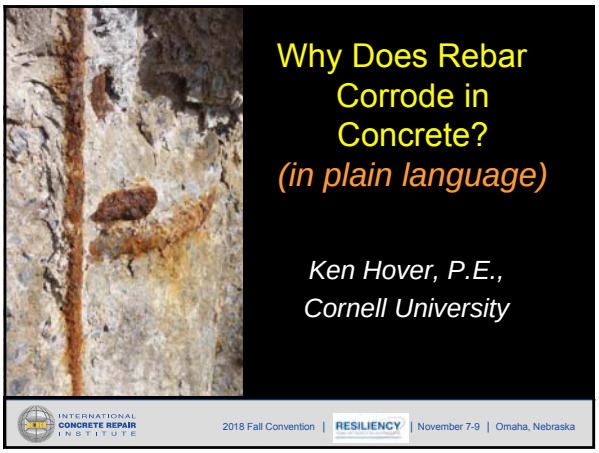
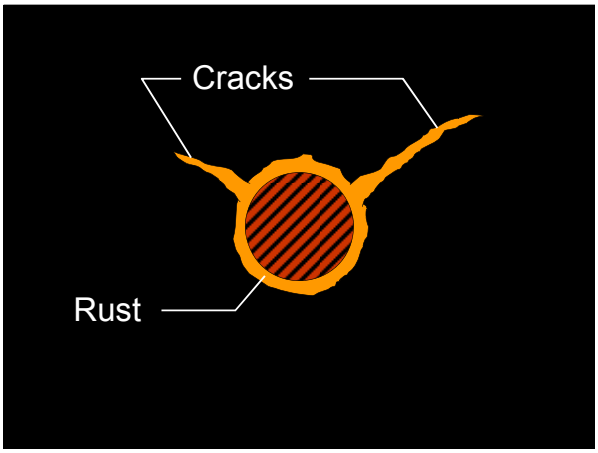


Corrosion of Reinforcing Steel

Sequence of Deterioration

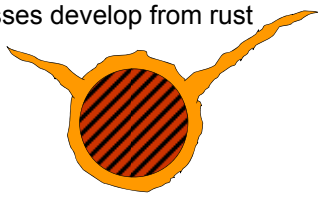
- Penetration of oxygen, salt, CO_2, water
- Volume expansion of rust
- Concrete cracking
- Accelerated corrosion
- Loss of steel cross section

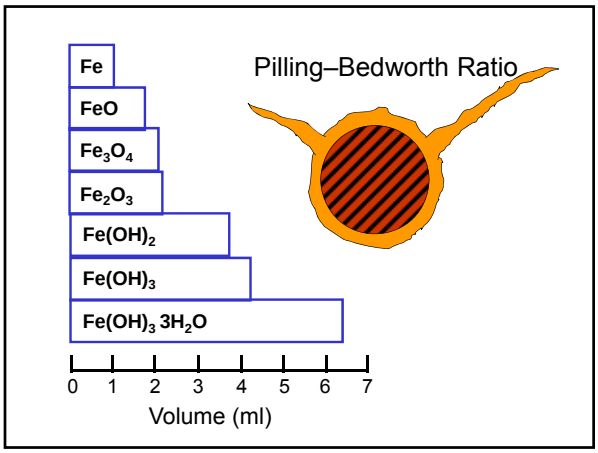


Expansion of corrosion products

"Piling-Bedworth Ratio": volume of rust occupies 4 to 10 times the volume of parent metal.

- Bursting stresses develop from rust expansion



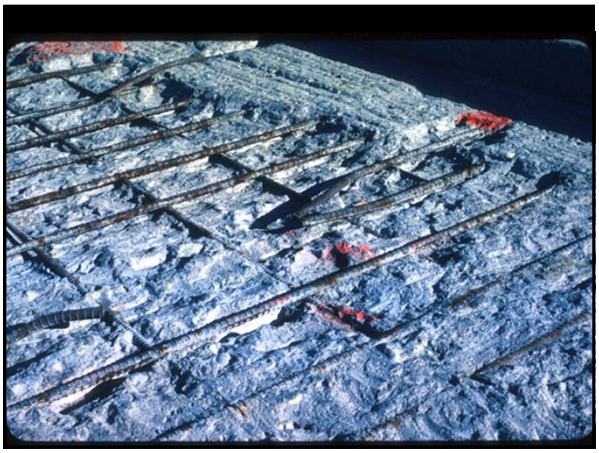


Principal Causes

- Chloride induced corrosion:
  - Deicing salts
  - Seawater
  - Chloride admixtures
- Carbonation effects

Impact of corrosion

- Rust-stains, reduction in ride-quality
- Loss of Serviceability
  - Cracking, increased penetration
- Loss of load capacity and reliability
  - Loss of concrete cover
  - Loss of bond
  - Loss of steel cross section



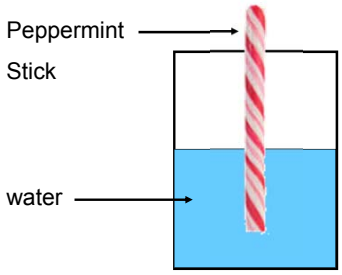
Loss of Steel Section

- Can be critical for shear
- Critical for non-redundant sections

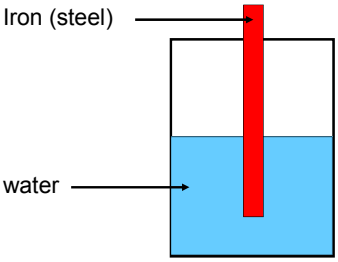
Background

Rodents!

