Introduction to Corrosion

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Your Friendly TSC Corrosion Staff:

Daryl Little **Ph.D. Materials Science & Engineering** **dlittle@usbr.gov** **303-445-2384**
Lee Sears **Ph.D. Materials Science & Engineering** **lsears@usbr.gov** **303-445-2392**
Jessica Torrey **Ph.D. Materials Science & Engineering** **jtorrey@usbr.gov** **303-445-2376**
Roger Turcotte, PE, CPS **Materials Engineer** **rturcotte@usbr.gov** **303-445-2383**

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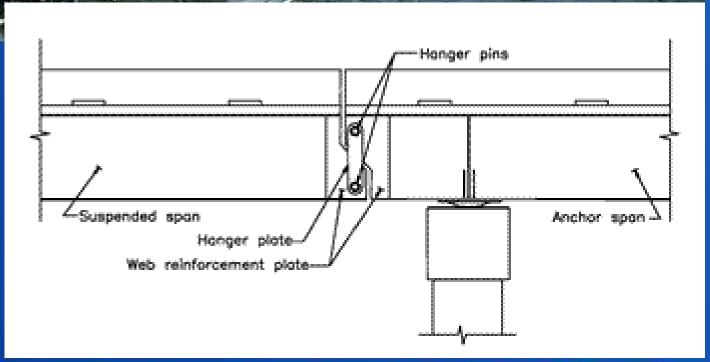
What is Corrosion?

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?

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.



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

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Reclamation Case Study- Folsom Dam

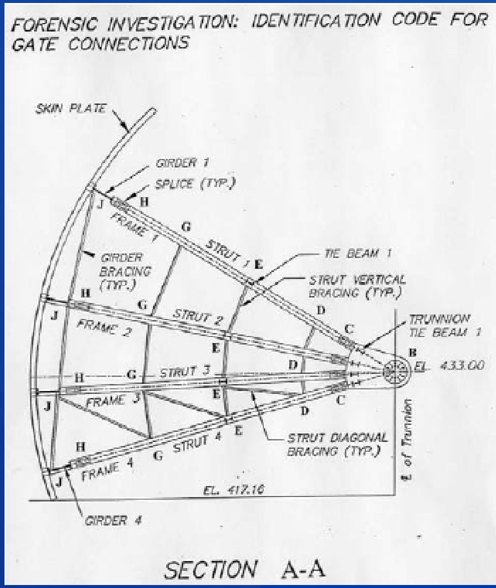
- Spillway gate No. 3 was damaged beyond repair, but no flooding occurred.

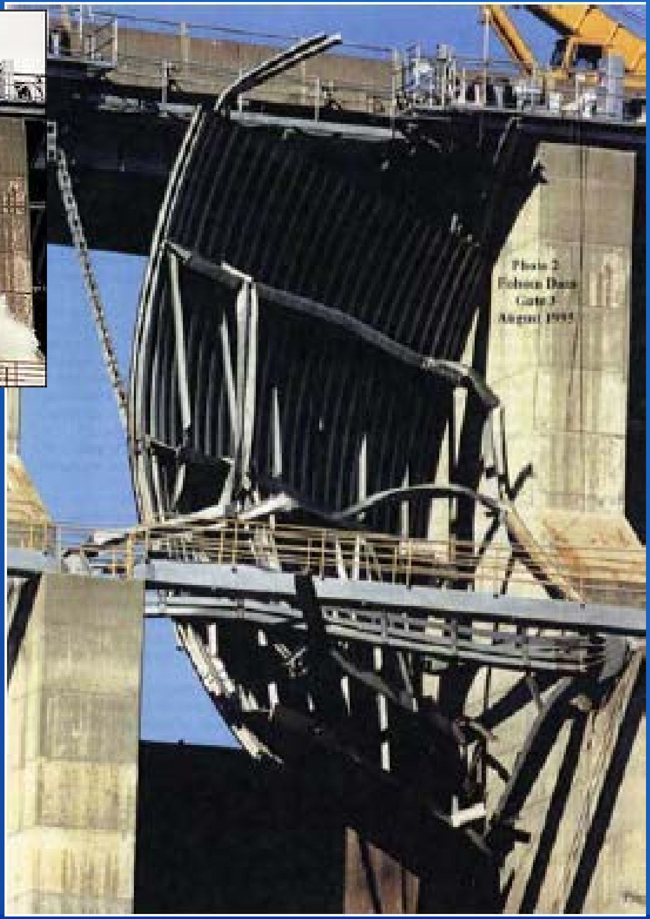
- Replacement of No. 3 and repair of other gates cost ~$20 million and required 40% drainage of reservoir

