

Corrosion and Our Infrastructure

by

Neville W. Sachs, P.E.

This is a railroad bridge



Do you feel comfortable?

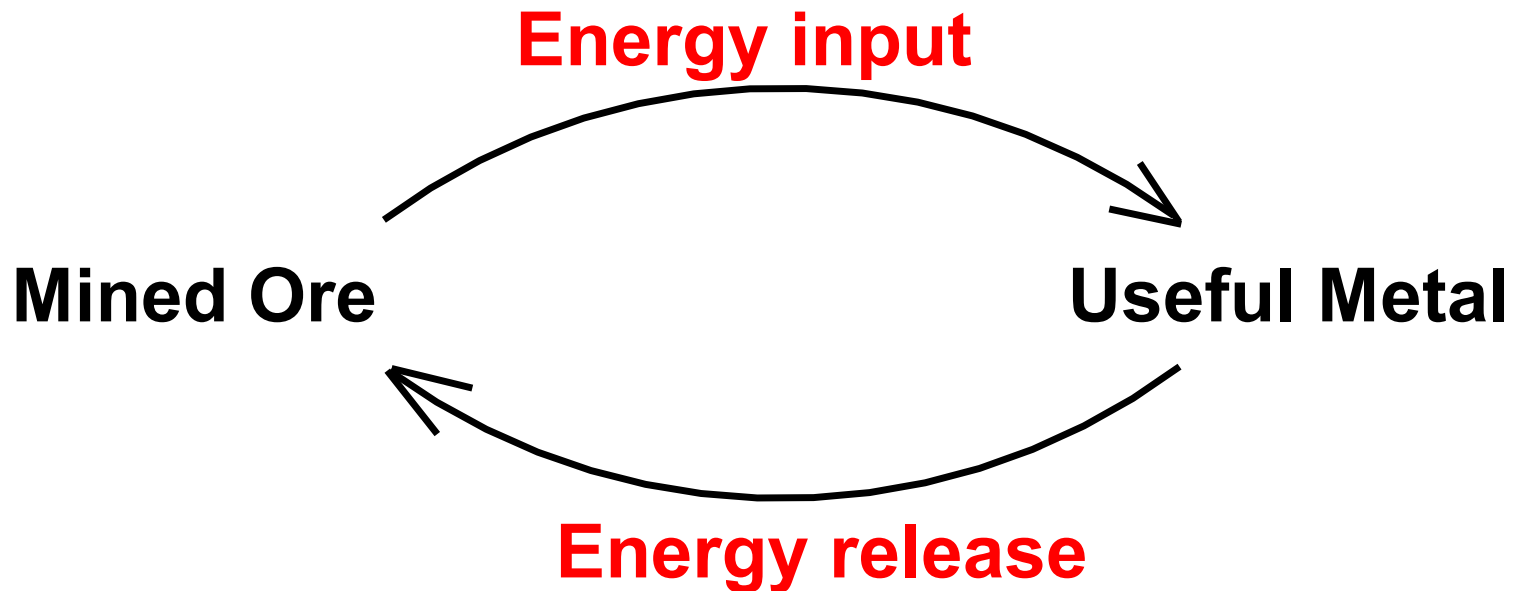


How comfortable?



Corrosion, Rusting, Oxidation

The reason it happens is that we put a lot of energy into the ore to make a useful metal, then Mother Nature tries to reclaim it ...



Quiz questions

1. What effect does temperature usually have on corrosion rates? When isn't that true?
2. There has to be a liquid present. Why?
3. Does the alloy order in the "galvanic series" ever change?
4. You repair a steel tank and add a stainless bottom. What area(s) of the tank interior should be painted?
5. How does corrosion affect fatigue strength?

What Does Corrosion Cost?

A detailed 1998 study by NACE (National Association of Corrosion Engineers) with the Federal Highway Administration showed that the **direct cost** was 3.1% of our country's GDP.

The **indirect costs** are estimated to double that. (Indirect costs include things like losses due to corroded equipment not being available, lost time due to delays, etc.)

... costs ...

Estimates are that corrosion costs 2% of the US Federal budget and currently about \$30 billion per year by the North American automotive industry.

Similar costs in other developed countries, but higher near equator - because they are warmer.

The World Corrosion Organization estimates that 20 to 25% of those losses can be saved with currently known techniques and practices.

Two Basic Corrosion Categories

Wet

- by far and large the most common
- requires liquid to be present
- eight major categories

Dry

- usually refers to direct conversion at elevated temperatures
- a relatively small number of situations

Direct Conversion

(Dry Corrosion)

Only happens at elevated temperatures when the oxide is formed without a liquid present

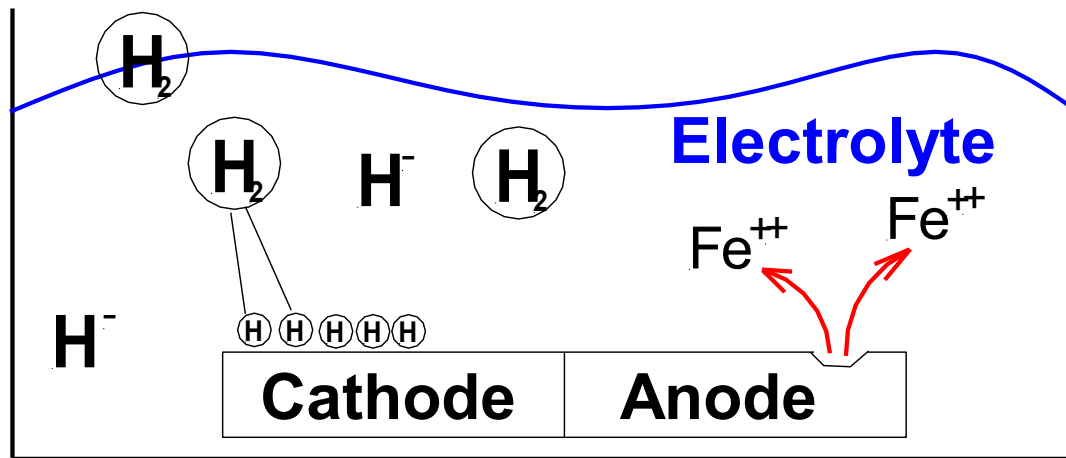
Not very common

The photo shows an overheated boiler tube



For most of us, the only time we'll see direct conversion is on the grates of our barbecue grills, as it flakes off chunks of oxide.

The Wet Corrosion Process

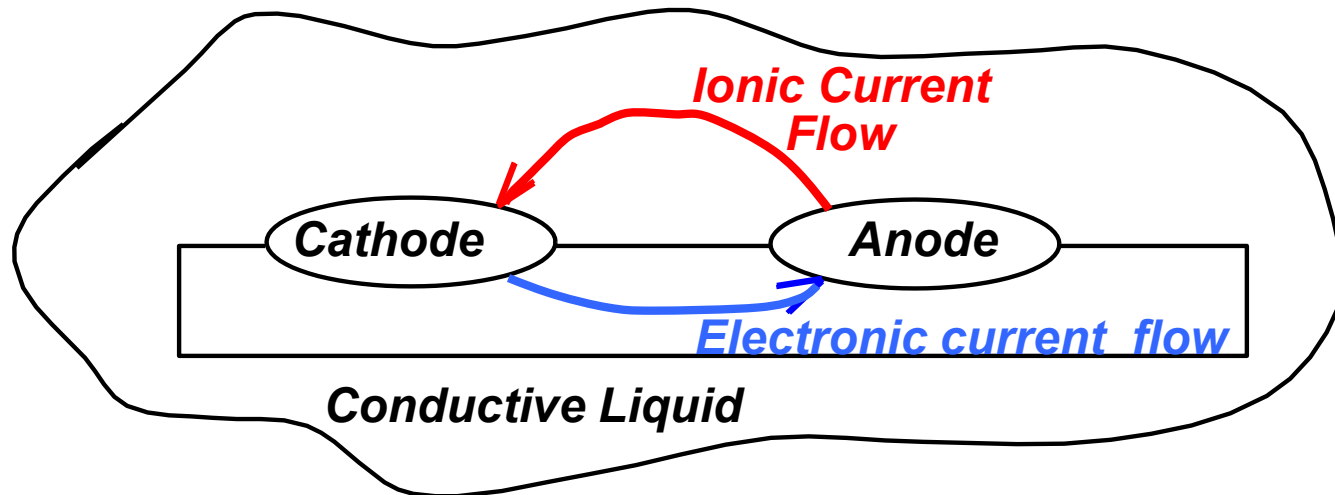


The metal bar, in this case steel, is being attacked. The end product depends on the specific liquid and metals, but the reactions are all similar.

Hydrogen liberation is a normal corrosion feature. Most of the hydrogen ions combine to form H_2 gas **(but there are always some free ions present to cause problems)**.

Electrons flow inside the metal bar then return through the liquid.

The Electrochemical Reaction that results in Corrosion



If there is ***no liquid present***, there would be no return current path and ***no corrosion***.

Electrochemical Reactions

Anode and cathode reactions must generate and consume electrons at the same rate.

So restricting either of these functions will slow the entire reaction.

