ENGINEERING SOLUTIONS FOR SUSTAINABILITY:
MATERIALS AND RESOURCES 3

Toward a Circular Economy

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Session 3: Educating the Future Engineer

Improvement in Resource Productivity through Corrosion Engineering Education

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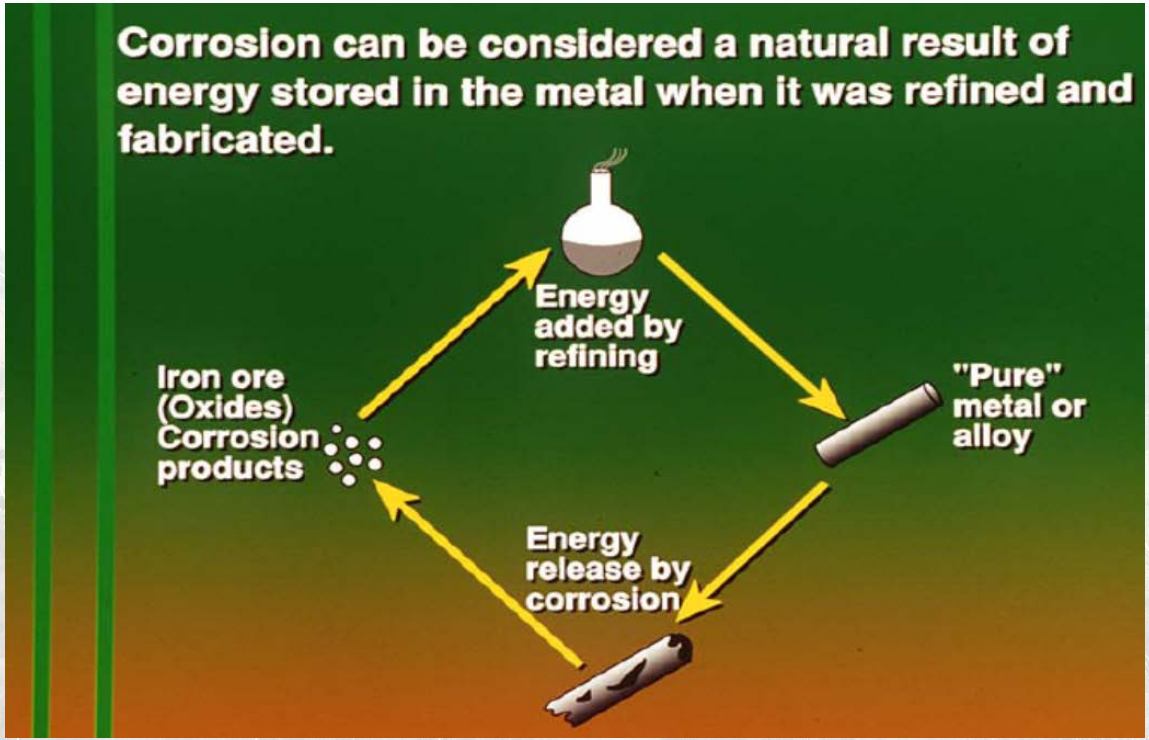
Resource Productivity

- Resource productivity is the quantity of good that is obtained through the expenditure of unit resource.
  - expressed as monetary yield per unit resource

    'crop per drop'
- Resource intensity is a measure of the resources (water, energy and materials) needed for the production, processing and disposal of a unit of good.
- Resource efficiency is maximizing the supply of materials to function effectively, with minimum wasted natural resources.
  - using Earth's limited resources in a sustainable manner while minimizing environmental impact.

Connections….

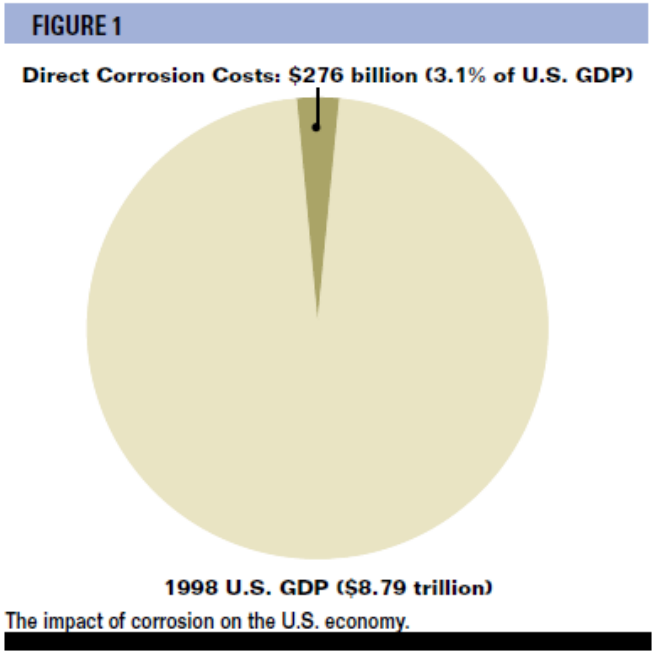


CORROSION

- Natural process that reverses extraction and production of particularly metallic materials.
- Dominant process limiting resource productivity
  - Material loss & replacement cost
  - Production loss: plant downtime
  - Pollution
  - Over design
  - Protection (over) costs
  - Inspection, repair, maintenance costs