Latin: Rōdere to gnaw,
Corrodere-to gnaw through.

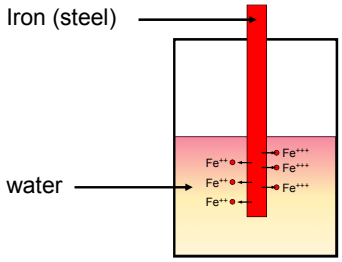


Sugar Dissolves in Water



Iron Dissolves in Water

EPA Drinking Water Standard:
0.3 mg Iron / Liter = 0.3g / 1000 Liters



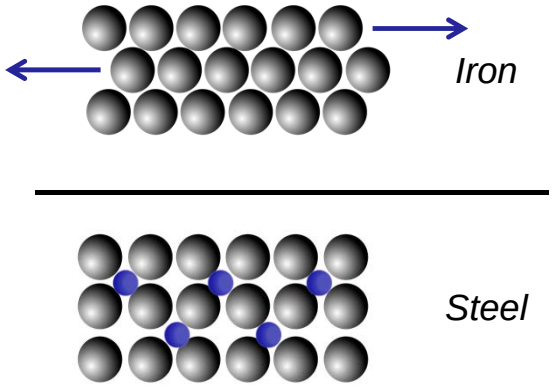
Red/Brown Tinge

At 0.3 mg/Liter

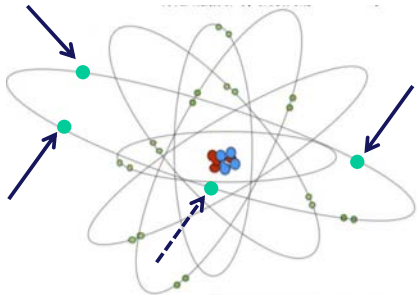
Positive metal ions go into solution

Corrosion is an electrochemical process

- Corroding element = anode
- Non corroding element = cathode
- Anode and Cathode in electrical contact
- Immersed in an Electrolyte
- Cathode reaction determines rate