In addition, the amount of metal lost is a function of the total corrosion current – greater current density (flow) means more rapid corrosion damage.

Conditions affecting the Corrosion Rate*

Temperature - Arrhenius' rule - for every 10⁰C the rate of reaction approximately doubles - is a good guide.

Concentrations - Amount of corrodent present

Contaminants - What is the solution contaminated with?

Mechanism - The surface conditions.

Oxygen availability – No oxygen, no oxidation

Exposure time – The corrosion rate usually slows with time.

pH – In more acidic and more alkaline solutions the rate usually increases (but not always).

Flow velocity – Increased flow rates usually increase the corrosion rate (FAC)

** With a given metal*

Side Topic!

How Do Stainless* Steel (and aluminum) Reduce Corrosion

Look at basic steel chemistry

Then add chromium. The chemical reaction with the chromium ion rapidly forms a chromium oxide that is difficult to attack and perforate. (Aluminum forms aluminum oxide.)

Then add other elements - nickel, molybdenum, etc., to strengthen that oxide film

Steel (Fe + C)

**Good Stainless Steel
(Fe + C + Cr)**

**Better Stainless Steel
(Fe + C + Cr + Mo + ...)**

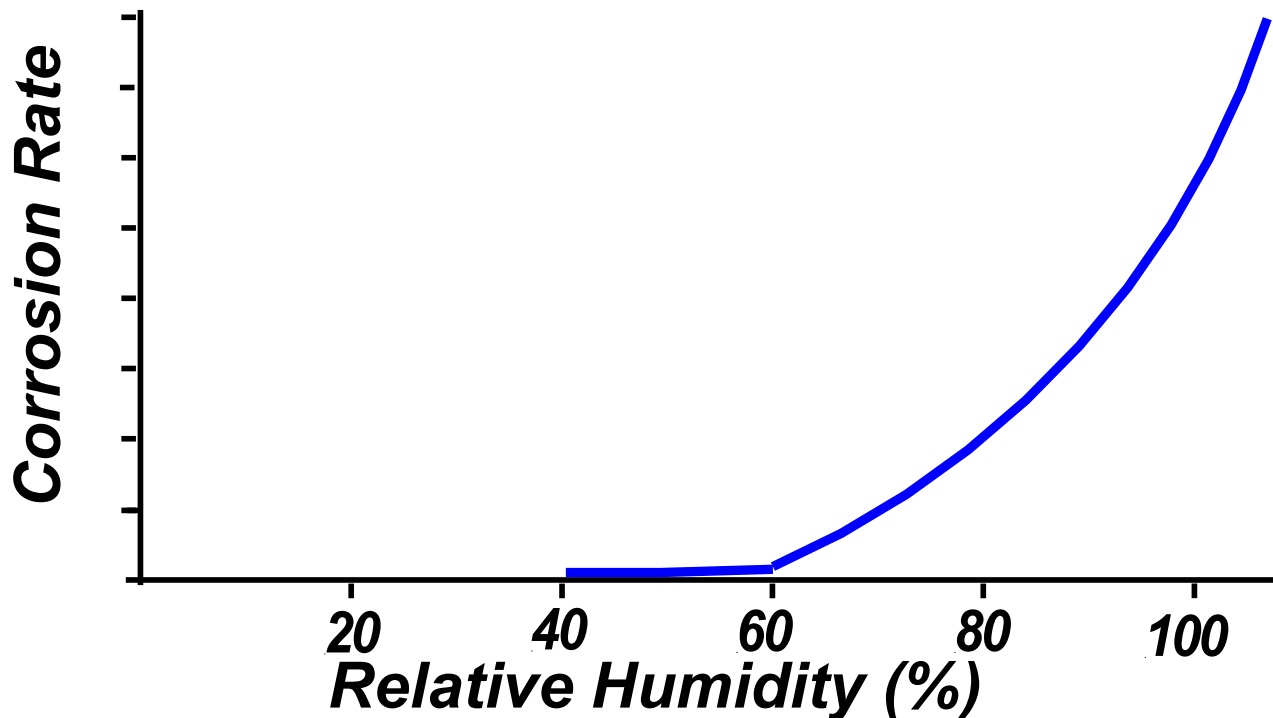
*** It really isn't "stainless" and it certainly isn't corrosion-proof!**

Affecting Corrosion Rates – Available Moisture

No moisture = no corrosion

Liquid has to be present to complete the circuit.

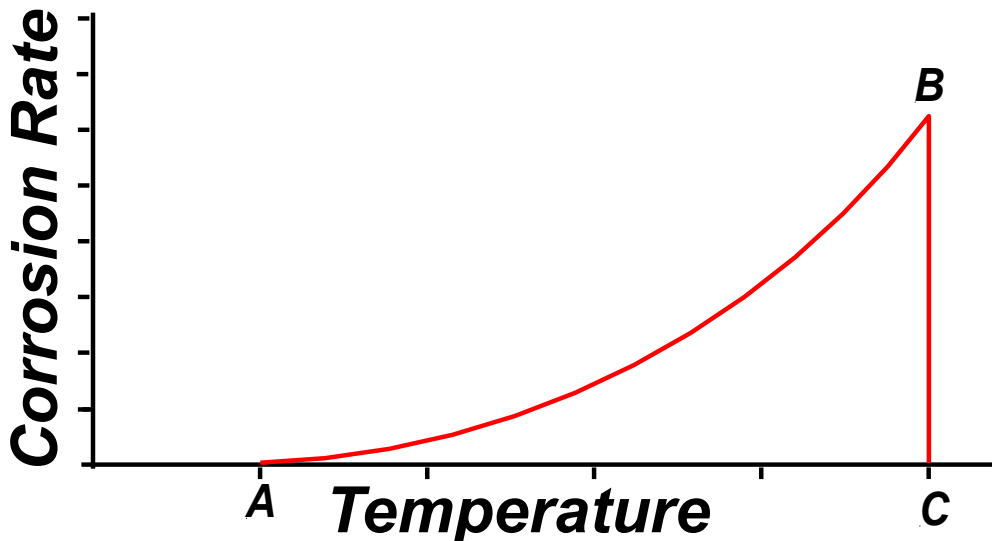
Attack will usually begin in nooks and crannies at about 60% relative humidity.



Temperature affect on Corrosion Rates

Frequently Arrhenius' rule is a rough guide. (10⁰C increase doubles the reaction rate)

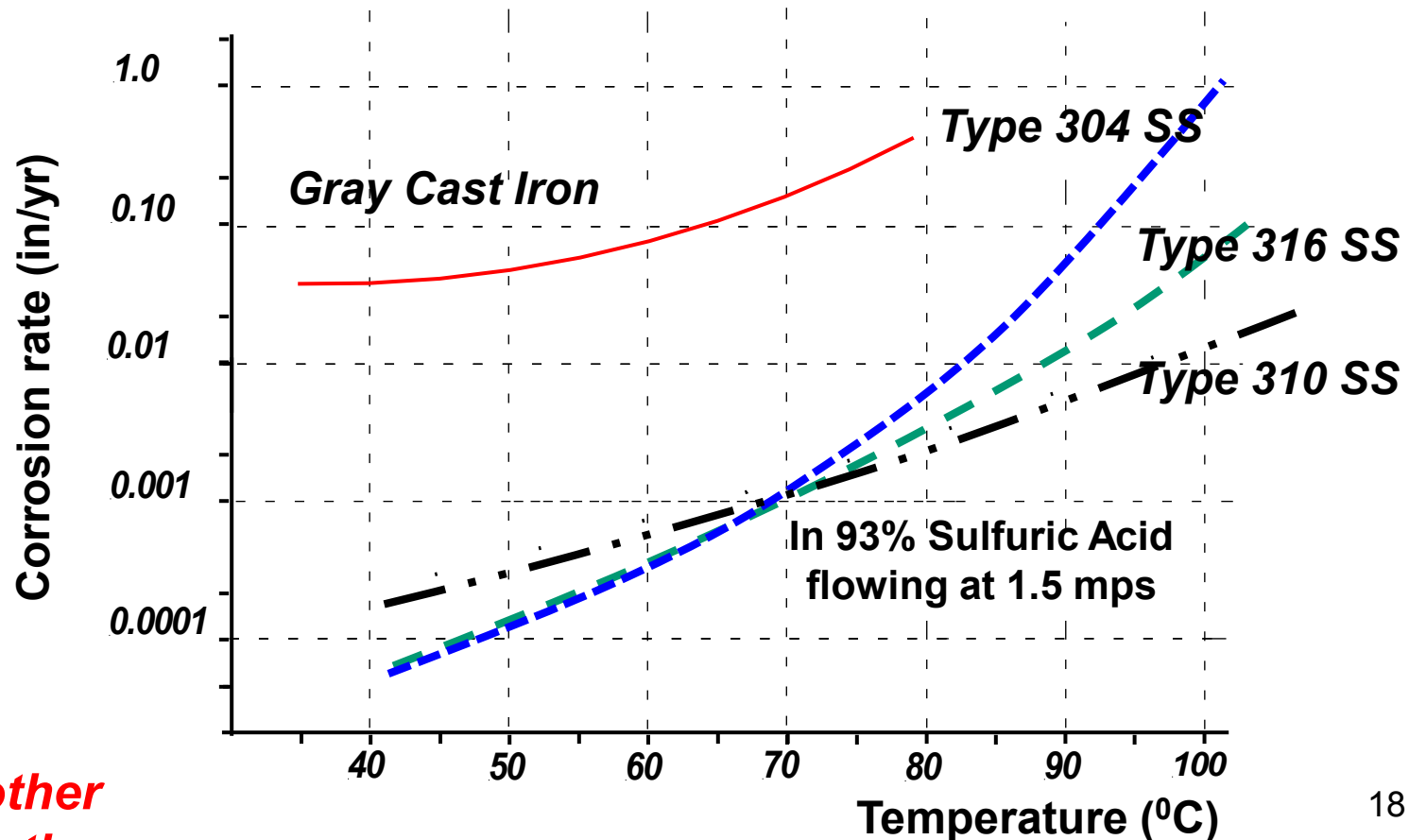
- In some applications, overstates the effect
- There is usually a base temperature to start at.



