The webinar will begin at 10:00 a.m. MST

Corrosion Website
http://www.usbr.gov/pmts/materials_lab/corrosion

Corrosion Webinar Series
June 2013
Intro to Cathodic Protection and CP Maintenance

Corrosion and Coatings School
October 22-24, 2013

Research Jam 2013
https://reclamation-research.ideascale.com

Introduction to Corrosion

RECLAMATION

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What is Corrosion?

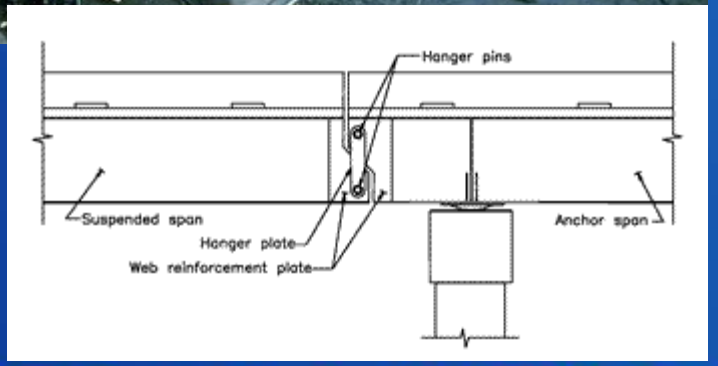
CORROSION IS DEFINED AS THE DETERIORATION OF A MATERIAL AND/OR ITS PROPERTIES CAUSED BY A REACTION WITH ITS ENVIRONMENT.

Why is Corrosion a Major Concern?

RECLAMATION

First and Most Important- Public Safety!

- June 28, 1983: Mianus River Bridge, Greenwich, CT (TIME photo archive)
- Northbound 3-lane section of I-95 bridge collapsed, killing 3 people
- “Pin and Hanger” design was compromised when pin was displaced due to extensive corrosion of load-bearing components, amplified by salt from road maintenance.
- Inadequate maintenance procedures were also cited as a contributing factor.
- Subsequent to this failure, extensive inspections were conducted on this type of bridge across the country, and design modification were made to prevent catastrophic failures of this kind.



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First and Most Important- Public Safety!

- April 28,1988, Aloha Airlines 737 Accident
- 18 feet of cabin skin ripped off, resulting in the death of a flight attendant and many injuries
- Attributed to corrosion fatigue

RECLAMATION

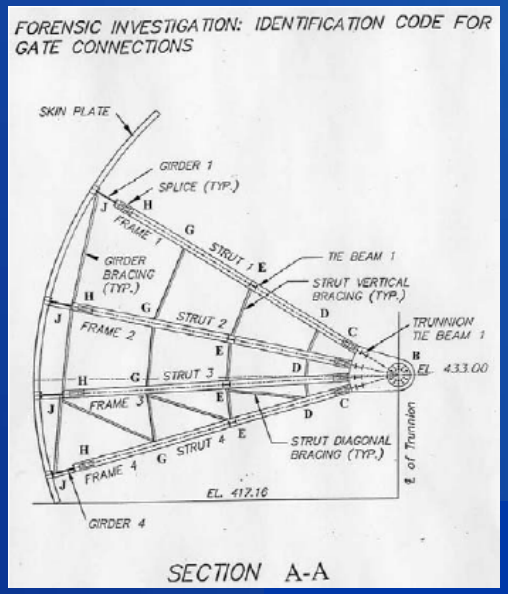
Reclamation Case Study- Folsom Dam

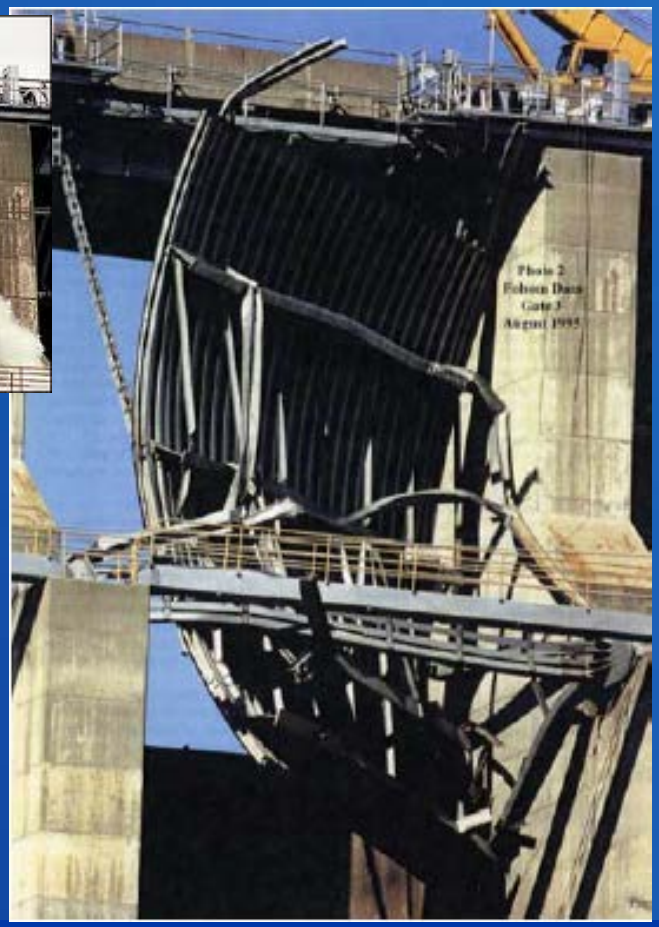
- Spillway gate No. 3 was damaged beyond repair, but no flooding occurred.

- Replacement of No. 3 and repair of other gates cost ~$20 million and required 40% drainage of reservoir

- Cause of failure: Increasing corrosion at the trunnion pin-hub interface raised the coefficient of friction and, therefore, the bending stress in the strut and the axial force in the brace exceeded limits.

- Nearly 40 years of operation without problems suggests that the failure resulted from a condition that developed over time

