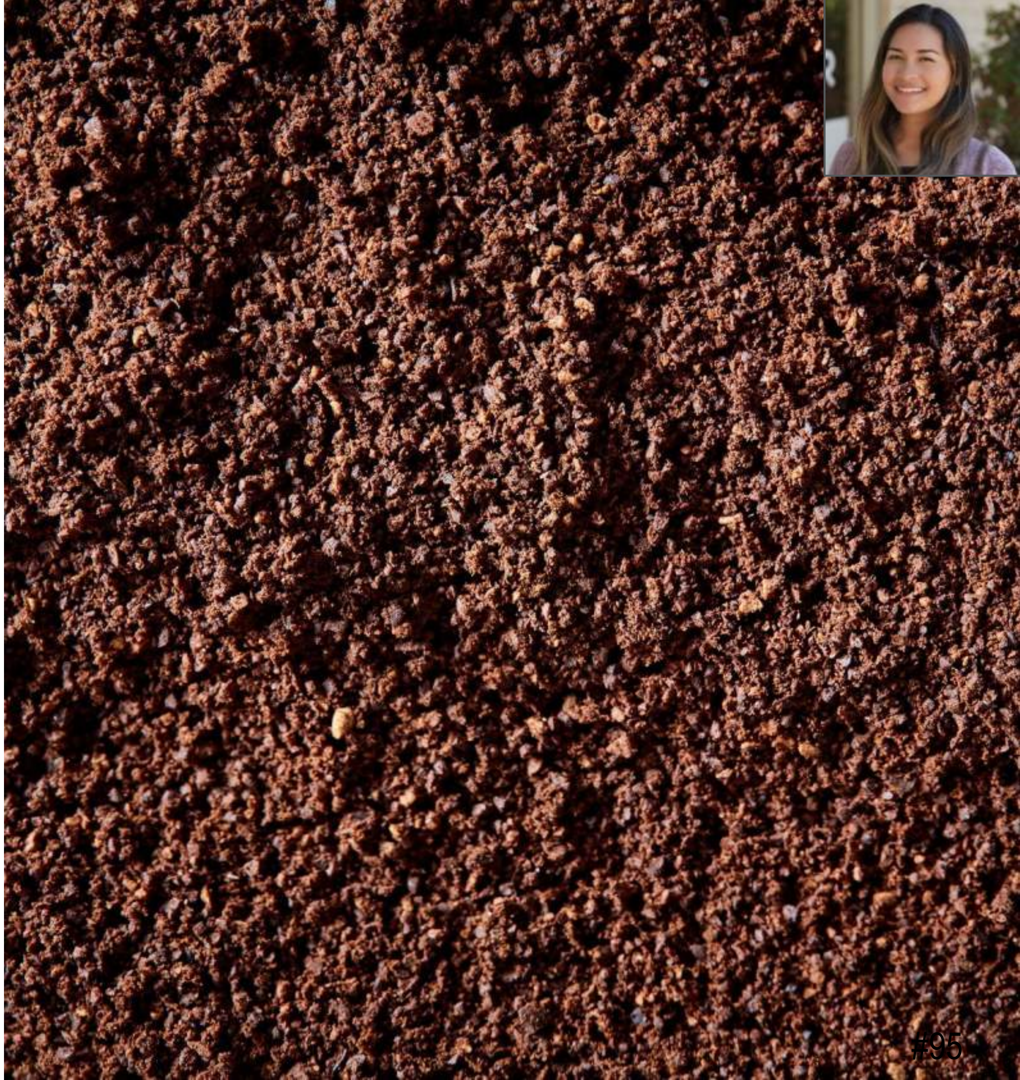
- AWWA C105: 10-point system is a guide when additional corrosion measures should be taken:
  - Resistivity (<1,500 = 10 points now)
  - pH <4
  - Sulfides, Redox Potential, neutral pH (SRB)
  - Drainage

STEEL REINFORCED CONCRETE

- Severe and very severe sulfate concentrations
- pH <5.5 may warrant concern of acid attack
- Chloride concentrations >350 ppm

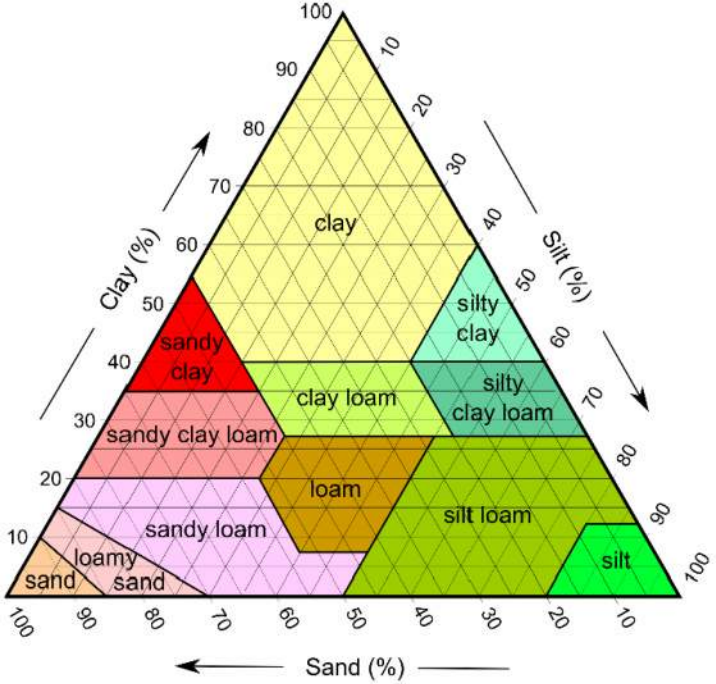
SOIL SELECTION REQUIRES INFORMATION BEYOND BORING LOGS

- Alignment/location are determined and previous soil data, if any, and site use(s) are reviewed.
- Information regarding the proposed structure and materials are collected.
- Geotechnical boring logs are reviewed.
- Samples are selected on the basis of:
  - Proximity to Structure of Interest
  - Diversity
  - Availability for Testing

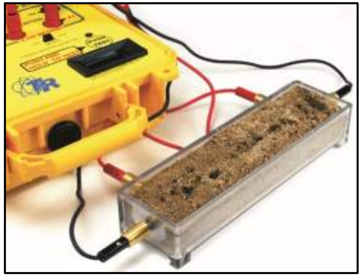


SAMPLES SHOULD GIVE CONSERVATIVE VIEW OF CORROSIVITY

- Fine-grained soils <u>generally</u> have higher chemical contents
- Anaerobic conditions can favor sulfate-reducing bacteria (rotten egg smell).
- In undulating topography, samples should be selected from low-lying areas where fines and moisture are concentrated
- Prior use of site can dictate additional soil analyses (e.g. nitrate, ammonia, etc.)
- Field testing locations should complement laboratory sampling.



HOW TO MEASURE CORROSIVITY?



- Electrical Properties
  - In-situ: Wenner Four Pin or EM Conductivity
  - Laboratory: As-received/saturated or minimum resistivity
- Chemical Content
  - Anions (Carbonate/Bicarbonate, Chloride, Sulfate)
  - Cations (Calcium, Magnesium, Sodium)
    - Indicates Chemical Form of Corrosive Anions
    - Chemical Balance (QA/QC)
- Additional Testing
  - Sulfides + REDOX Potential
  - Nitrogen Compounds
  - Total Acidity

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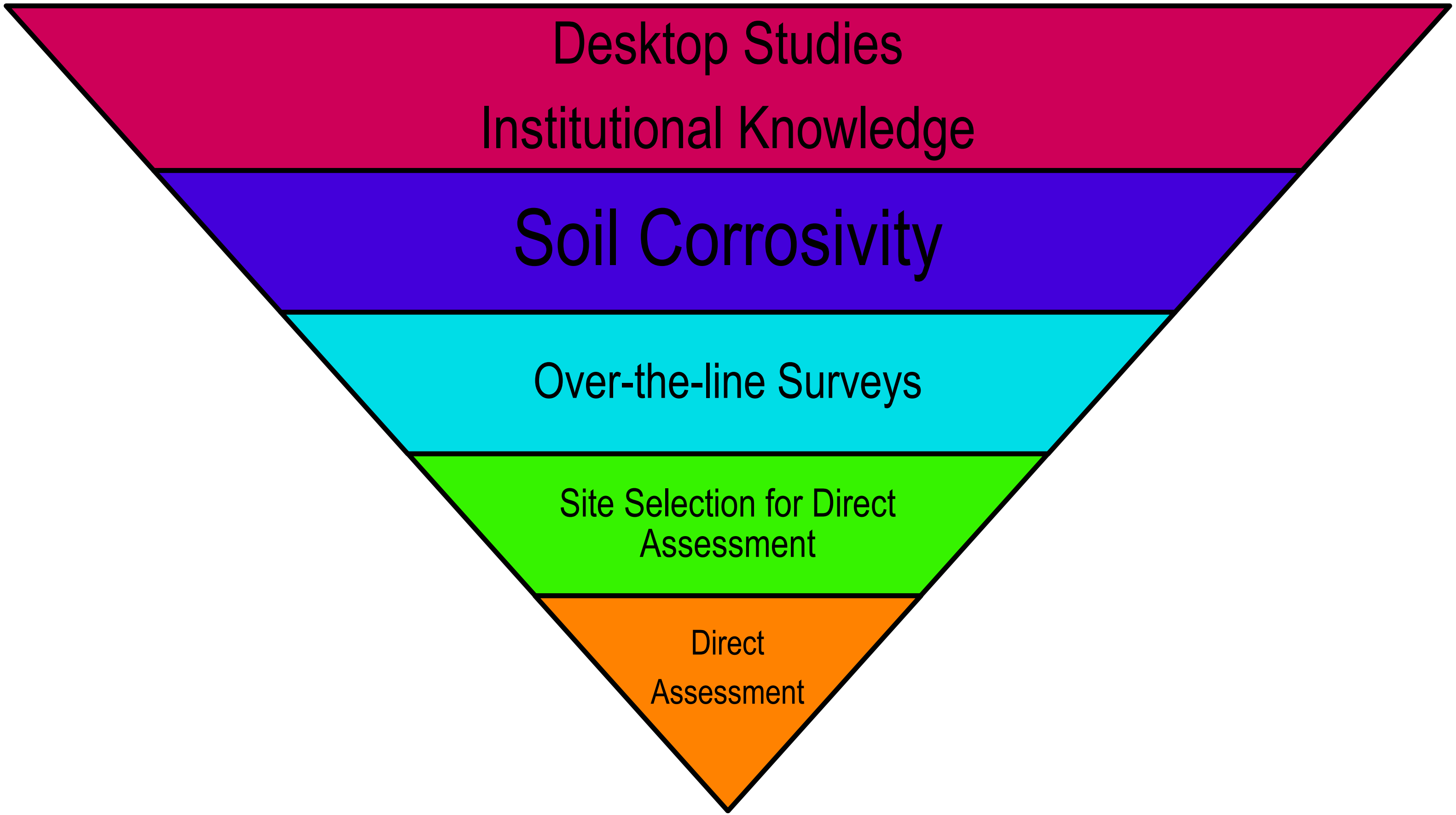

IDENTIFY VULNERABLE AREAS

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SOIL CORROSIVITY SURVEY

- Corrosive regions of alignment
- 3 survey methods

SOIL SURVEYS
EMAG – IDEAL FOR PIPELINES

- Tried and True
- Almost 100% coverage
- Ground contact-less
- Works even through pavement
- measures the average conductivity of the subsurface to a depth of approximately 15 feet (4.6 m)

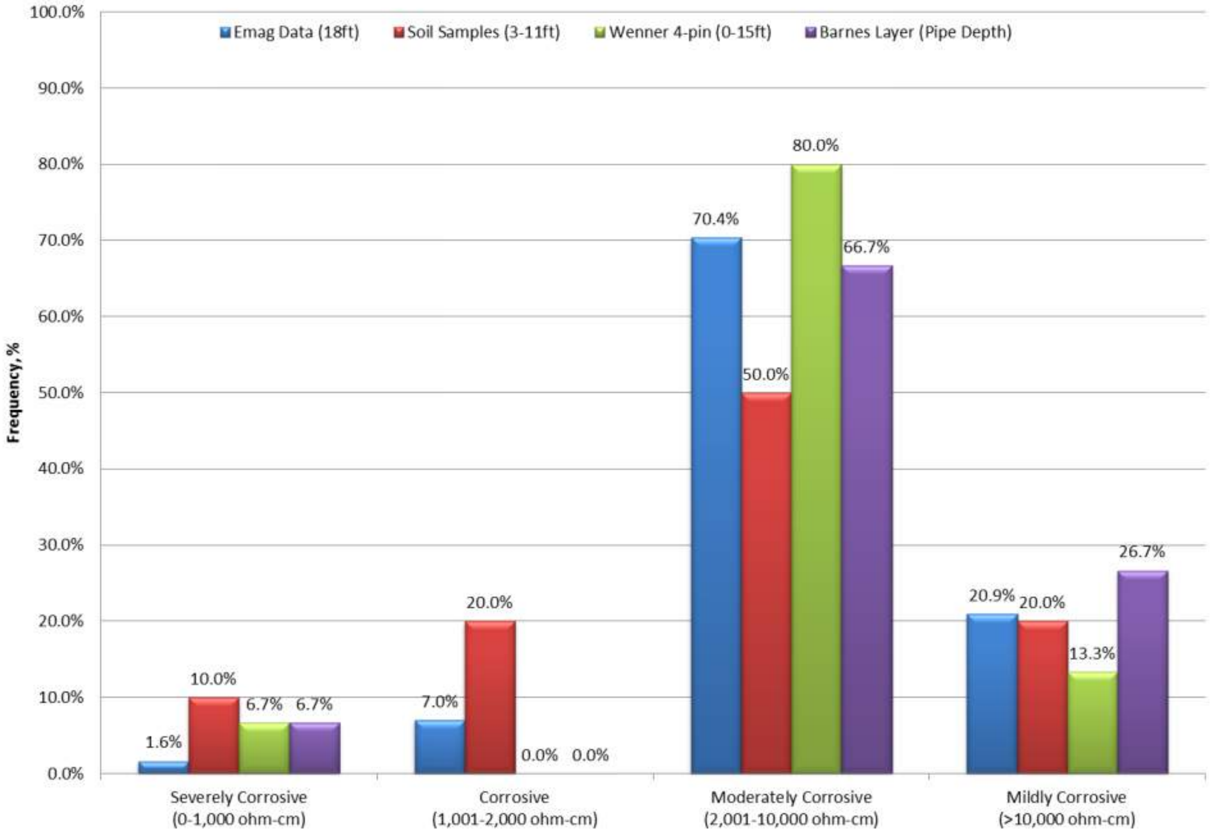
SOIL SURVEYS
WENNER 4-PIN

- Method per ASTM G57 — measures the average resistivity to a depth equal to the spacing between the pins.

SOIL SURVEYS LABORATORY ANALYSIS

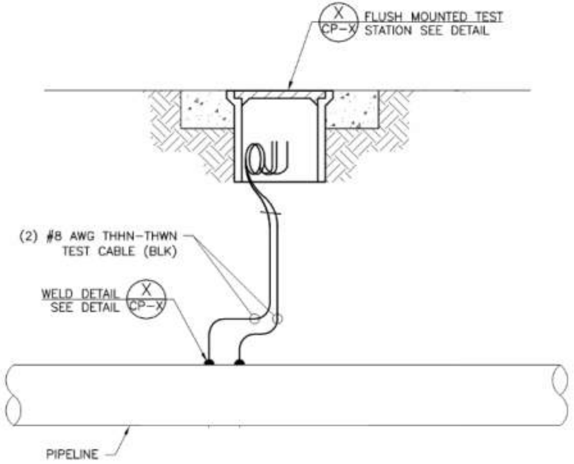
- Electrical Properties - Soil resistivity
- Chemical Content
  - pH
  - Anions (Carbonate/Bicarbonate, Chloride, Sulfate, Nitrate)
  - Cations (Calcium, Magnesium, Sodium, Ammonium)
  - Sulfide + REDOX Potential
  - Chemical Balance (QA/QC)
- Additional Testing - Linear polarization resistance (LPR)

SOIL CORROSIVITY DISTRIBUTION



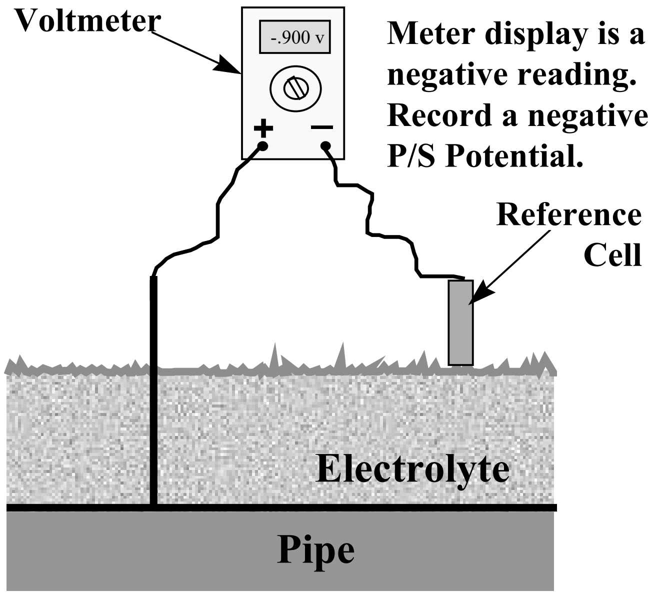
CORROSION TEST STATIONS – WHAT ARE THEY?

- Point of electrical contact to the pipe
- Flush or above grade
- Number and type of test stations varies
- Number of wires and configuration varies



FIELD MEASUREMENTS VOLTAGE/POTENTIAL SURVEYS

- Structure-to-electrolyte potential
- Close Interval Surveys



SECTION HIGHLIGHTS

Measuring Corrosion

- Corrosion can be anticipated by understanding how corrosive the soil is and other risk factors such as stray current and MIC

QUESTIONS?

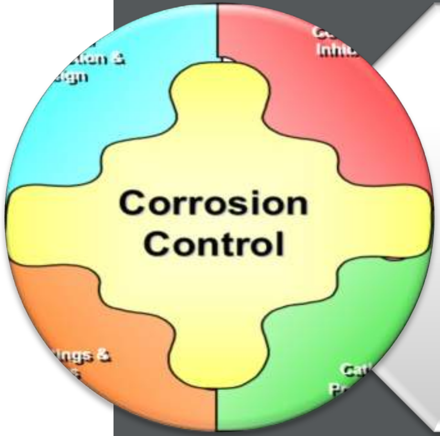
- For additional information, please contact:

- Brien Clark, PE
- Brien.Clark@hdrinc.com

GOOD TIME TO TAKE A BREAK?

LEARNING TOPICS:

- How to mitigate corrosion?
  - Material section, corrosion inhibitors, coatings/linings, cathodic protection
- What are the critical factors for successful coating application?
- Why use coatings in junction with cathodic protection?

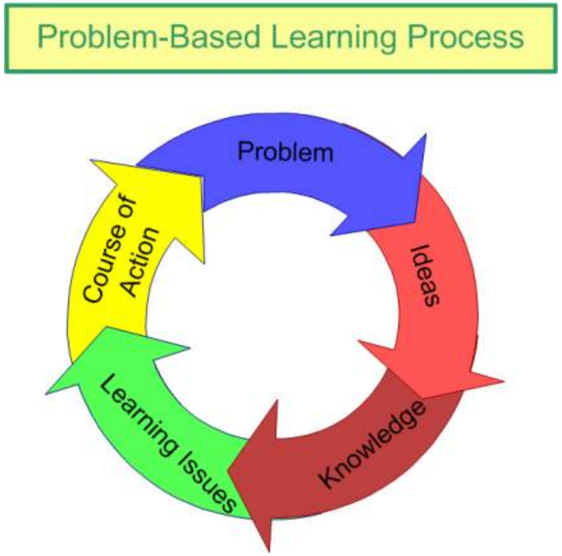


CORROSION PREVENTION TECHNIQUES

12:45 - 1:30 pm

WHY IS CORROSION CONTROL IMPORTANT?

- Preserve and extend the life of Assets
- Reduce Maintenance Costs
- Reduce Inspection Costs
- Environmental Compliance
- Preserve the Environment



Corrosion control is a process, not a project.