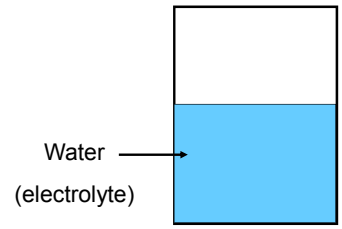


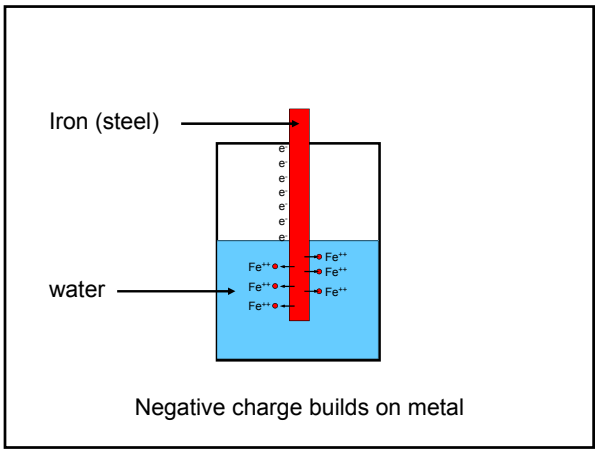
Iron Atom with 4 Free Electrons



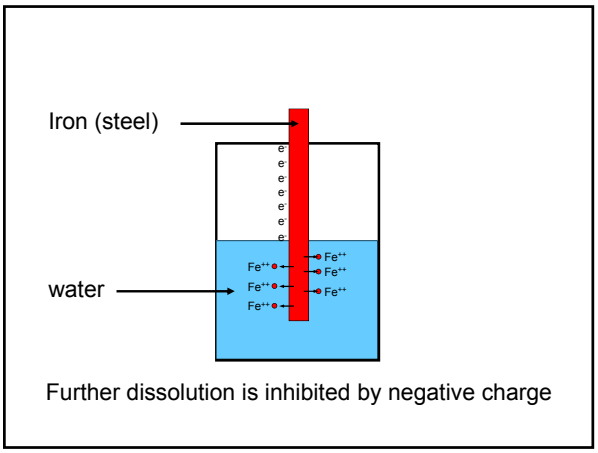
Iron can lose some of all of them

http://www.sciencemaster.co.uk/category/atomic-structure/element/

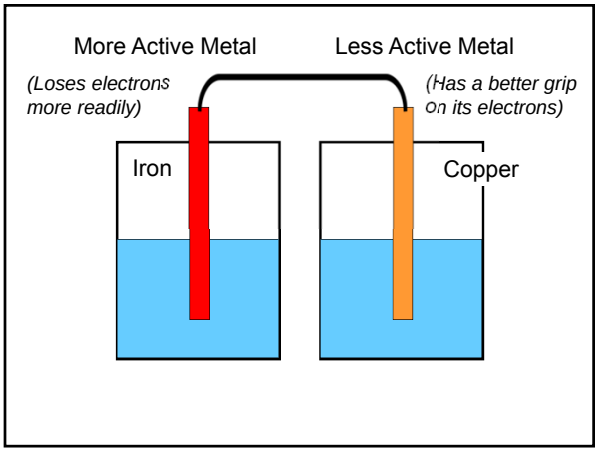


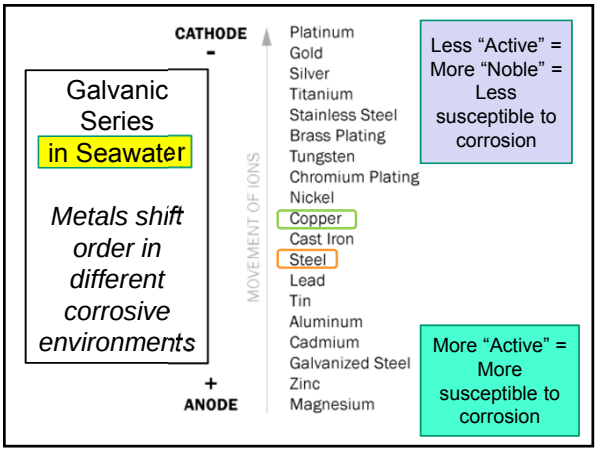


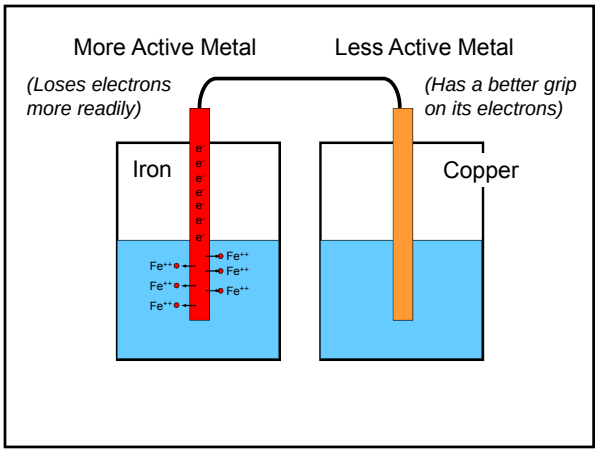
Negative charge builds on metal

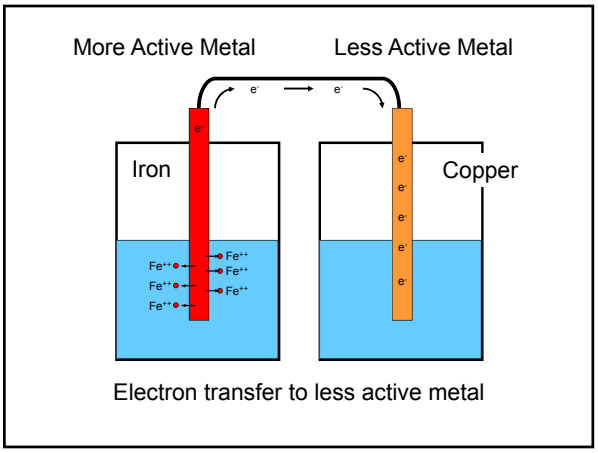


Further dissolution is inhibited by negative charge

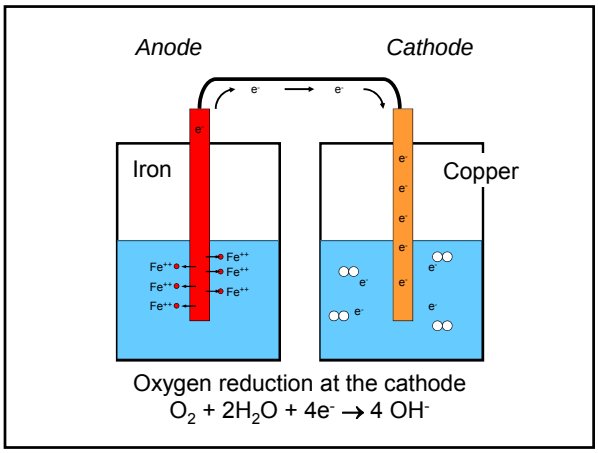