Natural but controllable process

CORROSION COSTS

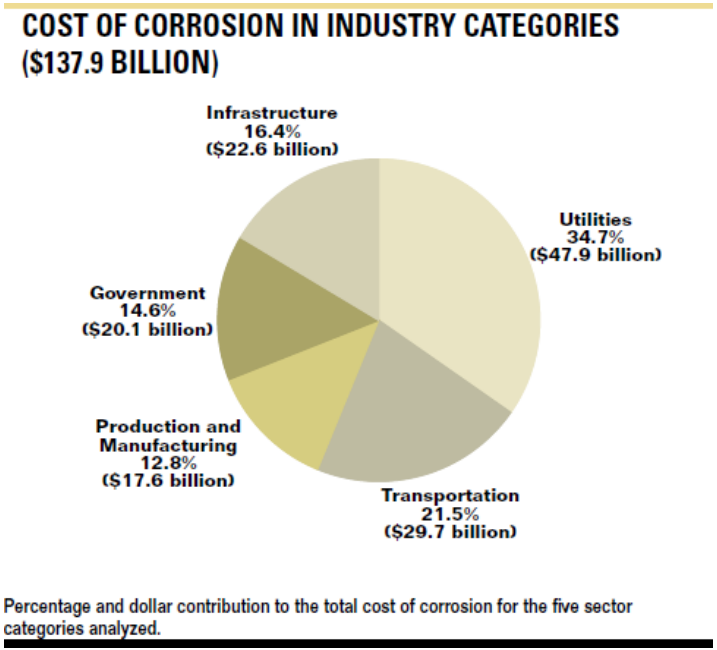


- 2015 GDP 17.7 trillion
- Direct cost of corrosion similar to indirect cost for a total of 6.2 % of GDP.
- Total corrosion cost in US approx. 1.1 trillion
- Global cost: 2.5 trillion
- Approx. 35% can be saved by best practices

Courtesy: NACE 2016 Report/G2MT Report

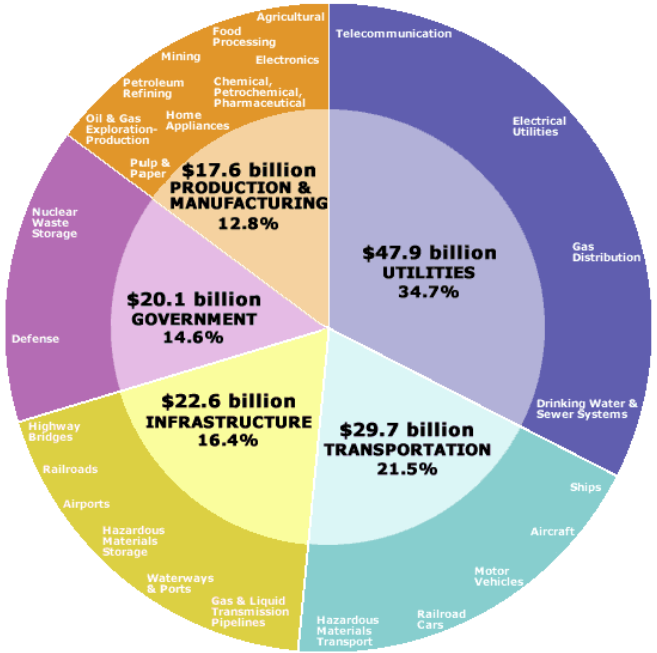
CORROSION COSTS: Sectorwise

1998



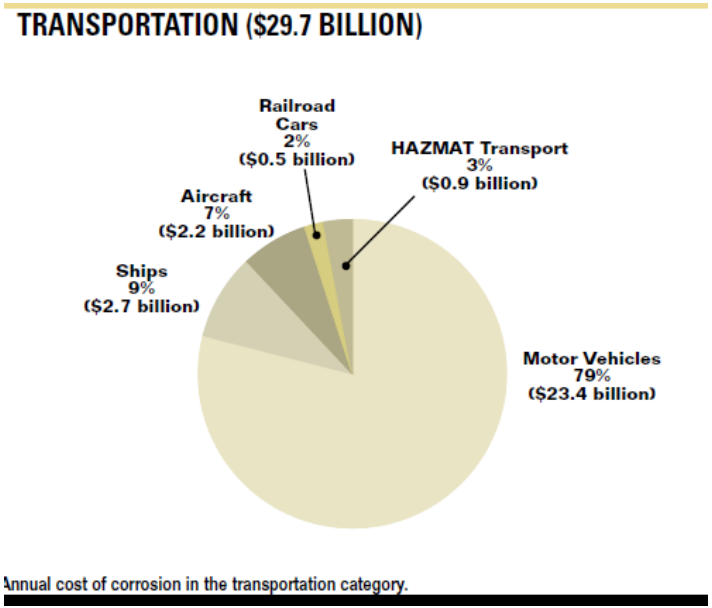
Percentage and dollar contribution to the total cost of corrosion for the five sector categories analyzed.