Solids and gases (ice and water vapor) don't conduct corrosion currents very well.

Temperature Affect on Corrosion Rates

Important to understand the mechanism!!



We'll have another example shortly

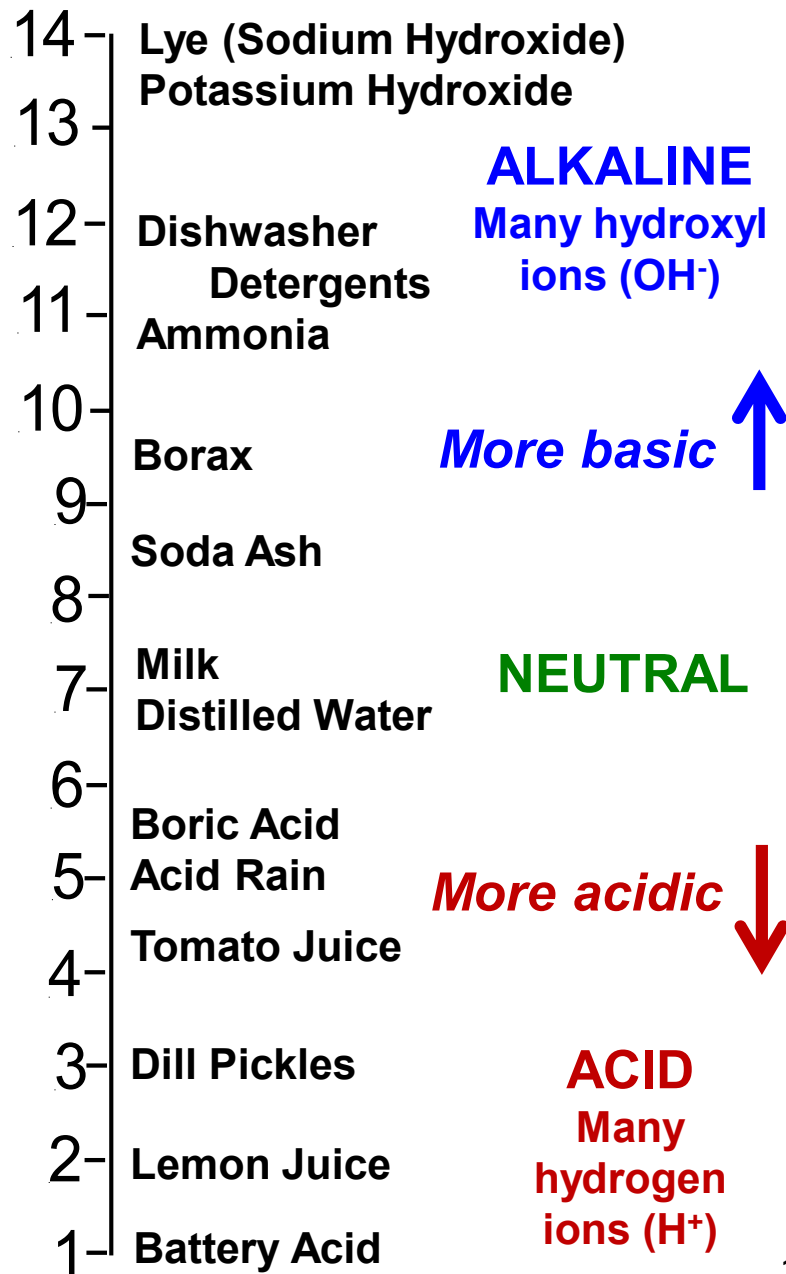
pH and Corrosion Rates

(pH is a measure of hydrogen ion concentration)

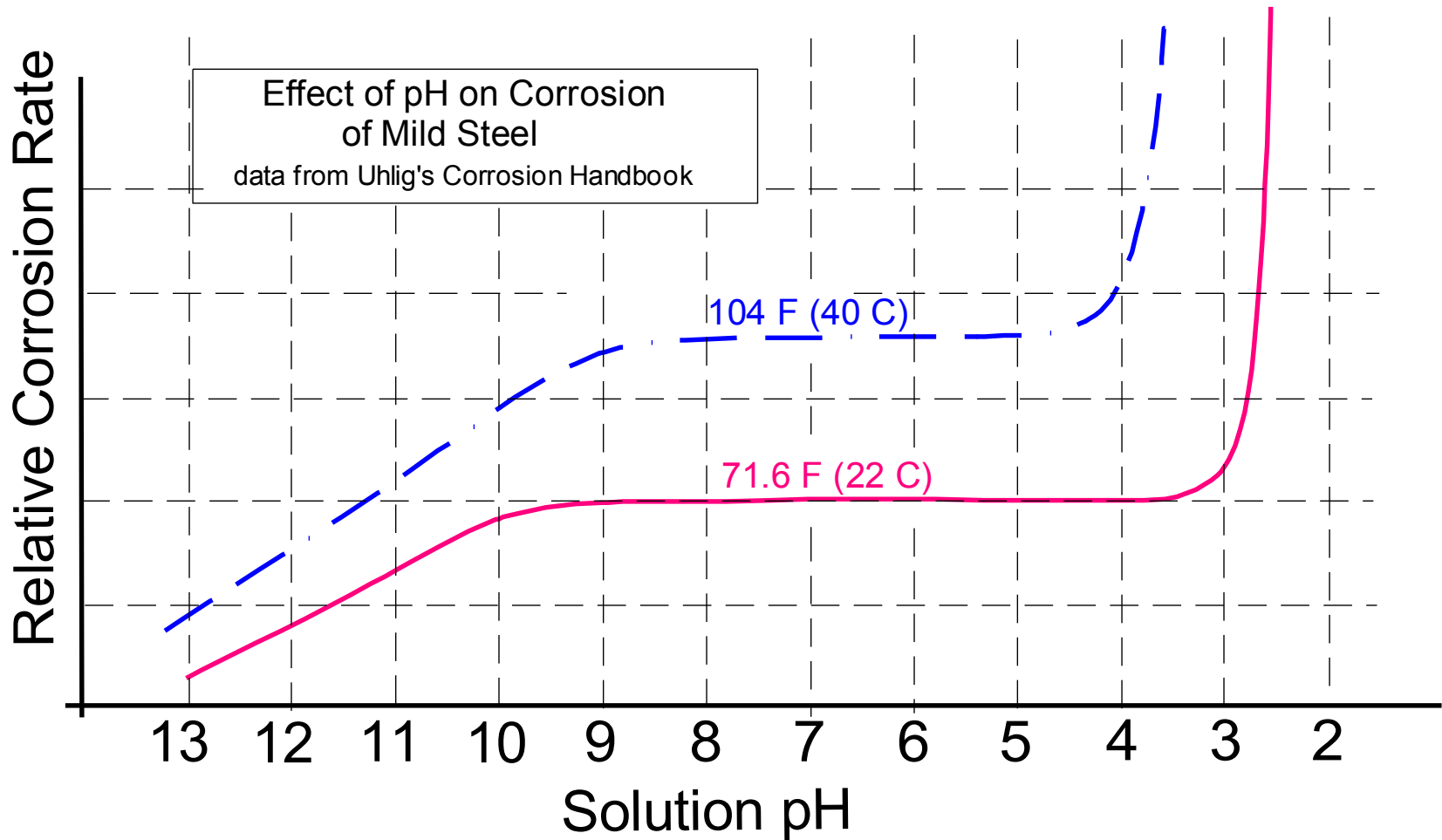
The pH scale is shown to the right.

As the pH increases from 1 (very acidic), the corrosion rate usually decreases as the solution approaches 7 (neutral).