- 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

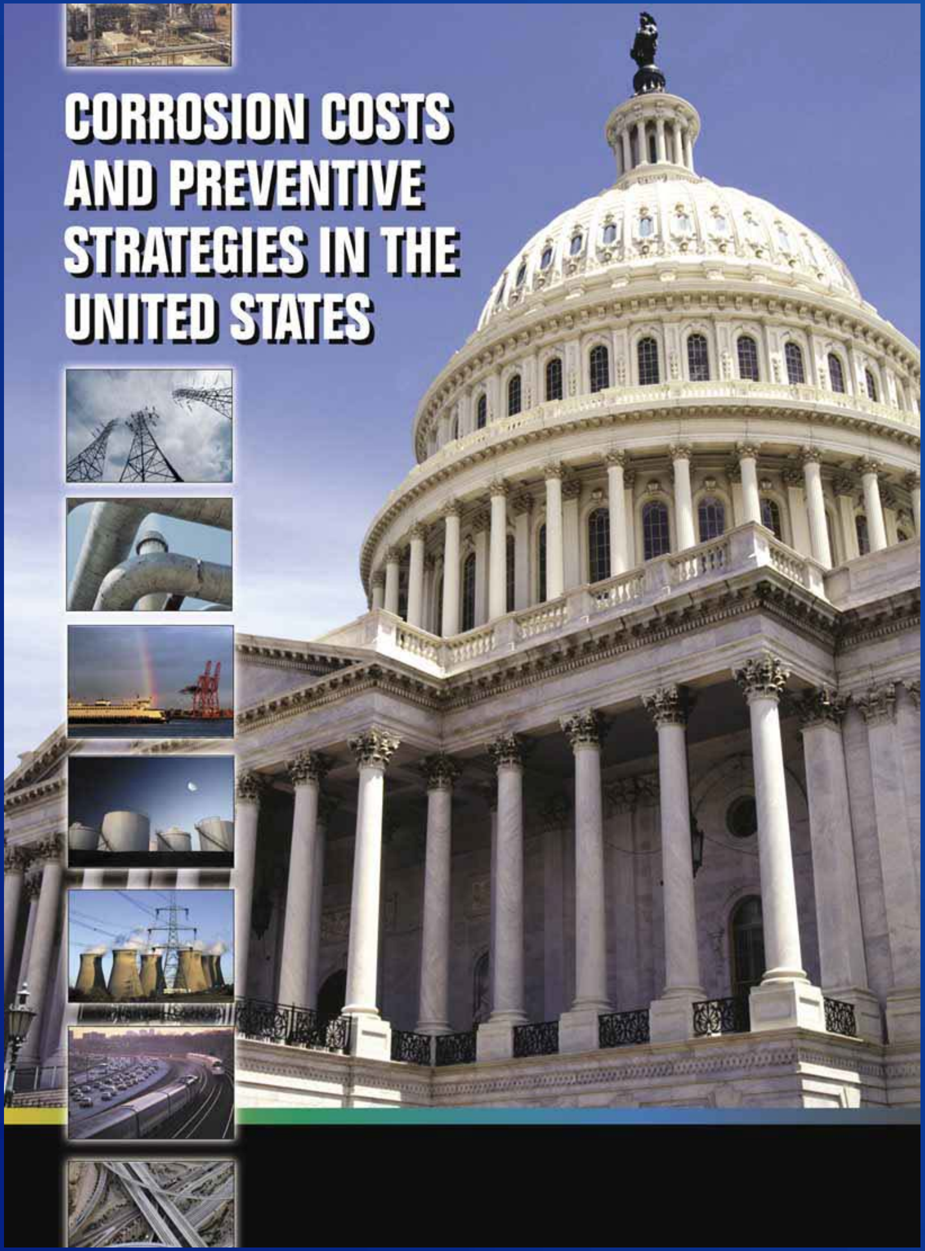
- Frequency of regular maintenance and lubrication had been decreased over time due to budget constraints.





- 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.

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

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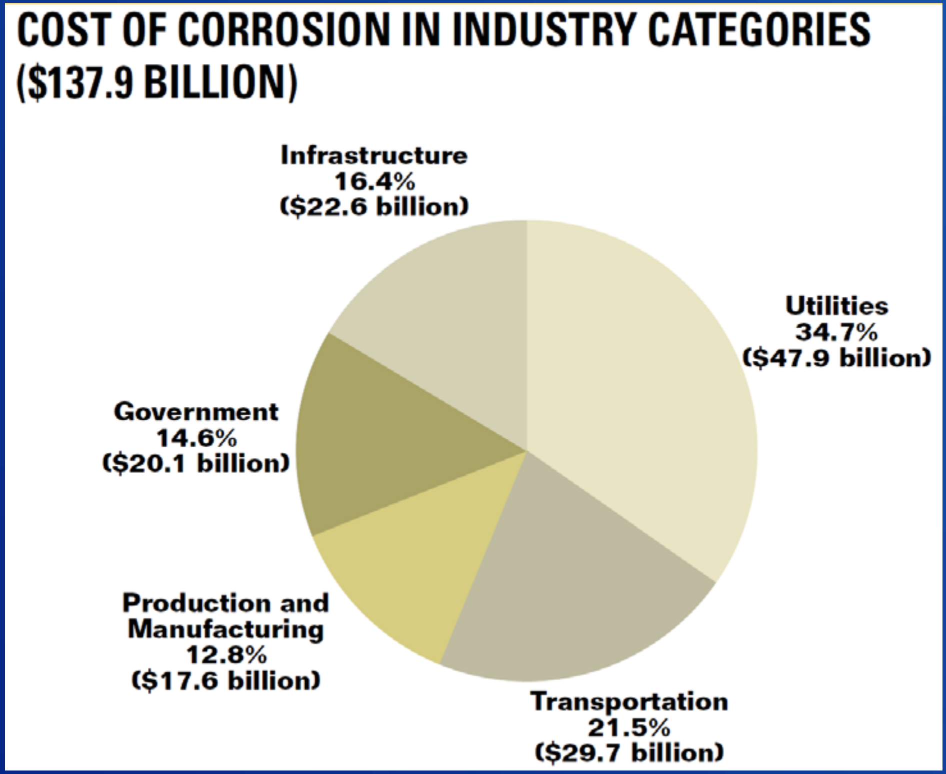
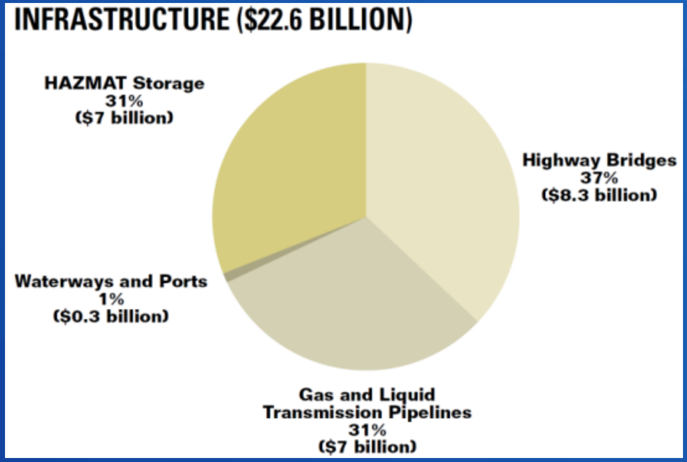
Economic Costs: $276 billion annually



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.**

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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