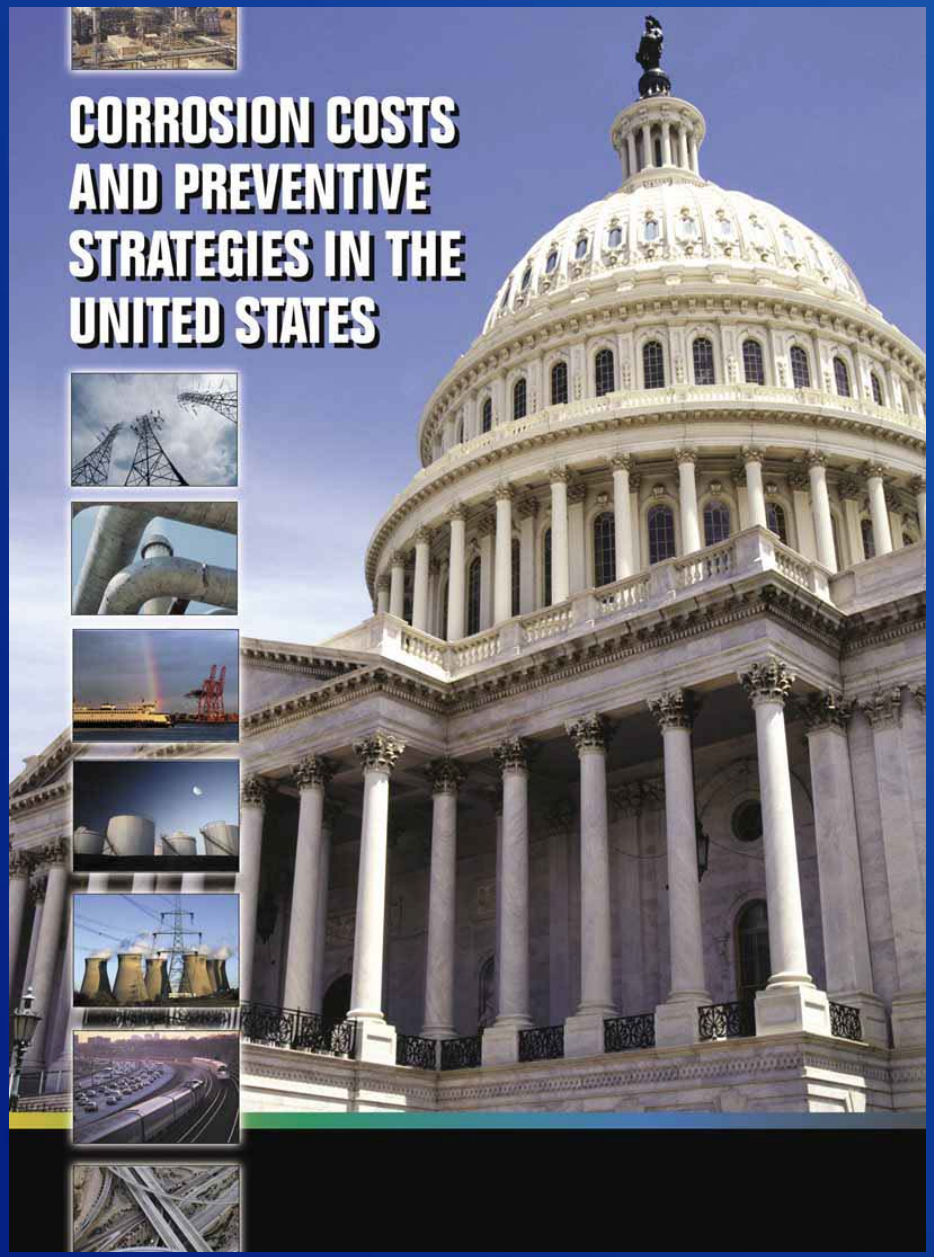




- July 17, 1995, Folsom Dam, Spillway Gate No. 3
- Concrete gravity dam on American River near Sacramento, CA, built by the Army Corps of Engineers.

- Frequency of regular maintenance and lubrication had been decreased over time due to budget constraints.

Economic Costs: $276 billion annually



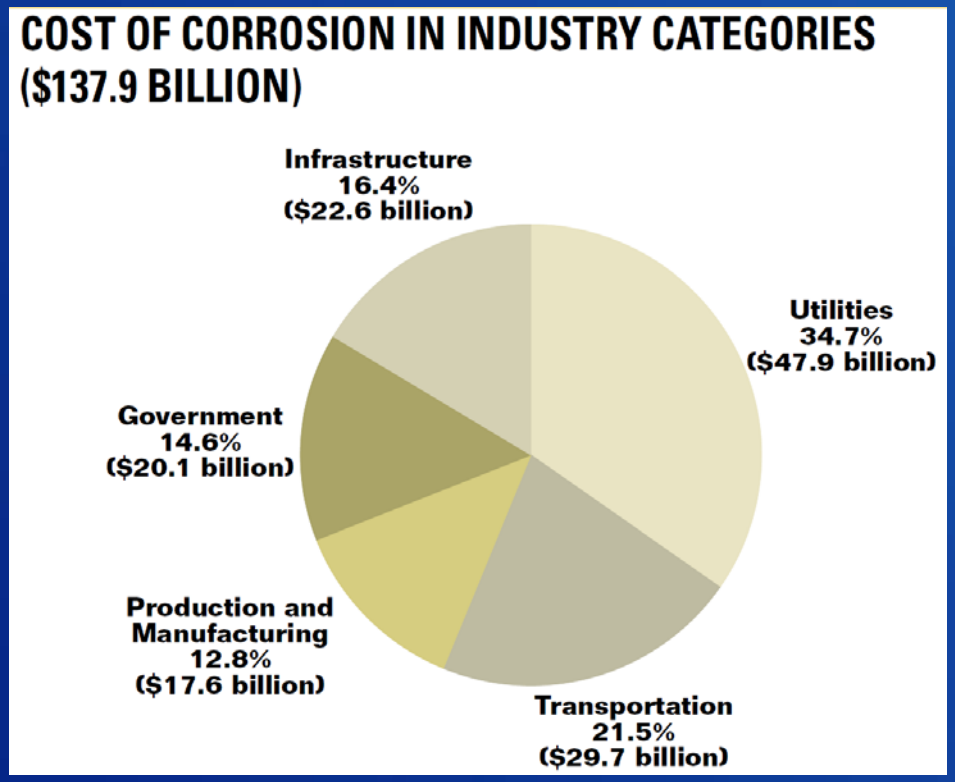
- "Corrosion Costs and Preventative Strategies in the United States," Publication No. FHWA-RD-01-156, *NACE International and U.S. Federal Highway Administration*, 2002.

- Estimates economic impact of corrosion for specific industries and extrapolated to a national total

- Total *Annual* Estimated Direct Cost of Corrosion:
  - $276 billion
  - ~ 3.1% of the country's GDP
  - Indirect costs double that to $552 billion or ~ 6% of the GDP

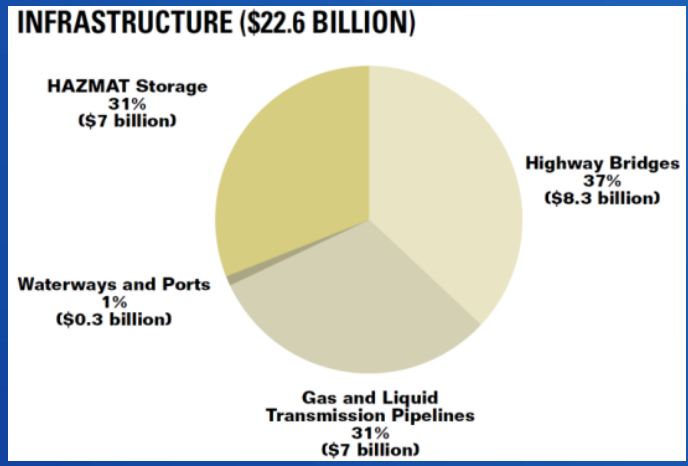
RECLAMATION

Economic Costs: $276 billion annually



Costs Include:

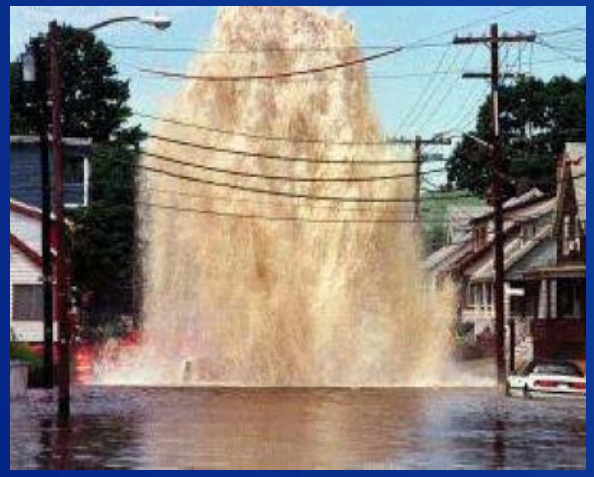
- Direct loss of public infrastructure and residential items
- Repairs, replacement , and maintenance
- Loss of product, production, and downtime
- Loss of consumer confidence
- Increased regulation and fines



- **Amounts determined in 1998 and represent the analyzed sectors.**
- **Estimated 25 to 30% of annual corrosion costs in the U.S. could be saved if optimum corrosion management practices were employed.**

RECLAMATION

Economic Costs: $276 billion annually



- Report identifies several preventative strategies:
  - Increase awareness of corrosion costs and potential cost savings
  - Change misconception that nothing can be done about corrosion
  - Change policies, regulations, standards, and management practices to increase corrosion cost savings through sound corrosion management
  - Improve education and training of staff in the recognition of corrosion control
  - Implement advanced design practices for better corrosion management
  - Develop advanced life-prediction and performance assessment methods
  - Improve corrosion technology through research, development, and implementation

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The Corrosion Reaction

ex. oxidation, “rusting,” electroplating, anodizing

Electrochemical Reaction Between a Metal and an Electrolyte

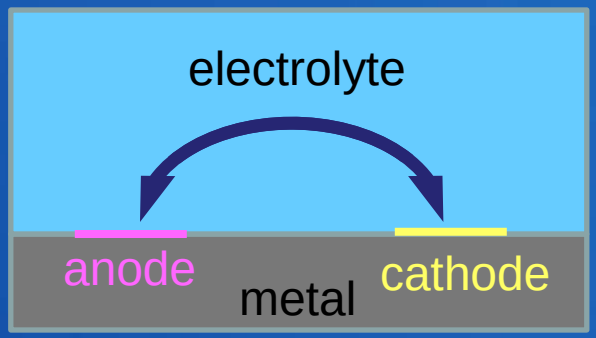
ex. steel, copper, aluminum

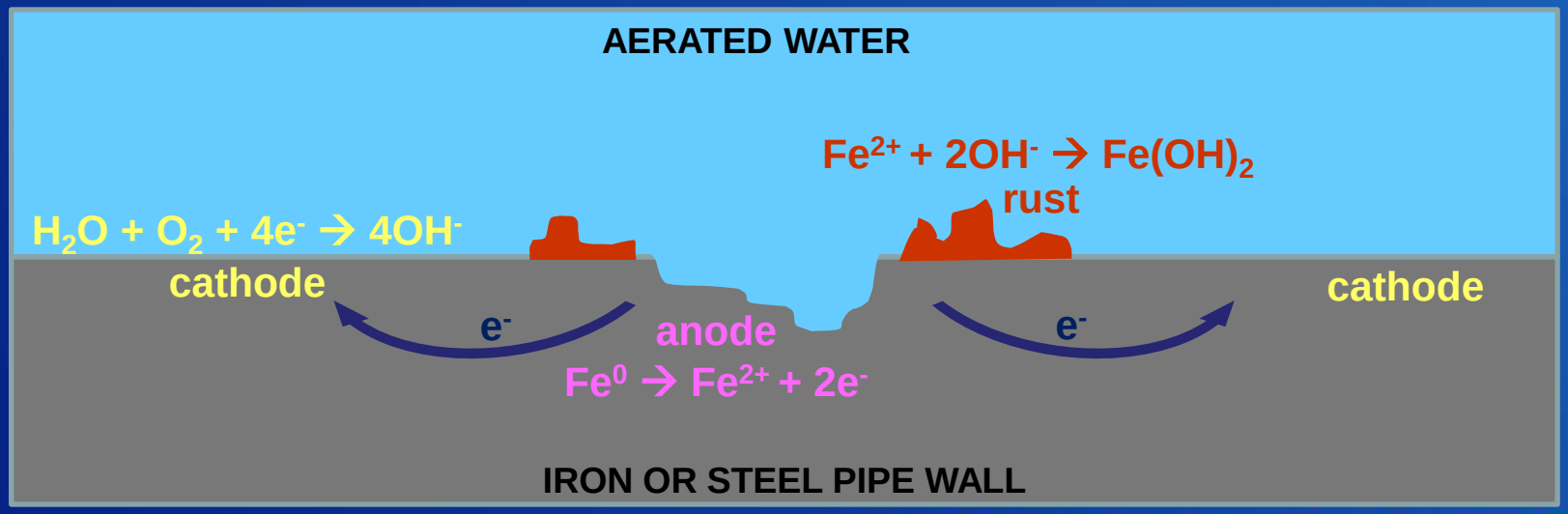
ex. soil, water

- Metals corrode because they are chemically unstable in natural environments- air, soil, water.
- Only noble metals (Au, Ag, Pt, Pd, etc.) and copper exists in their metallic form in nature.
- Some metals naturally passivate- or form a dense, adherent, protective oxide layer on their surface- which slows down corrosion. Examples: Al, Mg, Zn, Ti.

Corrosion Cell – Four Required Elements

1. Anode (Corrodes)
2. Cathode (Protected)
3. Electrolyte (Usually Soil or Water)
4. Metallic Return Path (ex. Pipe)





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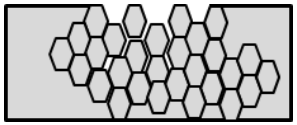
Forms of Corrosion