A FAILURE CAN BE FOUND, BUT A PENDING FAILURE IS HARDER TO FIND

- Breaks = leaks, fractures, blowouts
- Causes and triggers
  - General (uniform) corrosion
  - External corrosion pits
  - Internal corrosion pits
  - Strains (soil movement)
  - Surge events
  - Fatigue
  - Joint leaks

LIKELIHOOD OF FAILURE FOR PIPE

Physical factors	Environment factors	Operational factors
Pipe age and material	Pipe bedding	Internal water pressure, transient pressure
Pipe wall thickness	Trench backfill	Leakage
Pipe vintage	Soil type	Water quality
Pipe diameter	Goundwater	Flow velocity
Type of joints	Climate	Backflow potential
Thrust restraint	Pipe location	Operation and maintenance practices
Pipe lining and coating	Disturbances	
Dissimilar metals	Stray elecrical currents	
Pipe installation	Seismic activity	
Pipe manufacture		

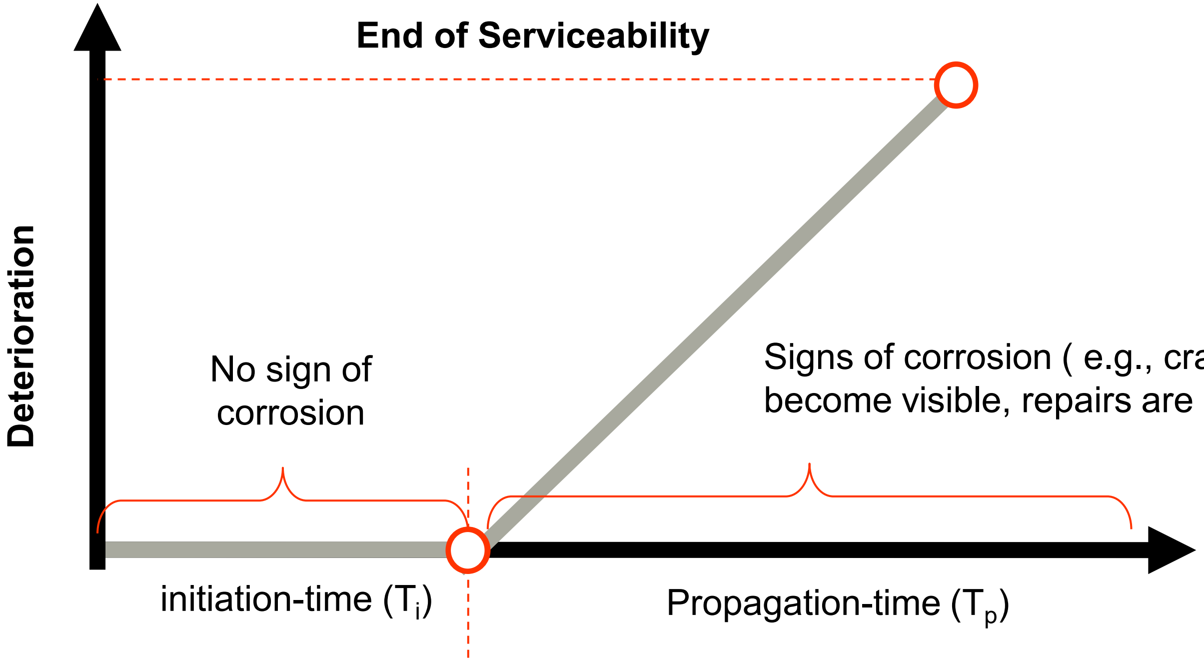
EPA/600/R-12/017 | March 2012

FOUR COMPONENTS NEEDED FOR CORROSION TO PROCEED

- Electrolyte
- Anodic reaction
- Cathodic reaction
- Electronic path

Electrochemical corrosion can be stopped by eliminating any one of the 4 components

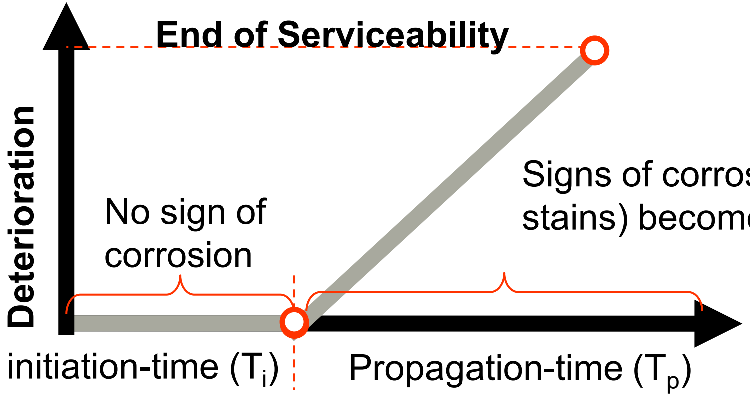
CORROSION MITIGATION APPROACH



CORROSION MITIGATION APPROACH

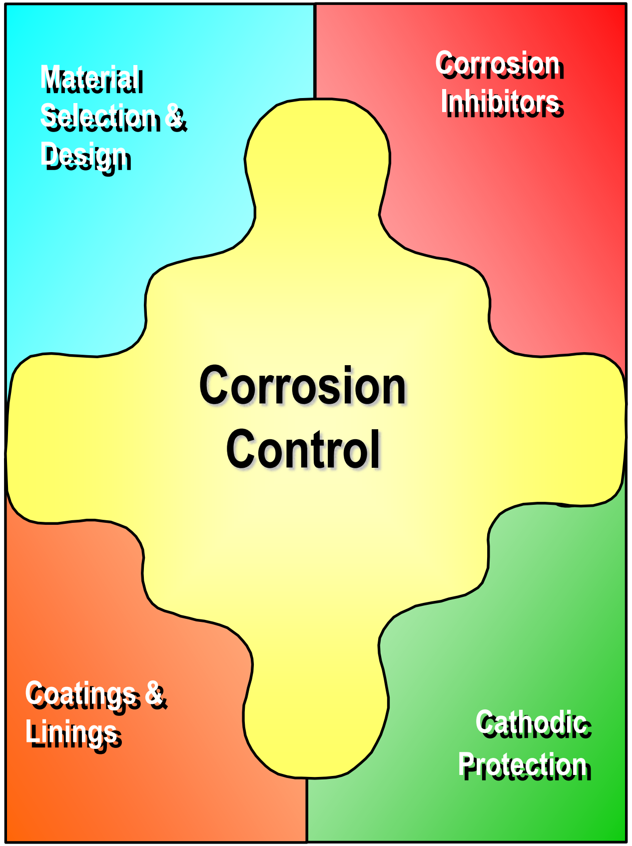
Two approaches for corrosion control:

1. **Prolong corrosion-initiation-time** (time before corrosion starts : T_i) **Design Phase**
2. **Prolong corrosion-propagation-time** (time from the moment that corrosion starts to the time of failure or loss of function: T_p) **Rehab Phase**



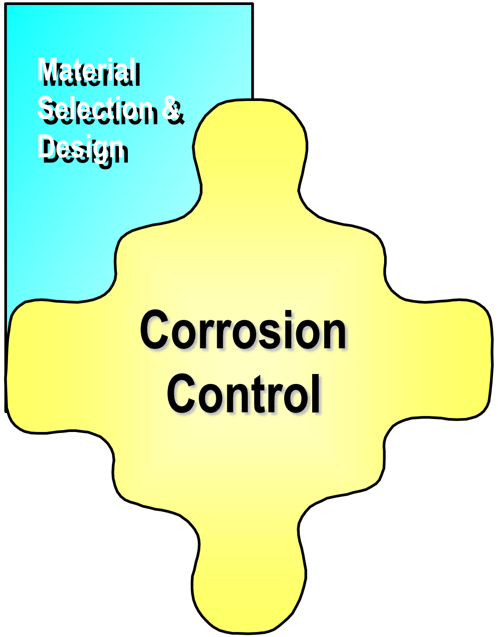
FOUR BASIC METHODS OF CORROSION CONTROL

- Material Selection/Design Details
- Corrosion Inhibitors
- Coatings
- Cathodic Protection



CORROSION MITIGATION
MATERIALS SELECTION & DESIGN

- Only Applicable for the design stage.
- Must characterize the environment (#1)
- Choose materials which are most compatible with the environment and cost constraints
- Do not create corrosion cells through design/construction details
- Increased use of PVC for distribution mains.
  -Other problems may limit or make the decision
  -Don't forget that the iron fittings will need corrosion control!



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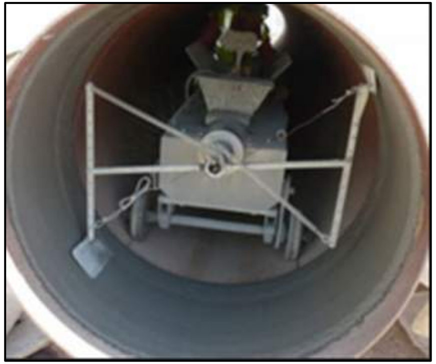
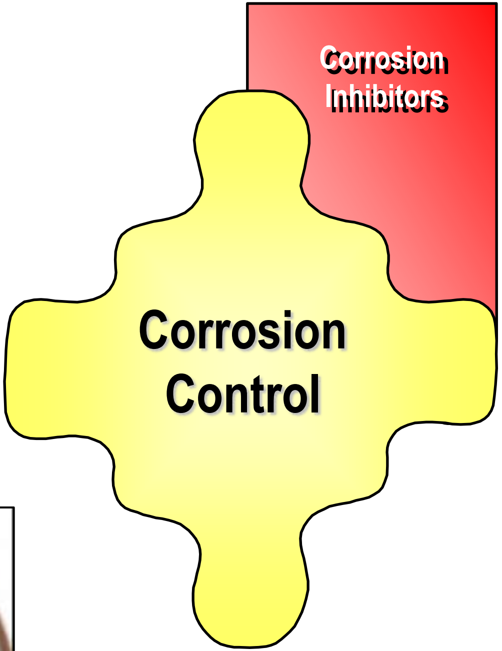
CORROSION MITIGATION
CORROSION INHIBITORS

- Alter the environment adjacent to the metal to passivate and protect the metal.
- Mortar/cement is the most common inhibitor for steel in the world.
- Admixtures can improve the resistance of encased steel, particularly to chloride

  -Prior to Fabrication
  -Can be Low Cost

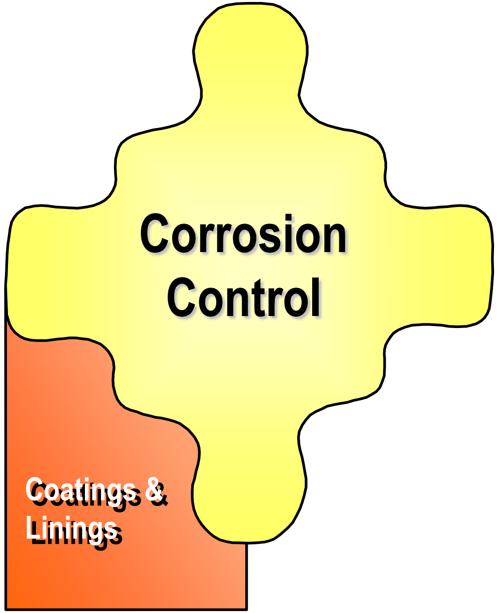
- Uniform inhibitor distribution is critical





CORROSION MITIGATION
PROTECTIVE COATINGS

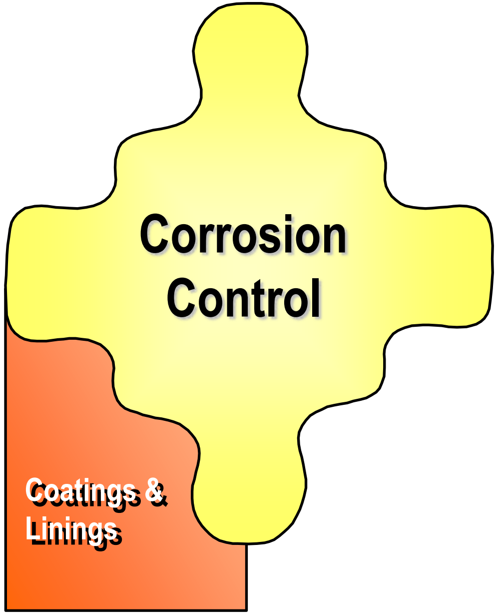
- Barrier protection
- Best applied during initial construction
- Needs additional protection in aggressive environments
- Usually dielectric material that prevents electron and ionic current flow.



CORROSION MITIGATION
PROTECTIVE COATINGS

Bonded Dielectric Coatings	
Hot applied coal tar enamel	AWWA C203
Liquid epoxy systems	AWWA C210
FBE	AWWA C213
Polyethylene tape	AWWA C214
Extruded polyethylene	AWWA C215
Polyurethane	AWWA C222

Other Coatings	
Cement Mortar	AWWA C205
Wax Tape	AWWA C217
Polyethylene encasement	AWWA C105
Vinyl Sheet Goods (T-Lock)	
Galvanizing (sacrificial metal)	
Inorganic Ceramic (Glass) Linings	



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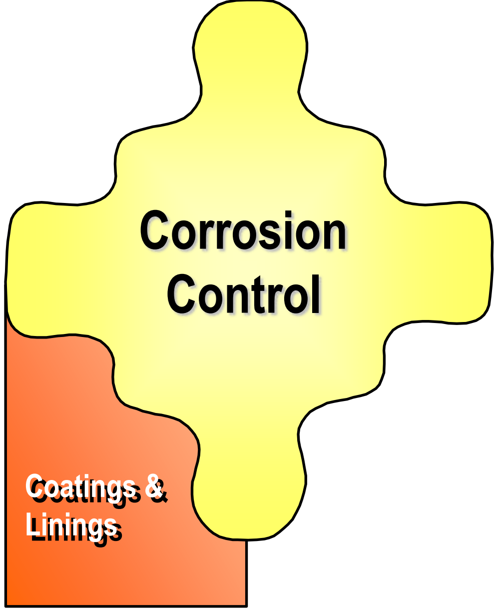
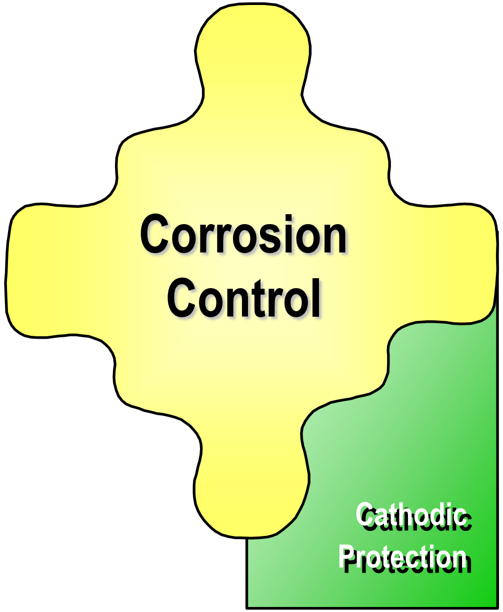
CORROSION MITIGATION
COATING AND LININGS

Critical factors for successful use of coatings

- Pre-surface preparation
- Post-surface preparation
- Proper application tools
- Experienced applicator
- Quality control during and after application
- Ambient condition control
- Quality control and proper application of abrasives



CORROSION MITIGATION
CATHODIC PROTECTION



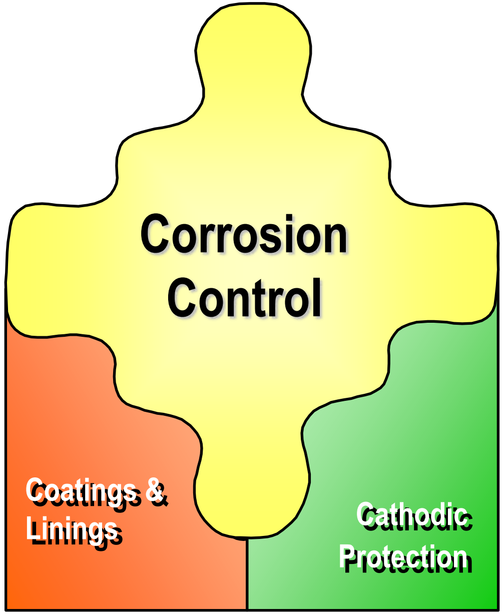
- Primary solution for existing structures
  - -Main must be metallic
  - -Best if installed with intentional electrical continuity
  - -Coatings or encasement reduce CP
- Basic Types of CP
  - -Galvanic
  - -Conventional Impressed Current

We will discuss this in more detail later!

CORROSION MITIGATION

Cathodic Protection Compliments and Supplements Coatings

- CP protects the uncoated or damaged metal
- Coatings reduce the CP current needed



NACE RP0388-95:
If water is sufficiently corrosive to justify the use of coatings, then cathode protection is justified and provides a greater degree of protection than when either method is used alone.

AWWA D104-97:
The combination of coatings and cathodic protection maybe more economical and effective than using coatings or cathodic protection alone.

BASIC PHILOSOPHY: “ZERO-MAINTENANCE”

- The best corrosion control measures are those which can be specified at the design stage, buried and forgotten with the structure.
  - Materials Selection and Specification
  - Coatings
  - Corrosion Control Considerations in Design.
- Cathodic Protection (CP) is the last resort.
- If conditions warrant or are borderline, make preparations for CP before you bury the structure.
  - Minimal Economic Impact
  - Simplify CP installation, if necessary.
  - Reduce current requirement

Avoid dissimilar metal corrosion cells by electrical isolation.

Bond underground piping or similar metal structures.

Coat buried iron and steel.

Provide means for corrosion monitoring.

Apply cathodic protection if warranted.

HOW TO DEVELOP AN EFFECTIVE MAINTENANCE PLAN FOR CORROSION CONTROL SYSTEM?

- Know your system

- Provide efficient communication between the operational group and the engineering team

- Get assistance from a professional corrosion specialist with related experience

HOW TO MONITOR THE EFFECTIVENESS OF CORROSION CONTROL MEASURES?

- Include sufficient budget and schedule for annual survey
  - Internally (O&M)
  - Externally, contracted out to professionals (Engineering)
- Transform the survey findings into useable and accessible data (e.g., GIS, MAXIMO)
- Analyze data and derive recommendations for maintenance of systems
- Keep up with maintenance as recommended by annual survey reports

SECTION HIGHLIGHTS

Corrosion Prevention Techniques

- Four basic method of corrosion protections are: proper materials selection and design, corrosion inhibitors, protective coating and linings, and cathodic protection.
- Depending on the project, one or multiple corrosion protection techniques may be implemented to reach the desired design life.
- Protective coatings commonly used in junction with cathodic protection for superior corrosion prevention.

- AMPP has various practice standards and guidelines for corrosion prevention.
- AWWA M27 provides guidelines for external corrosion
- WRF reports are great resource and are available to water utilities for free.

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LEARNING TOPICS:

- How does CP work?
- What is needed for CP?
- What are the types of CP?
- What are the benefits and determents of each type?
- How costly is CP?
- How to test CP?
- Are there case studies?
- What are the issues with existing pipelines and solutions?
- What is WRF4618 project all about?
- What is hot-spot and retrofit CP?
- What are related training and certification?

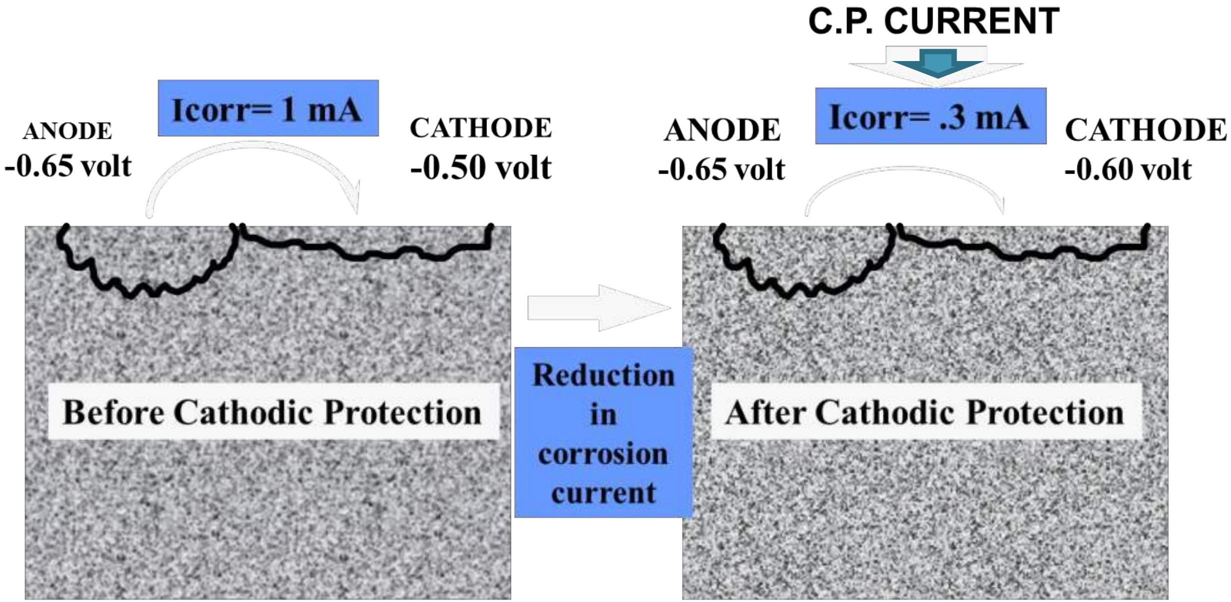
BASICS OF CATHODIC PROTECTION

1:30 - 2:30 pm

MA (2023)

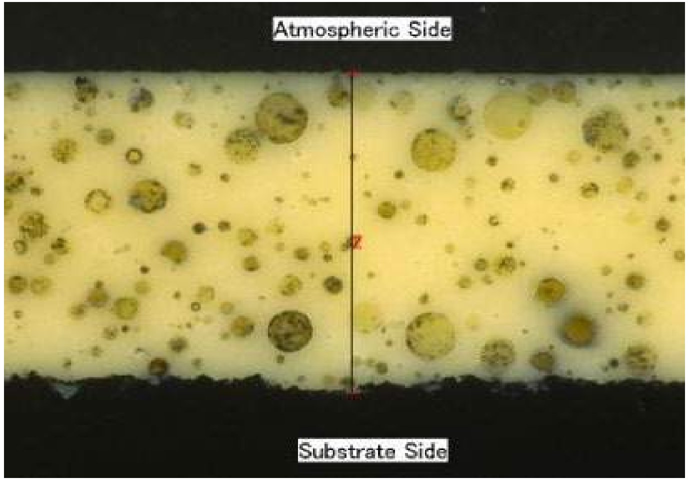
HOW CP WORKS…

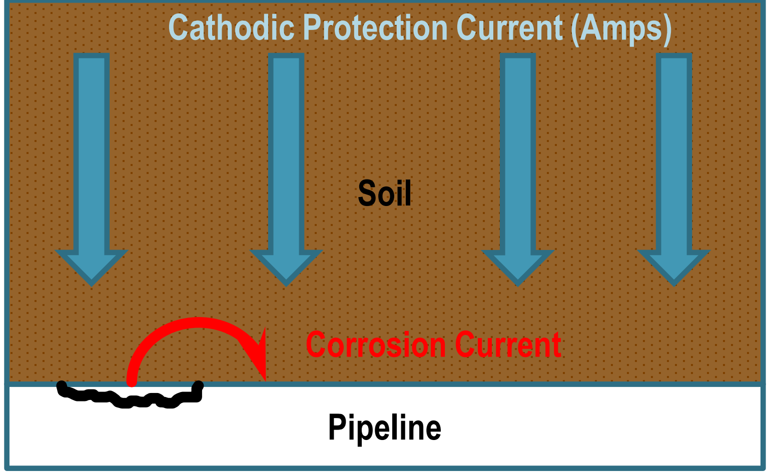
- CP seeks to make the entire protected structure the cathode of the corrosion reaction by supplying electrons from an "external" source….
- The external source of electrons is the cathodic protection system.