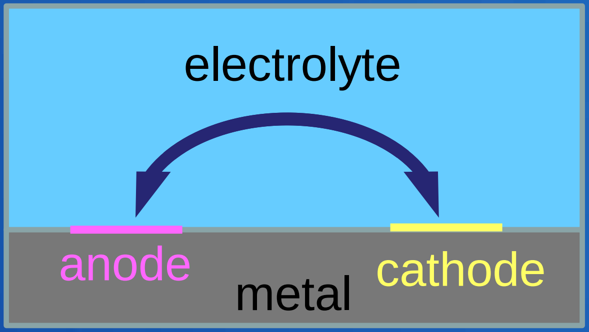
ex. steel, copper, aluminum

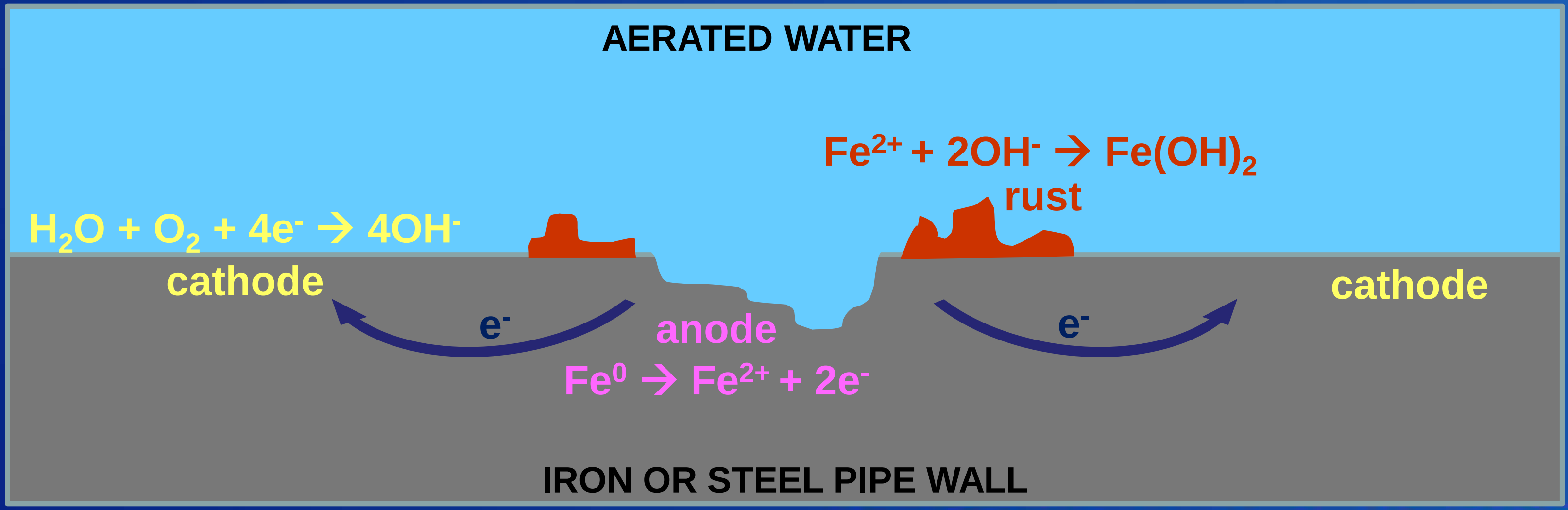
ex. soil, water

- 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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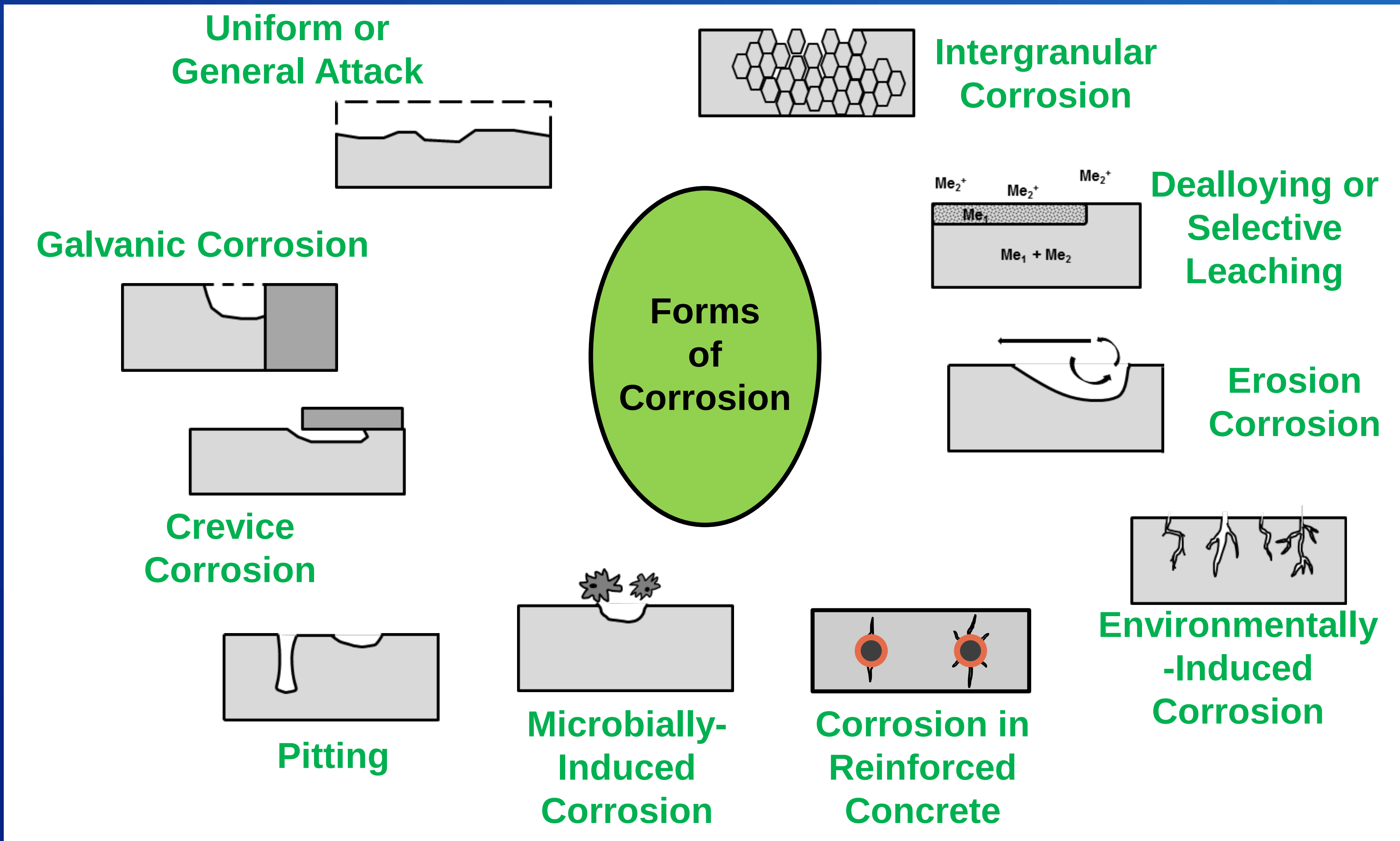
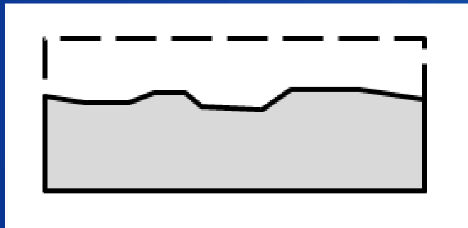
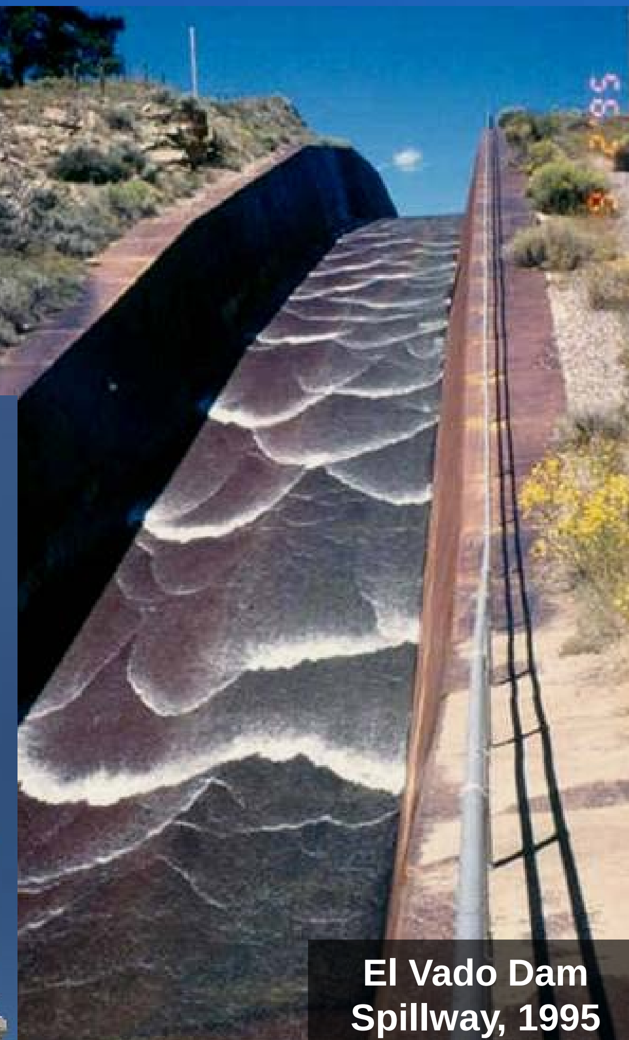
Forms of Corrosion