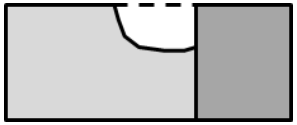
Forms of Corrosion

Uniform or General Attack

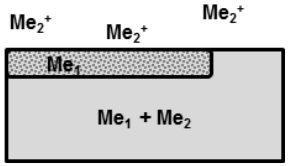
Intergranular Corrosion



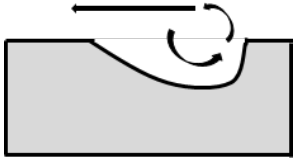
Galvanic Corrosion



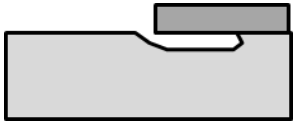
Dealloying or Selective Leaching



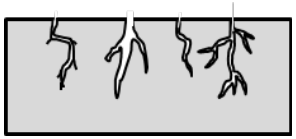
Erosion Corrosion



Crevice Corrosion

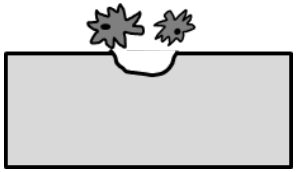


Environmentally-Induced Corrosion

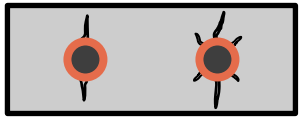


Pitting

Microbially-Induced Corrosion



Corrosion in Reinforced Concrete



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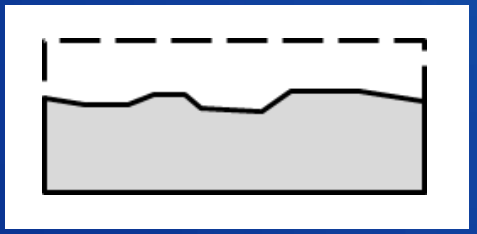
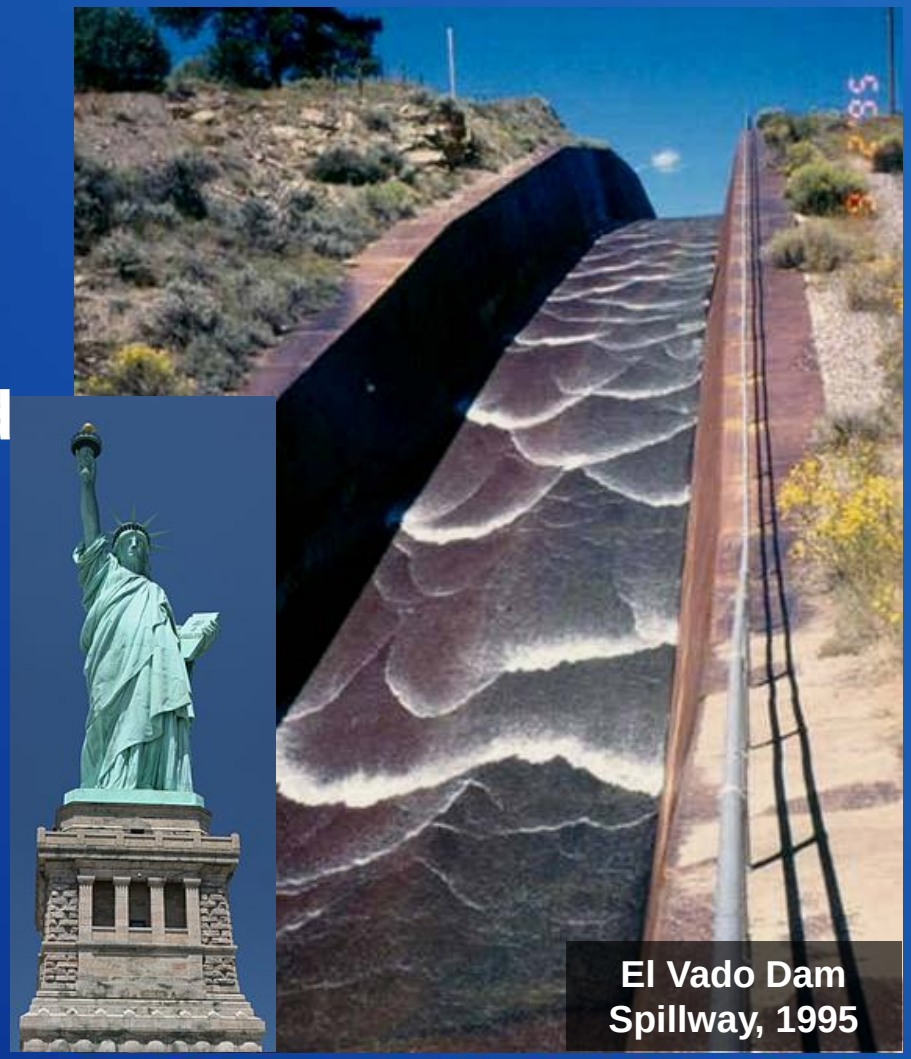


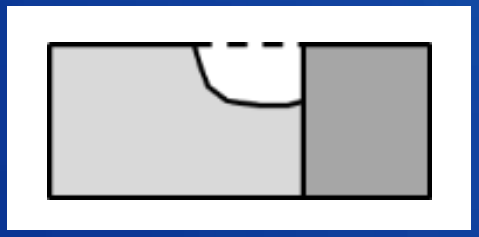
General or Uniform Corrosion

- Reactions occur uniformly over the surface, often at a steady and predictable rate
- Most important form based on weight of metal corroded
- Some Solutions:
  - Select a more corrosion resistant material
  - Apply protective coatings
  - Cathodically protect the structure
  - Specify corrosion allowance



El Vado Dam Spillway, 1995

RECLAMATION



Galvanic Corrosion

- Corrosion due to potential difference between two dissimilar metals in contact- one metal become anode and corrodes faster than normal
- Basis of galvanic anode cathodic protection
- Some Solutions:
  - Use Electrochemically Similar Metals
  - Avoid Large Cathode-to-Anode ratios
  - Use Insulating Fittings
  - Apply Protective Coatings
  - Apply Cathodic Protection

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Galvanic Series in Sea Water

*As referenced to a Ag/AgCl reference electrode

	Material	Potential (V) (approximate)
↑ Noble or Cathodic	Graphite	+0.20 to +0.30
	Platinum	+0.19 to +0.25
	Titanium	-0.05 to +0.06
	316 Stainless Steel (passive)	-0.10 to 0.00
	Nickel	- 0.2 to -0.1
	Bronze, Copper, Brass	-0.42 to -0.25
	316 Stainless steel (active)	-0.54 to -0.43
Active or Anodic ↓	Mild Steel & Cast Iron (clean)	-0.71 to -0.60
	Zinc	-1.03 to -0.98
	Aluminum	-1.10
	Magnesium	-1.63 to -1.60

Galvanic Corrosion

Mild Steel Anchor Bolts with Stainless Steel Guides

Protective environment of the concrete/grout is not enough to prevent corrosion due to the galvanic couple.

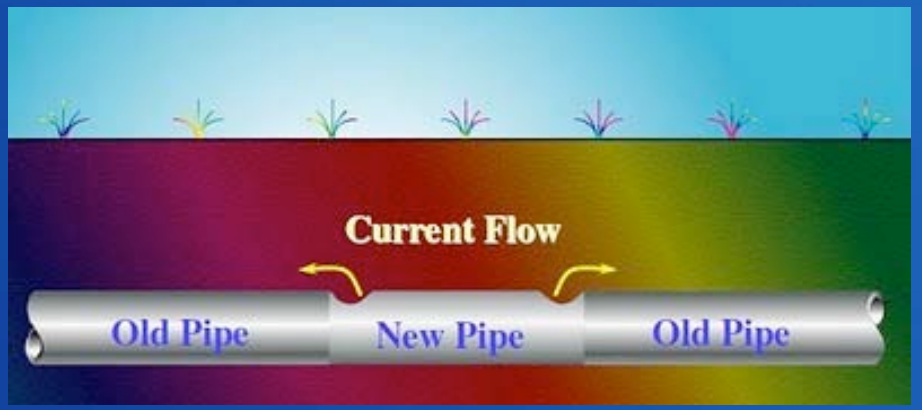
Canyon Ferry Dam Stop Log Guides, 2007

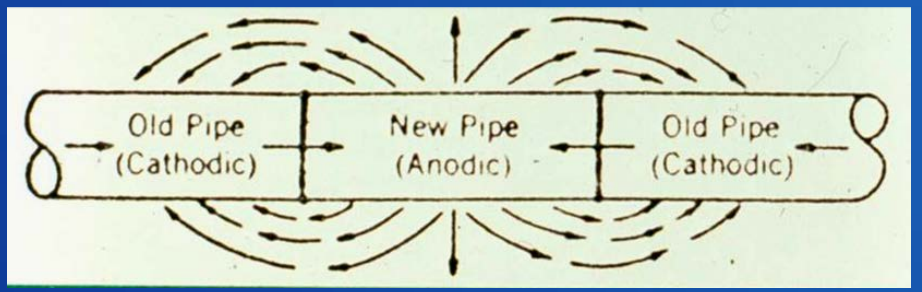
Galvanic Corrosion- New vs Old Steel

Passivity: when certain metals form thin, oxidized, protective films on their surface in corrosive environments; when passivated, metals are less affected by environmental factors and less likely to corrode