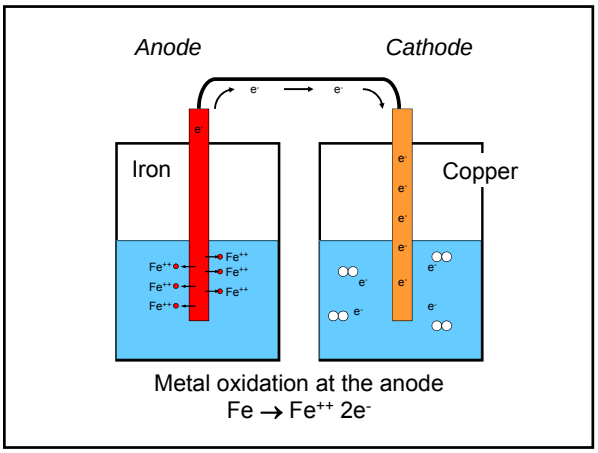


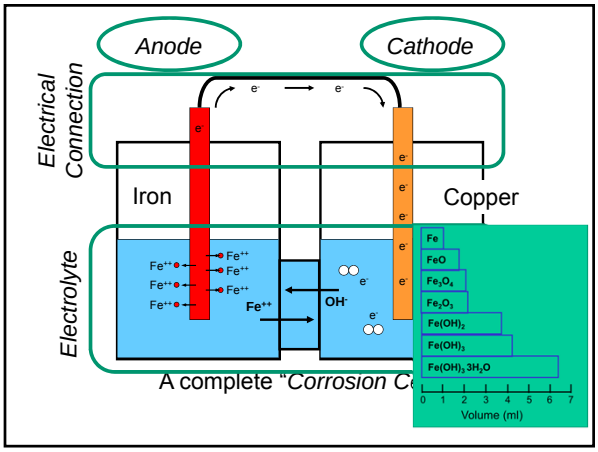


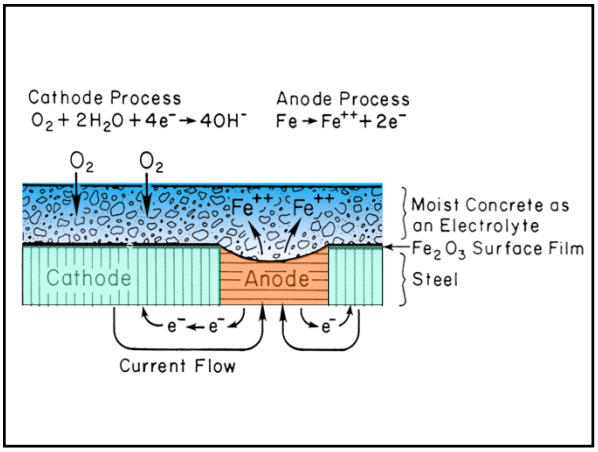


Electron transfer to less active metal







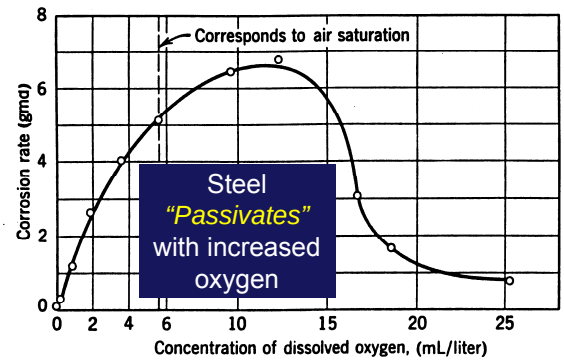


Required Components

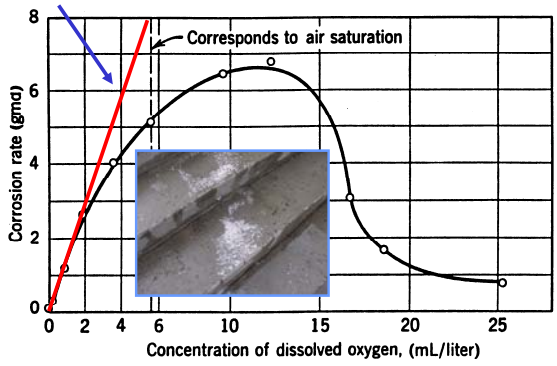
- Iron (steel)
- Water
- Oxygen

Influence of Salt (Sodium Chloride *or* Calcium Chloride)

- Crystallization pressure
- Osmotic pressure
- Thermal shock
- Chemical attack
- Increased electrical conductivity
- Destabilization of steel passivity