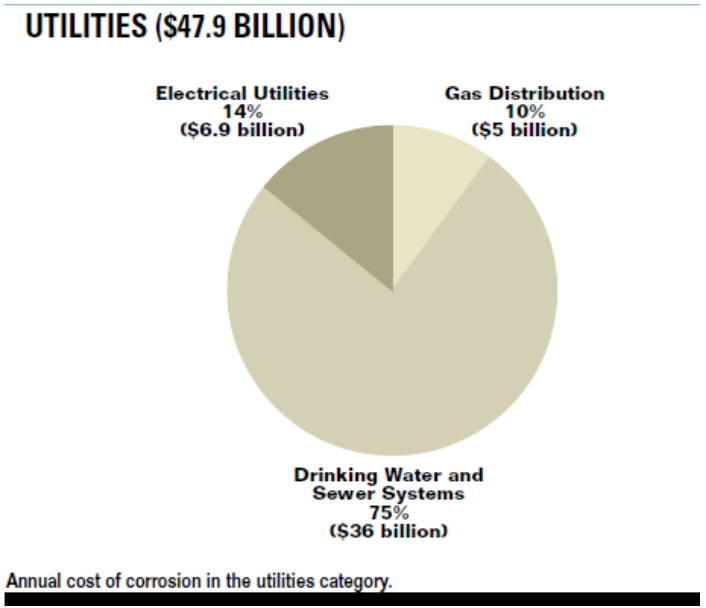
2003



Courtesy: NACE 1998 Report

CORROSION COSTS: Sectorwise





Courtesy: NACE 1998 Report

CORROSION COSTS:

1970's Industry Study of Failures

Method	% of Failures
Corrosion (all types)	33%
Fatigue	18%
Brittle Fracture	9%
Mechanical Damage	14%
Fab./Welding Defects	16%
Other	10%

Courtesy: GEKengineering.com

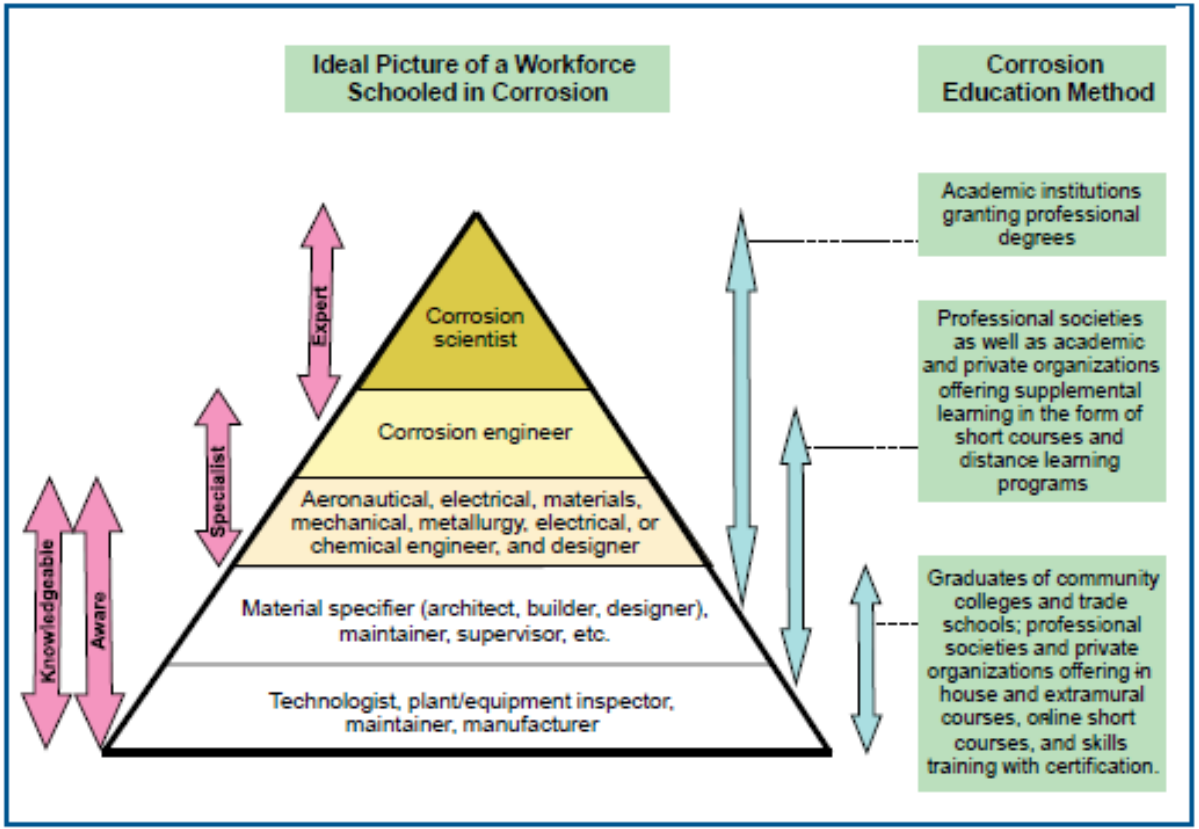
Corrosion Education

Improve resource productivity through corrosion education

Part of Sustainability Curriculum

- Realizing: science, mechanisms
- Recognizing: identify and measure
- Responding: protection