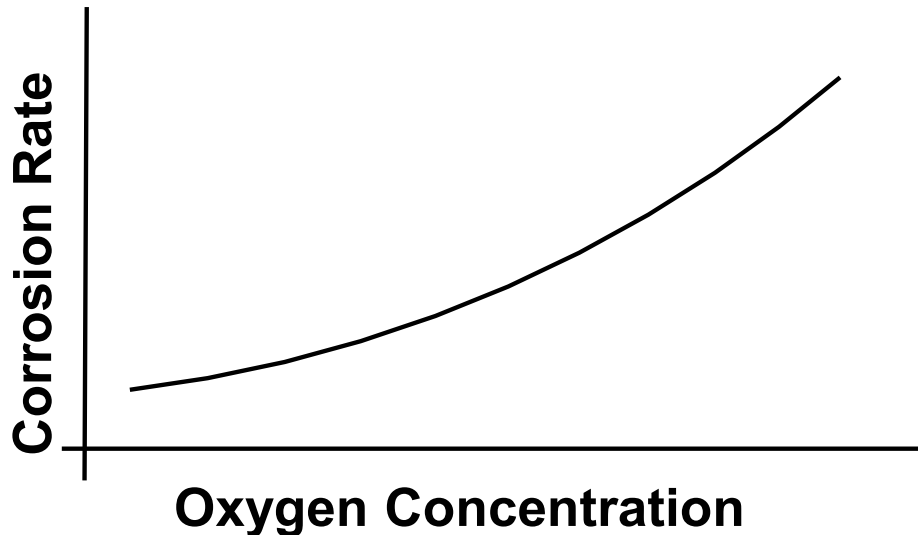
Corrosion sometimes increases again above 8 or 9, but it really requires knowledge of the specific example.



pH affect on Corrosion Rates



Affecting Corrosion Rates – Oxygen Availability



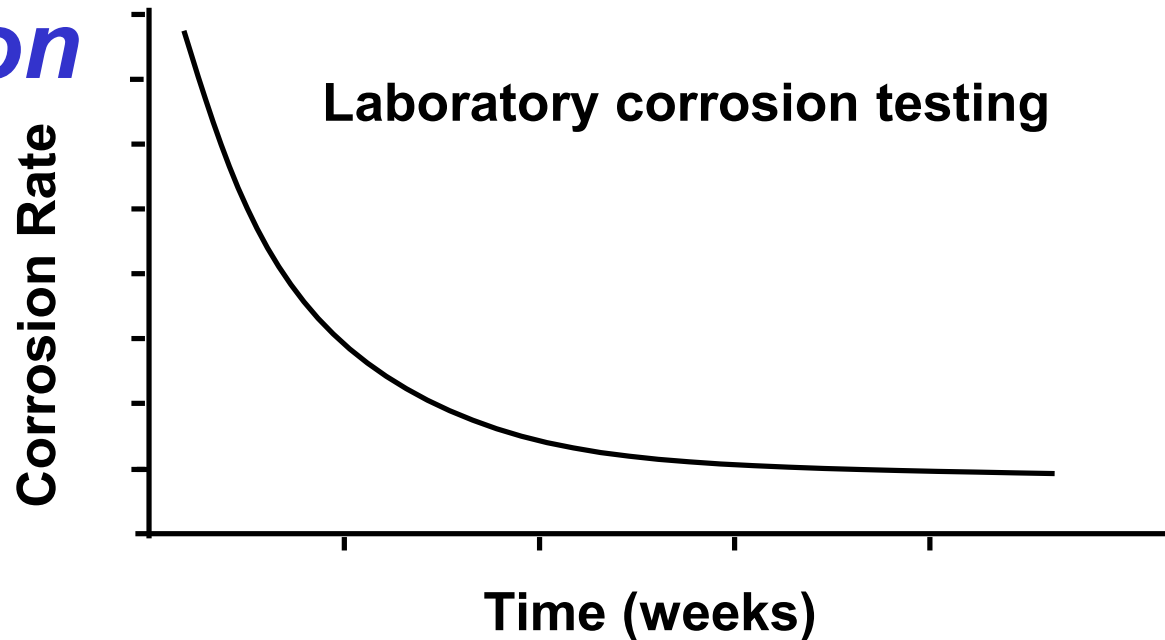
Examples:

At the interface between the typical solution level and the tank wall.

In the splash zone of a marine installation.

In boilers, deaerators are used to remove oxygen and reduce the internal corrosion rates.

Time affects on Corrosion



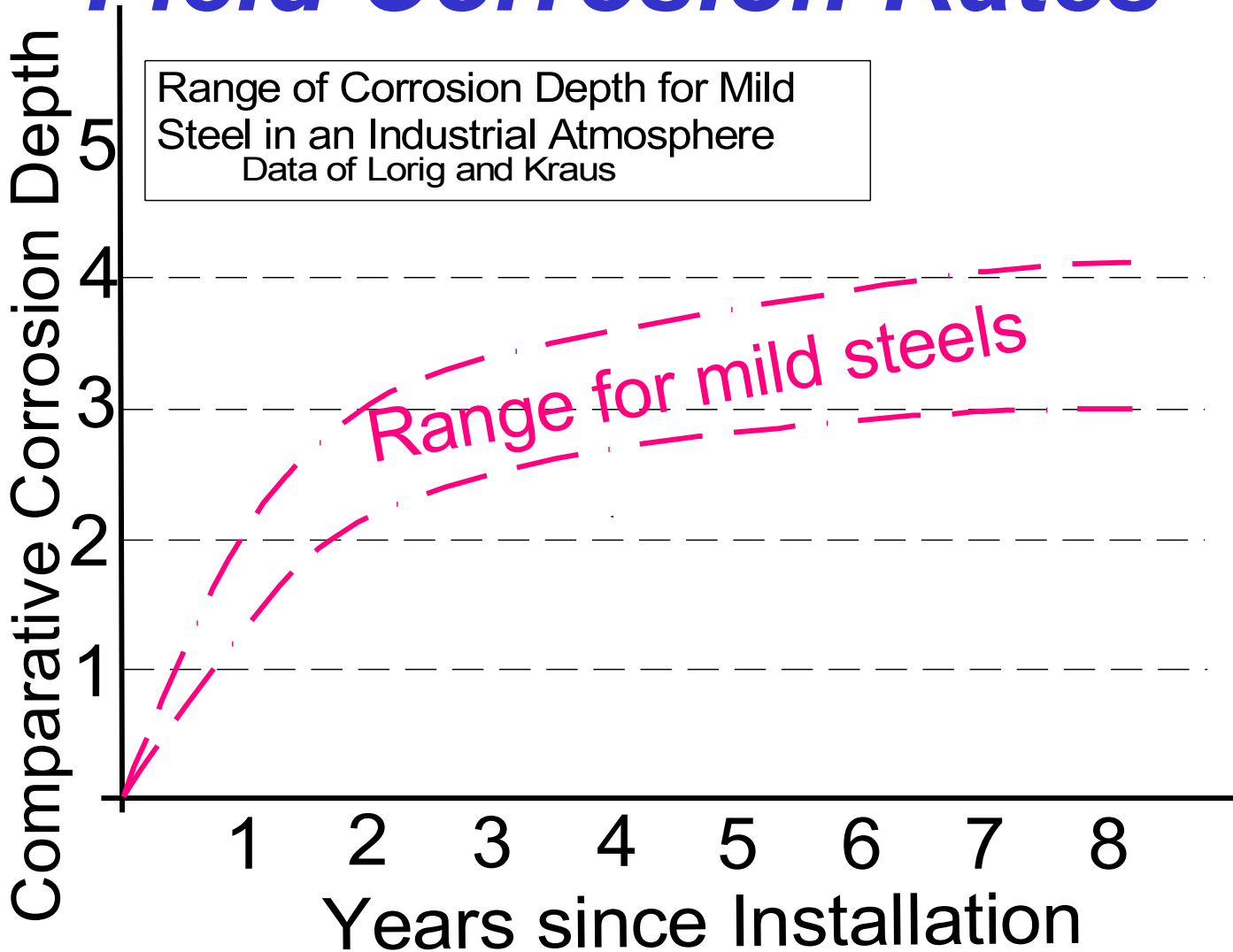
The corrosion rate usually slows with time because of:

Cathodic depolarization – sometimes there is a build-up of hydrogen gas bubbles on the cathode