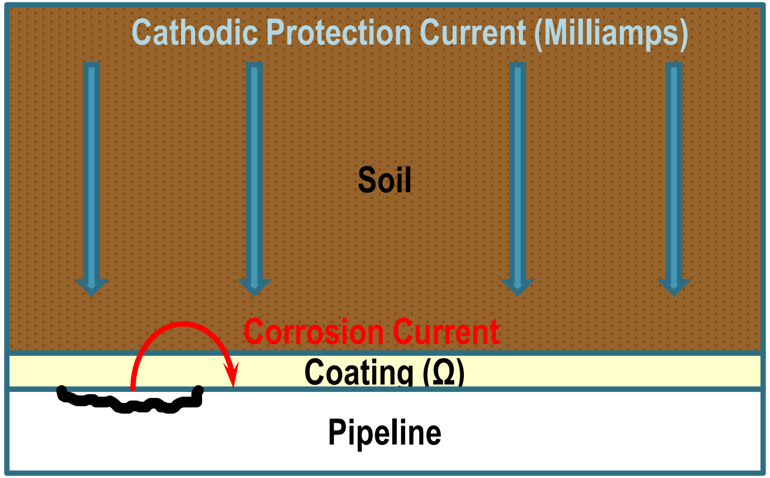


HOW CP WORKS…

- Used with or without a coating
- Coating reduces current demand
- Provides protection at coating holidays







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WHAT IS NEEDED FOR A CP SYSTEM?

- Cathode (something you want to protect, like your A$$et)
- Anode (something you want or will allow to corrode)
- Electrolyte (a conductive media through which current can pass)
- Metallic Path (low-resistant connection, like a wire, through which current can return to the anode and complete the circuit)
- Intentional electrical continuity of the cathode
- Testing Facilities

Bond cables

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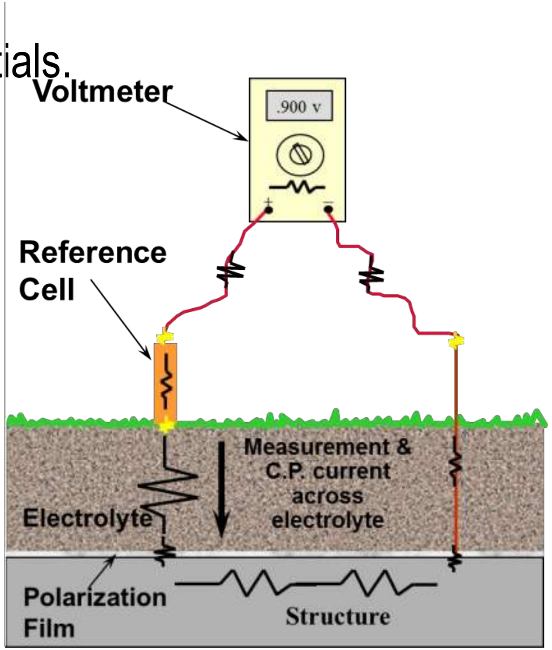
CP CRITERIA FOR SPECIFIED PROTECTION…

- Cathodic protection is a polarization phenomenon.
- Cathodic protection is achieved when the open circuit potential of the cathodes are polarized to the open circuit potential of the anodes.
- Practical application makes use of structure-to-electrolyte potentials.

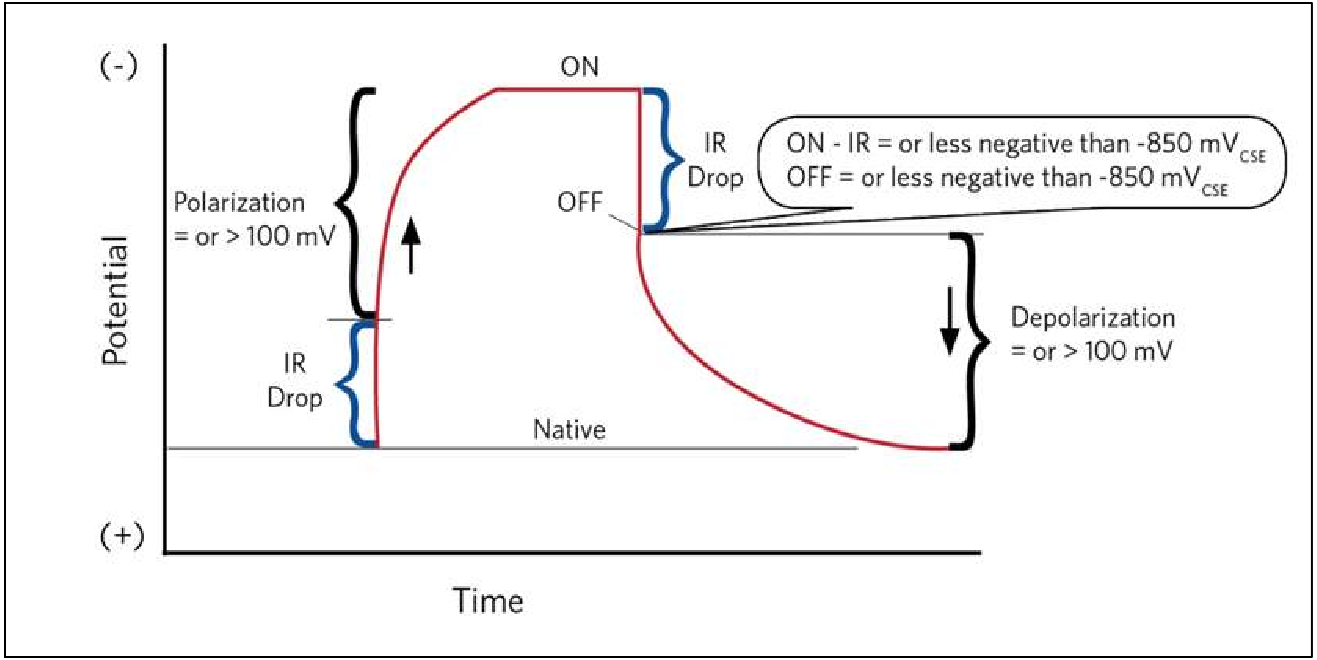


SOURCE: NACE INTERNATIONAL 2001

References:
SP0169 Control of External Corrosion on Underground or Submerged Metallic Piping Systems

SP0285 Corrosion Control of Underground Storage Tank Systems by Cathodic Protection

CP CRITERIA FOR SPECIFIED PROTECTION…



NACE International Standard SP0169-Control of External Corrosion on Underground or Submerged Metallic Piping Systems

ELECTRICAL CONTINUITY

- All components of a structure intended to receive cathodic protection from a common source must have electrical continuity.
- Some components requiring bonding:
  - mechanical couples
  - screw joints
  - pile groups
  - rebar in concrete

SOURCE: NACE INTERNATIONAL 2001

ELECTRICAL ISOLATION

The purpose of electrical isolation is to confine the cathodic protection current to the structure intended for protection.

MONOLITHIC ISOLATION JOINT

INSULATING UNIONS

FLANGE INSULATION KIT

SOURCE: NACE INTERNATIONAL 2001

TWO TYPES OF CP SYSTEM

- GACP – Galvanic Anode Cathodic Protection
  - Anodes produce a galvanic current due to the natural potential difference between the anode (zinc, magnesium) and cathode (steel, iron).

- ICCP – Impressed Current Cathodic Protection
  - A rectifier uses an external 120 or 240 Volts AC power source and converts it to low voltage DC current. The current is transmitted into the soil or water via anodes.

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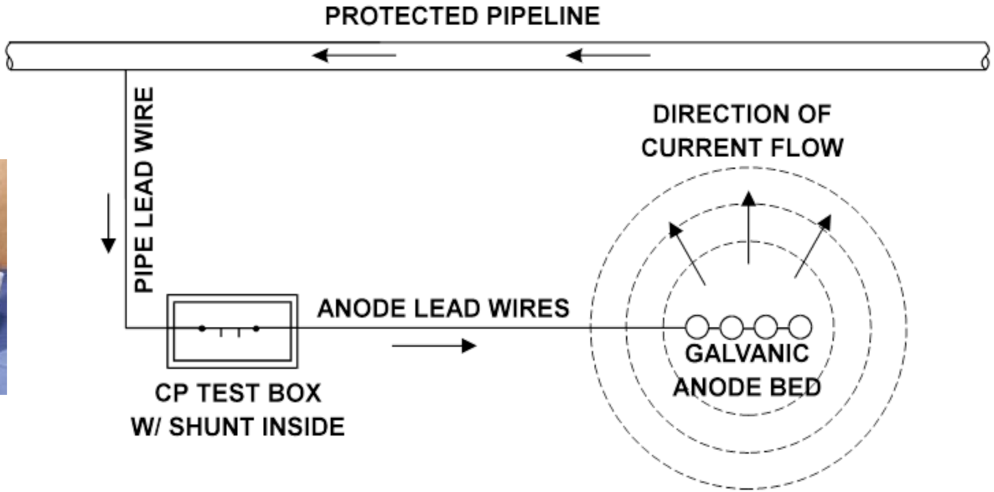
CATHODIC PROTECTION
GALVANIC SYSTEM



GACP Anodes:

Aluminum - **primarily used in seawater**.

Magnesium - **primarily used in soil and fresh water.**

Zinc - **one alloy for seawater and a second alloy for soil and fresh water applications.**

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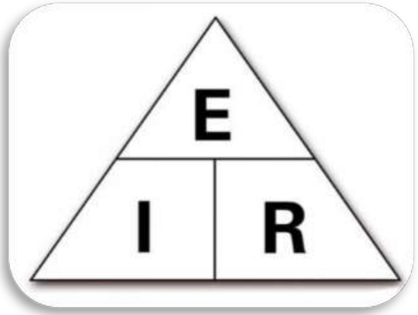
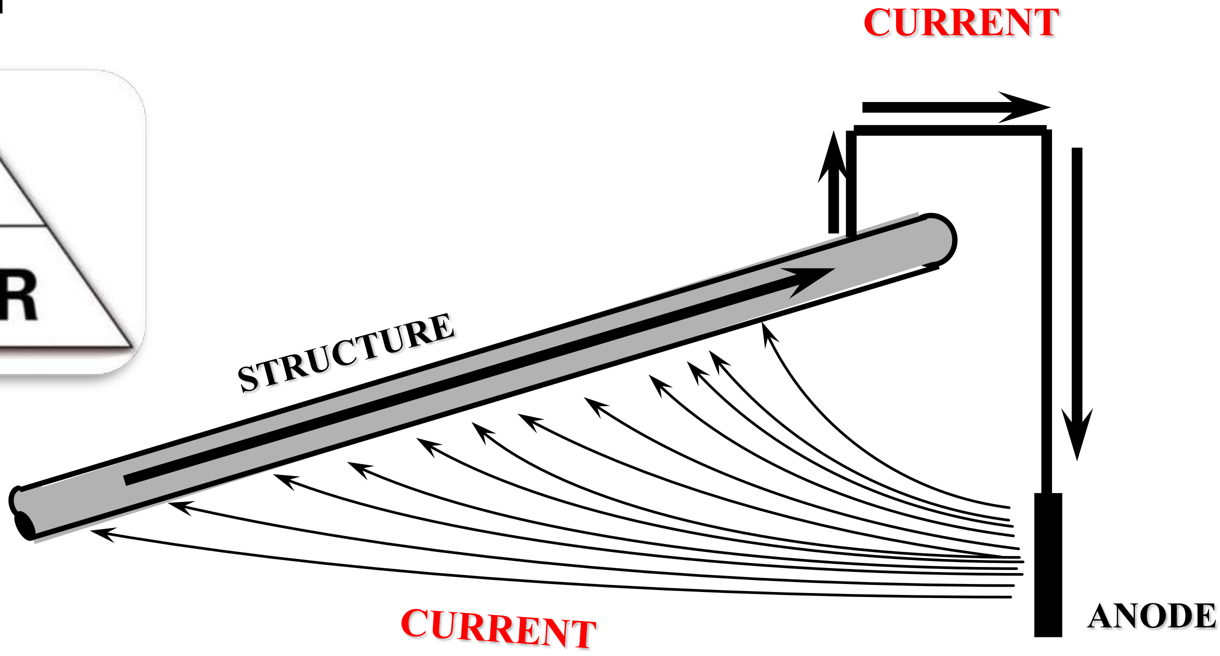
HOW CP WORKS…

- Galvanic CP





CORROSION MITIGATION
GALVANIC CP SYSTEM

Water Reservoirs

Suspended anodes

Test Box

ANODE INSTALLATION

Cathodic Protection
Galvanic System – Pipelines

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GACP CP SYSTEM

- **Benefits of GACP System**
  - Does NOT require an external power source.
  - Able to protect large structures with good coating systems
  - Life-long costs are less expensive than ICCP
  - Does not require monitoring other than annual survey
  - Can be remotely monitored (SCADA, LEOS)

- **Detriments of GACP System**
  - Has limited adjustment to compensate for coating system degradation.

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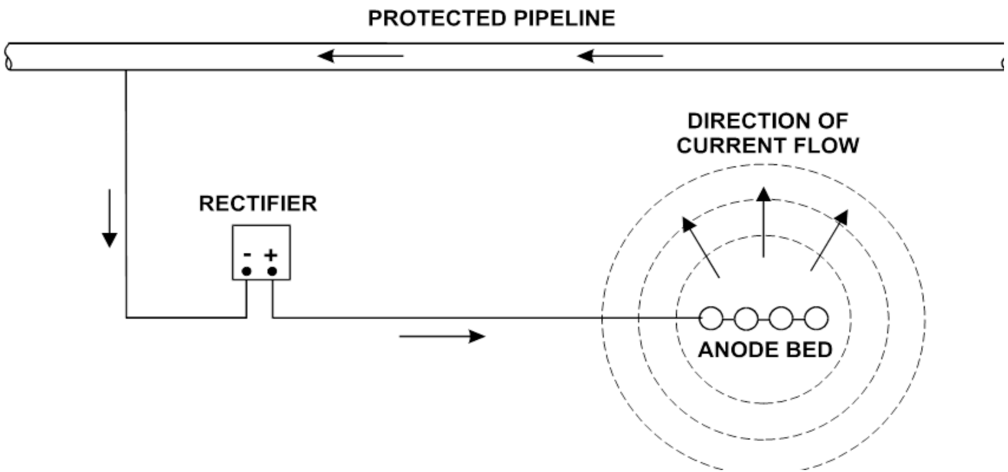
APPLICATION GUIDE FOR GALVANIC ANODES

- When relatively small increments of current are required and/or a low resistivity electrolyte exists
- Local cathodic protection to provide current to a specific area on a structure
- Additional current is need at problem areas
- Located at point of stray current discharge
- Provide protection to structures in congested areas
- Shorted casings
- Shielded areas
- Interior surface of vessels
- Offshore structures
- Poorly coated or bare valves

CATHODIC PROTECTION
IMPRESSED CURRENT SYSTEM



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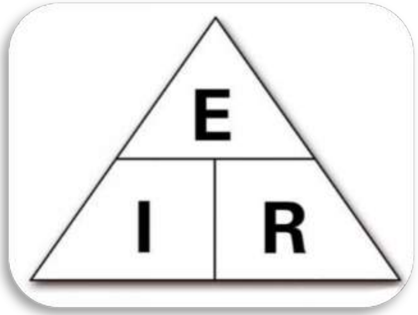
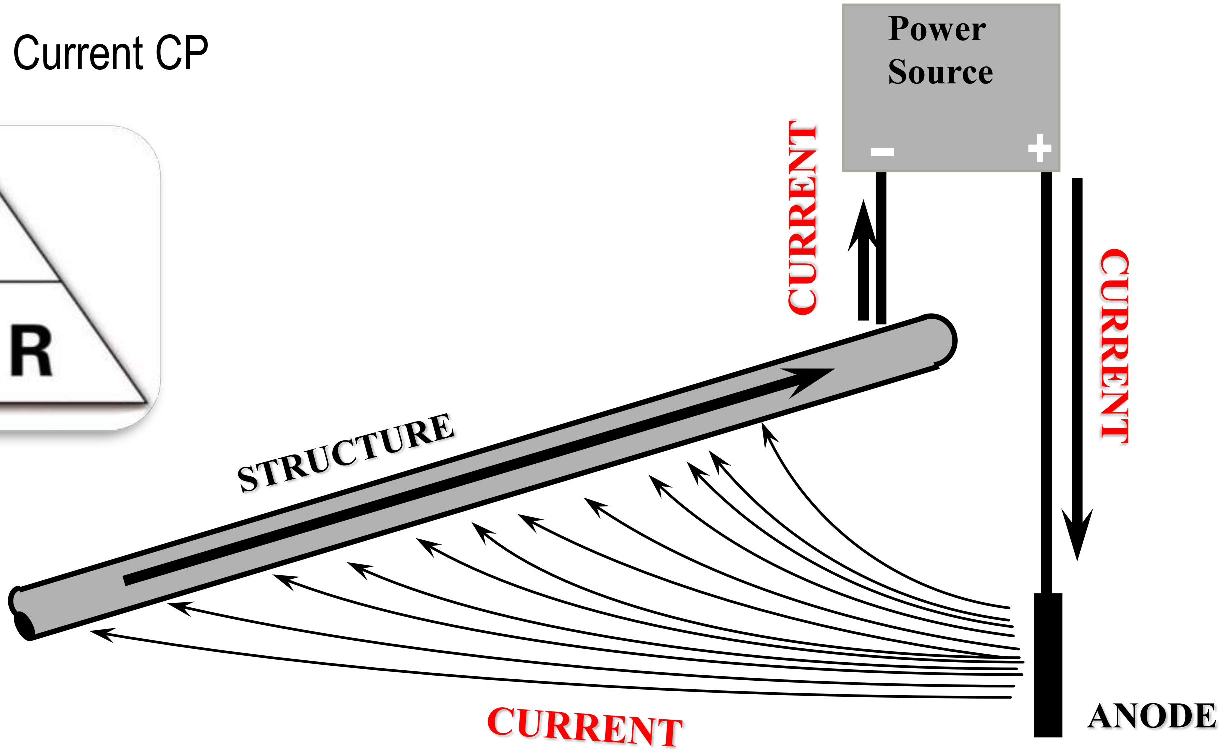
HOW CP WORKS…

- Impressed Current CP





CATHODIC PROTECTION
IMPRESSED CURRENT SYSTEM

CATHODIC PROTECTION
ICCP SYSTEM

- **Benefits of ICCP System**
  - Able to protect large structures with poor coating systems
  - Able to be adjusted to compensate for additional coating system degradation
  - Can be remotely monitored (SCADA, LEOS)

- **Detriments of ICCP System**
  - Requires an external power source, typically AC which is not always readily available.
  - Requires reading every couple of months
  - Lifelong costs are greater on average than GACP Systems
  - Can cause stray current problems

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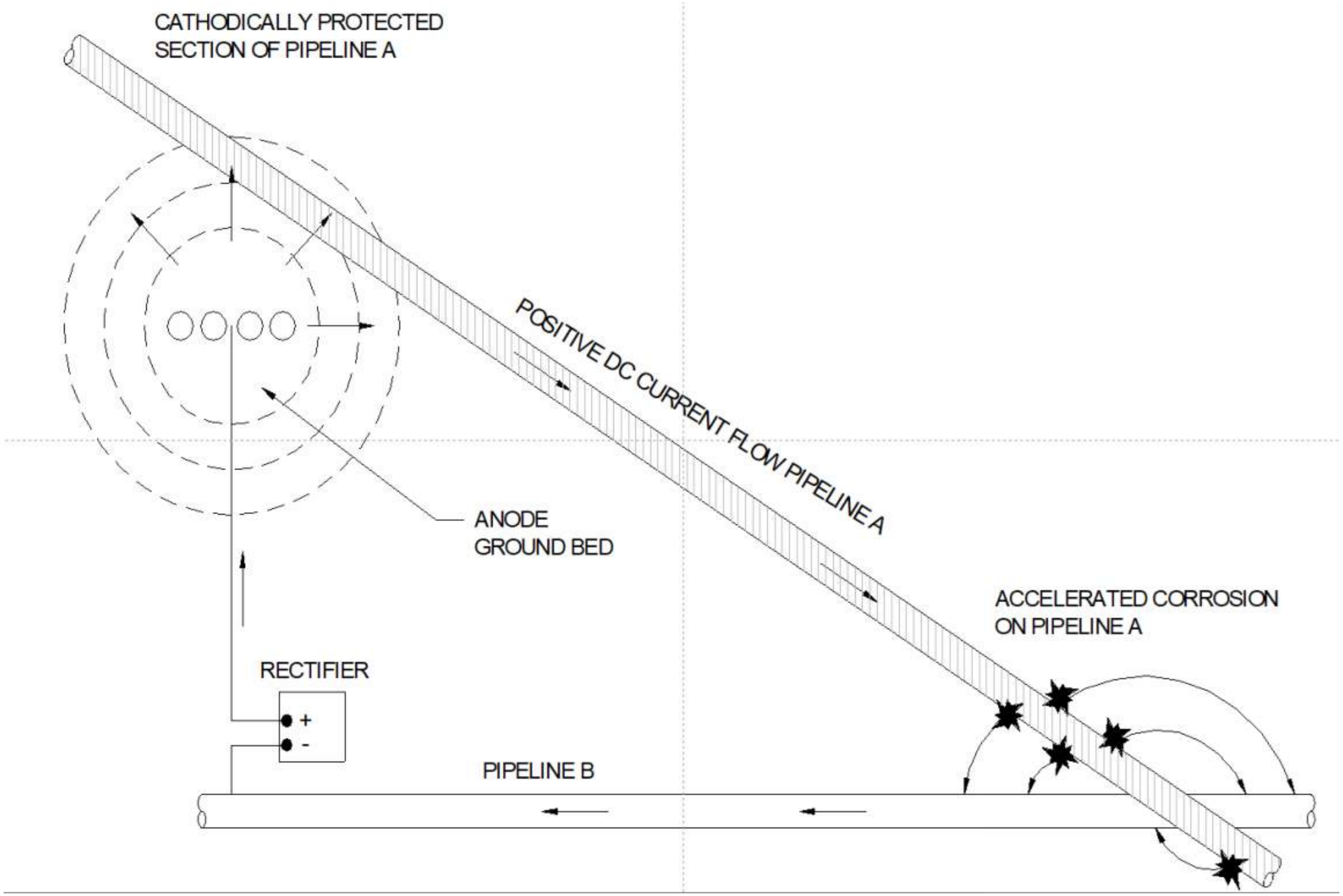
APPLICATION GUIDE FOR ICCP

- Large current requirement
- Depleted galvanic anodes
- Large heat exchangers
- Water tank interiors
- Large pipelines
- Foundation and sheet piling
- Ship hulls
- Any electrolyte resistivity
- Overcome stray current
- AST Bottoms
- Underground storage tanks
- Offshore structures

TOO MUCH OF A GOOD THING (CP) IS NOT ALWAYS WONDERFUL!