- Oxide layer on iron is not completely passivating- it has a low density and does not adhere well to the metal. However, it will slow further oxidation.

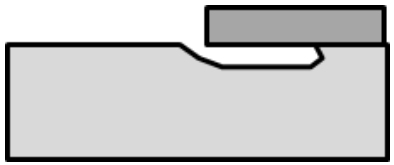
Material	Potential (V) (approximate)
316 Stainless Steel (passive)	-0.10 to 0.00
316 Stainless steel (active)	-0.54 to -0.43
Mild steel (corroded)	-0.55 to -0.4
Mild steel (clean and shiny)	-0.8 to -0.5





- Can be especially corrosive if a large section of less-active old steel is electrically connected to a small area of new steel, for example in the case of pipeline section replacement

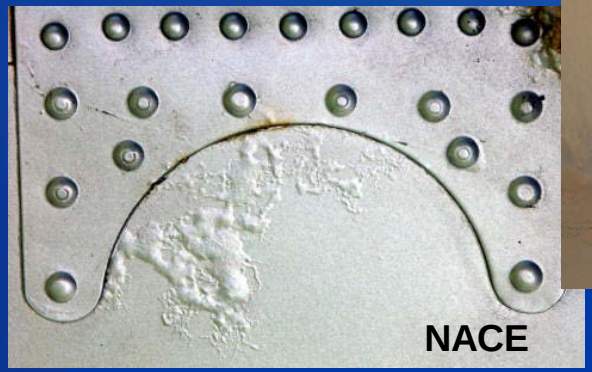
RECLAMATION



Crevice Corrosion

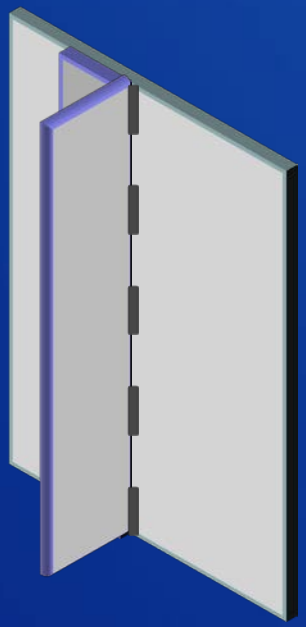
- **Intensive localized corrosion within crevices and under coatings**
- **Some Solutions:**
  - **Avoid designs with crevices (e.g. bolting or riveting, etc.); use non-absorbent gaskets.**
  - **Design equipment for complete drainage; avoid stagnant, wet deposits.**
  - **Close crevices in lap joints by welding or caulking.**
  - **Inspect for and remove deposits.**

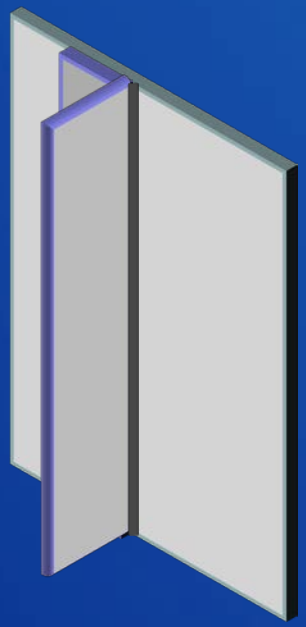
Palo Verde Diversion Dam Radial Gates, 2013

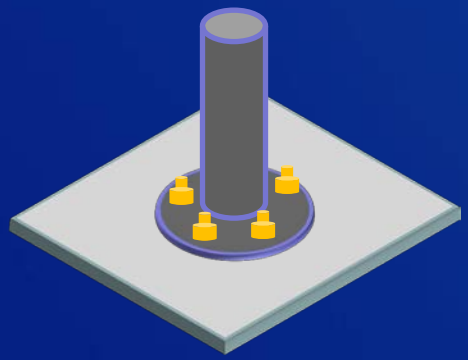


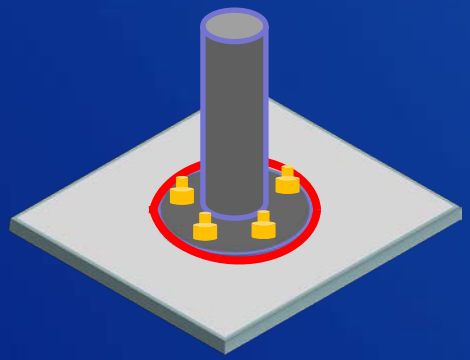
NACE

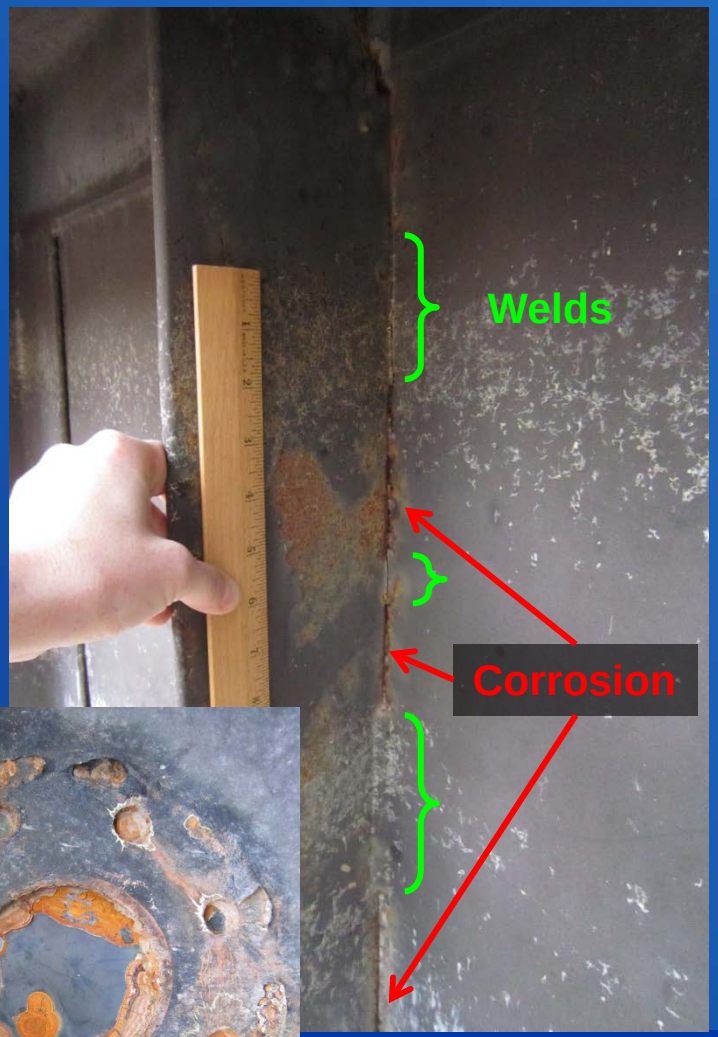
Avoid Skip Welding! Seal Joints!