Anodic depolarization – a build-up of corrosion products at the anode

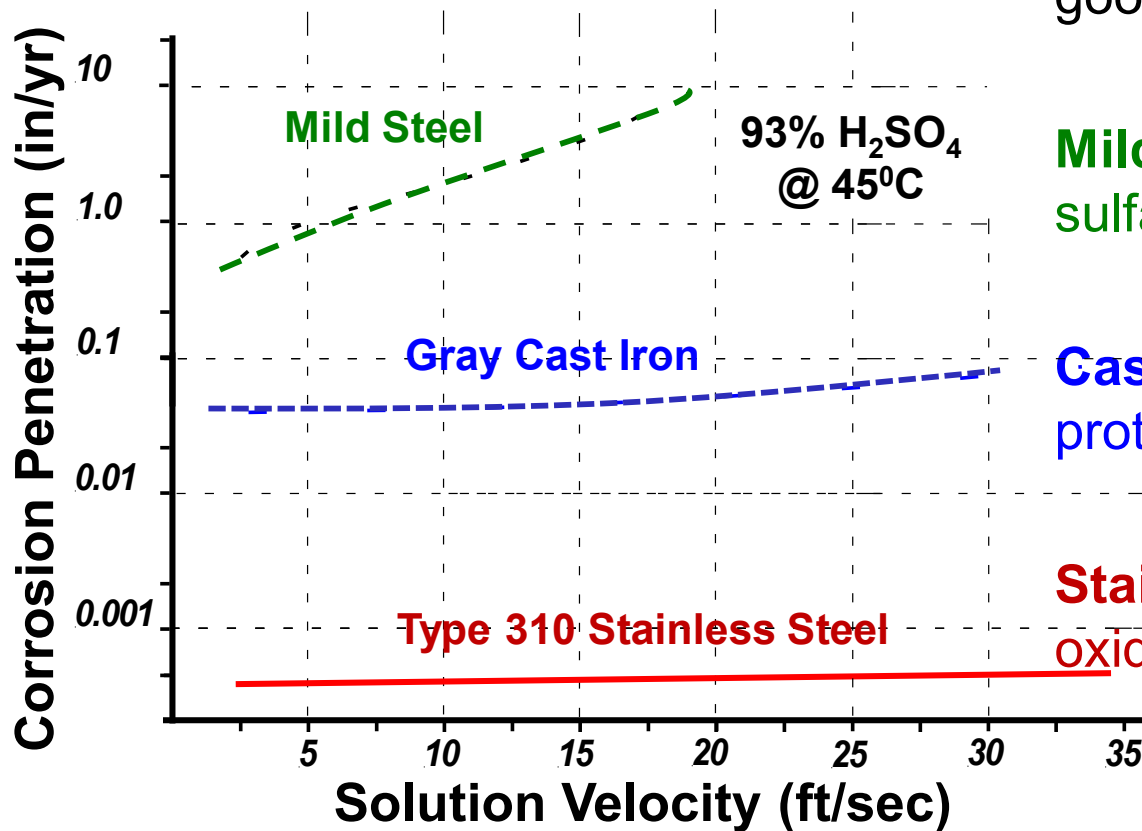
One of the evil effects of **chlorides** is that they tend to loosen the corrosion product (rust), allowing more fresh corrodents to get to the surface and increasing the corrosion rate. Conversely, Cor-Ten steels (ASTM A 242) use copper to help bind that rust and the rate decreases.

Exposure Time affect on Field Corrosion Rates



Affecting Corrosion Rates – Solution Velocity

Comment – Tremendous differences depending on mechanism and sulfuric acid is a good example



Mild steel – depends on ferrous sulfate layer

Cast iron – graphite matrix protects iron

Stainless Steel – the chromium oxide film (as explained earlier)

The Different Kinds of Corrosion

Before we look at some examples -

- All corrosion is the result of electrical currents.
- About 35% of all corrosion is affected by microbiological action. It's referred to as **MIC - Microbiologically Influenced Corrosion**
- **With wet corrosion, moisture of some sort is always needed to conduct the external current.**

In the 1960's Fontana and Greene popularized the idea that there are eight basic forms of corrosion. That is the way it is commonly taught.

Uniform Attack - most common, large areas

Galvanic Corrosion - involving two metals

Crevice Corrosion - damage occurs in the gap

Pitting - isolated attack sites

Intergranular Corrosion - destroyed grain boundaries

Selective Leaching - one component of a mixture attacked

Erosion Corrosion - greatly increased material loss due to flow rates

Stress Corrosion and Hydrogen Damage

However, looking carefully, it seems (to me) that Fontana's "basic forms" only apply to appearances

Uniform Attack - most common, large areas

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Erosion Corrosion - greatly increased material loss due to flow rates

Stress Corrosion and Hydrogen Damage – Both of these mechanisms result in cracking

Uniform Corrosion – Frequently doesn't look very uniform!

This is the most common form of corrosion and probably causes 75 to 80% of all corrosion damage.

The term “uniform” refers to the process where the anode and cathode sites uniformly (continually) reverse positions and the attack rate is relatively predictable.

We try to control it by preventing water and oxygen from reaching the metal surface.



Uniform Corrosion – Frequently doesn't look very uniform!

Looking at this pair of pliers, if we left them out in the grass, would they rust in grooves – or be rusted all over?



They would rust all over by the mechanism of “uniform corrosion”

What would happen if there was a spot of grease on them?

Galvanic Corrosion – Where the anode and cathode don't change positions – and the anode is always attacked.

Active (corrodes)

Metal	Voltage
Magnesium	- 1.75
Zinc	- 1.10
Aluminum-Zinc Alloy	- 1.05
Aluminum (pure)	- 0.8
Mild Steel (clean)	- 0.5 to 0.8
Mild Steel (rusted)	- 0.2 to 0.5
Gray Cast Iron	- 0.5
Copper, Brass	- 0.2
High Silicon Cast Iron	- 0.2
Mill Scale on Steel Sheet	- 0.2
Graphite	+ 0.4
Platinum	+ 0.4

Noble (gets protected)

This Galvanic Series is the result of using flowing sea water at 20°C. *Other conditions may change the way the metals interact.*

For example, above about 170°F, zinc becomes cathodic to steel!



***Still zinc coated,
i.e., galvanized***

***Zinc used up and
now zinc hydroxide***

***Protection gone and
steel corrodes***

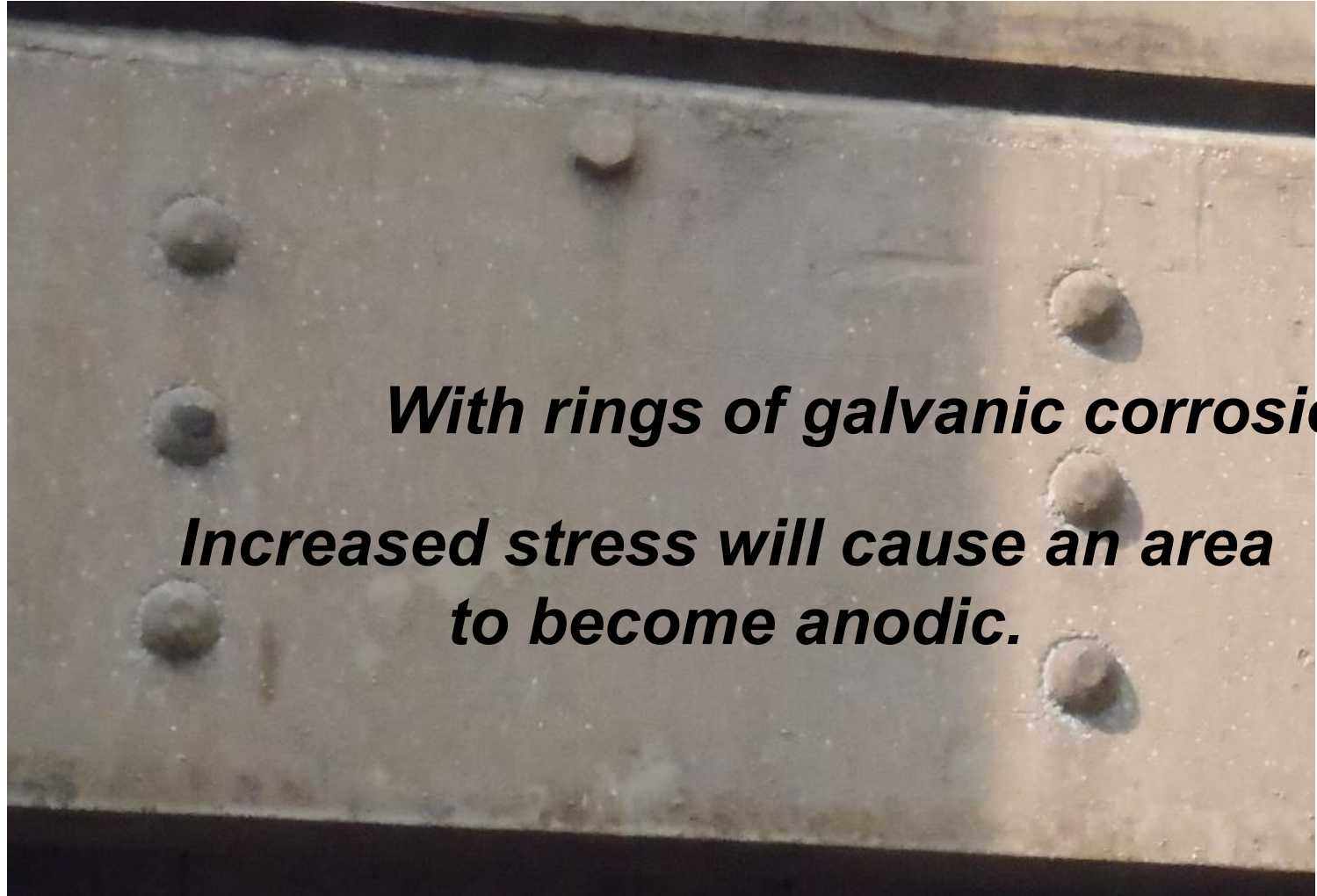
***This was helpful galvanic
corrosion for a while - but then ...***

What happens when you reuse an old galvanized nipple, cut new threads, then attach it to a bronze valve?