Corrosion Education



Scully & Harris: NRC Report

Corrosion Education

> One of the greatest enduring challenges in engineering education today is to make broadly available and attract students to classes covering subjects such as materials science, applied electrochemistry, and corrosion of engineered materials.

> The committee strongly felt that engineering classes in corrosion with specific learning outcomes should be available to undergraduate engineers who will practice design, undergraduate materials engineers who will perform materials selection, and graduate level engineering students specializing in corrosion.

Scully & Harris: NRC Report

CORROSION COMPETENCIES

20			Theory - The Corrosion Cell			
		A	Apply knowledge of anode/cathode/electrolyte/return path			1
		a1	Explain the reactions and the galvanic series			1
		a2	Describe the different environmental, soil, atmospheric and aqueous conditions			1
		a3	Describe the impact of temperature and pH on corrosion			1
		a4	Discriminate the formation/ differences/value of common corrosion products			1
		a5	Describe the ways polarization can impact corrosion			1
		a6	Conduct an accurate root cause analysis (taproot) SPC			1
		a7	Determine electrochemical, thermodynamic and electrode potential			1
		a8	Use a Pourbaix diagram to determine the stability of a metal as a function of pH and potential			1
		a9	Follow diagrams: water and dissolved oxygen, iron, aluminum, other metals			1
		a10	Describe resistivity as it relates to surface and soil			1

CORROSION COMPETENCIES

21			Corrosion Mechanisms			1
		a1	Detail the types of corrosion mechanisms and their characteristics.			1
			Uniform Corrosion Galvanic Corrosion Crevice Corrosion Pitting Corrosion Environmental Induced Cracking Hydrogen Damage Intergranular Corrosion Dealloying and Dezincification Erosion, Corrosion, and Fretting			1
		a2	Appraise stray current testing and mitigation.			1
		a3	Determine environmental factors affecting corrosion such as:			1
			Atmospheric Underground High Temperature Liquid			1

CORROSION COMPETENCIES

22			Corrosion Control			
		A	Describe Types and Uses of Coatings			1
		a1	Analyze galvanic or metallurgical bonding for protection optimization			1
		a2	Describe the advantages of using an organic coating			1
		a3	Analyze when to use a Dialectic barrier			1
		a4	Apply application techniques/surface preparation for coatings			1
		B	Use Cathodic Protection to prevent corrosion in pipelines.			1
		a1	Application of cathodic protection to protect buried or submerged metals - system types, design, monitoring performance			1
		a2	Describe how cathodic protection interferes w/corrosion reaction			
		a3	Apply the cathodic protection specific to metals			1
		a4	Use the Pourbaix Diagrams to determine which species (metals or alloys) is thermodynamically stable at a given electrode potential.			1

CORROSION COMPETENCIES

D	Inhibitors and Coatings			1
a1	Determine when and how to apply Liquid Applied Organic Coatings			1
a2	Determine what commonly applied materials are used to form Thick Non-metallic Coatings			1
a3	Determine which materials are appropriate to use as Metallic Coatings			1
a4	Identify which Inhibitors are most appropriate for specific materials			1
a5	Use Electrochemical Behavior knowledge to assess the state of corrosion in a concrete or metal element			1
a6	Demonstrate knowledge of the fundamental attributes/uses of Inhibitors, chemical safety concerns, MSDS, installing injection equipment/quills, sampling and monitoring for effectiveness, use of corrosion coupons			1
a7	Demonstrate knowledge of the fundamental attributes/uses of Vapor-Phase Inhibitors			1

Corrosion Topics

Realizing:

- Facts & impacts
- Thermodynamics, Chemical Equilibrium & Nernst's Equation
- Mixed potential theory, Exchange current density
- Electrode Potential, Reversible cell potential
- Reference electrodes
- Polarization & Evan's Diagram
- Pourbaix's Diagram
- Galvanic & Concentration Cells