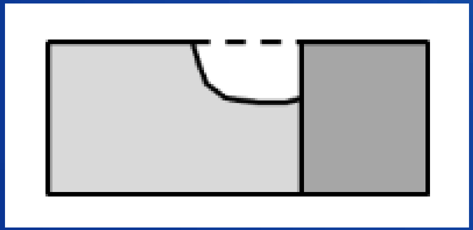


General or Uniform Corrosion

- 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



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.

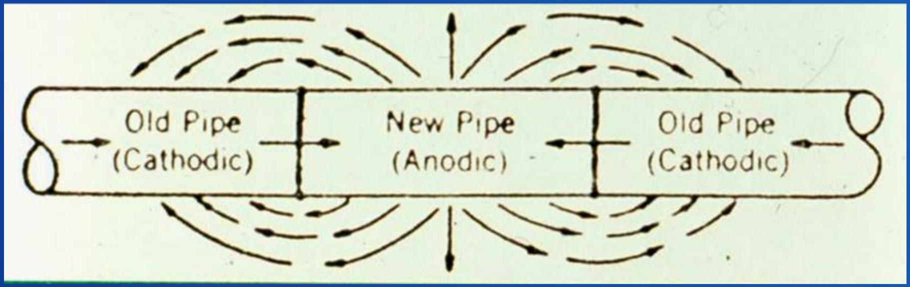
Canyon Ferry Dam Stop Log Guides, 2007

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

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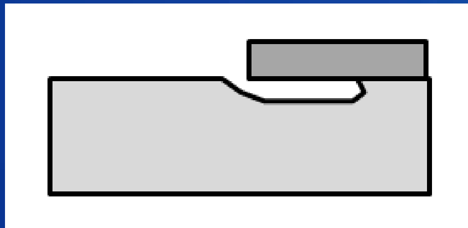
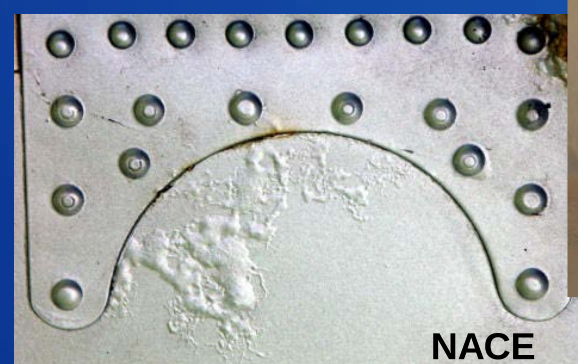