Galvanic corrosion happens when two metals are electrically connected. One acts as the cathode, and generates hydrogen, while the other is the anode and get attacked. (9 months in CNY well water)₃₂

Aluminum rivets in an aluminum structure



With rings of galvanic corrosion

***Increased stress will cause an area
to become anodic.***

Galvanic Corrosion

CONTROL and PREVENTION

- Avoid electrically different metals in contact in a conductive solution.
- If that can't be avoided, select materials that are close together in the **Galvanic Series**.
- Electrically isolate the two components.
- Keep the cathode small and the anode large (the area effect).
- ***If there are coatings they should be on the cathode or both parts. Never paint the anode alone! (Because that will concentrate the attack at the holiday!)***

Pitting

Characteristics and Comments - An intermediate stage between uniform (or general) corrosion and no corrosion.

- Usually happens where there is slow or no flow and, with ***stainless steels, attack can be as fast as 0.025 mm (0.001") per day.***
- Common on materials that depend on oxides for corrosion protection such as aluminum and stainless steel and on stainless steels under deposits.
- The pit is anodic and tends to be self propagating.

Pitting Resistance Number (PRN) for stainless steels

- Pitting index = %Cr + 3.3Mo + 16N
 - For base metal only - treat welds with caution.

SERIOUS CAUTION

Published material loss rates can be unintentionally deceptive!

If the loss is due to uniform corrosion, or even galvanic corrosion, it is distributed over a large area.

But if it results from pitting, the damage is very localized and may cause unexpected perforation.

YOU have to know what you're dealing with.

Pitting

*A Tank
Example*



Selective Leaching is

A Galvanic Mechanism within a Mixture

- Happens frequently in brass alloys and cast irons when one component of the mix is attacked.
- In cast iron the graphite is the anode while the iron is leached out. The remaining graphite structure looks to be unaffected, however the iron is gone! Frequently seen in buried lines with slow moving corrodents.
- In brass components the more active zinc portion is removed (dezincification).



Corrosion and cracking mechanisms

(What those hydrogen ions can do!)

Corrosion can directly result in fractures from:

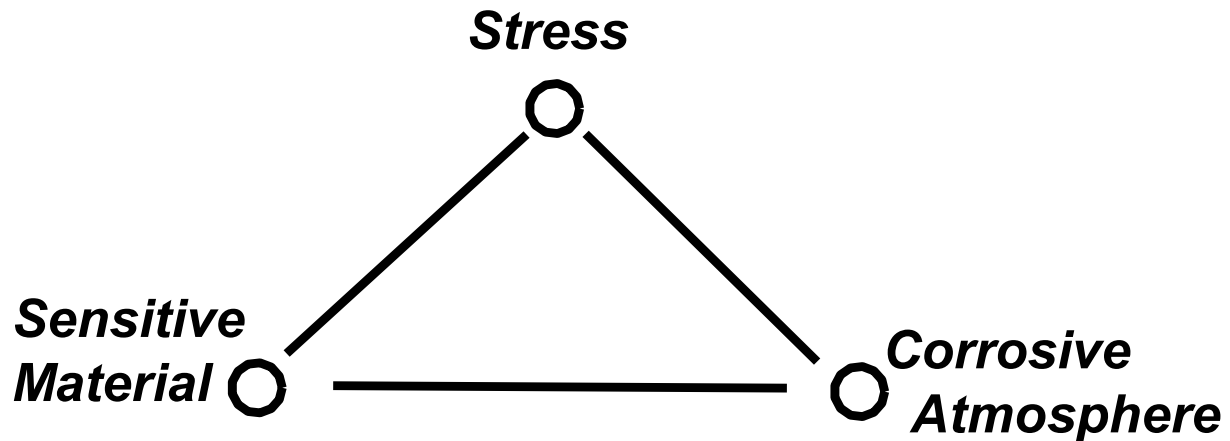
- ***Stress Corrosion Cracking (SCC)*** – most common with stainless steel, but every commercial metal has an environment where it can fail from SCC
- ***Hydrogen Damage*** – generally only causes problems with higher strength metals

Corrosion will also ***continuously reduce the fatigue strength of a metal.*** The effect becomes apparent with elevated humidity and is roughly proportional to the severity of the corrosion. It more seriously affects the stronger materials.

SCC and Hydrogen Damage

SCC - Irregular frequently branched cracks

- MUST have a combination of stress, sensitive material, and a corrosive atmosphere.
- The sketch below shows the “**SCC Triangle**”.
- Cracking has occurred with stresses ranging from 10 to 70% of the tensile strength.



SCC and Hydrogen Damage

SCC – Irregular, frequently branched cracks



In the wall of a stainless steel pipe



Alongside a weld

Hydrogen Damage

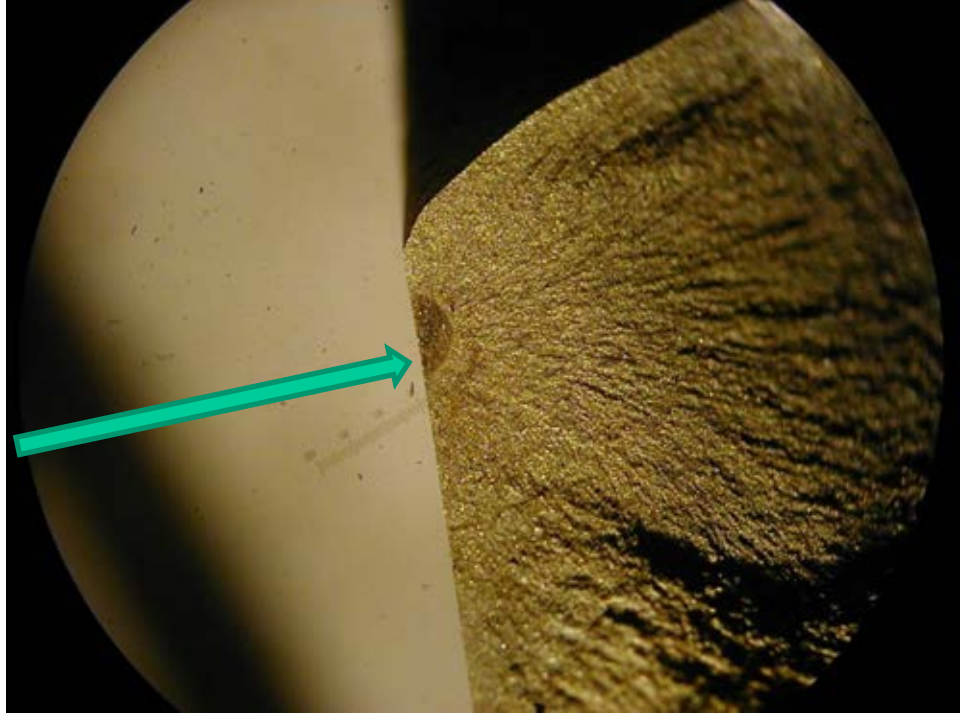
HIC (Hydrogen Induced Cracking) – Irregular, frequently branched cracks

**In a high strength martensitic stainless stud used in tire mfg.
(This is a wet fluorescent magnetic particle inspection)**



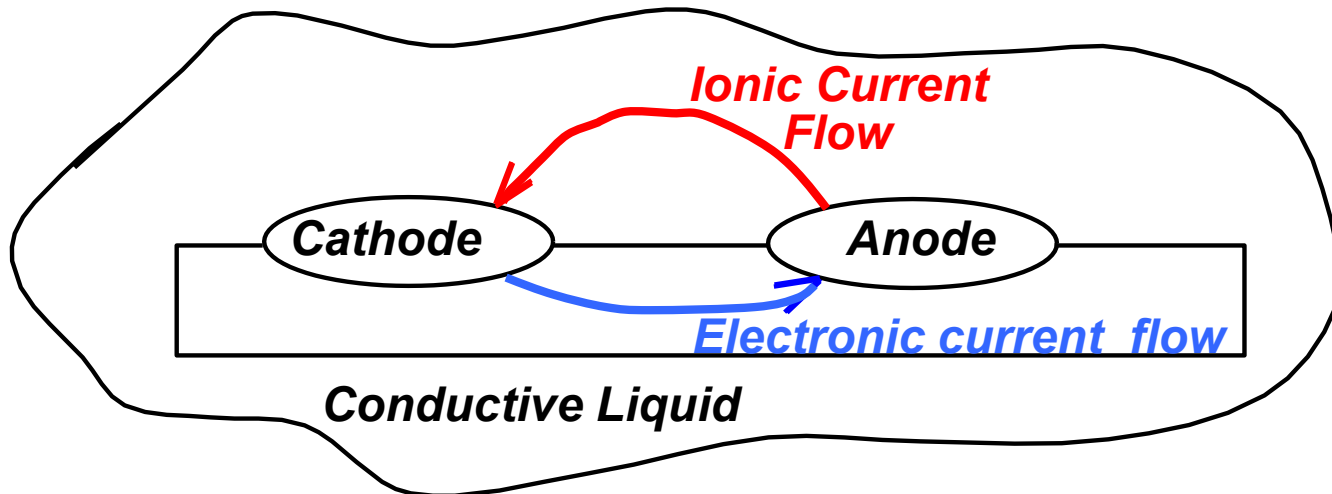
Of a steel spring used in a pharmaceutical plant

Crack origin



The multiple-branched and irregular cracks are an indication that serious metallurgical problems are involved.

Applying what we've seen above to our infrastructure



A major problem is that chlorides and sulfur compounds increase the conductivity of the liquid, allowing it to conduct a greater corrosion current with the resultant increase in corrosion rate.