CATHODICALLY PROTECTED
SECTION OF PIPELINE A
POSITIVE DC CURRENT FLOW PIPELINE A
ANODE
GROUND BED
ACCELERATED CORROSION
ON PIPELINE A
RECTIFIER
+
-
PIPELINE B

$$ ARE DIRECTLY PROPORTIONAL TO CURRENT CAPACITY (AMPS)

- Life Cycle Costs = Construction + Operating Costs
- Initial/Construction costs ~ Amps
  - $2K-3K per installed ampere
- Operating/Maintenance Costs ~ Amps
- Anything and everything you do to reduce current requirement saves $$$.

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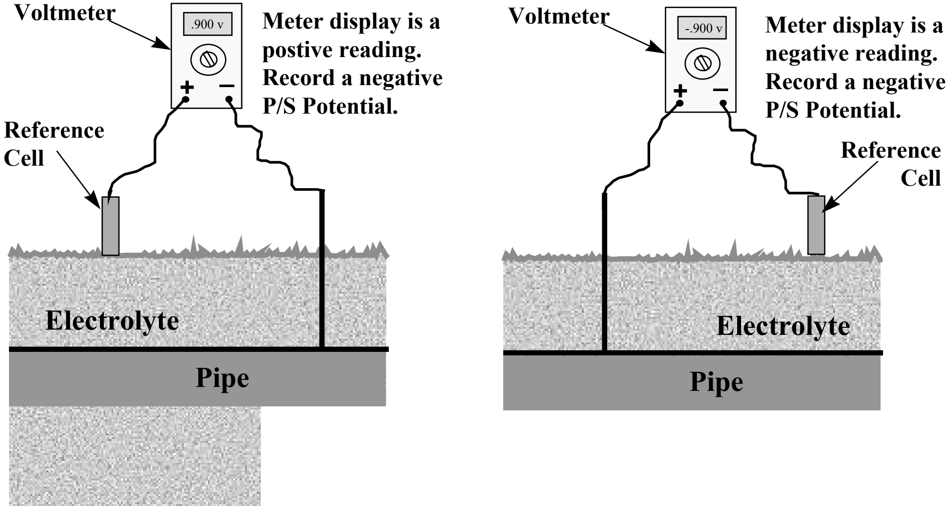
CP FIELD MEASUREMENTS

- Voltage
  - Circuit Connections
  - Voltmeter
  - Reference Cells
- Resistance
  - Ohmmeter
  - Resistivity Meter

- Current
  - Circuit Connections
  - Ammeters
  - Current Shunts
  - Amp-Clamps
- pH
- Pipe Locators
- Current Interrupters

CP FIELD MEASUREMENTS VOLTAGE/POTENTIAL SURVEYS

- Driving voltage of galvanic anode system
- Rectifier voltage output
- Structure-to-electrolyte potential
- Voltage drop across a pipe span
- Voltage across a current shunt



WRF REPORT#4618

Best Practice Manual for CP retrofit and hot spotting:

- Where to start our CP program?
- What can be done with exiting pipelines that are not electrically continuous?
- Are there any case studies?
- How can I justify the cost?

Retrofit and Management of Metallic Pipe with Cathodic Protection: Guidance Document on Technical Feasibility and Economic Value

Prepared by:

Graham E.C. Bell, PhD, PE
Mereseh Akhoondan, PhD
Steve Pool, PE
Addison Smith, PE
HDR Engineering

Neil Grigg, PhD
Colorado State University

Balvant Rajani, PhD
Rajani Consultants

Jian Zhang, PhD
Dale Claassen,
Andrew Hughes,
Jeff An
Water Research Foundation

Sponsored by:

Water Research Foundation
6666 West Quincy Avenue, Denver, CO 80235

Published by:

Water Research Foundation

Water Research Foundation

CASE STUDIES SHOWING THE EFFECTIVINESS OF CATHODIC PROTECITON FOR WATER INDUSTRY

- Preserves your A$$ets
- Reduces Maintenance Costs
- Reduces Inspection Costs
- Extends the effective life of the coating system
- Increased life cycle

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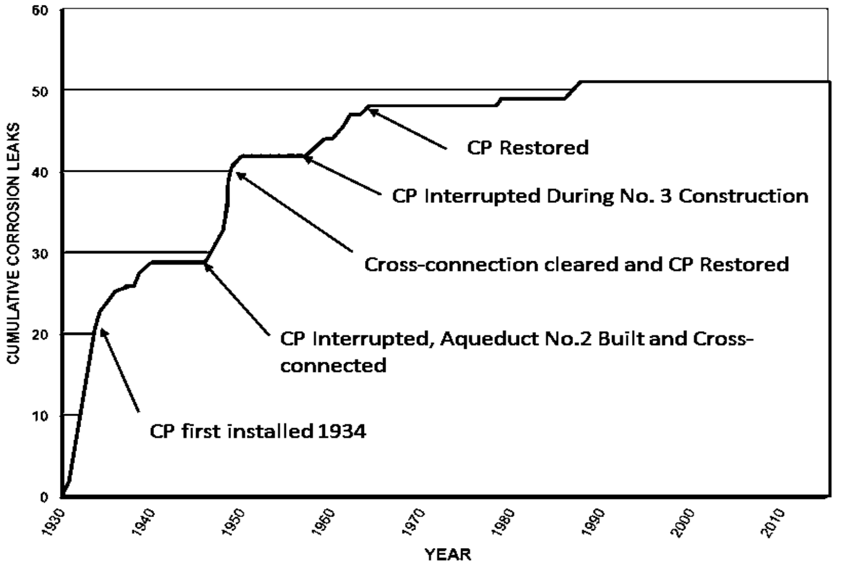
WRF 4618
A great reference on hot spot and retrofit CP

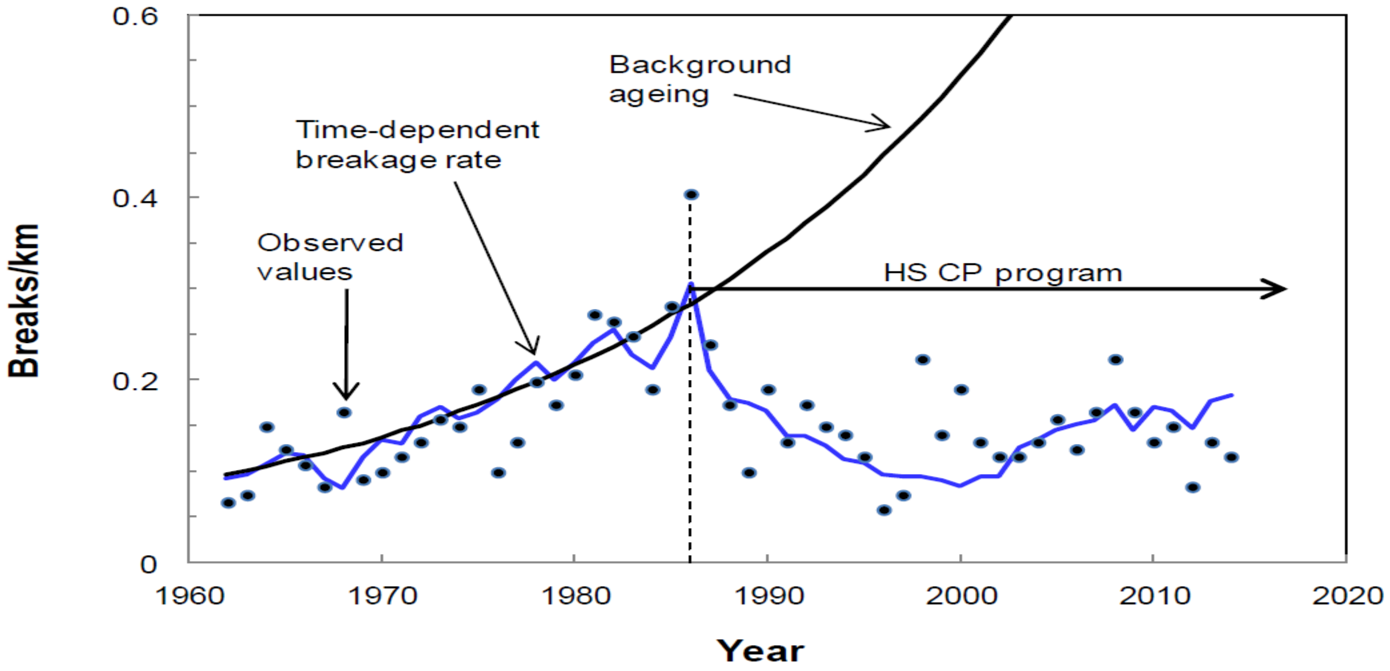
WRF 4618:
Chapter 1: Introduction
Chapter 2: Literature Review
Chapter 3: Workshop Summaries
Chapter 4: Utility Decision Framework for Cathodic Protection
Chapter 5: Qualitative Case Studies
Chapter 6: Numerical Case Studies
Chapter 7: Hot Spot : No Brainer!!
Chapter 8: Financial Models
Chapter 9: Best Practice Manual
Chapter 10: Conclusions

EAST BAY MUNICIPAL UTILITY DISTRICT (EBMUD)

- **Mokelumne Aqueduct**
  - Completed in 1928
  - ~93 miles (~81 miles of steel)
  - ~71 miles buried
  - Variety of soil: Rocks to peat lands.



CALGARY: 6" CIP CASE STUDY



HOT SPOTTING

Opportunistic

- Install anodes every time you excavate for routine repairs
- Not labor intensive
- $ insignificant compared to excavation cost (O&M cost)
- Install and forget…but keep record of locations
- Delay future breaks (stabilize the rate of breaks)
- May take **6-10 years transition period** to show a significant breakage reduction

RETROFIT

Systematic

- Need to establish electrical continuity
- Labor training and resources
- Require maintenance for long effective function
- $$ planning (CIP cost)
- Stops the breaks and reduces the break rates
- May take **up to 5 years** to see the effect

Picture: Courtesy of Dr. Rajani

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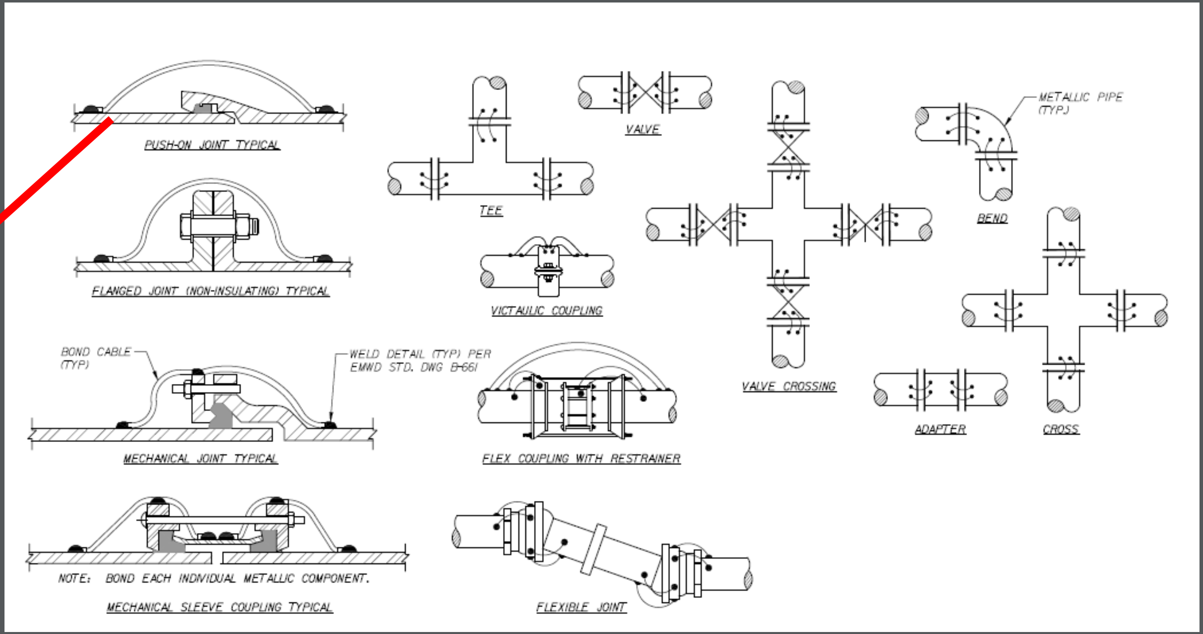
EXAMPLE DRAWING DETAILS

- **Cathodic Protection:**
  - At-Grade Test Stations
  - Terminal Boards
  - Corrosion Coupons
  - Reference Electrodes
- **Isolation and Bonding**
  - Insulating Flange Kit
  - Insulating Flange Kit at Vault
  - Joint Bonding
- **Welding Connections**
  - Wiring to Structure Detail

Electrical Continuity

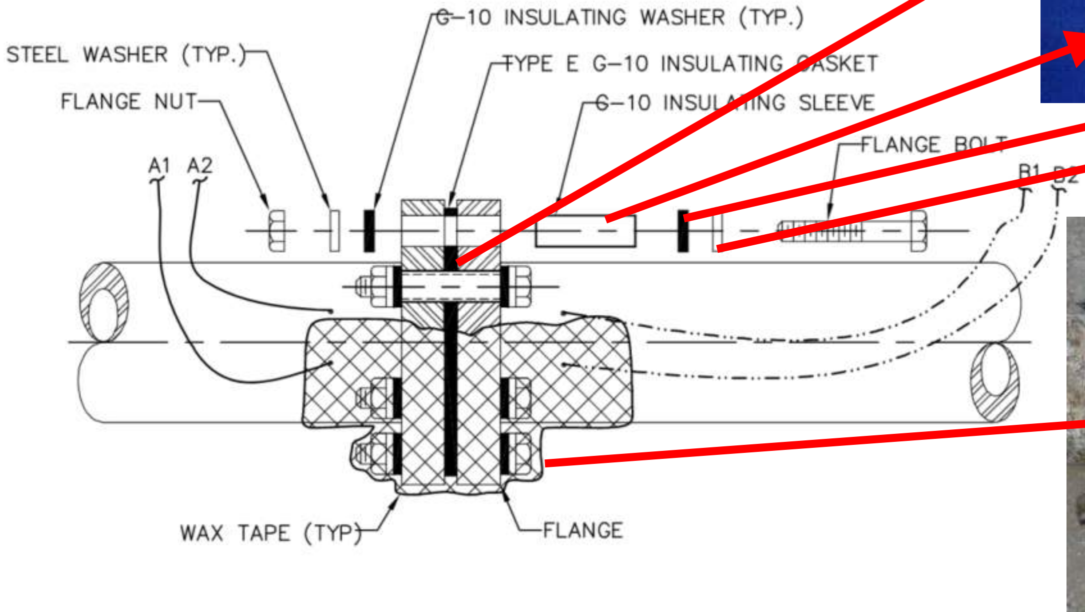


NOTES:

1. ALL BOND WIRES SHALL BE STRD. COPPER WIRE W/HMWPE INSULATION, INSTALLED AT MIN. LENGTH.
2. TWO #8 BOND CABLES ARE REQUIRED PER JOINT FOR PIPE DIAMETERS 16" AND SMALLER. THREE #4 BOND CABLES ARE REQUIRED PER JOINT FOR PIPE DIAMETERS GREATER THAN 16".
3. BOND WIRES SHALL BE SPACED 6" APART MIN.
4. ALL WIRE CONNECTIONS SHALL BE MADE BY THE EXOTHERMIC PER EMWD STANDARD DRAWING B-661.
5. WAX TAPE ALL BURIED BOLTED FITTINGS PER AWWA C217.