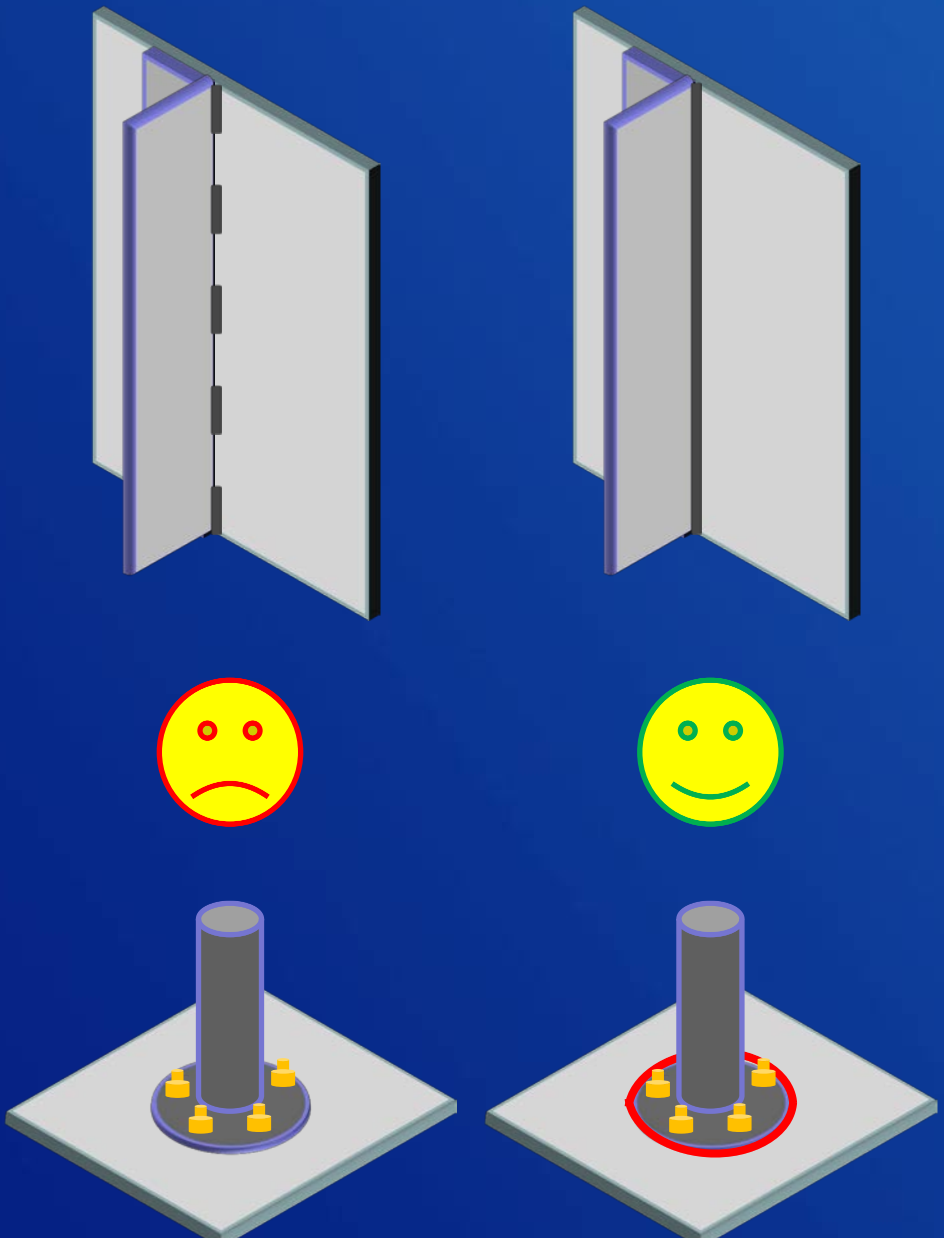
Crevice Corrosion

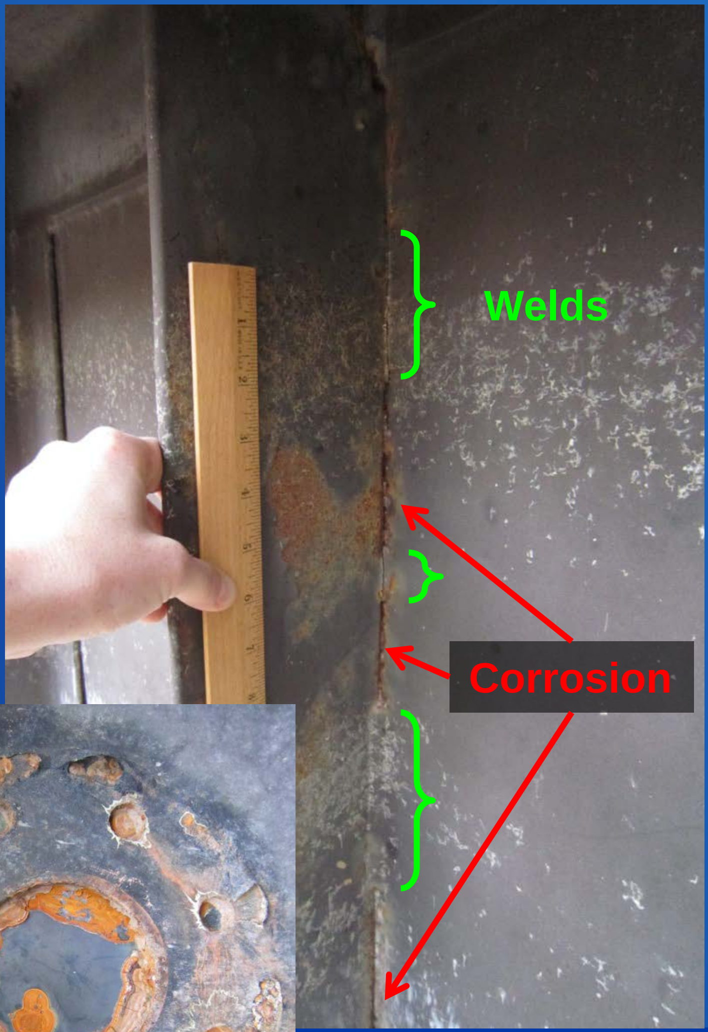
- **Intensive localized corrosion within crevices and under coatings**
- **Some Solutions:**
  - **Avoid designs with crevices (e.g. bolting or riveting, etc.); use non-absorbent gaskets.**
  - **Design equipment for complete drainage; avoid stagnant, wet deposits.**
  - **Close crevices in lap joints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

Palo Verde Diversion Dam Radial Gates, 2013

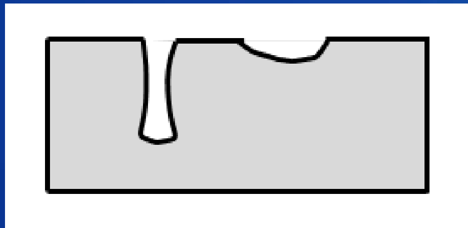


Avoid Skip Welding! Seal Joints!