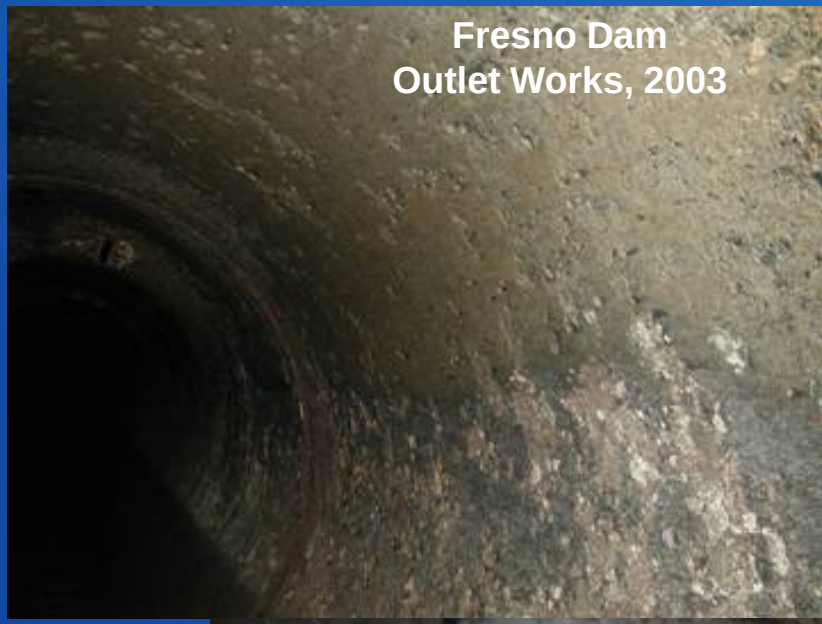




Seminoe Dam Bulkhead Gates, 2012

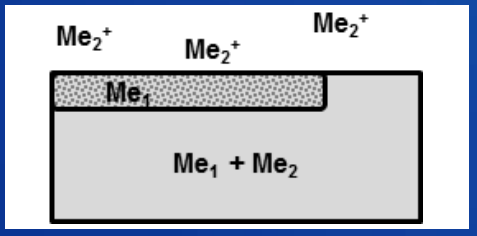
Pitting Corrosion

- **Localized attack in an otherwise resistant surface**
- **Often occurs when protective coating breaks down**
- **Some Solutions:**
  - **Select suitably resistant material (316 vs. 304 SS)**
  - **Apply Protective Coating**
  - **Cathodic Protection**
  - **Avoid designs where stagnation, or alternate wetting and drying, can occur in pits**



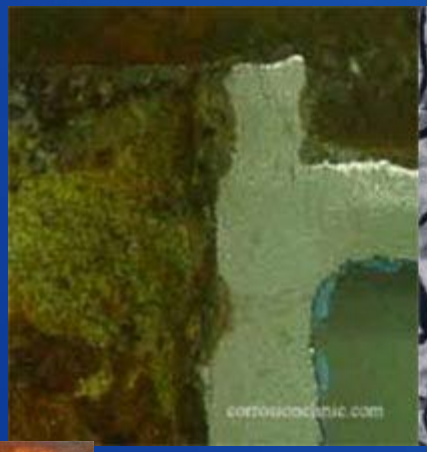
Fresno Dam
Outlet Works, 2003

RECLAMATION



Dealloying or Selective Leaching

- **Preferential corrosion of one element from a solid alloy with no appreciable change in appearance**
  - **Dezincification (Zn leaches out of brass, leaving porous low-strength Cu)**
  - **Graphitic Corrosion (Fe leaches from cast iron, leaving porous low-strength graphite)**



- **Some Solutions:**
  - **Change Alloys**
  - **Cathodic Protection**
  - **Protective coating**

Graphitic corrosion in cast iron gas mains caused several fatal explosion in Allentown, PA, area from 1979-2011.

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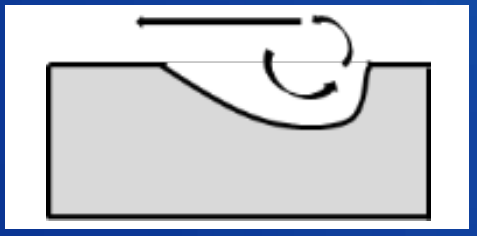
Denver Federal Center, 2004

Fountain Valley Conduit, 2007

Graphitic corrosion- not apparent on visual inspection; extent of corrosion could only be realized by tapping with hammer to observe loss in strength due to iron leaching

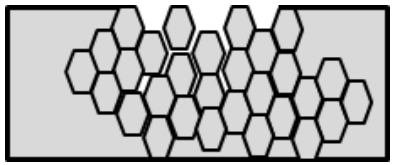
RECLAMATION



Erosion Corrosion

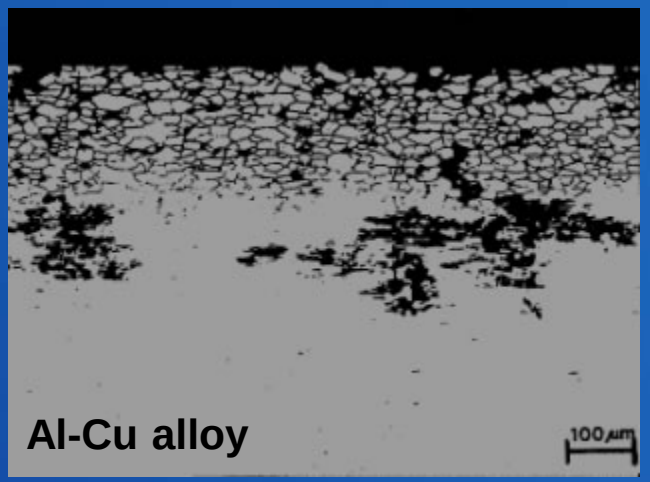
- Accelerated corrosion due to flow of a corrosive fluid across a metal surface
- Electrochemical and Mechanical Process
- Very High Corrosion Rates
- Some Common Forms:
  - Cavitation
  - High Velocity
  - Abrasion