2 / CP-04 JOINT BONDING
NO SCALE

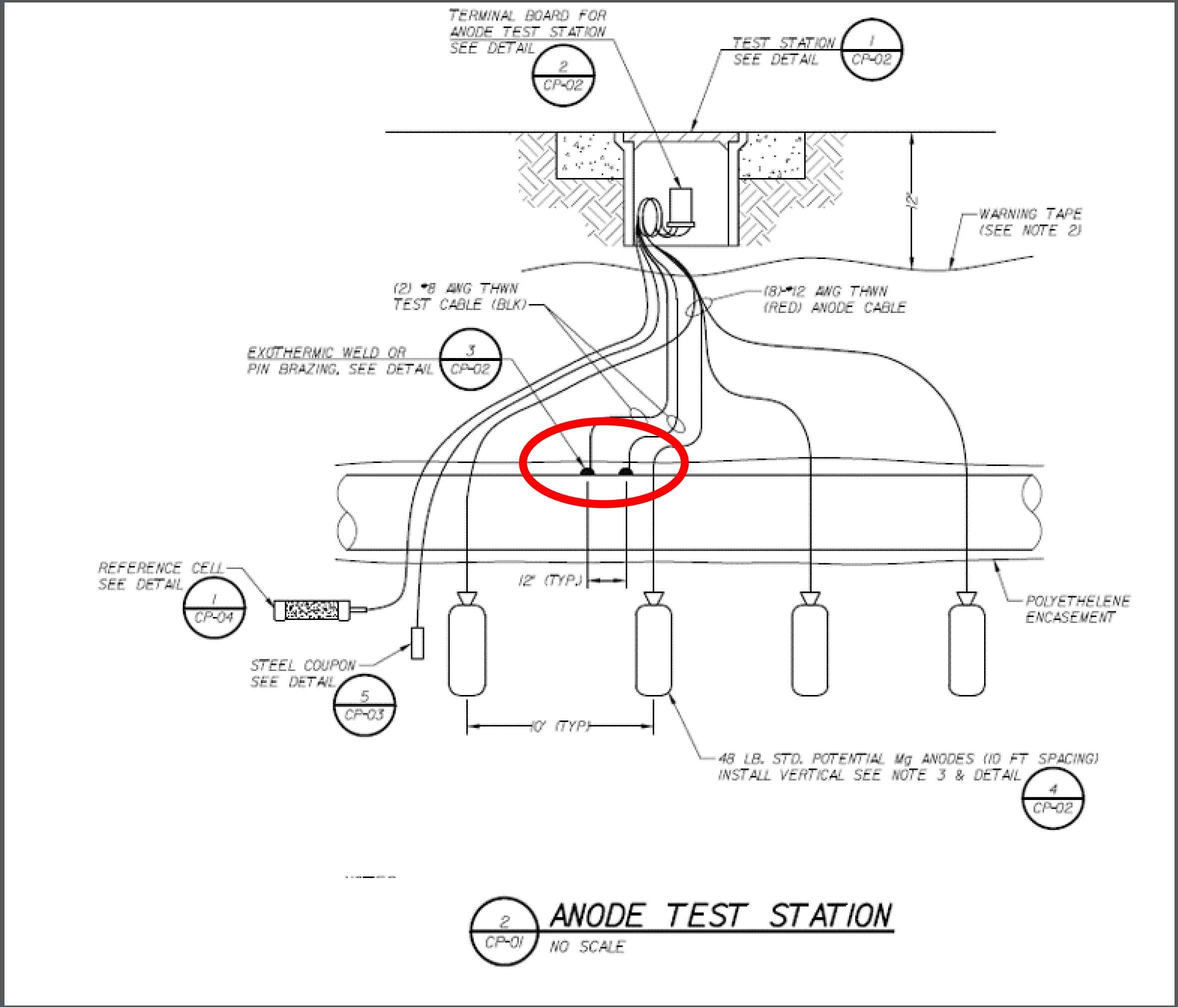
ELECTRICAL ISOLATION



FLANGED JOINT

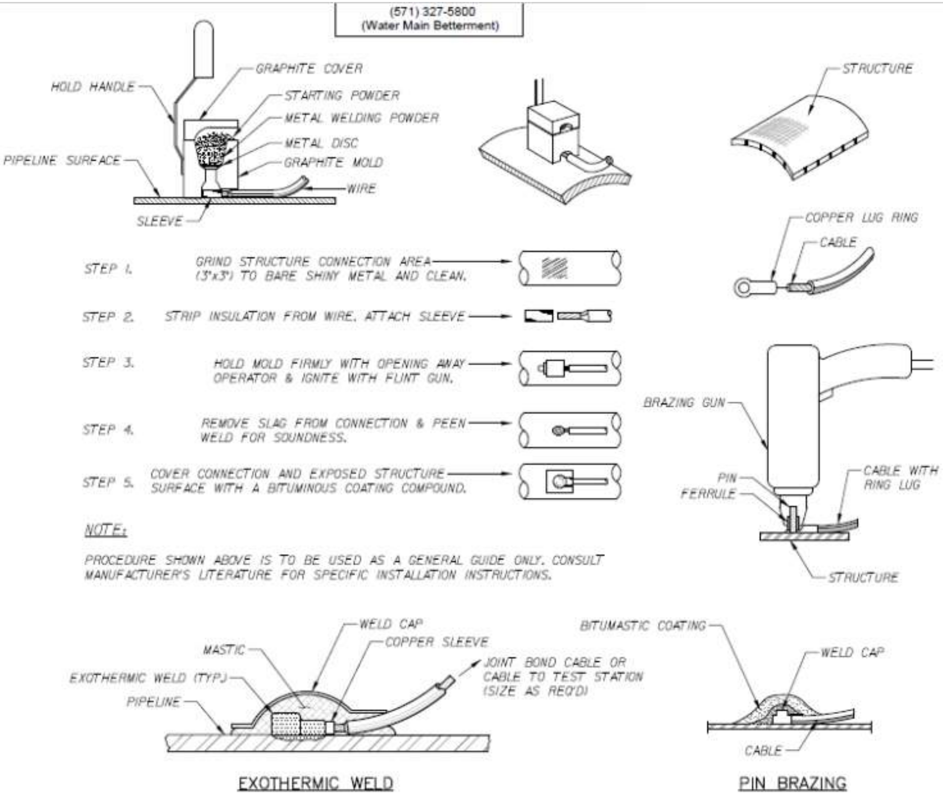
Isolating Flange Kit

Wax Tape

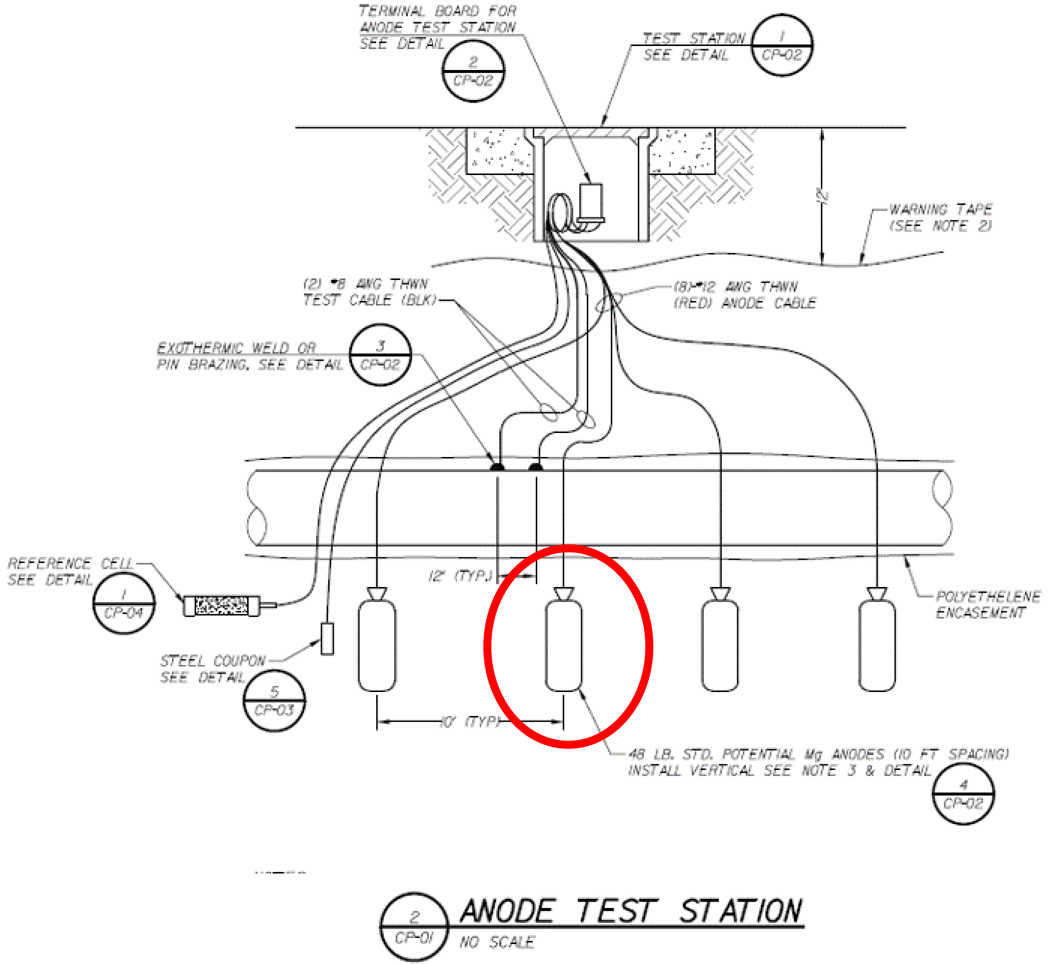


TERMINAL BOARD FOR
ANODE TEST STATION
SEE DETAIL
2
CP-02
TEST STATION
SEE DETAIL
1
CP-02
12"
WARNING TAPE
(SEE NOTE 2)
(2) #8 AWG THWN
TEST CABLE (BLK)
(8)-#12 AWG THWN
(RED) ANODE CABLE
EXOTHERMIC WELD OR
PIN BRAZING, SEE DETAIL
3
CP-02
REFERENCE CELL
SEE DETAIL
1
CP-04
12" (TYP.)
POLYETHELENE
ENCASEMENT
STEEL COUPON
SEE DETAIL
5
CP-03
10' (TYP)
48 LB. STD. POTENTIAL Mg ANODES (10 FT SPACING)
INSTALL VERTICAL SEE NOTE 3 & DETAIL
4
CP-02
2
CP-01
ANODE TEST STATION
NO SCALE

WIRE ATTACHMENT TO PIPE



Referenced from Dr. Rajani (Rajani Consultants Inc.)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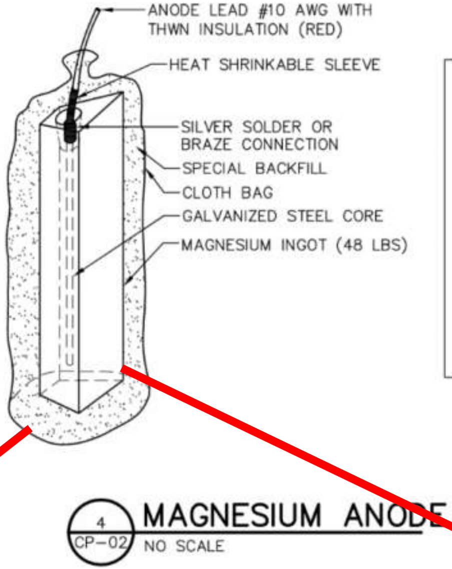
48 LB. STD. POTENTIAL Mg ANODES (10 FT SPACING)
INSTALL VERTICAL SEE NOTE 3 & DETAIL
4
CP-02
2
CP-01
ANODE TEST STATION
NO SCALE

GALVANIC ANODE



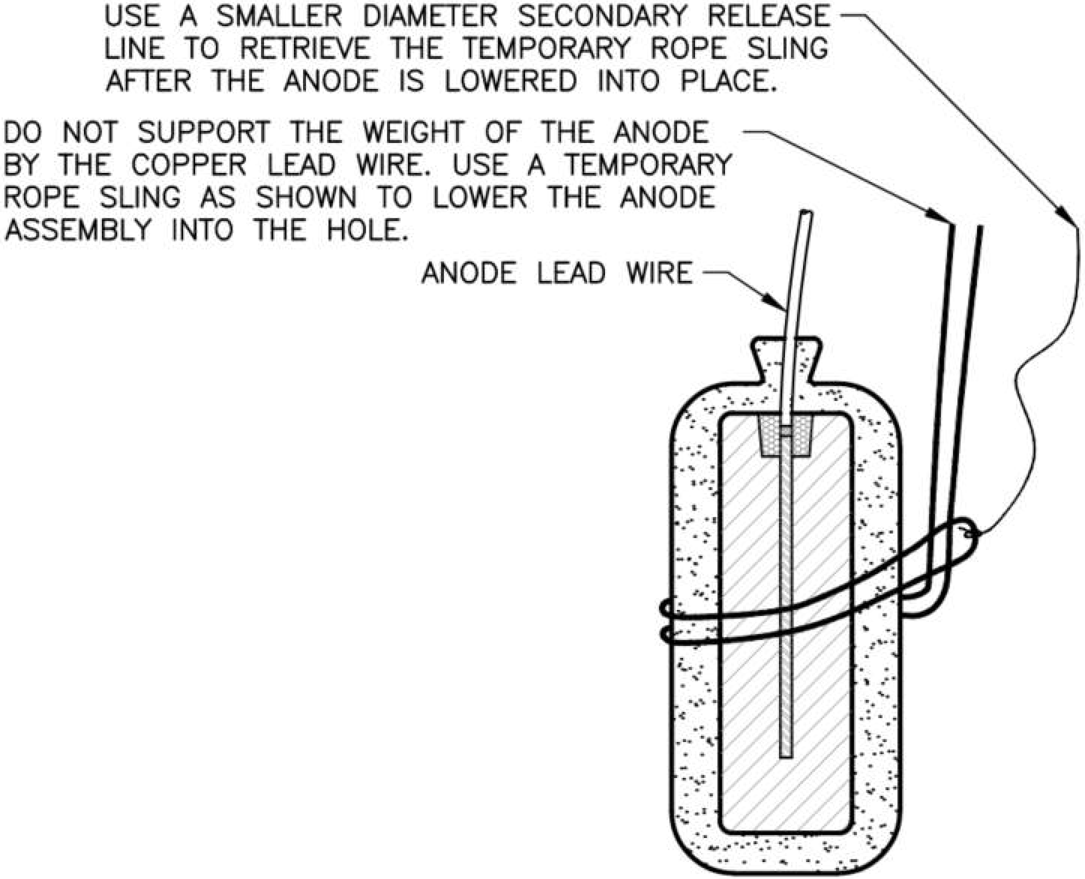
MAGNESIUM ANODE
STANDARD POTENTIAL
Alloy Composition

Element	Weight %
Al	5.3–6.7
Zn	2.5–3.5
Mn	0.15–0.7
Si	0.10 Max
Cu	0.02 Max
Ni	0.002 Max
Fe	0.003 Max
Other	0.3 Total Max
Mg	Balance

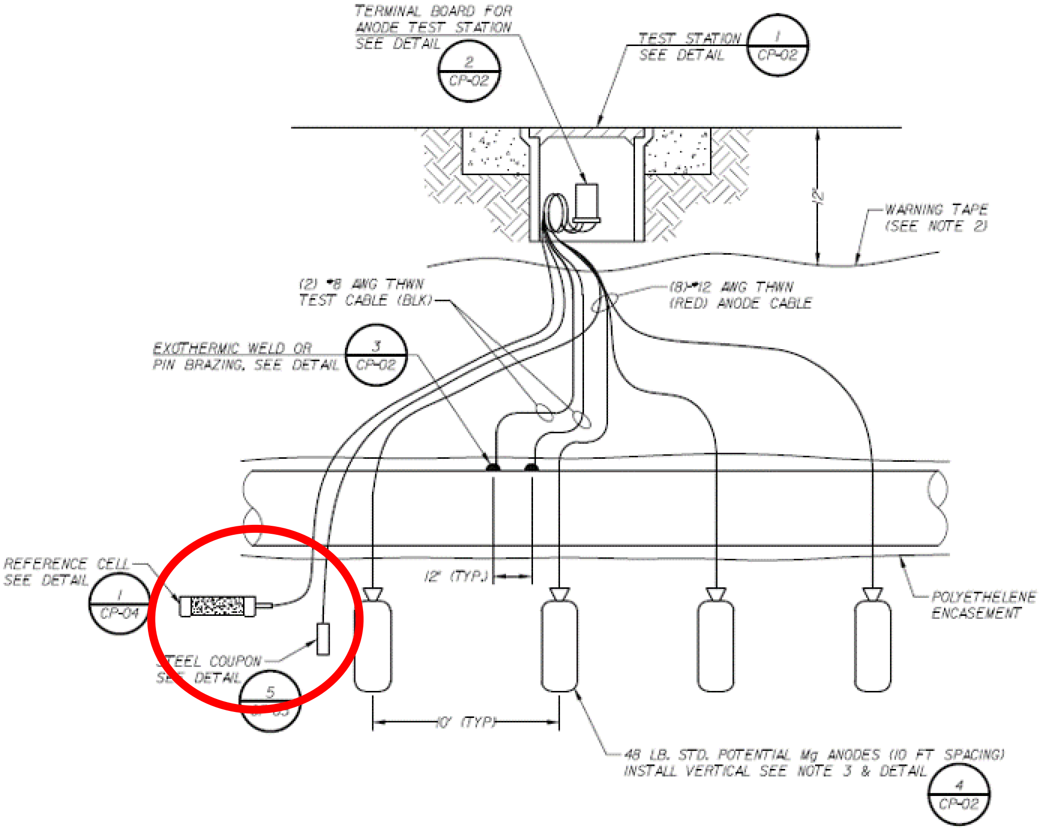
SPECIAL BACKFILL COMPOSITION

75% GYPSUM
20% BENTONITE
5% SODIUM SULFATE

LOWERING ANODES



ANODE LOWERING SLING

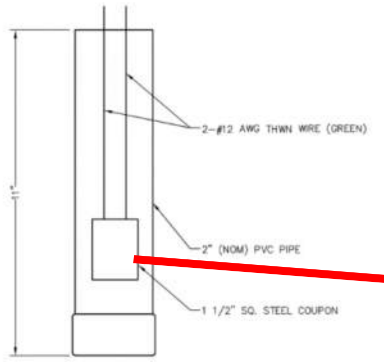


2
CP-01

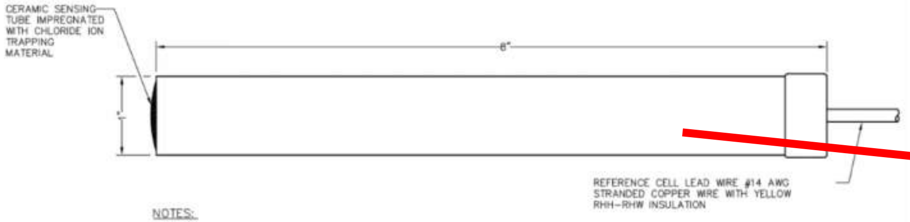
ANODE TEST STATION

NO SCALE

STATIONARY REFERENCE ELECTRODE AND COUPON



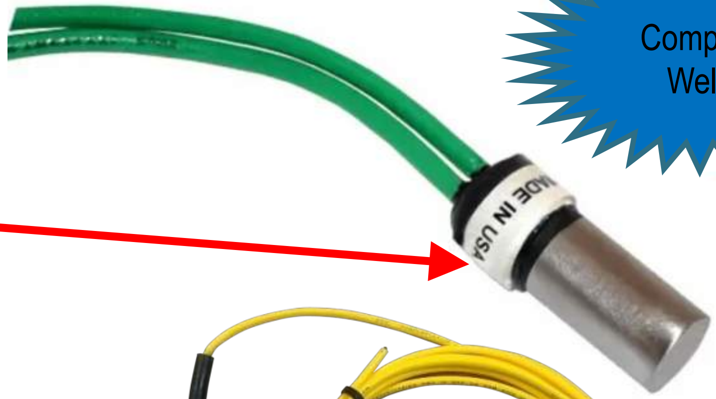
5 CP-03 STEEL COUPON
NO SCALE



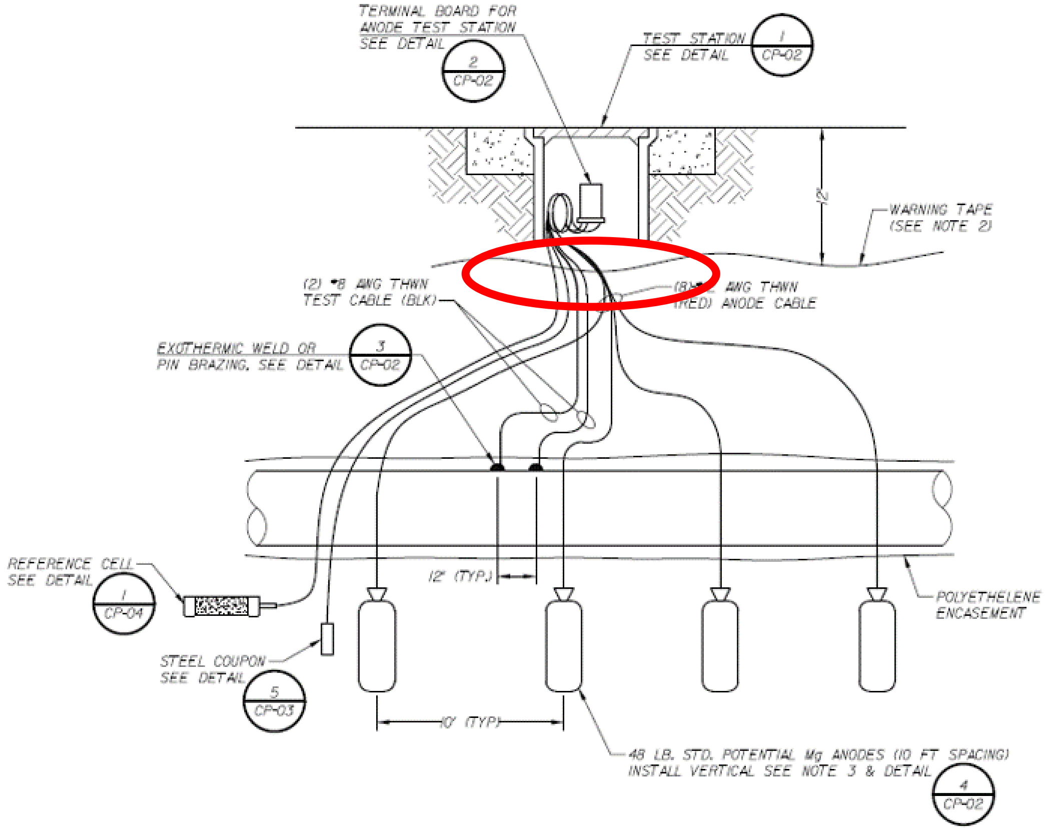
NOTES:

1. REFERENCE ELECTRODE SHALL BE CAPABLE OF MAINTAINING A STABLE POTENTIAL WITHIN PLUS OR MINUS 10 MILLIVOLTS TO THAT OF A FRESHLY MADE COPPER SULFATE REFERENCE ELECTRODE WHILE A 3 MICROAMPERE ELECTRICAL CURRENT IS APPLIED TO IT. PROVIDE STELTH 2 MODEL SRE-002-CFY BY BORIN MANUFACTURING OR STAPERM BY GMC CORROSION, OR APPROVED EQUAL
2. MEASURE THE ACCURACY OF EACH COPPER SULFATE REFERENCE ELECTRODE BEFORE INSTALLING IT BY MEASURING THE DC VOLTAGE DIFFERENCE BETWEEN IT AND ONE OR MORE REFERENCE ELECTRODES OF KNOWN ACCURACY. THE MEASUREMENTS SHALL BE LESS THAN PLUS OR MINUS 0.010 DC VOLTS FOR ALL REFERENCE ELECTRODES. PERFORM THESE MEASUREMENTS AFTER TOTALLY SUBMERGING THE REFERENCE ELECTRODES IN A FIVE-GALLON BUCKET OF WATER FOR A MINIMUM PERIOD OF 15 MINUTES. USE ONLY POTABLE DRINKING WATER FOR THIS TEST. BRACKISH WATER OR SALTWATER WILL AFFECT THE TEST RESULTS AND DAMAGE THE REFERENCE ELECTRODE. PROVIDE FIVE DAYS WRITTEN NOTICE TO THE ENGINEER TO ALLOW THESE TESTS TO BE WITNESSED.

1 CP-04 COPPER SULFATE REFERENCE ELECTRODE
NO SCALE

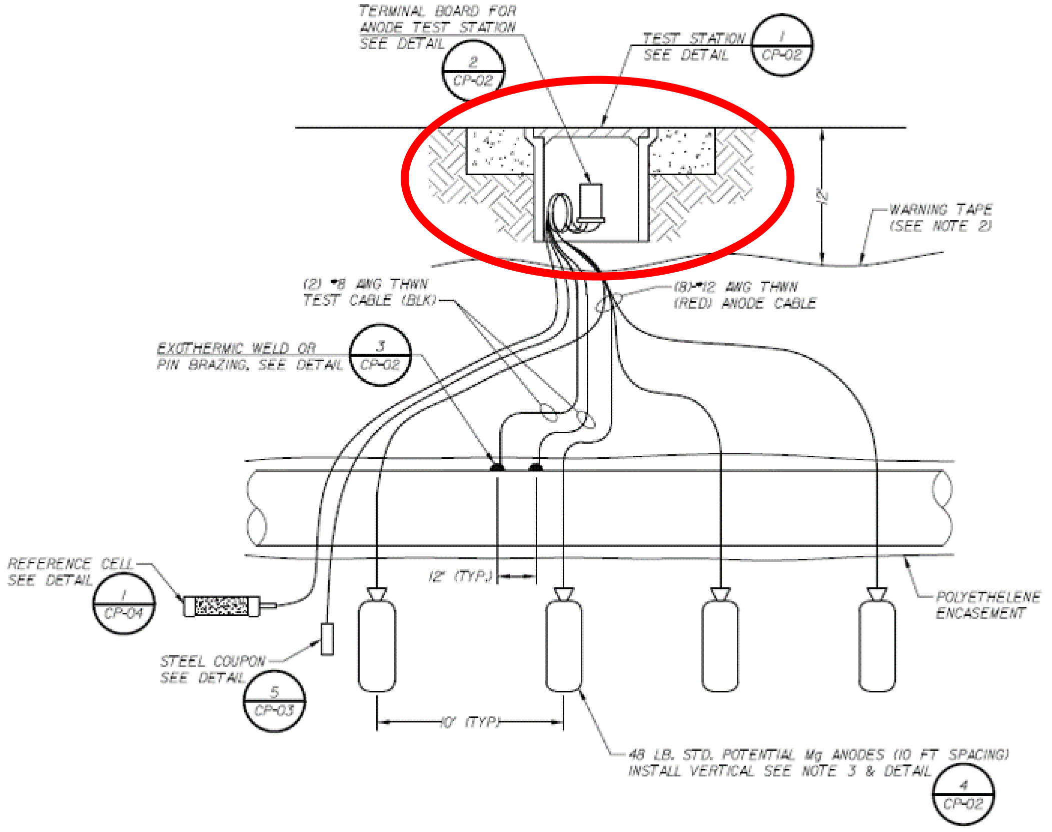


Compact Well!