Corrosion rate with 165 ppm $CaCl_2$

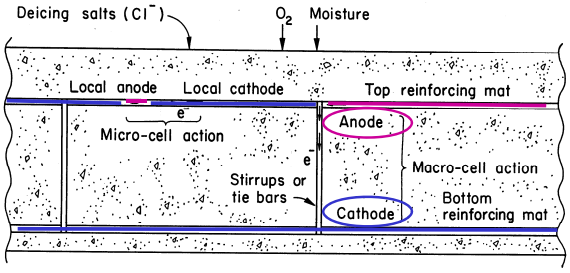


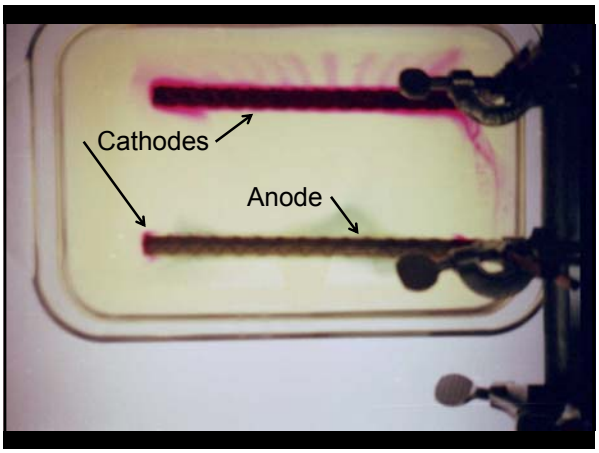
ACI 222R

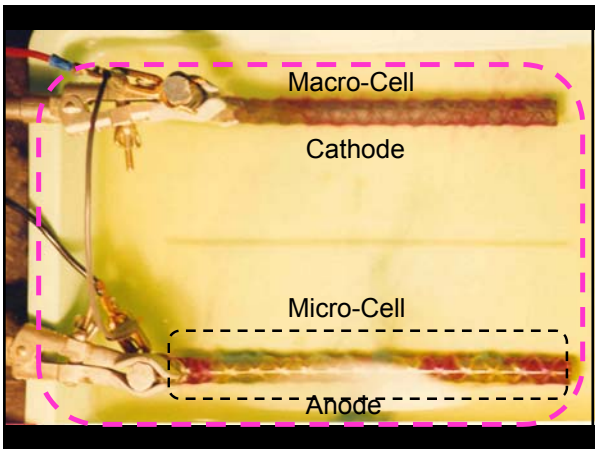
	Chloride Limit (new constr.) % of cement		
	Test Method		
	Acid Sol.	Water Soluble	
Category	ASTM C1152	ASTM C1218	Soxhlet
Pretressed	0.08	0.06	0.06
Reinf wet	0.10	0.08	0.08
Reinf dry	0.20	0.15	0.15

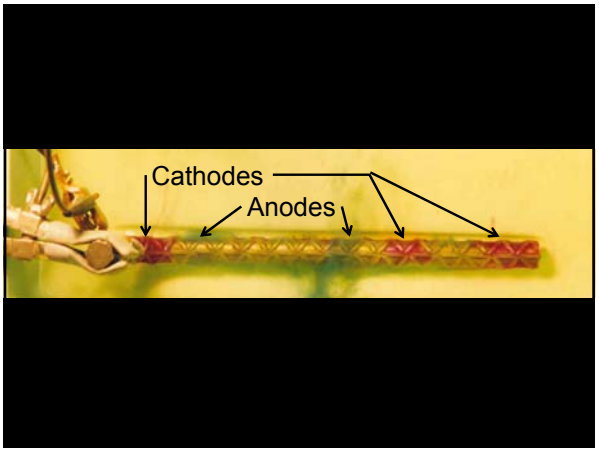
Corrosion Cells Applied to Concrete Structures

- Macro cells
- Micro cells



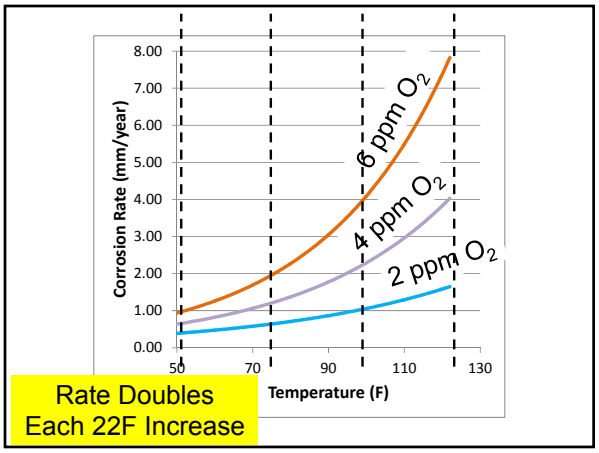






Rate-Limiting Step

- Oxygen Reduction
- Anode Size
- Oxygen partial pressure
- Oxygen permeability
- Temperature (accumulate salt in winter, corrode in summer) Warm garage, warm sea water, hot water heater

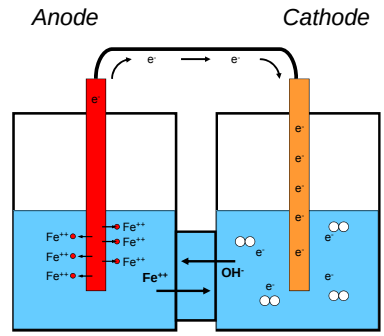


Types of Cells

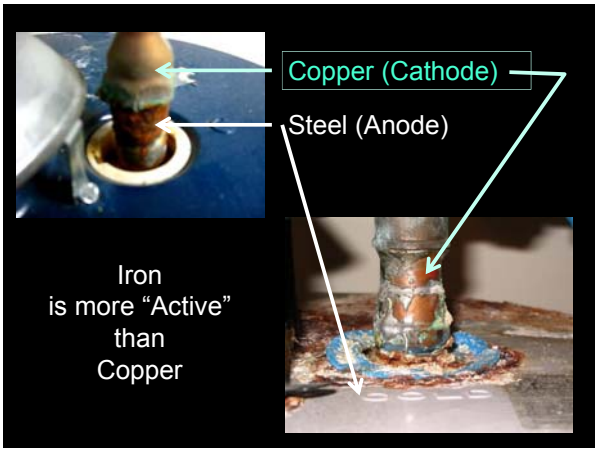
- Differential
  - Metals Steel water tank / Copper pipe
  - Salt Concentration Parking garage
  - Oxygen Concentration Bridge deck
  - Temperature
- Stray Current
- Pitting
- Under-film