Typical Atmospheric Corrosion Rates

Rural -

- Sub arctic - 2.5 to 25 $\mu\text{m}/\text{year}$ (0.0001 to 0.001")
- Temperate - 8 to 80 $\mu\text{m}/\text{year}$ (0.0003 to 0.003")

Industrial - 20 to 200 $\mu\text{m}/\text{year}$ (0.0009 to 0.008")

Marine - 25 to 250 $\mu\text{m}/\text{year}$ (0.001 to 0.010")

Local conditions that vary the temperature, contamination, wind direction, etc., can result in tremendous differences in corrosion rates. (80 vs. 800 ft from the ocean = $\approx 10\text{X}$)

ISO Atmospheric Corrosion Categories

Category	General Description	First Year Steel Corrosion Rate (ipy)
C1	Hot dry areas, no pollution	0.00003 - 0.00005
C2	Low temperature areas with low pollution rates – rural villages, etc.	0.0002 – 0.001
C3	Medium temperature areas with medium pollution – small cities with low chlorides	0.001 – 0.002
C4	Warm areas with mild pollution – costal cities with some chlorides, etc.	0.002 - 0.004
C5	Warm humid temperate areas with significant chlorides and industrial contaminants	0.004 - 0.009

Corrosion is highly dependent on moisture, chlorides and contamination

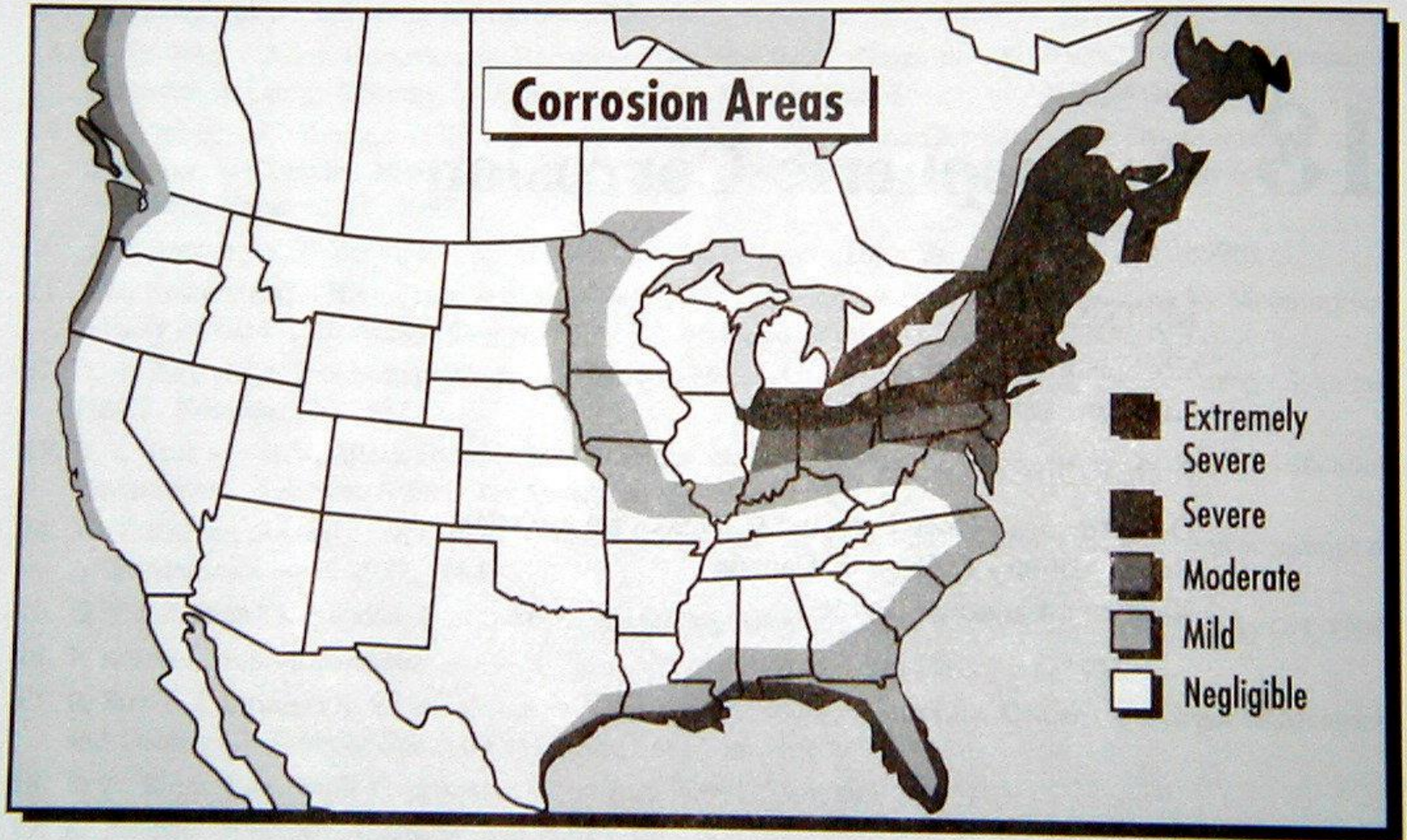
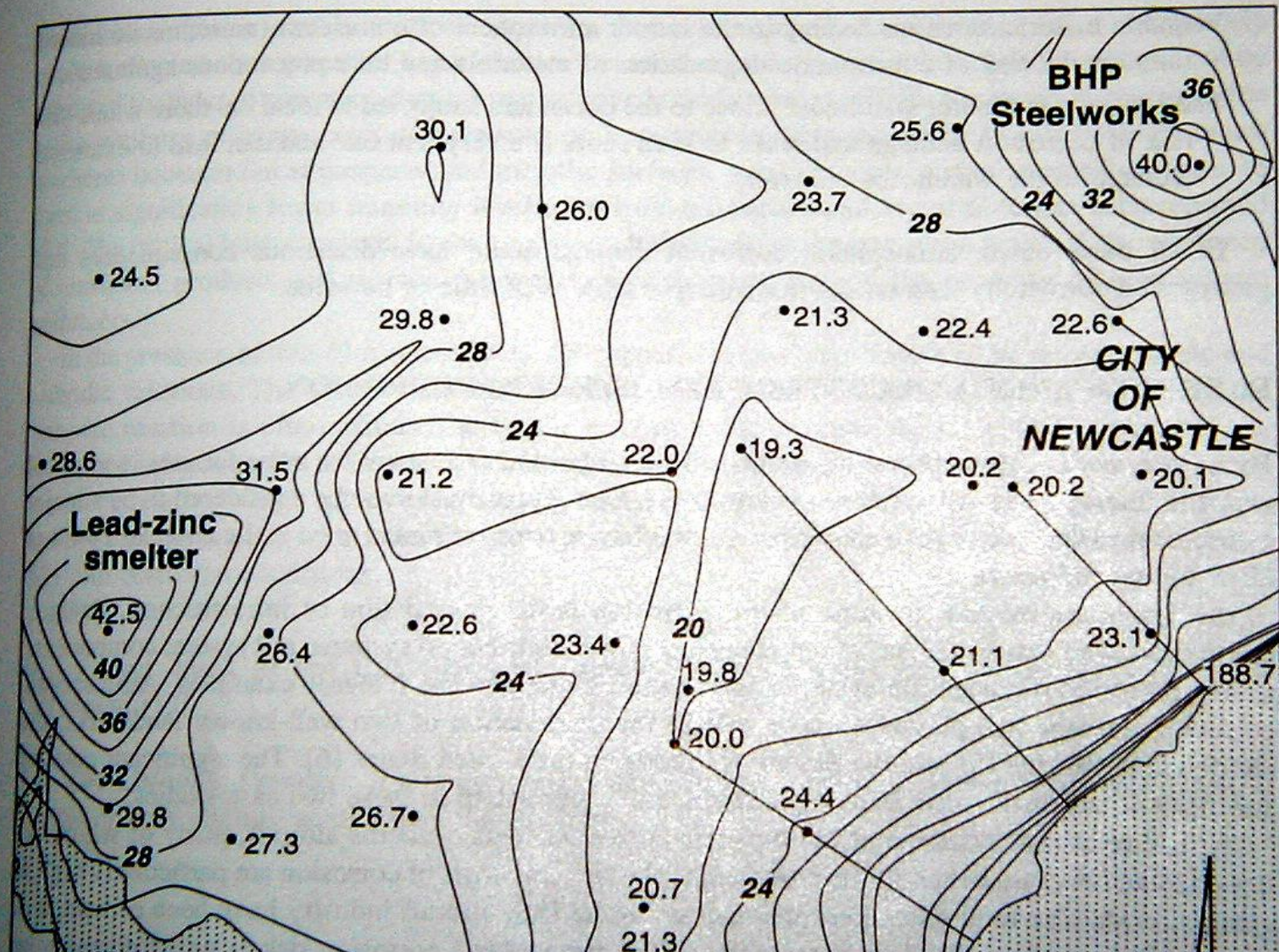


FIGURE 1. Corrosivity map of North America.

From *Uhlig's Corrosion Handbook*

From Uhlig's Corrosion Handbook



Some examples of Atmospheric Corrosion

The process is uniform while the appearance and the attack may not be!