2
CP-01
ANODE TEST STATION
NO SCALE

WIRE TRENCHING



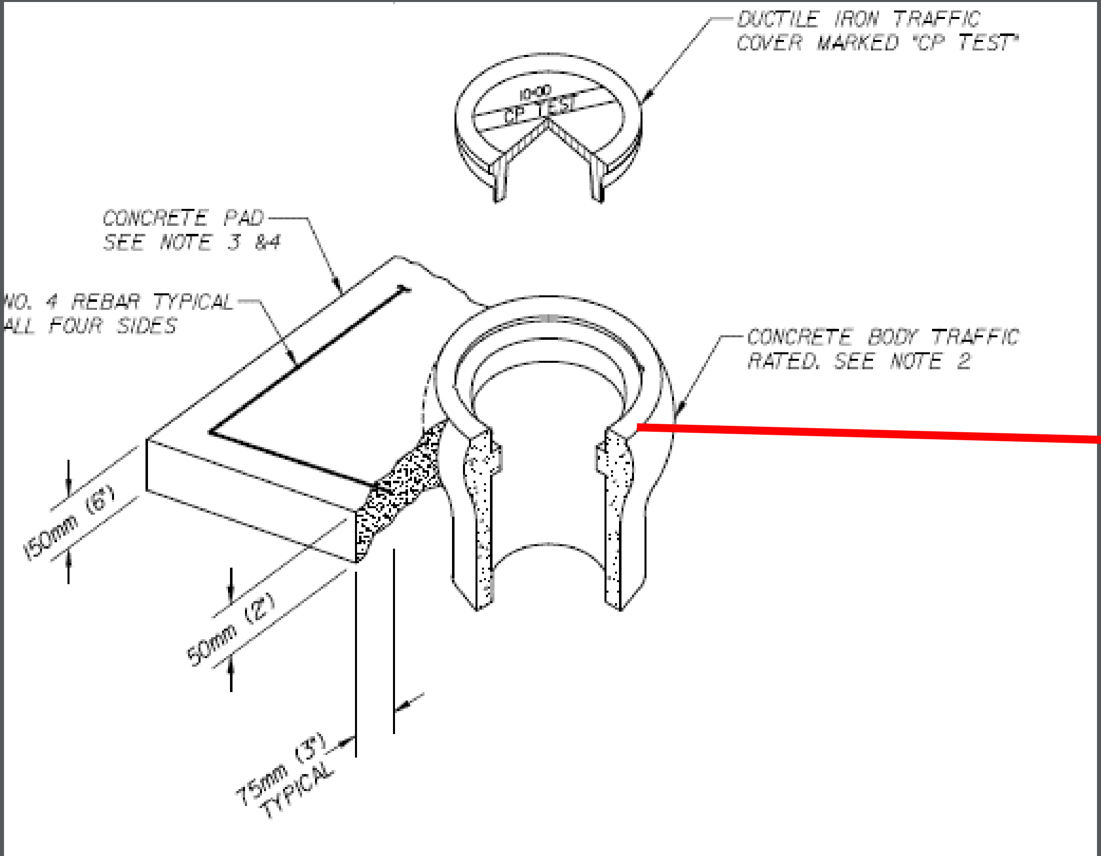
2
CP-01

ANODE TEST STATION

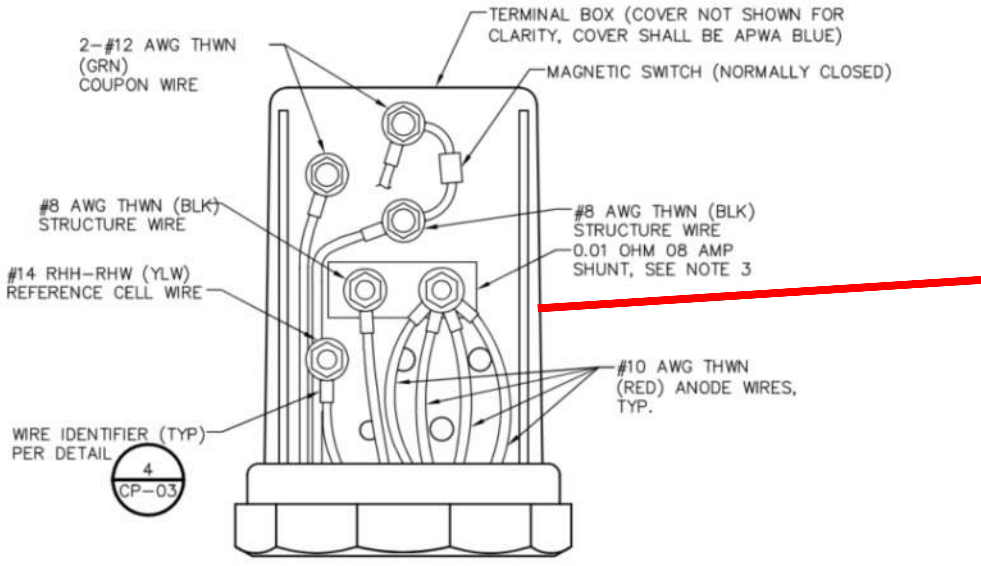
NO SCALE

#170

Test Box / Valve Box (Test Station)



Test Terminal Board (Inside Test Station)

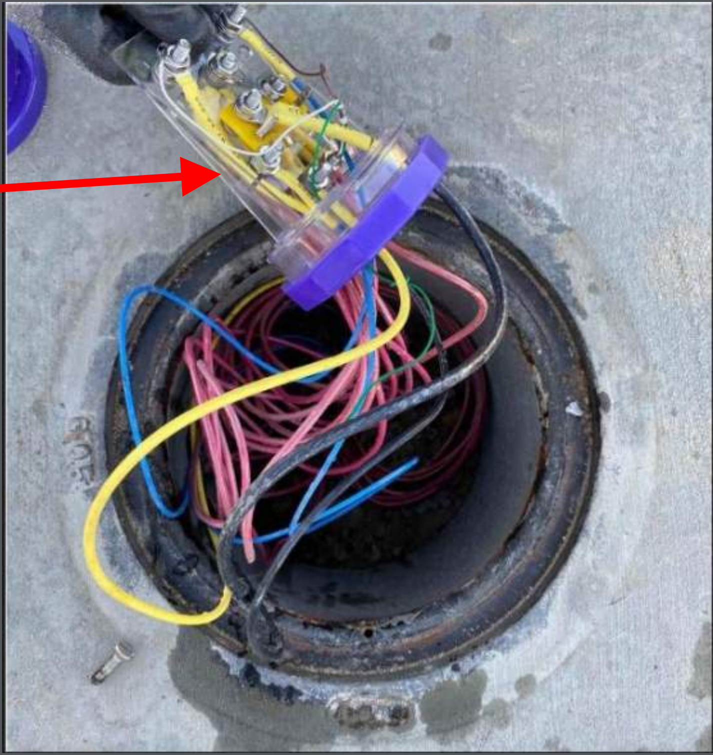


NOTES:

1. NUMBER OF WIRES VARIES. CONNECT EACH WIRE ON A SEPARATE TERMINAL LUG EXCEPT FOR ANODE WIRES.
2. NUMBER OF ANODES VARIES. SEE CTS SCHEDULE ON SHEET CP-04.
3. DO NOT CONNECT SHUNT BETWEEN PIPE AND ANODES DURING CONSTRUCTION. SHUNT TO BE CONNECTED BY THE CONTRACTOR'S CORROSION ENGINEER DURING OPERATIONAL TESTING PER CORROSION CONTROL NOTES 1 THROUGH 3.

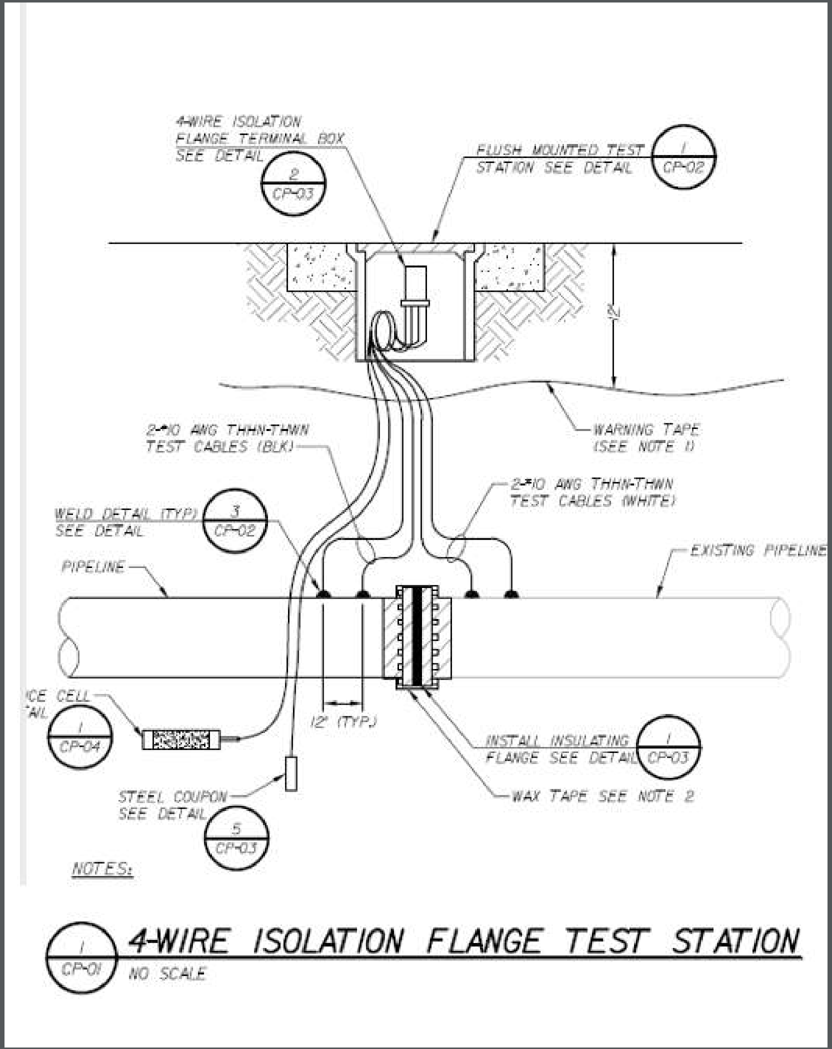
2 / CP-02 TERMINAL BOARD FOR ANODE TEST STATION

NO SCALE

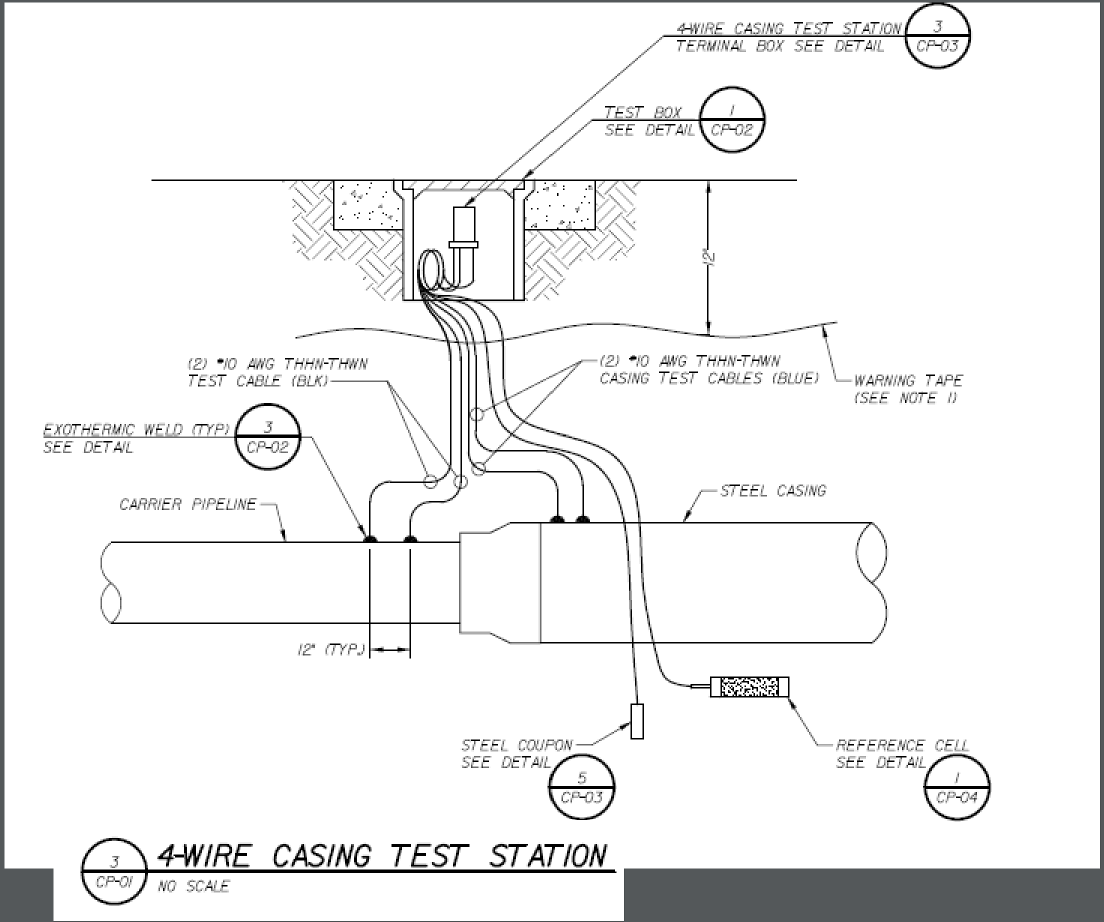


Why This Test Station Setup?

Isolation Tester



Casing Isolation



CTS SCHEDULE				
STATION	DRAWING	TYPE OF TEST STATION	CP DETAIL/SHEET	NO. ANODES
10+00	PP-21(1)	4-WIRE ISOLATION FLANGE TEST STATION	1/CP-01	–
11+39	PP-21(2)	2-WIRE TEST STATION WITH ANODE BED	2/CP-01	6
14+25	PP-21(2)	4-WIRE CASING TEST STATION	3/CP-01	–
15+33	PP-21(2)	4-WIRE CASING TEST STATION	3/CP-01	–
18+39	PP-21(2)	2-WIRE TEST STATION WITH ANODE BED	2/CP-01	6
19+25	PP-21(3)	2-WIRE TEST STATION WITH ANODE BED	2/CP-01	6
22+28	PP-21(3)	4-WIRE ISOLATION FLANGE TEST STATION	1/CP-01	–
23+60	PP-21(3)	4-WIRE ISOLATION FLANGE TEST STATION	1/CP-01	–
26+25	PP-21(4)	2-WIRE TEST STATION WITH ANODE BED	2/CP-01	5
29+00	PP-21(4)	2-WIRE TEST STATION WITH ANODE BED	2/CP-01	5
33+90	PP-21(5)	2-WIRE TEST STATION WITH ANODE BED	2/CP-01	5
34+14	PP-21(5)	4-WIRE ISOLATION FLANGE TEST STATION	1/CP-01	–
34+30	PP-21(5)	4-WIRE ISOLATION FLANGE TEST STATION	1/CP-01	–

3
CP-04

CTS SCHEDULE

NO SCALE

ITEMS TO INCLUDE IN SPECS

- **Materials**
  - Types of GACP anodes
  - At-grade test stations
  - Wires
  - Insulating flange kits
  - Exothermic weld kits
  - Weld coatings
  - Weld caps
  - Pin brazing
  - Reference electrodes
  - Magnetic switch
  - Steel coupon/holder

- **Execution**
  - Test station
  - Anode installation
  - Coating of welds
  - Reference electrode
  - Steel coupon
  - Testing of insulating flanges
  - Electrical isolation testing between pipeline and foreign metallic structures
  - Casing isolation testing
  - Testing of welds
  - Joint bond testing
  - CP test station testing
  - Wax tape coating testing
  - CP activation

SECTION HIGHLIGHTS

Basics of Cathodic Protection

- CP is a polarization phenomena.
- There are two types: galvanic CP and impressed current CP
- NACE SP0169 & SP0285 provide guidance on protection criteria and testing methods.
- There are various case studies showing the effectiveness of CP in controlling/reducing the pipe break/failure rates.
- CP requires electrical continuity for segments to be protected. Most water/wastewater pipelines do not have intentional electrical continuity due to properties of joints.
- WRF 4618, provides excellent guidelines (best practice) for CP retrofit of existing pipelines (even without electrical continuity).

QUESTIONS?

- For additional information, please contact:

- Brien Clark, PE
- Brien.Clark@hdrinc.com

GOOD TIME TO TAKE A BREAK?

LEARNING TOPICS:

- What variables cause the deterioration of piling?
- What are the approaches to reaching a design life?
- What standards and procedures for the estimation of corrosion rates and corrosion allowances?
- What are the options and approaches for corrosion protection of piling?

CORROSION ALLOWANCE FOR PILES

2:45 - 3:45 pm

Typical ASTM Steel Grades

- A572 covers Grades 42, 50, 55, 60, and 65 of high-strength low-alloy columbium-vanadium structural shapes like sheet piles
- A690 covers high-strength low-alloy nickel, copper, phosphorus steel piling for dock walls, bulkheads, excavations (typical in marine environments).
- A588 is a high-strength low-alloy (resistant to atmospheric corrosion over regular carbon steel)
- A123 Hot Dip Galvanized Steel

Reference: The Pile Driving Contractors Association (PDCA)

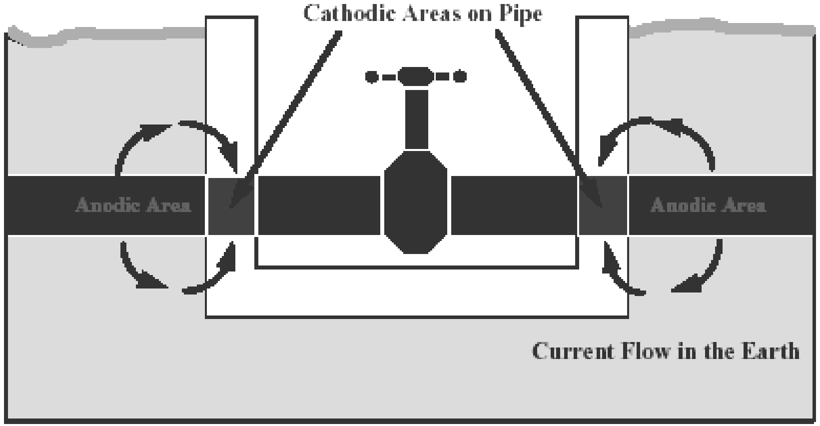
FACTORS CONTRIBUTING TO CORROSION

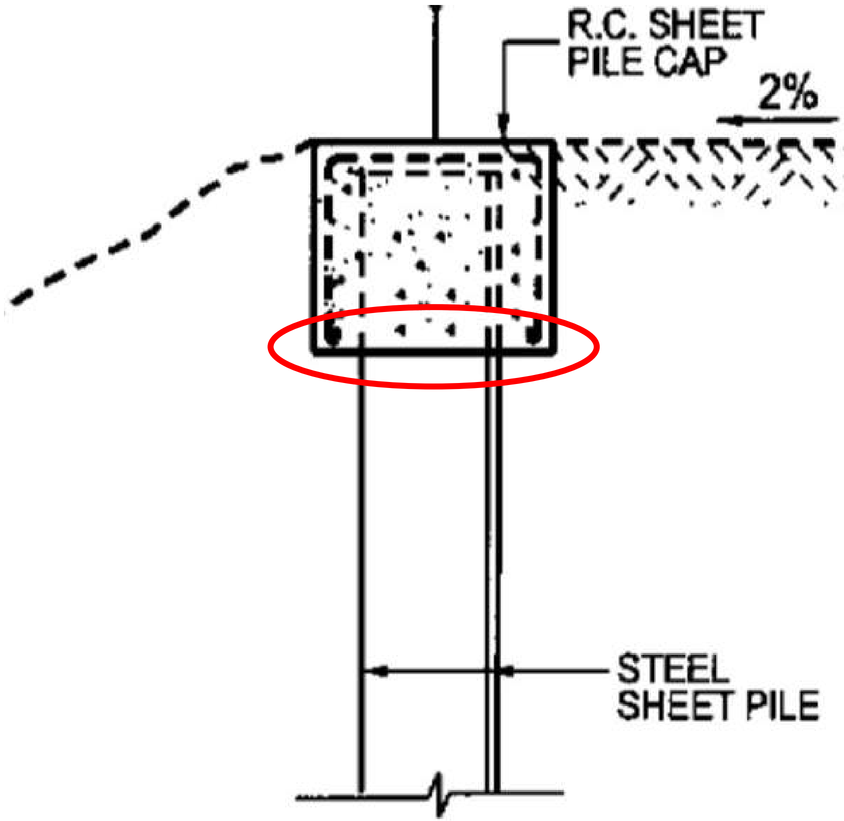
- Presence of soluble salt
- Soil and water electrical resistivity
- Soil and water pH
- Presence of oxygen (e.g., disturbed soil, driving operation)
- Corrosive atmosphere (airborne chloride, pollution, etc)
- Vegetation built up

Picture reference: Causes, Prevention, & Designing for Corrosion Resistance on Sheet Pile Structures ... Form Group | PPT (slideshare.net)

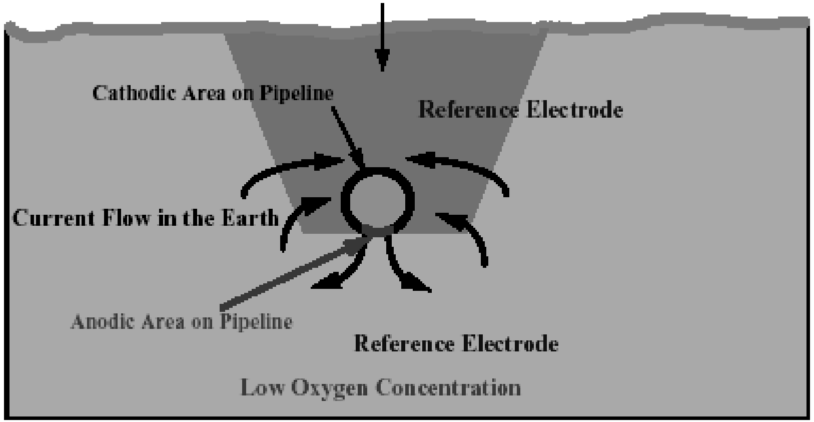
CORROSION CELLS IN PILES
PH DIFFERENTIAL

- Concrete pile caps
  - Need to avoid corrosion cells at transition





CORROSION CELLS DIFFERENTIAL AERATION SHEET PILES



- Different oxygen concentration
- Presence of oxygen (e.g., disturbed soil, driving operation)

AGGRESSIVE ENVIRONMENTS
PILES

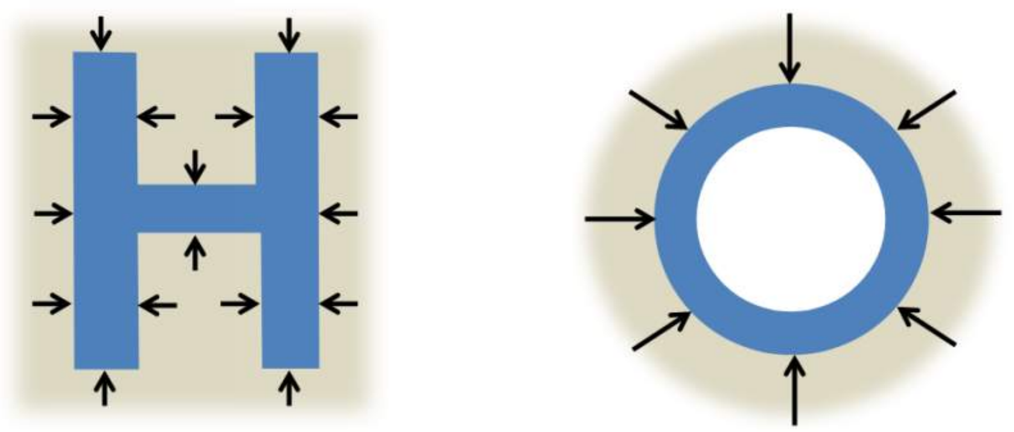
Corrosive Soils:

- High concentration of aggressive ions
- High groundwater
- Low electrical resistivity
- Expansive soils
- Low pH, acidic soils

Discussed in the 9:00 to 10:30 AM session!