Differential metal cells

- Metal forms & embedments
- Galvanized components
- Bar Deformations

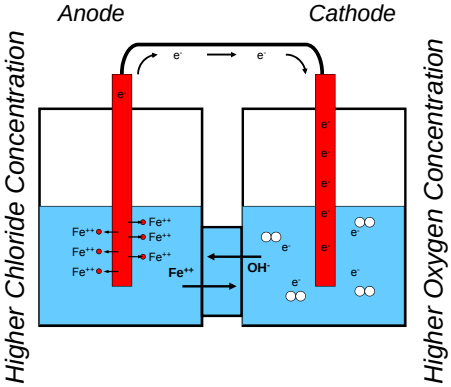


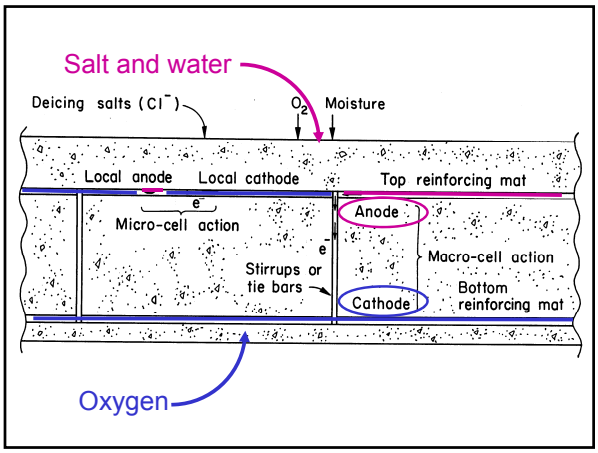
A complete "*Corrosion Cell*"



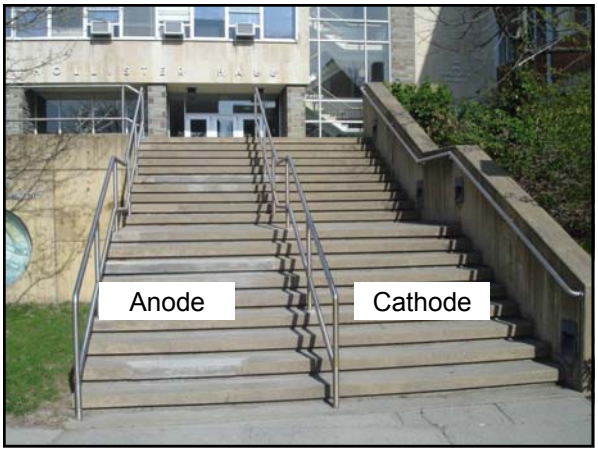
Differential concentration cells

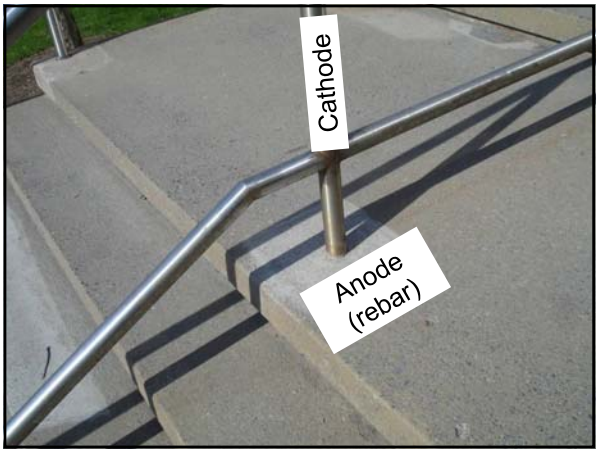
- Variations in chloride content
- Variations in moisture content
- Variations in Oxygen concentration




Salt and water
Deicing salts (Cl^-)
O_2
Moisture
Local anode
Local cathode
Top reinforcing mat
e^-
Micro-cell action
Anode
e^-
Macro-cell action
Stirrups or tie bars
Cathode
Bottom reinforcing mat
Oxygen

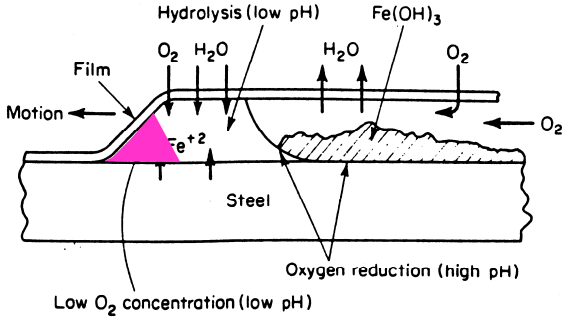

CLOSED


Anode
Cathode


Cathode
Anode (rebar)