Corrosion Topics

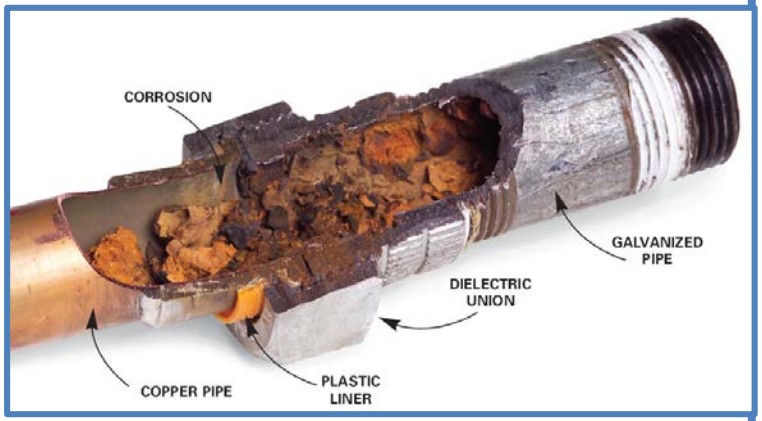
Recognizing:

- Forms of Corrosion
- Corrosion rate, Faraday's Law, Efficiencies
- Identifying localized forms
    - Stress corrosion cracking & Hydrogen Cracking
    - Galvanic
    - Intergranular, Pitting, Crevice and Erosion Corrosion
    - Microbiologically induced
- Non-destructive measurements
- Remote sensing
- Data acquisition and management

Corrosion Topics

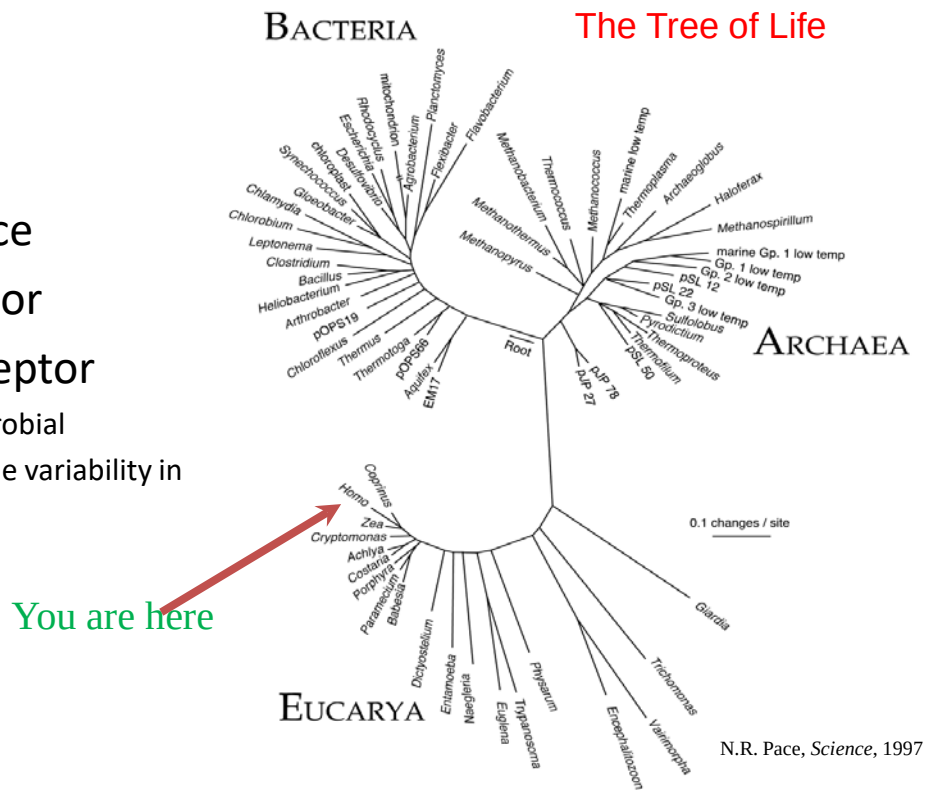
Responding:

- Cathodic & anodic protection
- Material substitutions
- Coatings
- Inhibitors
- Designing and fabrication
- Risk analysis
- Economics

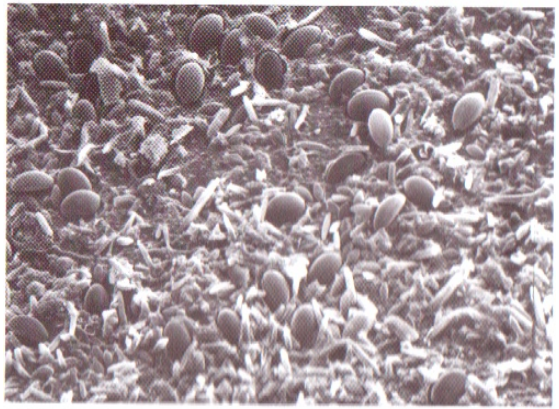


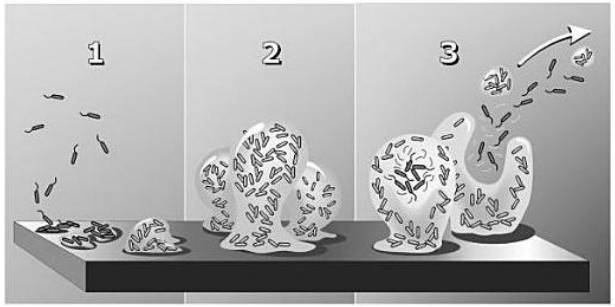
Microbial Diversity

- 4 Necessities of Life:
  - Water
  - Carbon Source
  - Electron Donor
  - Electron Acceptor
- The majority of life is microbial
- Microbes show remarkable variability in "lifestyles"