SINGLE VS DOUBLE-SIDED CORROSION

- Bare steel pile corrosion
  - H-piles
  - Cylinder piles

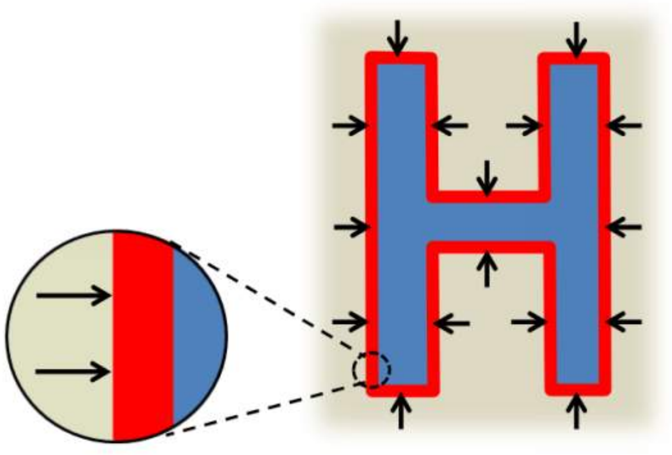


Double-Sided Corrosion

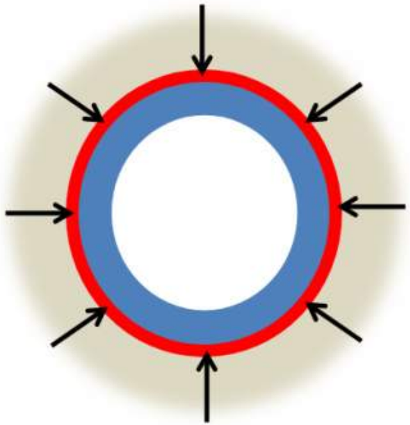
Single-Sided Corrosion

SINGLE VS DOUBLE-SIDED CORROSION

- Galvanized steel pile corrosion
  - H-piles
  - Cylinder piles

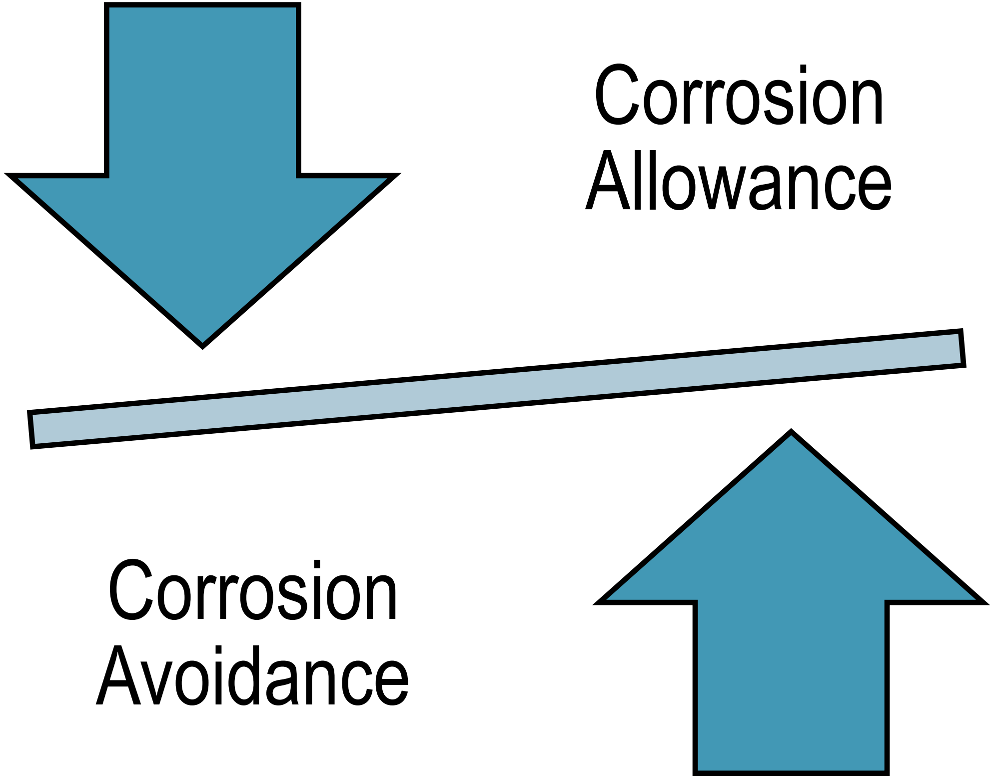


Single-Sided Corrosion



Single-Sided Corrosion

METHODOLOGIES FOR REACHING DESIGN LIFE



Methodologies for Reaching Design Life

Corrosion Allowance vs. Corrosion Avoidance

- Corrosion-allowance relies on information derived from Romanoff (1957) and other modeling to calculate corrosion rates and therefore the amount of steel expected to be lost over the infrastructure performance period.

→ Additional steel thickness is used to meet the corrosion loss over a defined period

METHODOLOGIES FOR REACHING DESIGN LIFE

CORROSION ALLOWANCE VS. CORROSION AVOIDANCE

- Corrosion prevention relies on functionality of different types of physical barriers (e.g., coatings, concrete encasement) and cathodic protection systems and monitoring those systems.

→ Requires installation of coatings / encasements/ cathodic protection

CORROSION ALLOWANCE (DIFFERENT STANDARDS, GUIDELINES)

Caltrans

The Department currently uses the following corrosion rates for steel piling exposed to corrosive soil and/or water or marine exposures (see Section 6 of these Guidelines) as specified in ***Section 10.7.5*** of ***Section 10: Foundations of California Amendments (to the AASHTO LRFD Bridge Design Specifications)*** (see References).

Soil Embedded Zone	**0.001 in (0.025 mm) per year**
Fill or Disturbed Natural Soils	**0.0015 in (0.0381mm) per year**
Atmospheric Zone (marine)	**0.002 in (0.051 mm) per year**
Immersed Zone (marine)	**0.004 in (0.102 mm) per year**
Splash Zone (marine)	**0.006 in (0.152 mm) per year**

FDOT

2.3.1 Substructure for the conditions of the soil and/or water:

A. Slightly Aggressive when **all** of the following conditions exist:
   1.) pH greater than 6.6.
   2.) Resistivity greater than 3,000 ohm-cm.
   3.) Sulfates less than 150 ppm.
   4.) Chlorides less than 500 ppm.

B. Moderately Aggressive: This classification shall be used at all sites not meeting requirements for either Slightly Aggressive or Extremely Aggressive Environments.

C. Extremely Aggressive when **any one** of the following conditions exists:
   1.) For concrete structures: pH less than 5.0.
   2.) For steel structures: pH less than 6.0.
   3.) Resistivity less than 500 ohm-cm.
   4.) Sulfates greater than 1,500 ppm.
   5.) Chlorides greater than 2,000 ppm.

FDOT rates for partially buried pile:

0.001 inch/year

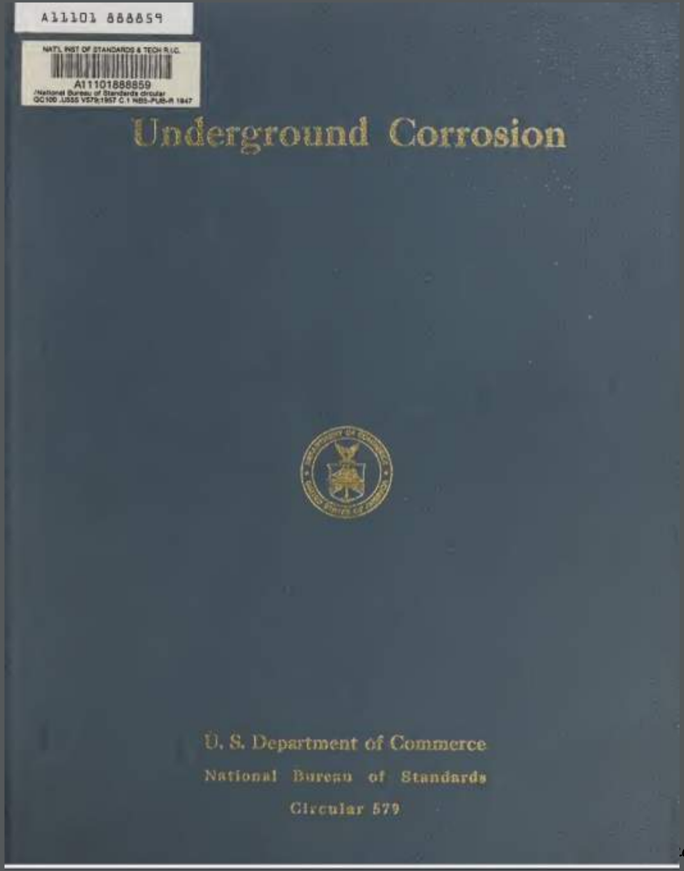
0.002 inch/year

0.003 inch/year

Corrosion Allowance (Different Standards, Guidelines)

Romanoff:

- A similitude analysis -using a corrosion database compiled by Melvin Romanoff (National Bureau of Standards - Circular 579 entitled Underground Corrosion)
- Considers: electrical resistivity values, pH, chloride, sulfate concentrations, geographic location, and site drainage conditions
- Estimated corrosion rates in mils/year (mpy)
- Limitation and need for Corrosion Safety Factor:
  - The limited nature of the reference used to conduct the similitude
  - Analysis considers samples buried at particular locations over a discrete timeframe
  - Various local corrosion effects that cannot be easily modeled (e.g, dissimilar metal contacts, MIC, etc)



Romanoff

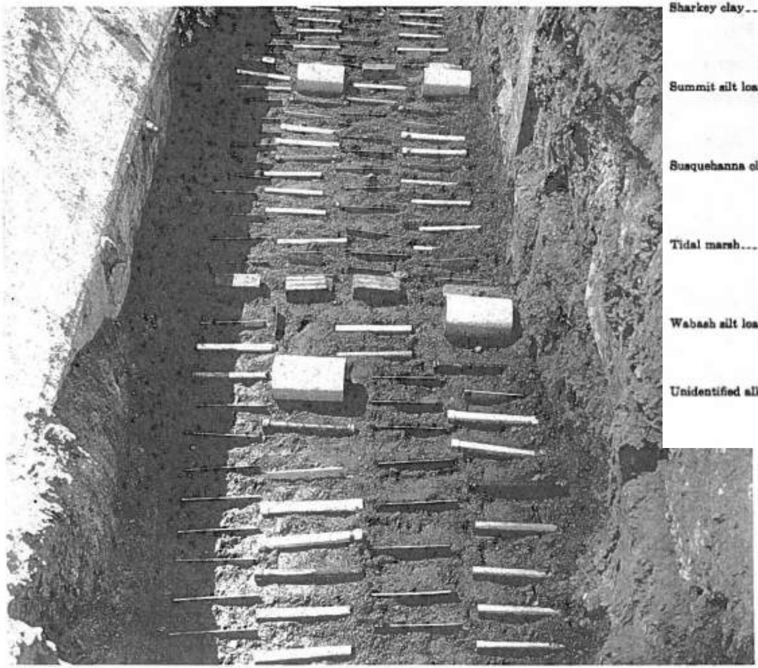


Figure 7. *Arrangement of specimens buried in cinders at Milwaukee, Wis., in 1937.*

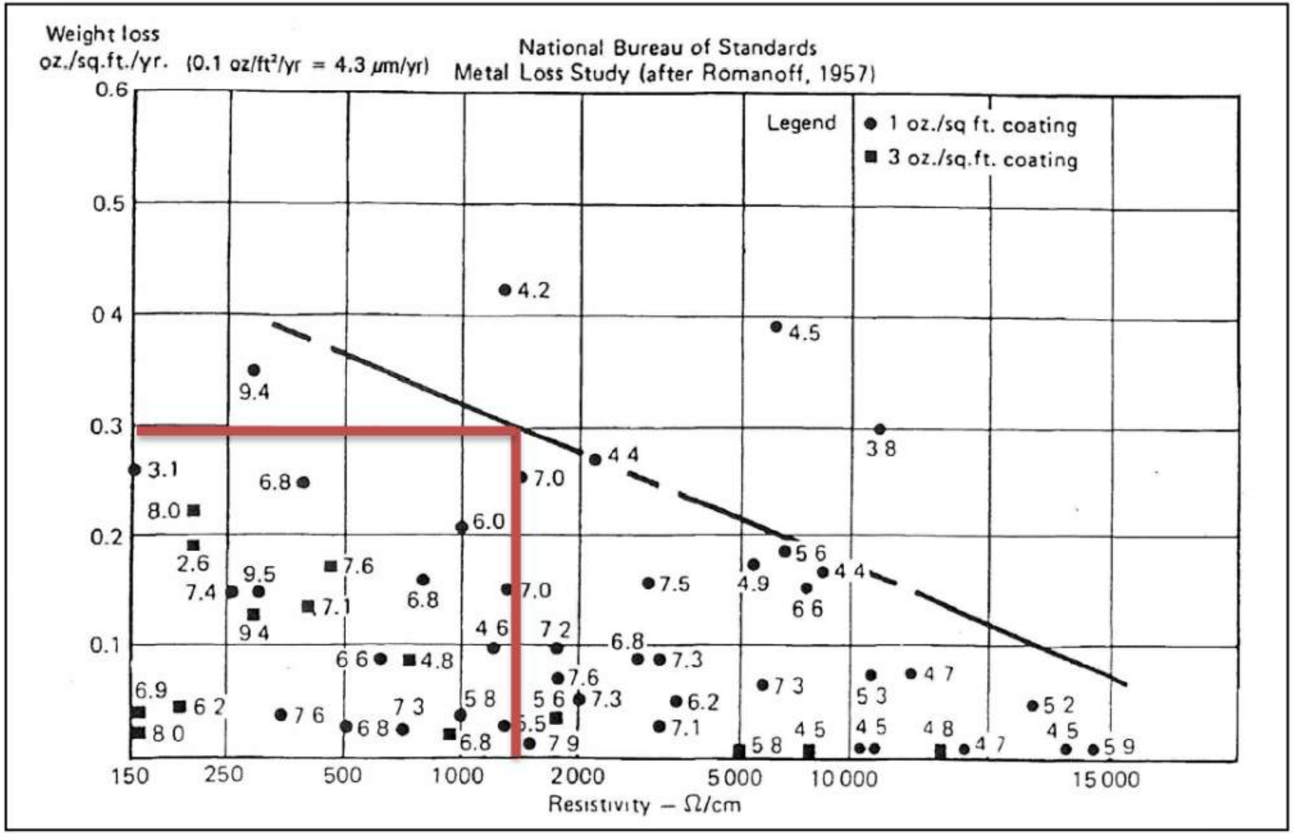
Table 13. *Loss in weight and maximum penetration of wrought black ferrous pipe buried in 1922* [a, b]—Continued

(Average of two specimens)

Soil type	Duration of exposure	Loss in weight (oz/ft²), 1½-in. pipe: Open-hearth iron (a)	1½-in.: Wrought iron (b)	1½-in.: Bessemer steel (e)	1½-in.: Bessemer steel (scale-free) (y)	3-in. pipe: Wrought iron (B)	3-in.: Open-hearth steel (K)	3-in.: Bessemer steel (M)	3-in.: Open-hearth steel with 0.22 percent Cu (Y)	Maximum penetration (mils), 1½-in. pipe: Open-hearth iron (a)	1½-in.: Wrought iron (b)	1½-in.: Bessemer steel (e)	1½-in.: Bessemer steel (scale-free) (y)	3-in. pipe: Wrought iron (B)	3-in.: Open-hearth steel (K)	3-in.: Bessemer steel (M)	3-in.: Open-hearth steel with 0.22 percent Cu (Y)
	Years																
Sharkey clay	2.0	2.1	2.1	2.1	2.0	2.3	2.5	2.2	2.8	46	28	38	31	28	41	32	42
	4.1	4.0	4.3	3.9	3.7	4.2	4.3	4.6	4.2	61	52	43	35	41	46	44	46
	6.0	5.4	5.5	5.0	5.3	6.1	6.6	6.1	5.6	61	69	70	60	65	88	74	84
	8.0	6.4	6.5	6.5	5.5	7.0	7.1	8.2	7.7	86	101	64	74	70	99	96	92
	10.0	6.9	7.2	7.3	6.0	8.1	7.2	9.3	7.5	75	62	87	62	65	72	64	86
	12.0	6.9	7.9	7.2	6.7	8.6	8.6	7.0	8.3	139	68	69	82	69	91	78	75
Summit silt loam	1.5	0.8	0.5	0.5	1.0	0.6	0.6	0.4	0.4	19	39	33	40	44	30	42	32
	4.0	2.7	3.6	3.0	3.0	2.7	2.9	2.4	2.5	34	36	40	45	47	38	43	46
	6.0	4.6	4.7	4.5	4.2	3.2	3.6	4.1	3.9	53	50	48	60	55	52	67	52
	7.9	4.8	5.4	5.0	4.7	4.2	4.2	4.6	4.4	61	65	55	60	58	58	62	56
	12.0	6.0	6.2	6.3	5.3	6.5	6.3	6.0	6.0	101	94	79	91	86	72	85	80
	17.4	5.9	7.4	6.9	7.0	5.5	5.5	7.0	7.0	122	94	92	101	86	67	101	78
Susquehanna clay	2.0	3.0	3.6	3.3	3.1	2.9	2.4	2.9	1.9	53	58	59	50	54	62	78	55
	4.1	4.5	7.3	5.7	5.9	4.8	3.4	5.1	3.4	64	74	73	76	79	85	82	74
	6.0	7.0	8.0	7.7	7.3	5.7	6.9	6.2	6.6	77	92	84	74	78	86	95	81
	8.0	5.9	7.7	8.2	9.3	6.4	6.8	6.7	5.6	76	89	113+	111+	80	93	88	90
	10.1	11.5	10.6	12.1	12.5	8.8	11.1	9.3	9.2	84	84	104	92	96	129	103	104
	12.0	10.6	17.1	12.5	17.4	8.9	11.2	11.0	13.4	94	89	111	86	88	125	92	116
Tidal marsh	1.3	1.4	1.7	1.9	2.8	2.0	2.2	2.3	2.4	18	36	24	28	44	45	66	47
	4.1	3.6	7.2	4.6	4.8	4.7	5.2	6.9	6.4	39	44	35	46	101	79	83	59
	6.2	5.8	8.0	9.7	7.4	7.2	6.2	7.7	8.3	88	82	67	76	104	132	119	53
	8.0	9.1	15.3	10.3	11.4	10.1	10.8	9.0	14.4	84+	102+	76	70	116	136	78	90
	9.9	11.6	11.4	10.5	17.0	10.4	11.2	9.8	12.0	94	76	70	73	186	100	116	155
	12.0	15.5	16.6	19.5	17.6	14.1	12.7	13.1	16.3	90	80	100	105	138	78	74	72
Wabash silt loam	1.1	0.3	0.6	0.4	0.5	0.4	0.3	0.4	0.4	38	36	28	32	26	39	32	38
	3.6	1.4	1.8	2.0	1.8	1.4	1.4	1.2	1.3	78	43	54	55	46	44	44	50
	5.7	2.3	2.2	2.3	2.4	2.1	2.2	2.0	2.0	70	52	51	66	56	72	60	68
	7.6	1.7	2.3	2.2	2.0	1.9	2.1	2.0	2.1	72	49	62	50	56	50	62	88
	11.6	2.9	4.1	4.7	3.5	3.4	2.8	3.4	3.2	87	56	63	69	65	58	82	74
Unidentified alkali soil	1.2	1.2	1.4	1.4	1.3	1.1	1.0	1.7	1.4	<10	20	15	13	<10	17	30	28
	3.8	3.6	3.0	2.9	3.3	2.9	3.2	2.8	3.3	36	28	24	24	32	36	31	49
	5.8	2.9	3.2	2.3	3.1	3.3	3.1	3.2	3.0	45	43	40	34	47	36	48	52
	7.7	3.5	[4]5.6	4.2	3.8	4.1	3.9	3.8	4.2	50	[4]46	60	45	56	60	60	66
	9.8	13.7	11.9	11.9	12.1	12.5	13.1	12.3	13.5	143	114	138	117	118	138	128	158
	11.7	9.7	9.0	9.7	9.3	10.6	11.3	9.3	11.2	82	78	84	82	85	112	98	124
	1.5	0.8	1.3	1.2	0.9	1.0	1.1	1.2	1.2	57	54	55	54	50	40	56	79

MA (2024)

Romanoff



Zinc loss vs. Resistivity

Corrosion Allowance (Different Standards, Guidelines)

AMPP SP 21460 Prescriptive Rates:

AMPP SP 21460-2022

- Aggressive disturbed soil is 3.14 mils/side/year
- Undisturbed soil without the presence of groundwater 0.41 mils/side/year

3.6.3.2	For fill soils and other industrial soils:
3.6.3.2.1	For non-aggressive disturbed soils, corrosion rates of 0.025 mm/side/year (1.0 mils/side/year) shall be used unless an engineering evaluation of the soil conditions shows that a different corrosion rate can be expected. (EN 1993-5).
3.6.3.2.2	For aggressive disturbed soils, a corrosion rate of 0.08 mm/side/year (3.14 mils/side/year) shall be used unless an engineering evaluation of the soil conditions shows that a different corrosion rate can be expected. (EN 1993-5).