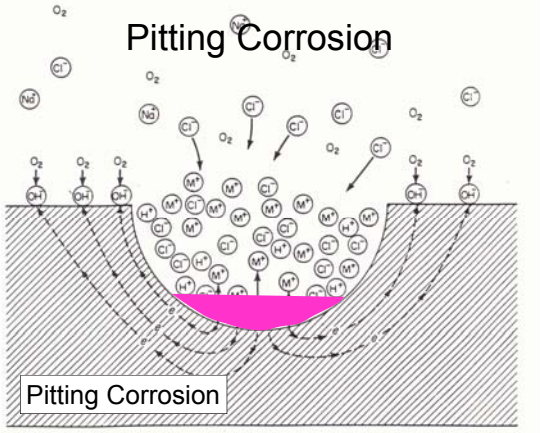

Anode

Under-film Corrosion

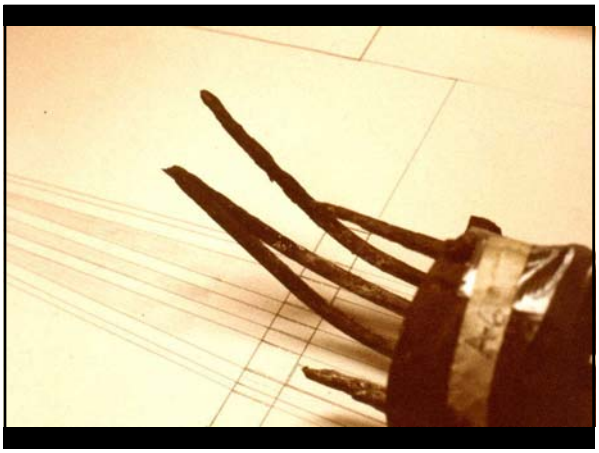


Under-film Corrosion

Pitting Corrosion



Pitting Corrosion

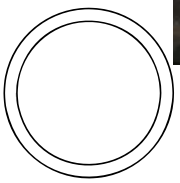


Corrosion Rate Determined by Cathode Reaction

- Large cathode-small most rapid corrosion.
- The bottom mat cathode; top mat anode.
- Pinholes in epoxy coatings become small anodes; uncoated steel becomes large cathode.