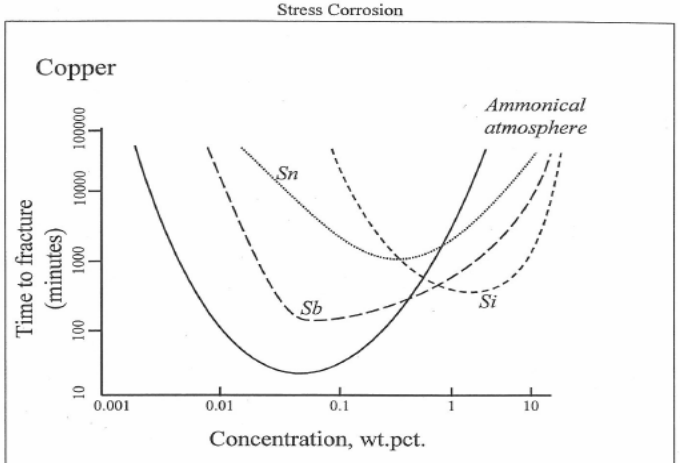


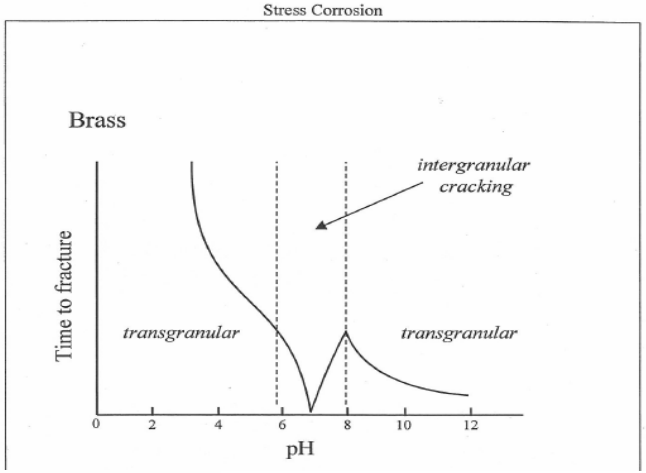
Microbial Corrosion

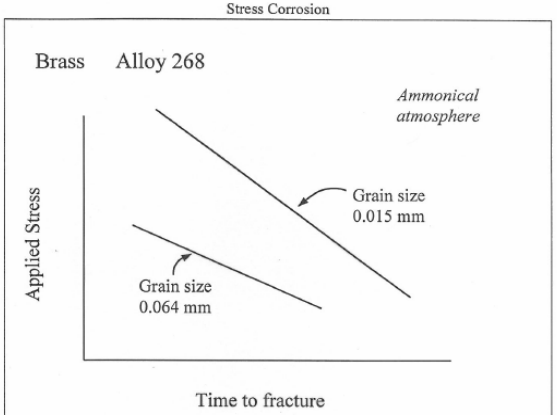




Stress Corrosion Cracking



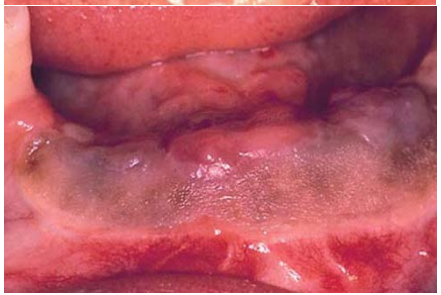


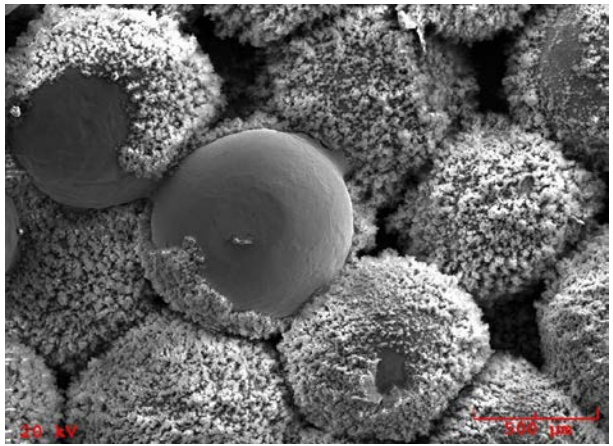


SCC of copper:

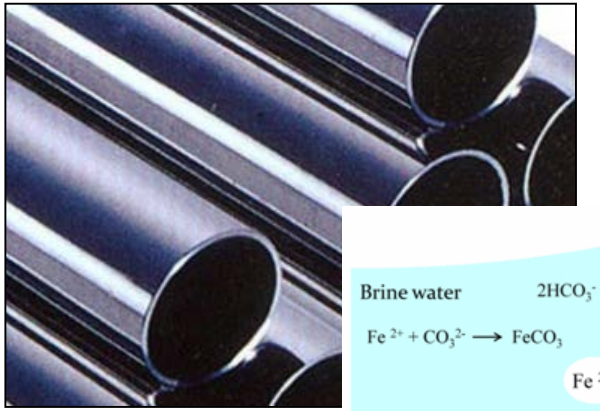
- **The alloy**
- **The environment**
- **The Stress**

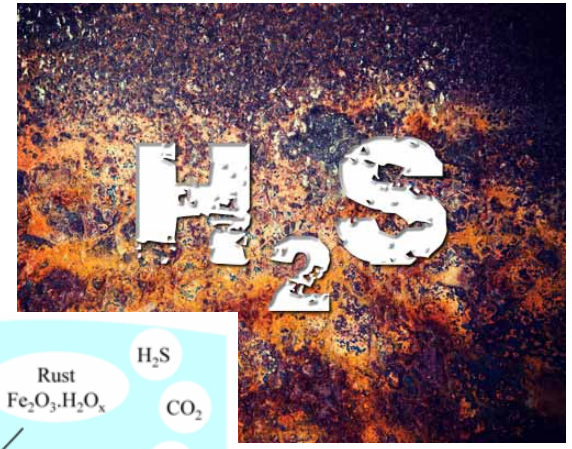
Medical Devices

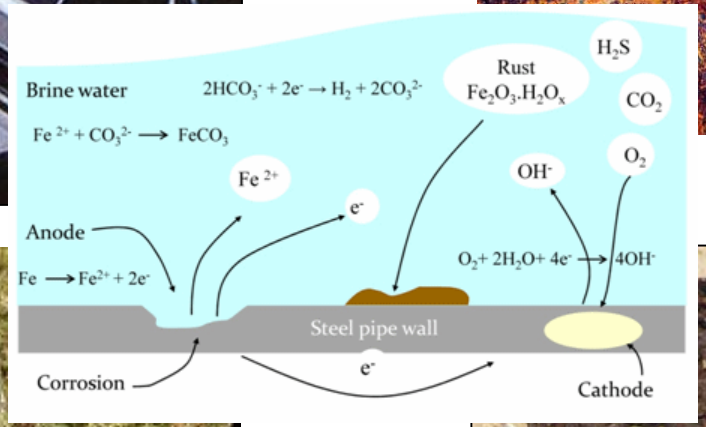


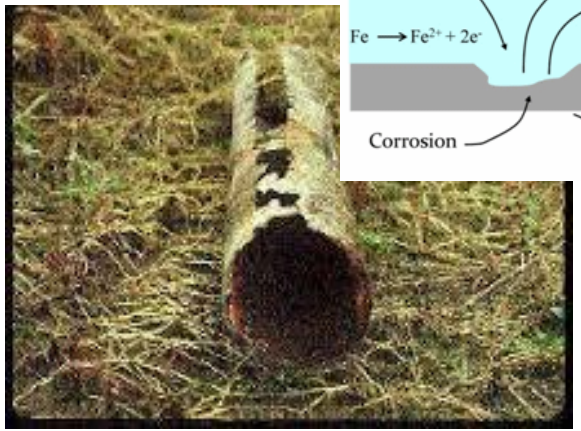


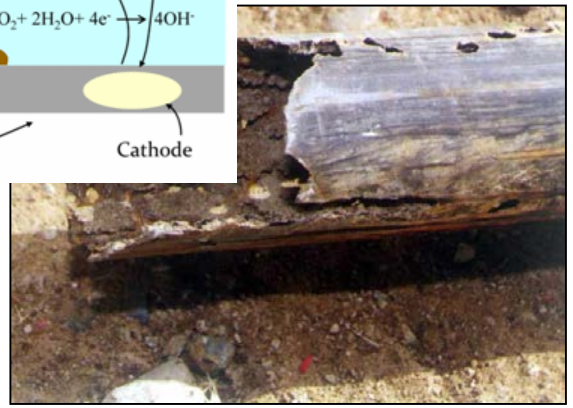
Sour Corrosion



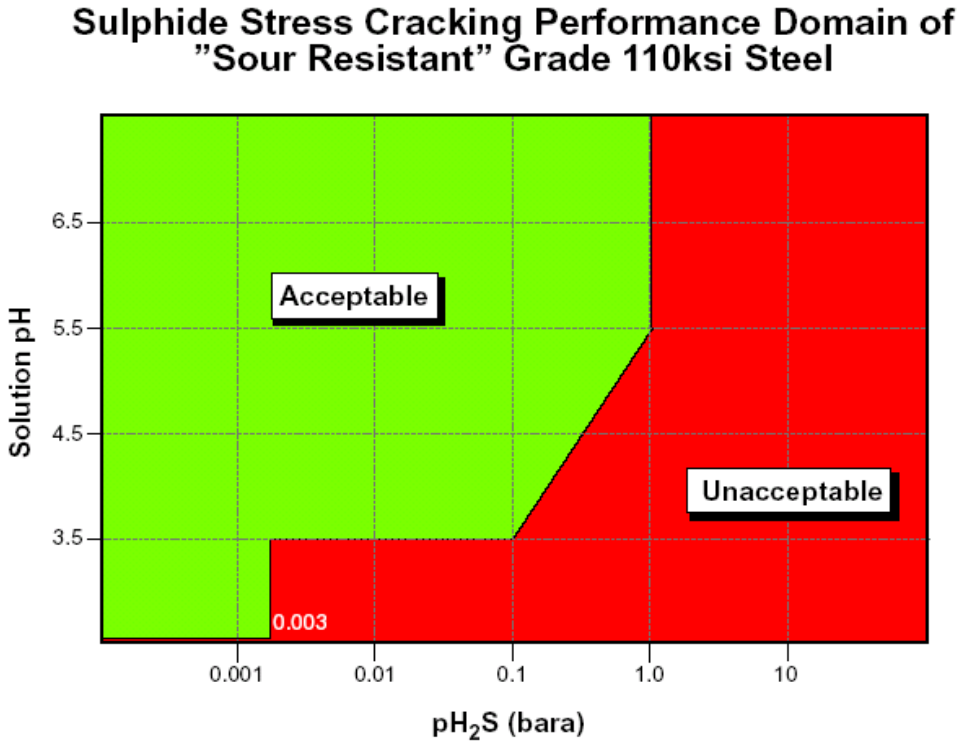






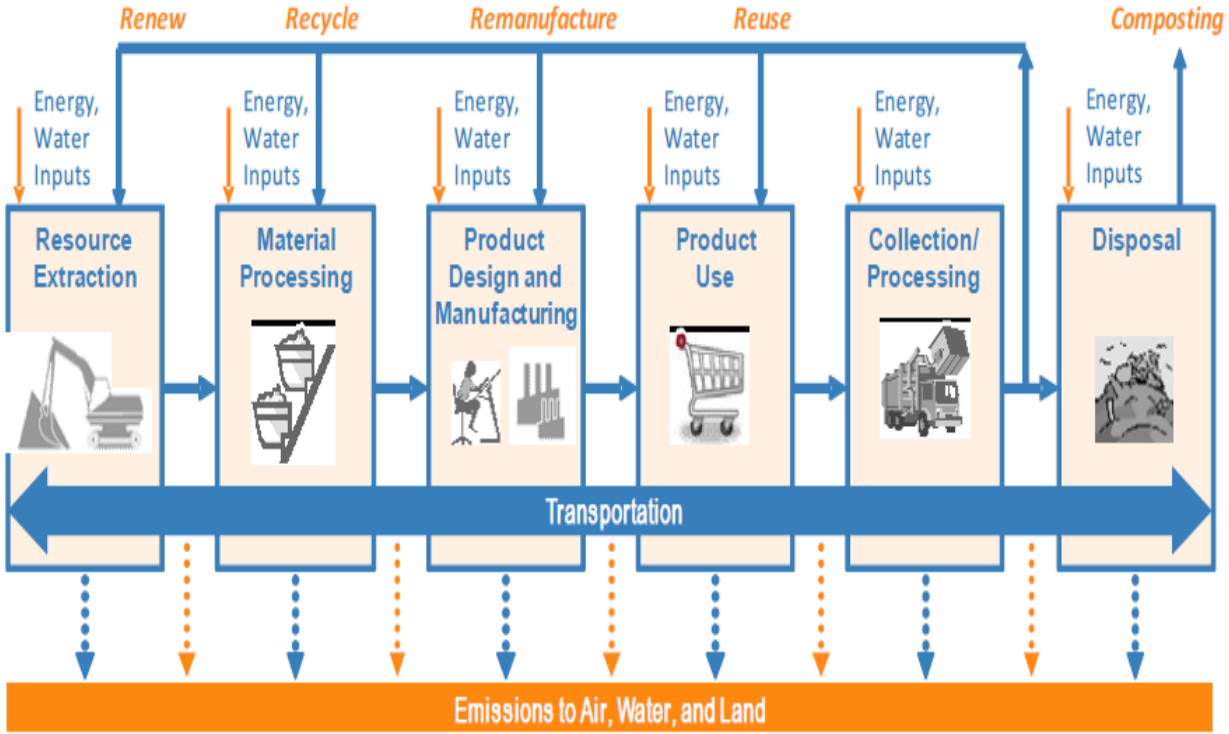


KNOWLEDGE TO SOLVE



Courtesy: GEKengineering.com

The flow of materials



Materials are non-renewable!

Source: EPA

Summary

- Corrosion impacts materials sustainability extensively
- Cost of corrosion significantly impacts economies
- Protection against corrosion can improve resource productivity
- Knowledge of corrosion is essential for practicing engineers