AMPP

AMPP SP21460-2022
Approved December 14, 2022

Corrosion Control of Pilings in Non-marine Applications

AMPP SP21460-2022

Corrosion Allowance (Different Standards, Guidelines)

British Standard BS EN 1993-5:2007
prescriptive corrosion rates

Table 4.1 – Loss of thickness (mm) per face due to corrosion of bearing piles and sheet piles in soils, with or without groundwater

Required design working life	5 years	25 years	50 years	75 years	100 years	125 years
Undisturbed natural soils (sand, silt, clay, schist…)	0,00	0,30	0,60	0,90	1,20	1,50
Polluted natural soils and industrial sites	0,15	0,75	1,50	2,25	3,00	3,75
Aggressive natural soils (swamp, marsh, peat…)	0,20	1,00	1,75	2,50	3,25	4,00
Non-compacted and non-aggressive fills (clay, schist, sand, silt…)	0,18	0,70	1,20	1,70	2,20	2,70
Non-compacted and aggressive fills (ashes, slag…)	0,50	2,00	3,25	4,50	5,75	7,00

NOTE 1 Corrosion rates in compacted fills are lower than those in non-compacted ones. In compacted fills the figures in the table should be divided by two.

NOTE 2 The values given for 5 years and 25 years are based on measurements, whereas the other values are extrapolated.

neters described in BS EN 1993-5:2007 *(continued)*

UK decision

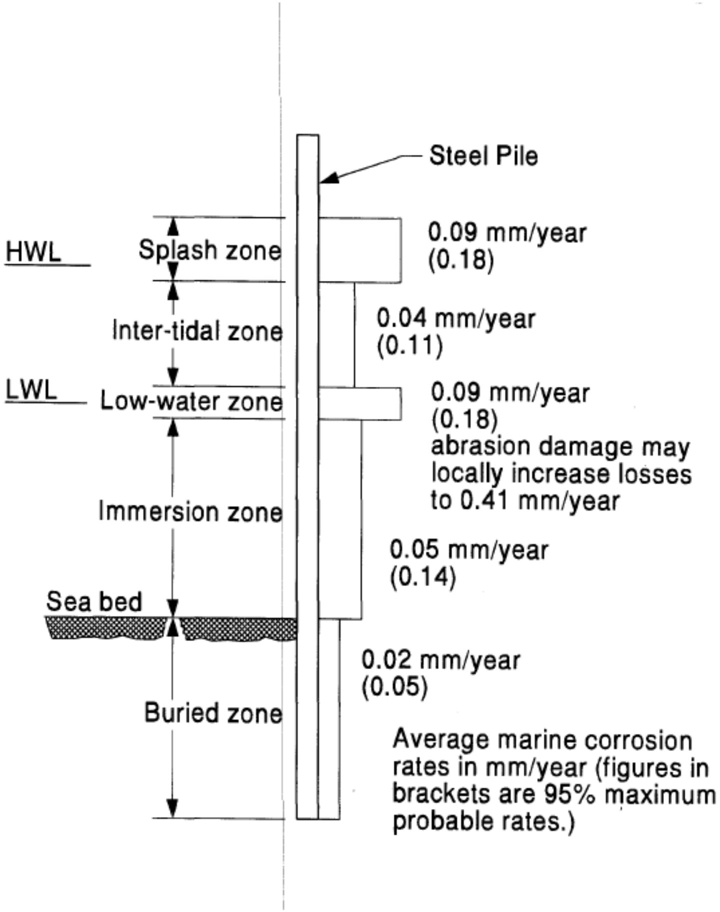
Table 4.2 – Loss of thickness (mm) per face due to corrosion of bearing piles and sheet piles in fresh water or seawater

Required design working life	5 years	25 years	50 years	75 years	100 years	125 years
Common fresh water (river, ship canal) in the zone of high attack (water line)	0,15	0,55	0,90	1,15	1,40	1,65
Brackish or very polluted fresh water (sewage, industrial effluent…) in the zone of high attack (water line)	0,30	1,30	2,30	3,30	4,30	5,30
Sea water in temperate climates in the high tide splash zone or in the low water zone (see Note 3)	0,55	1,90	3,75	5,60	7,50	Protection system required
Sea water in temperate climates in the zone of permanent immersion or in the intertidal zone	0,25	0,90	1,75	2,60	3,50	4,40

BS NA EN 1993-5 (2007) (English): UK National Annex to Eurocode 3: Design of steel structures.
Piling

Corrosion Allowance (Different Standards, Guidelines)

Federal Highway and Administration (FHWA)
Design and Construction of Driven Pile Foundations



MA (2024)

ATMOSPHERIC-CORROSIVITY

- Corrosivity categories defined by ISO 12944

Category		Examples of typical environments, exterior
C1	Very low	-
C2	Low	Atmospheres with low level of pollution. Mostly rural areas.
C3	Medium	Urban and industrial atmospheres, moderate sulphur dioxide pollution. Coastal areas with low salinity.
C4	High	Industrial areas and coastal areas with moderate salinity.
C5-I	Very high (industrial)	Industrial areas with high humidity and aggressive atmosphere.
C5-M	Very high (marine)	Coastal and offshore areas with high salinity.

CORROSION MITIGATION
PROTECTIVE COATINGS

- Traditional coal tar epoxy
- Newer systems:
- One or two primers followed by a top coat.
    - A zinc primer is often chosen
    - The topcoat for chemical resistance/ UV/ abrasion
- Epoxies (Polyamide and Flake reinforced)
- Polyurethane
- MCU Coal tar
- Galvanization
- Duplex coating system (hot dipped galvanized and paint)

- Shop application vs. field application

Picture source: Fusion Bonded Powder Coating for Reinforcement Bars (lanscoatings.com)

CORROSION MITIGATION
PROTECTIVE COATINGS

Critical factors for successful use of coatings for piles

- Pre-surface preparation
- Post-surface preparation
- Proper application tools
- Experienced applicator
- Quality control during and after application
- Ambient condition control
- Quality control and proper application of abrasives

Mostly shop-applied coatings with field touch-ups

Photo reference: Fusion Bonded Powder Coating for Reinforcement Bars (lanecoatings.com)

MA (2024)

CORROSION MITIGATION
PROTECTIVE COATINGS

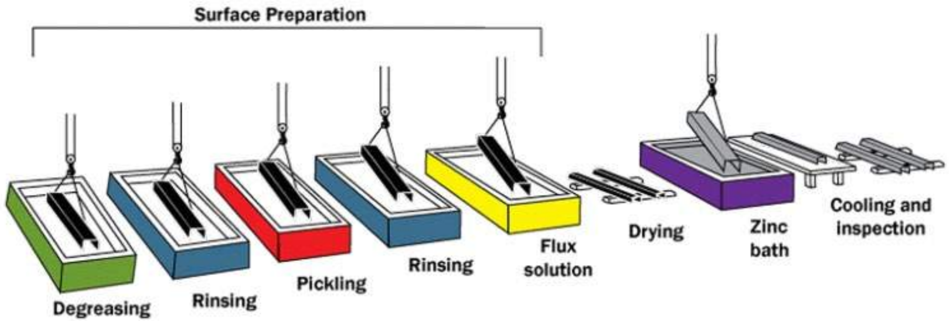
- Case Study:
  - Extracted driven pile
  - Coating damage was not as severe as expected

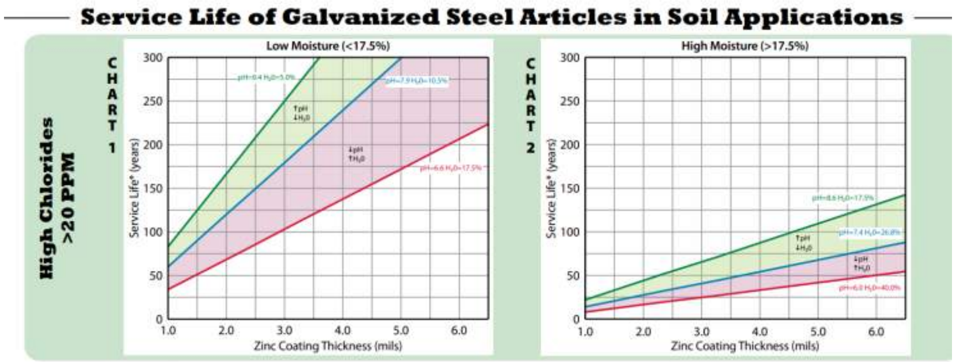
MA (2024)

CORROSION MITIGATION
PROTECTIVE COATINGS

Hot dipped galvanized coating
ASTM A123

- Galvanizing provides a barrier
- Zinc provides cathodic protection
- Recommended for non-tidal, fresh water applications
- Good atmospheric corrosion protection





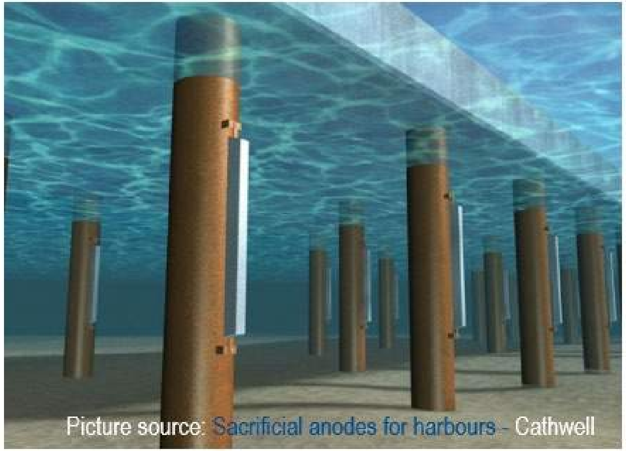
Reference: https://galvanizeit.org/

MA (2024)

CORROSION MITIGATION
CATHODIC PROTECTION

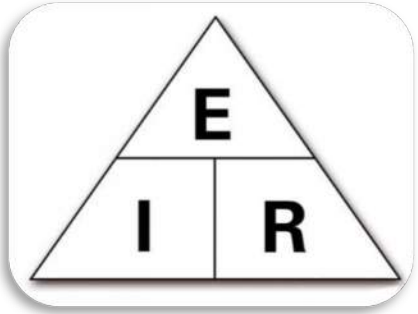
- Basic Types of CP
  - -Galvanic
  - -Conventional Impressed Current

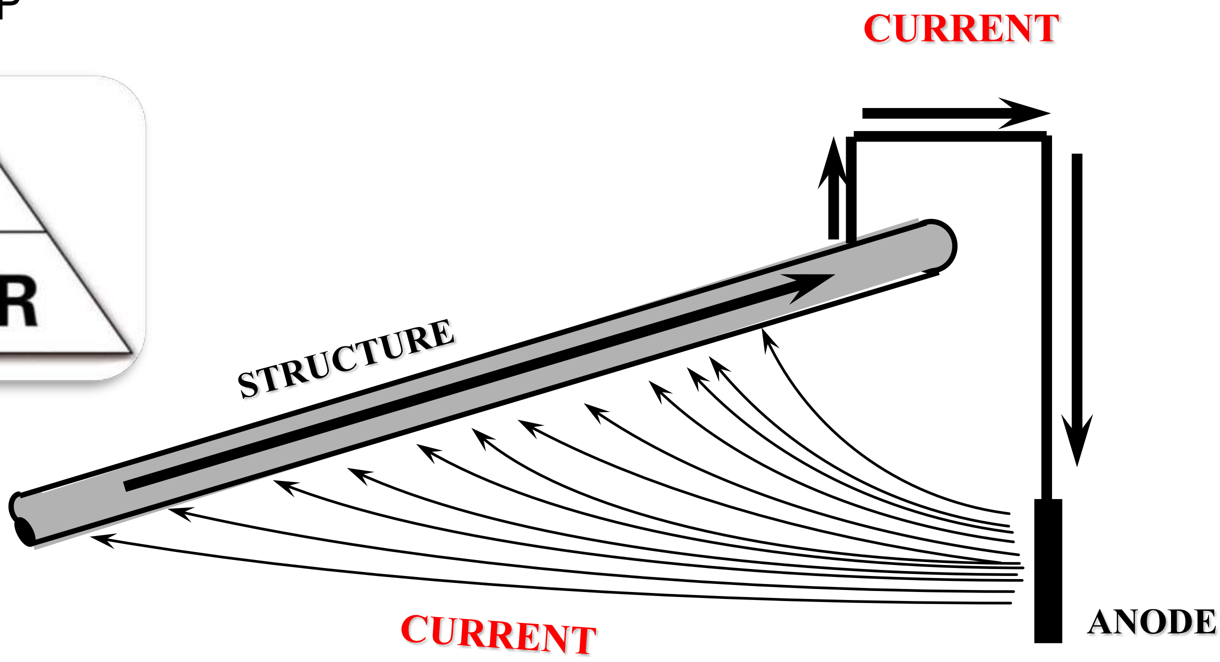
Discussed in 12:45 - 1:30 pm session



HOW CP WORKS…

- Galvanic CP

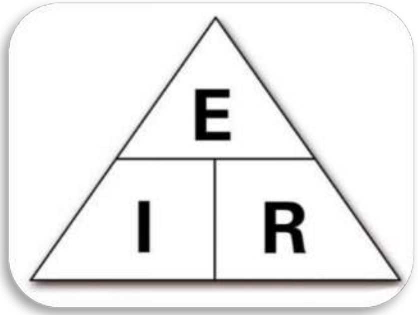


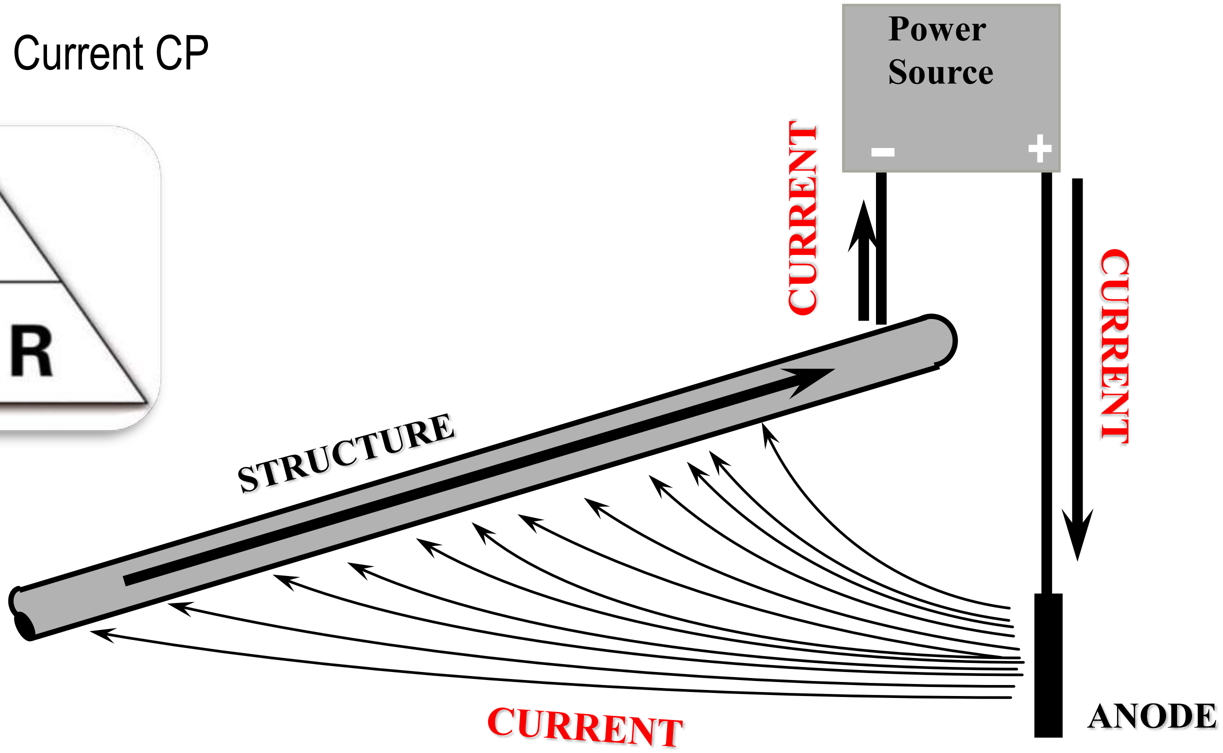


MA (2023)

HOW CP WORKS…

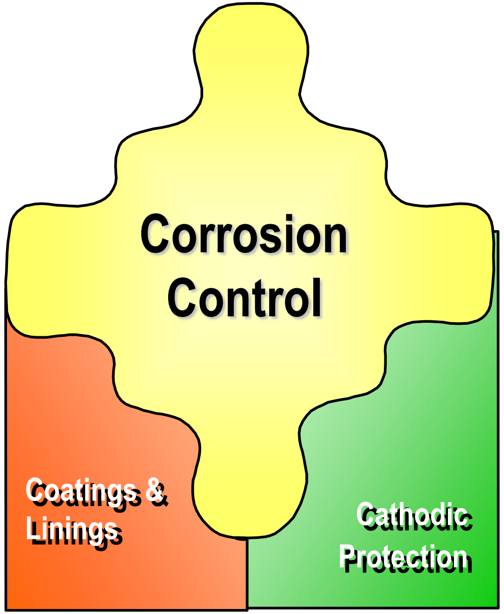
- Impressed Current CP





CORROSION MITIGATION

Cathodic Protection Compliments and Supplements Coatings



- CP protects the uncoated or damaged metal
- Coatings reduce the CP current needed

NACE RP0388-95:
If water is sufficiently corrosive to justify the use of coatings, then cathode protection is justified and provides a greater degree of protection than when either method is used alone.

AWWA D104-97:
The combination of coatings and cathodic protection maybe more economical and effective than using coatings or cathodic protection alone.

MA (2024)

DESIGN LIFE AND COST COMPARISON

Corrosion Protection Method	Costs	Durability	Lead time/ Availability/ Installation time
Cathodic	$$$$$$	XXXXXX	
Coating	$$$	XXX	
Galvanizing	$$$$$	X	
Corrosion allowance	$$$$	XXXX	

Source: Roll Form Group, a division of Samuel, Son & Co., Limited.

TYPICAL CORROSION RECOMMENDATIONS

- Option 1: Provide Corrosion Allowance for Bare Piles. → Thicker Steel , Higher Cost

- Option 2: Coat the Pile.
  - Coat entire piling (e.g, apply to 25-mil)

  OR
  - Coat upper portion and consider a corrosion allowance for remainder

  → Easily damaged, proper maintenance and touch up

- Option 3: Galvanization and corrosion allowance → Not suitable for all applications , added cost

- Option 4: Cathodic Protection → Requires monitoring and maintenance , added cost

Avoid connection to any other grounded metal, including reinforcing steel if concrete pads are placed, and to the concrete itself should concrete pads be constructed, to eliminate the formation of unfavorable corrosion cells.

LEARNING TOPICS:

- Where to find additional resources
- What trainings are available
- What certifications are recognized by the industry

RELEVANT TRAININGS & CERTIFICATIONS

Useful Resources

- Association for Materials Protection and Performance (AMPP)
  - www.ampp.org
  - Formerly known as NACE International and SSPC
  - Industry recognized certification programs
  - Variety of virtual and in-person training courses
  - Industry recognized standards
  - Standardized test methods
  - Technical conferences
  - 25 years of conference research papers

AMPP®

NACE® INTERNATIONAL
75th Anniversary 1943 - 2018

SSPC.org The Coatings Society.

USEFUL RESOURCES

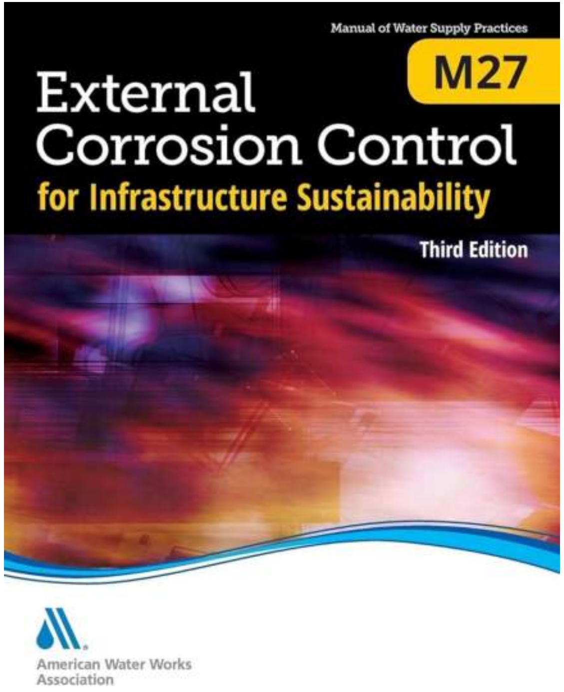
- AMPP – Popular Standards
  - NACE SP0169 Control of External Corrosion on Underground or Submerged Metallic Piping Systems
  - NACE SP0285 Corrosion Control of Underground Storage Tank Systems by Cathodic Protection
  - NACE SP0100-2014 formerly RP0100 Cathodic Protection to Control External Corrosion of Concrete Pressure Pipelines and Mortar- (21090-SG)
  - NACE SP0408-2019 Cathodic Protection of Reinforcing Steel in Buried or Submerged Concrete Structures

Useful Resources

- AMPP – Popular Courses and Certifications
  - Cathodic Protection
    - Tester (CP-1), Technician (CP-2), Technologist (CP-3), Specialist (CP-4)
  - Coatings Inspection
    - Basic (CIP-1), Certified (CIP-2), Senior (CIP-3)
  - General Corrosion
  - Pipeline Industry
    - Internal Corrosion and Pipeline Corrosion Integrity Management (PCIM)
  - Specialty and Advanced Programs
    - Corrosion Specialist
    - Protective Coating Specialist
    - Material Selection / Design Specialist

Useful Resources

- American Water Works Association (AWWA)
  - www.awwa.org
  - Manual M27 – External Corrosion Control for Infrastructure Sustainability, 3rd Edition
  - Annual Conferences



QUESTIONS

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HDR