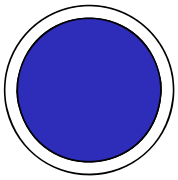
Ohio Steel Fabricators Fiasco

Steel pipe for Oxygen



Ohio Steel Fabricators Fiasco

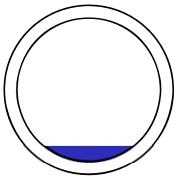
Steel pipe for Oxygen



Pressure-Test with water

Ohio Steel Fabricators Fiasco

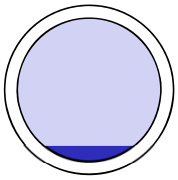
Steel pipe for Oxygen



Drain water (mostly) after successful test

Ohio Steel Fabricators Fiasco

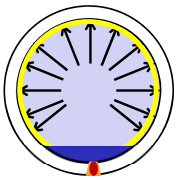
Steel pipe for Oxygen



Pressurize with Oxygen

Ohio Steel Fabricators Fiasco

Steel pipe for Oxygen



Large Cathode

Small Anode

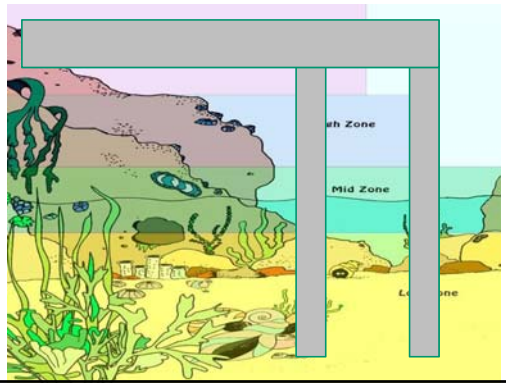
Continuous Perf. Of Pipe

Pressurize with Oxygen

Yet Another Corrosion Cell of Sorts

Sometimes we feed the anode,
Sometimes we feed the cathode

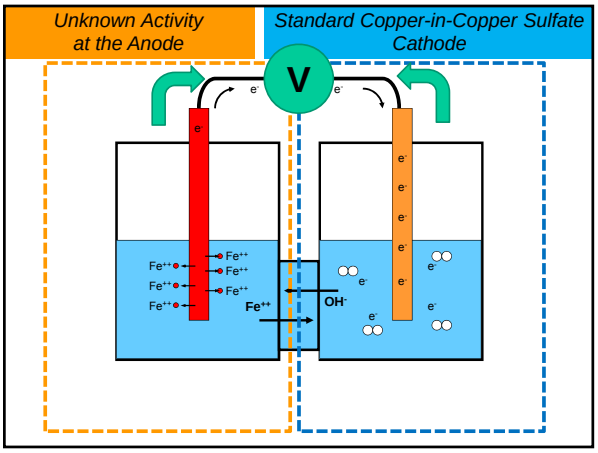
Tidal Zones

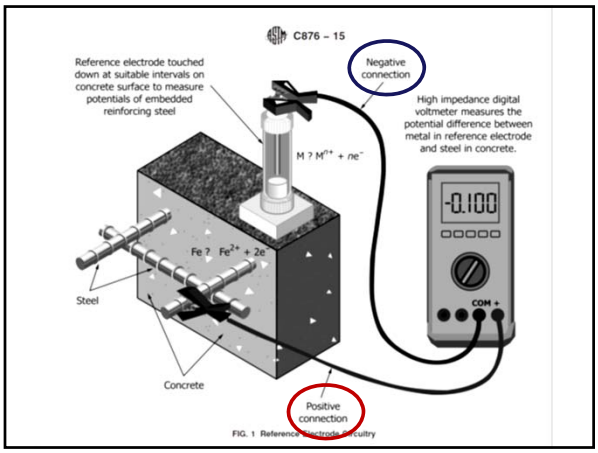


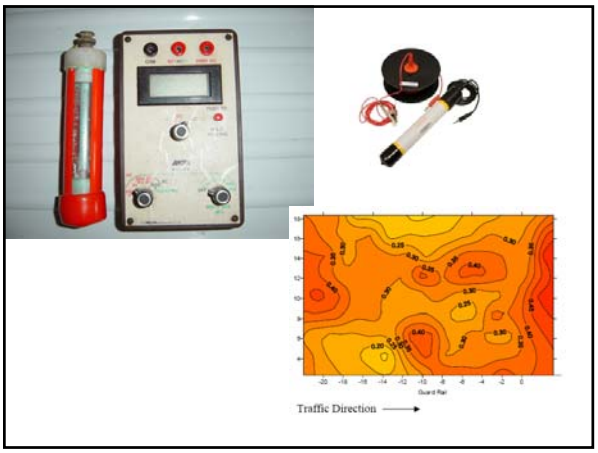
Monitoring Ongoing Electrochemical Corrosion Activity

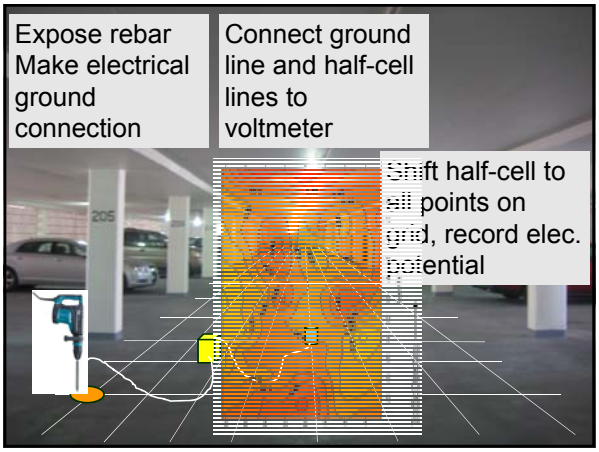
- Electrical potential

ASTM C876 - 15
Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete





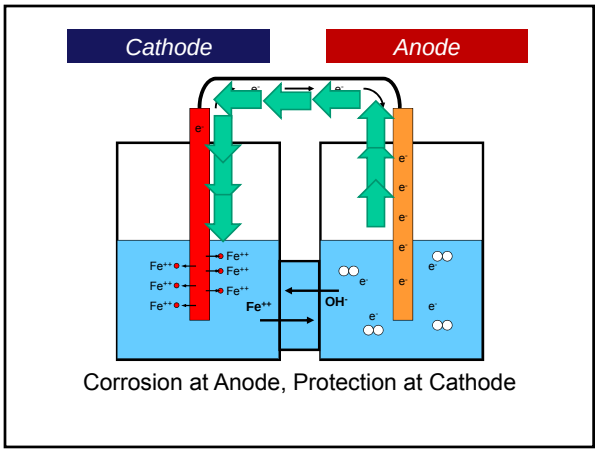




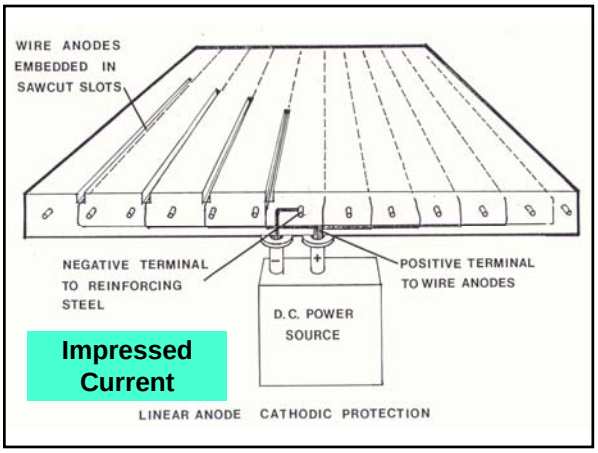
Cathodic Protection

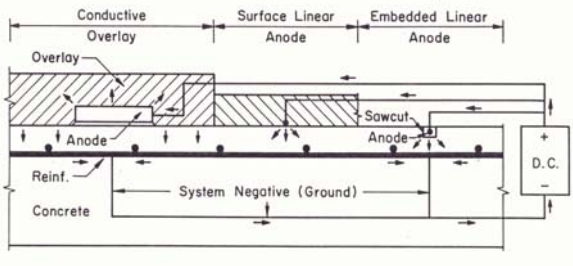
General principles

- Negatively charge steel
- Generate OH^- at cathode
- Sacrificial Anodes
- Impressed current



Corrosion at Anode, Protection at Cathode



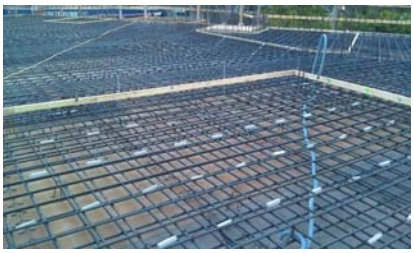


Impressed Current

Impressed Current

Impressed Current

Impressed Current



Sacrificial Anodes

Thank you very much!

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kch7@cornell.edu