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**

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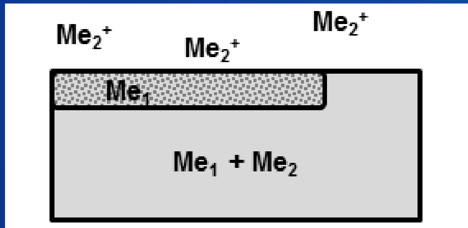
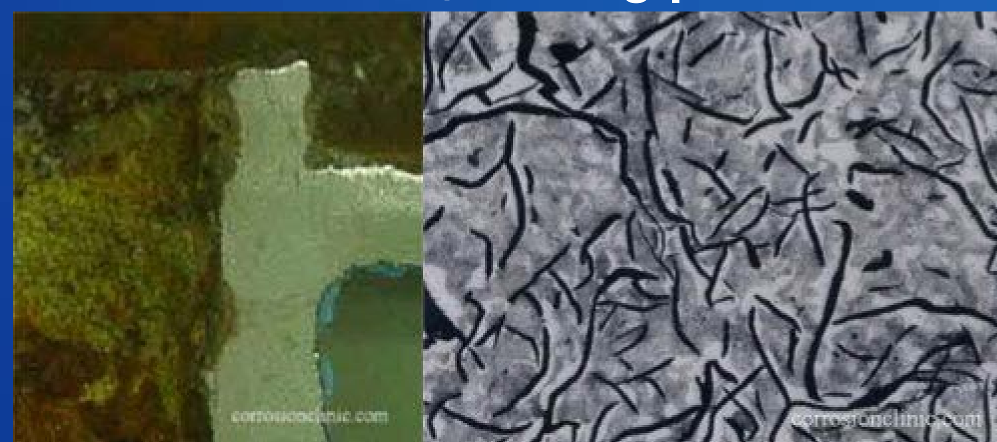


Dealloying or Selective Leaching

- **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)**



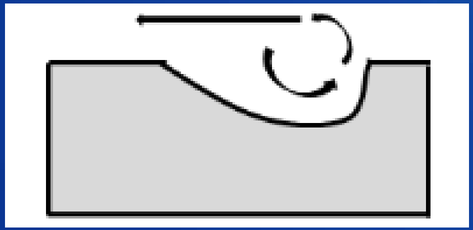
- **Some Solutions:**
  - **Change Alloys**
  - **Cathodic Protection**
  - **Protective coating**

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

Denver Federal Center, 2004

Fountain Valley Conduit, 2007

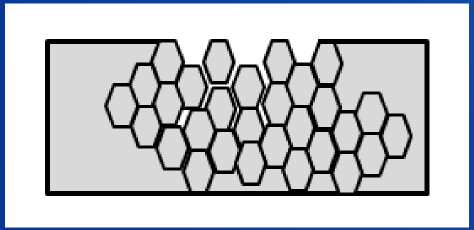
Graphitic corrosion- not apparent on visual inspection; extent of corrosion could only be realized by tapping with hammer to observe loss in strength due to iron leaching



Erosion Corrosion

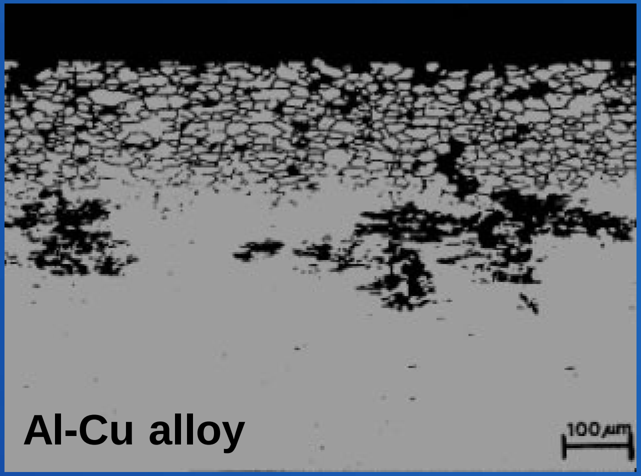
- Accelerated corrosion due to flow of a corrosive fluid across a metal surface