Minor problems with a highway bridge



Another bridge



Underneath a parking deck



Beneath a highway bridge



How to prevent it or reduce the damage rate

- Blast clean the surface and check to ensure there are no chlorides.
- Coat the surface with a primer (such as inorganic zinc) and then topcoat it to prevent moisture from getting to the surface.

or

- Change the material
 - Galvanize it – with the zinc acting as the anode.
 - Use a more corrosion resistant steel (**Cor-Ten**)



Galvanizing in action

Two “corrosion test chambers” where galvanizing is used to lengthen the pole life.



What about buried tank and lines, etc.?

Soil corrosivity depends primarily on the electrical conductivity – and that depends on moisture, alkalinity, acidity, oxygen availability, chemical contamination (salts), stray currents, and microbiological action.

***An example of
“graphitic
corrosion” of
gray iron pipe.***

***This is a galvanic
corrosion that takes
place within the cast
iron structure with a
carbon cathode and
iron anode.***

Thank you Phil Peterson



A fire water line from a NJ chemical plant

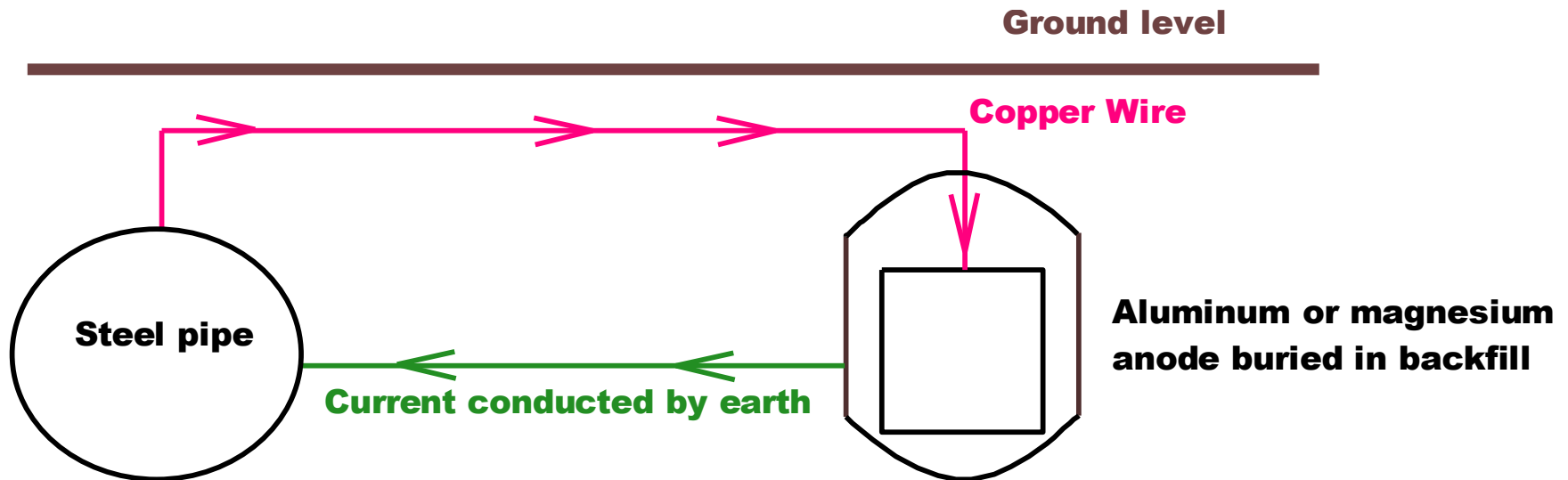


Soil corrosiveness can change significantly in 50 feet!

Soil surveys can tell the probability of buried equipment corrosion.

Corrosion prevention of buried metals

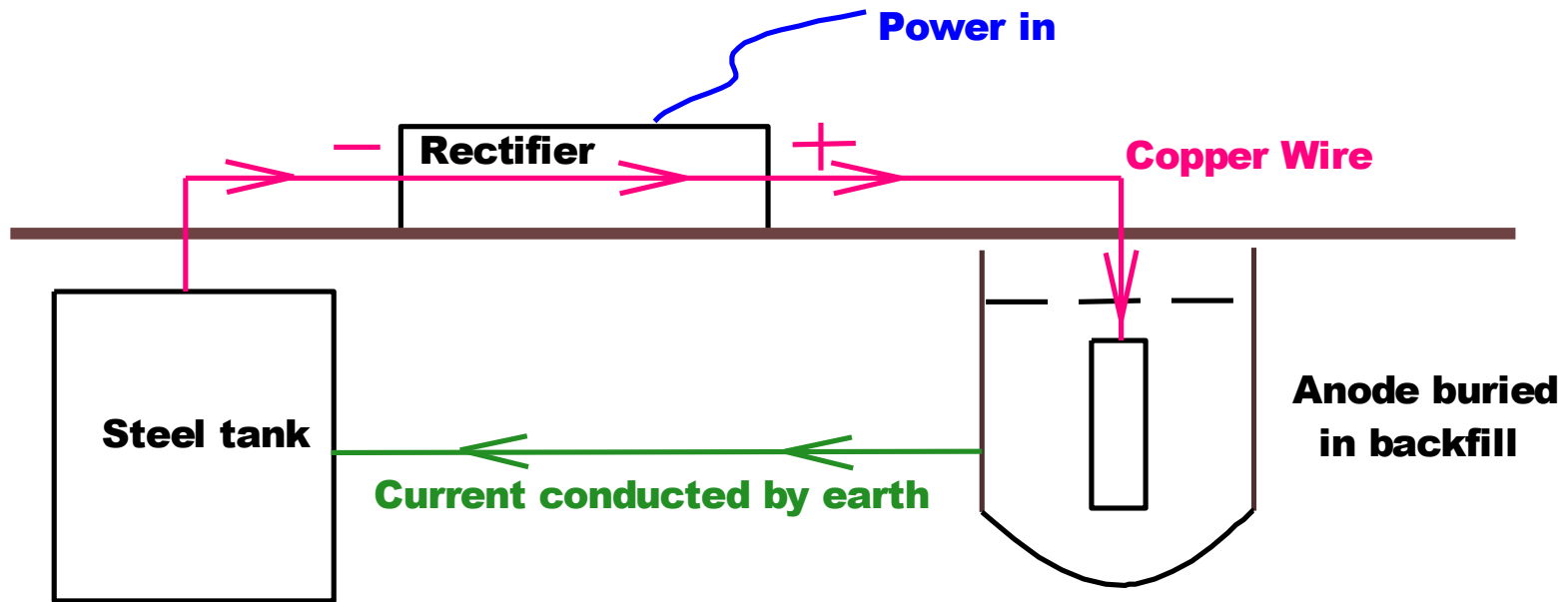
#1 – anodic protection



1. This is what is used in your home water heater with its replaceable aluminum anode.
2. The anode has a limited effective protection radius.

Corrosion prevention of buried metals

#2 – cathodic protection



Both cathodic and anodic protection usually require coating of the metal surface to improve their efficiency

Choosing Materials for an Environment

1. Ask how long does it really have to last? Then double that length of time.
2. Don't believe what "they" tell you about the conditions. Look at it and verify.
3. Document the variations with long term monitoring.
4. Study and understand the most probable attack in those environments.
5. Remember – temperature, moisture, and contamination are the keys. Remember Arrhenius' rule!

Corrosion causes a reduction in Fatigue Strength

There are many variables, but corrosion **ALWAYS** reduces fatigue strength.

As the corrosion gets worse, the fatigue strength drops more.

Almost always, the stronger the material is, the faster to fatigue strength drops.

Recipe for disaster -

***Not preloaded,
fatigue stressed and
corroding anchor***



Summary

- There is some dry corrosion at elevated temperatures, but almost everything we see is wet corrosion.
- The typical US practice has been to teach that there are eight forms of corrosion. But think it as of two, one involving large scale converting metals into oxides (rusting) while the other causes metals to crack (SCC, HIC).
- An electrochemical reaction with the flow of both ionic and electrical currents is needed for corrosion.
- Atomic hydrogen generated at the cathode is the cause of SCC and HIC.

Why did it corrode there?



Damage from a combination of additional contamination (in the dirt that wasn't cleaned off for a long time) and retained moisture.

Why did it corrode at the bottom?

This shows the effect of the combination of higher chemical concentrations, the mixture of several chemicals in the debris, and longer wet times.



Similar corrosion takes place at ground level in many structures and is particularly aggressive in areas covered by vegetation.

Quiz questions

1. What effect does temperature usually have on corrosion rates? When isn't that true?
2. There has to be a liquid present. Why?
3. Does the alloy order in the "galvanic series" ever change?
4. You repair a steel tank and add a stainless bottom. What area(s) of the tank interior should be painted?

What should you paint with a new mild steel bottom?

5. How does corrosion affect fatigue strength?

Extra quiz question –

For the longest vehicle body life, in wintertime in snowy climates, should you park your car in a heated garage?

Thank you for listening!

1. If you have additional questions or comments, please don't hesitate to call or email me.
2. Thank you to ATS for allowing me to use some slides that were developed when I taught classes for them.