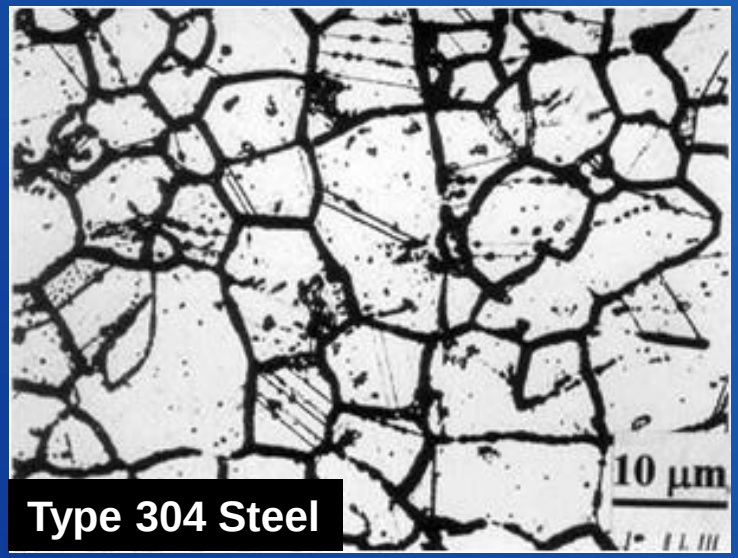
- Some Solutions:
  - Design to prevent turbulence/impingement
  - Select suitably resistant material
  - Protective coatings
  - Cathodic Protection to help with the electrochemical part
    - High flow rates may require large currents for protection



Intergranular Corrosion

- Corrosion along highly reactive or segregated grain boundaries
- Common in many alloy systems, ex. Grain boundary Cr depletion in austenitic stainless steel
- Some Solutions:
  - Choose alloys that have been properly heat treated to prevent elemental segregation
  - Choose low carbon steels

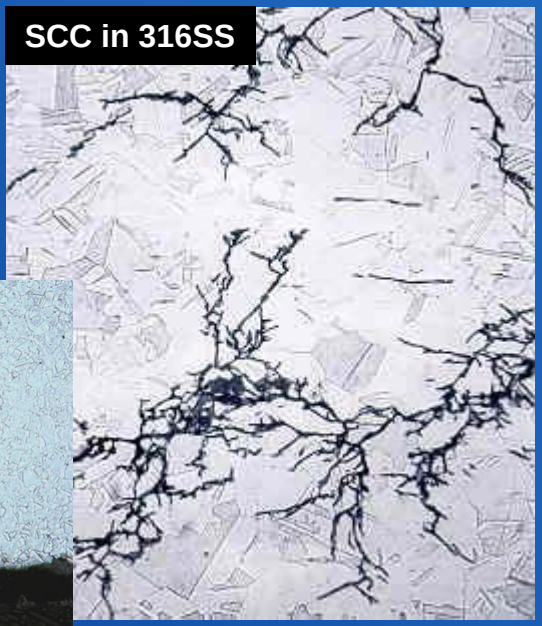


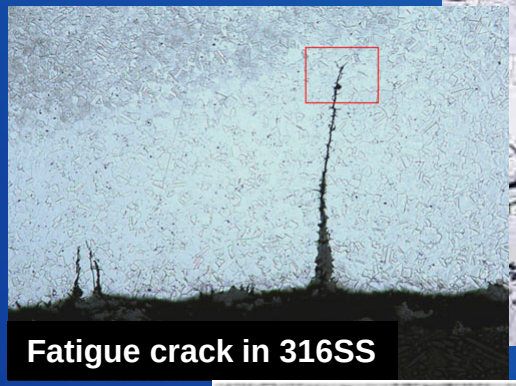


RECLAMATION

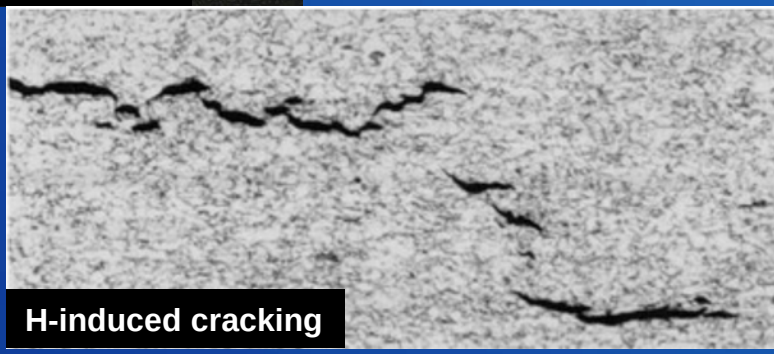
Environmentally-Induced Corrosion

- Cracking of a material due to mechanical stress and a corrosive environment
  - Stress-corrosion
  - Corrosion fatigue
  - Hydrogen-induced cracking


SCC in 316SS


Fatigue crack in 316SS

- Some Solutions:
  - Select suitably resistant material
  - Protective Coatings
  - Cathodic Protection


H-induced cracking

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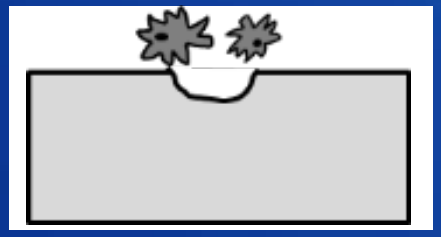
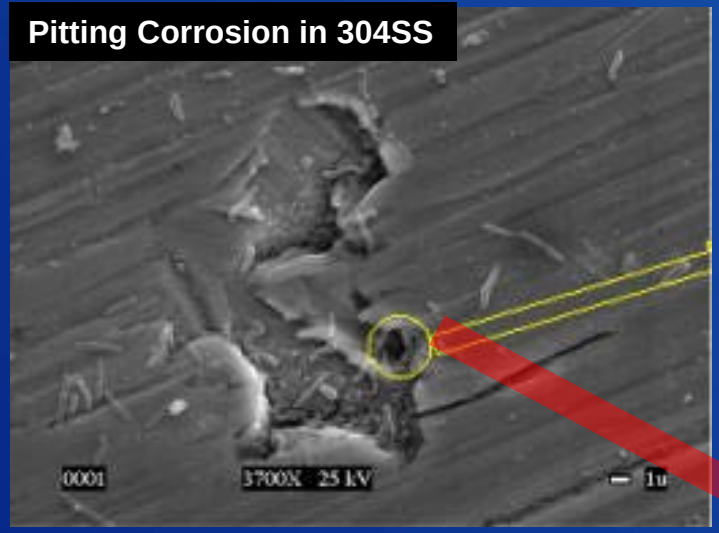


Microbial Corrosion

Pitting Corrosion in 304SS

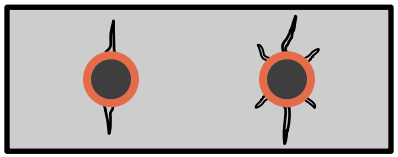


- Corrosion caused or accelerated by microorganisms- bacteria, fungi
- With or without oxygen present
- Biological action can increase the severity of corrosion as a result of:
  - Bio-deposits on the material surface
  - Production of corrosive chemical species (i.e. H_2S from sulfate reducing bacteria - SRB's)
  - Disruption of normal electrochemical reactions and film formation

Some Solutions:

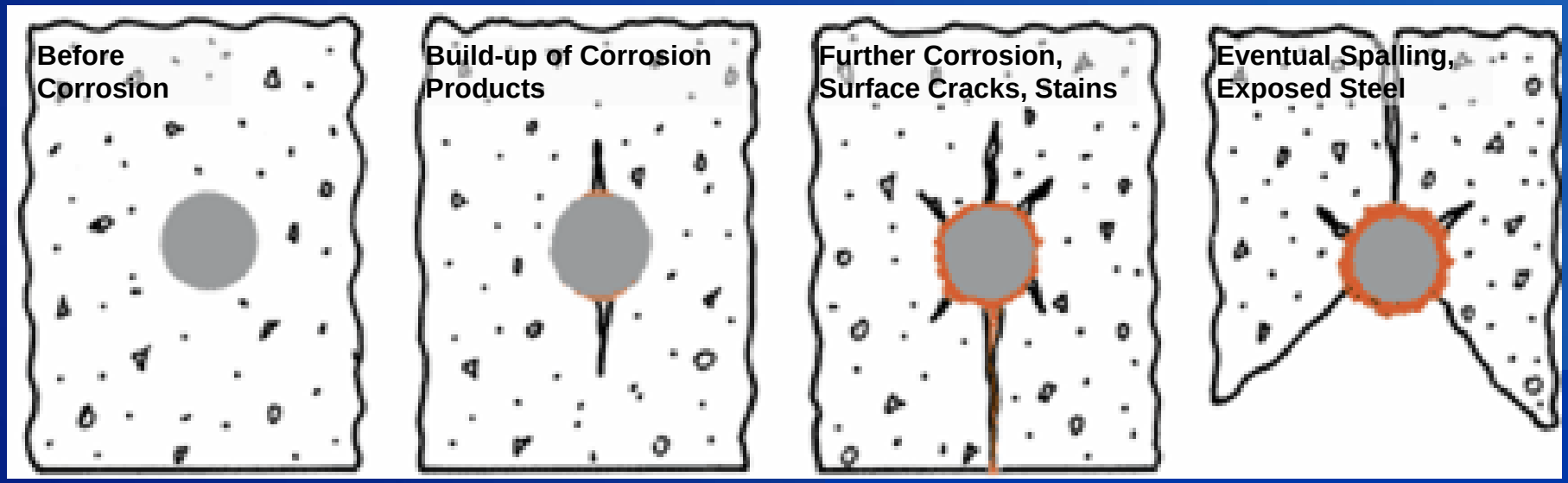
- Select resistant materials
- Frequent cleaning
- Use of biocides
- Apply anti-fouling coating
- Cathodic Protection

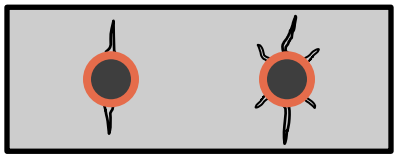
caused by sulfate-reducing bacteria



Corrosion in Reinforced Concrete

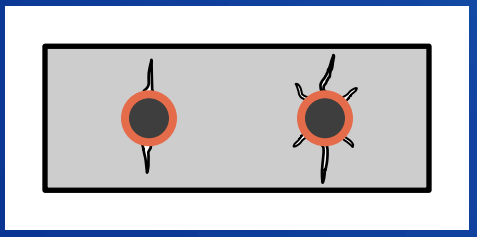
- Concrete is excellent in compression but poor in tension
- Rebar provides support in tension
- Corrosion of rebar can crack and damage the concrete
- Cracks allow more access to oxygen and other corrosive species (e.g. chlorides) and electrolyte
- Concrete can deteriorate and structures can fail





Corrosion in Reinforced Concrete

Corrosion products from the steel cause ***cracking or spalling*** of the concrete which increases the exposure of the steel and increases the corrosion rate.



Corrosion in Reinforced Concrete

Some Solutions:

- **Galvanized steel**
- **Stainless Steel or similar material**
- **Epoxy-coated steel**
- **Ensure proper curing of concrete**
- **Treatments applied to surface of concrete**
- **Cathodic Protection**

Capabilities of TSC Corrosion Team

Corrosion Mitigation Engineering:

- Cathodic Protection Systems
  - · Development of Specifications
  - · Design of Galvanic and Impressed Current CP Systems
- Materials Selection

Field Inspections, Testing, Monitoring:

- Field Testing and Troubleshooting of Underperforming CP Systems
- Inspection During and After Construction/ Installation
- Inspection of Aging and Corroding Infrastructure including Failure Analysis

Other Corrosion Mitigation and Damage Repair Techniques:

- electro-osmotic pulse technique
- fiber-reinforced polymer repair of concrete

Corrosion Chemistry:

- Quantitative analysis of soil and water chemistry including sulfate and chloride concentrations

Education and Manuals:

- Corrosion and Coatings School
- Corrosion Webinar Series and Online Instructive Videos
- Corrosion-related guides and manuals

Corrosion Research

RECLAMATION

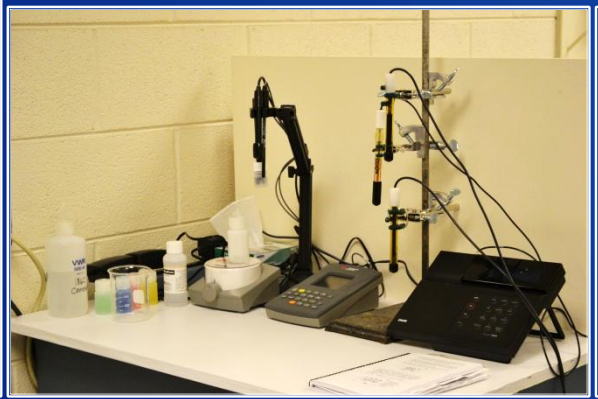
Newly Published Manual

Published December 2012:

Guidelines for Field Installation of Corrosion Monitoring and Cathodic Protection Systems

RECLAMATION

Corrosion Research Lab



Corrosion Research Lab

- **Laboratory Capabilities**
  - Water and soils chemistry (Cl^-, SO_4^-, arsenic, selenium, etc)
  - pH, dissolved oxygen, conductivity
  - Corrosion rate testing in various environments

- **Research Projects**
  - Effect of Chlorine vs. Chloramine Treatment on Degradation of Infrastructure Materials (S&T-funded scoping study FY13)
  - Concentration Corrosion Cells in PCCP (project-funded)
  - Ideas for Future
    - Off-grid power sources for CP systems
    - Carbonation of concrete and its effect on corrosion of rebar
    - Galvanic series for Reclamation materials in water
    - Effect of Controlled Low-Strength Materials (CLSM) on pipeline degradation
  - We want to hear your ideas!

RECLAMATION

Upcoming Events

- **Corrosion Webinar Series**
  - Next Webinar June 2013
  - Topic: Intro to Cathodic Protection and CP Maintenance
  - What do you want to hear about? Please suggest topics for future webinars!
- **Corrosion and Coatings School**
  - October 22-24, 2013
- **Corrosion Website Update**
  - Summer 2013
- **Research Jam 2013** (https://reclamation-research.ideascale.com/)
  - Ongoing until March 15, 2013
  - Submit your ideas for research to the R&D Office (USBR only)

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Questions? Comments?

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