- 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

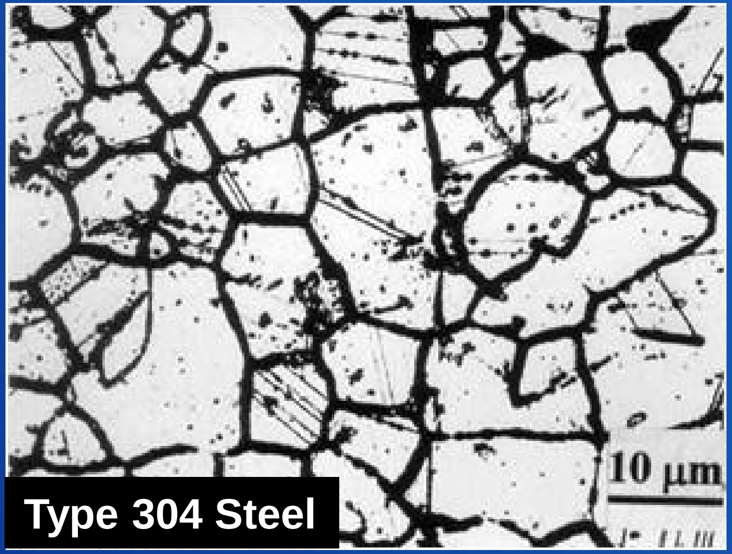


Intergranular Corrosion

- **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**



Al-Cu alloy



Type 304 Steel

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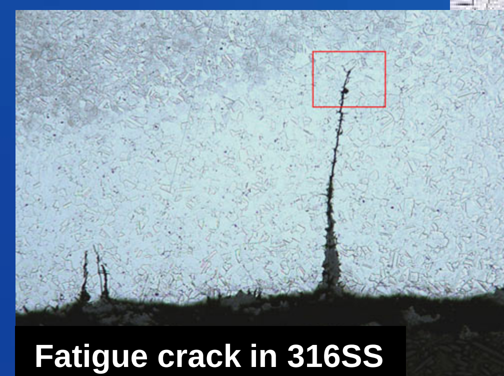
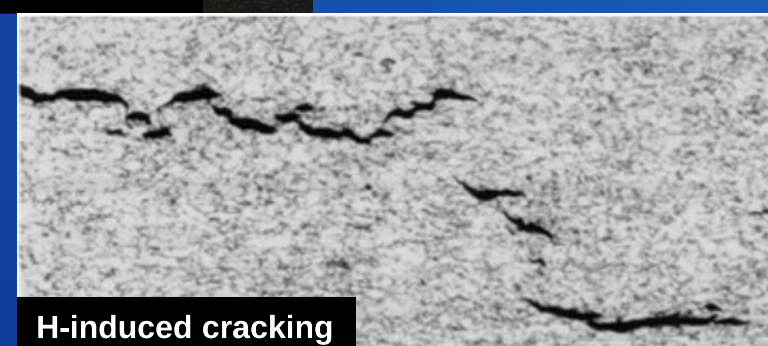
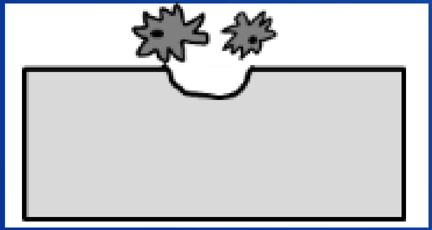
Environmentally-Induced Corrosion

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

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

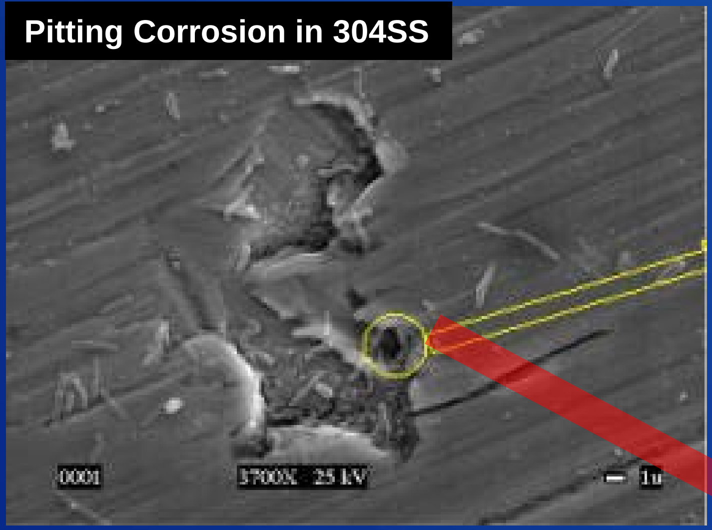






Microbial Corrosion

Pitting Corrosion in 304SS

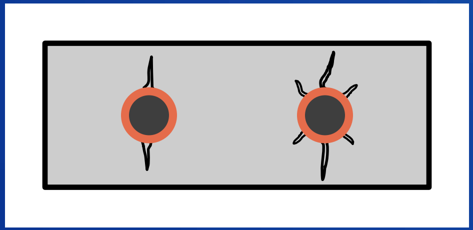


- Corrosion caused or accelerated by microorganisms- bacteria, fungi
- With or without oxygen present
- Biological action can increase the severity of corrosion as a result of:
  - Bio-deposits on the material surface
  - Production of corrosive chemical species (i.e. H_2S from sulfate reducing bacteria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

Some Solutions:

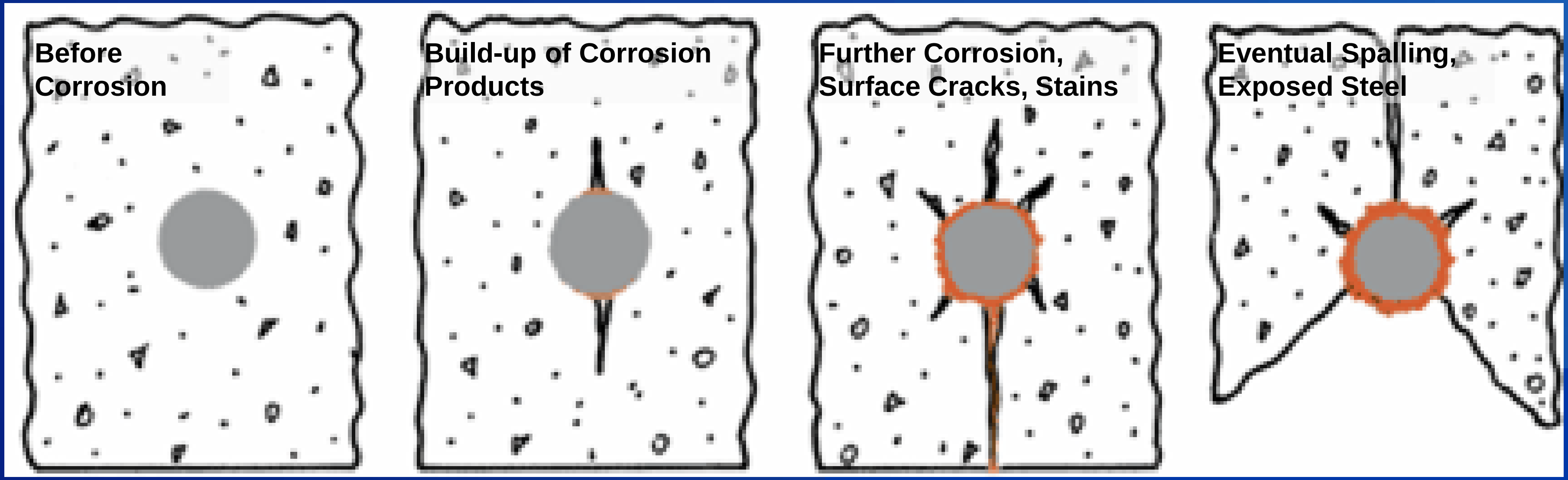
- Select resistant materials
- Frequent cleaning
- Use of biocides
- Apply anti-fouling coating
- Cathodic Protection

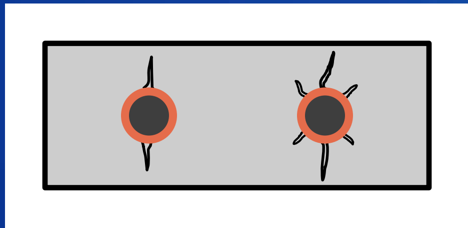
caused by sulfate-reducing bacteria



Corrosion in Reinforced Concrete

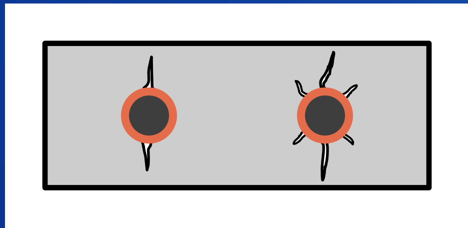
- Concrete is excellent in compression but poor in tension
- Rebar provides support in tension
- Corrosion of rebar can crack and damage the concrete
- Cracks allow more access to oxygen and other corrosive species (e.g. chlorides) and electrolyte
- Concrete can deteriorate and structures can fail





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

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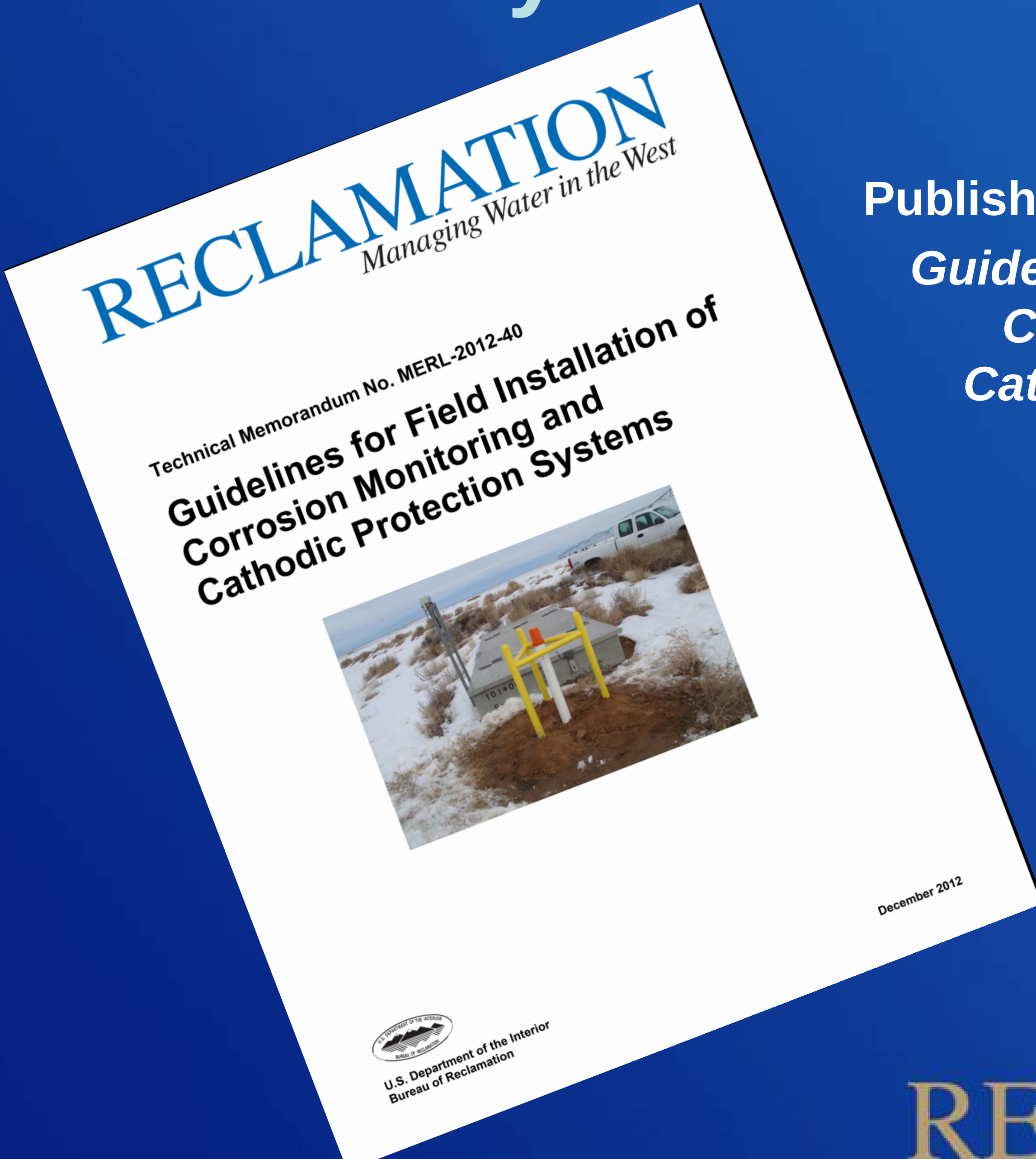
Newly Published Manual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Managing Water in the West

Technical Memorandum No. MERL-2012-40

Guidelines for Field Installation of Corrosion Monitoring and Cathodic Protection Systems

December 2012

U.S. Department of the Interior
Bureau of Reclamation

Published December 2012:

Guidelines for Field Installation of Corrosion Monitoring and Cathodic Protection Systems

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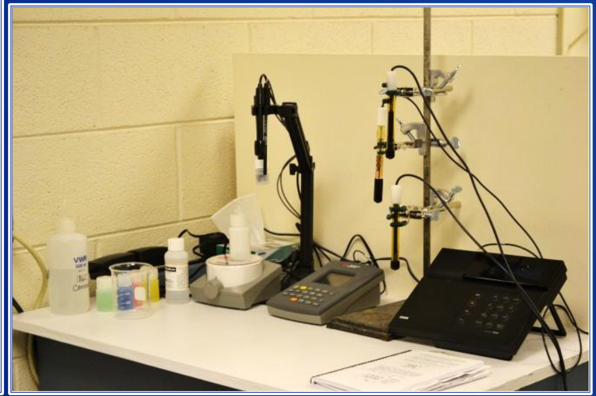
Corrosion Research Lab



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!

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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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