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Corrosion principles, cost, damages & its prevention

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CORROSION

Principles, damages, cost & its prevention

ABSTRACT

This article focuses on corrosion principles & its prevention. Corrosion is the destructive attack of a material (metal & nonmetal) by chemical or electrochemical reaction with its environment. For causing corrosion, the metal or alloy must be unstable in that particular environment. Thus, changing the environment of a metal can greatly affect its rate of corrosion in either direction. Lack of corrosion control may affect our lifestyles and economy a lot. Thus, the study of corrosion processes helps in choosing designs and materials necessary for maintaining high safety standards. Safety is the primary consideration in preventing corrosion, but economics are also of major importance. Most corrosion processes are electrochemical in nature or are a combination of physical/chemical and electrochemical processes. The corrosion resistance of steel can be greatly increased by alloying with chromium to form stainless steels. Metals may be protected from corrosion by using a metal in an environment in which it is immune, by making a physical barrier between the metal and its environment, by means of an electric current, or by changing the environment. This article contains corrosion, cost and importance of corrosion; electrochemical and thermodynamic principles of corrosion; different types of corrosion, methods of corrosion prevention, prevention by design improvement; inhibitors, cathodic protection, anodic protection.

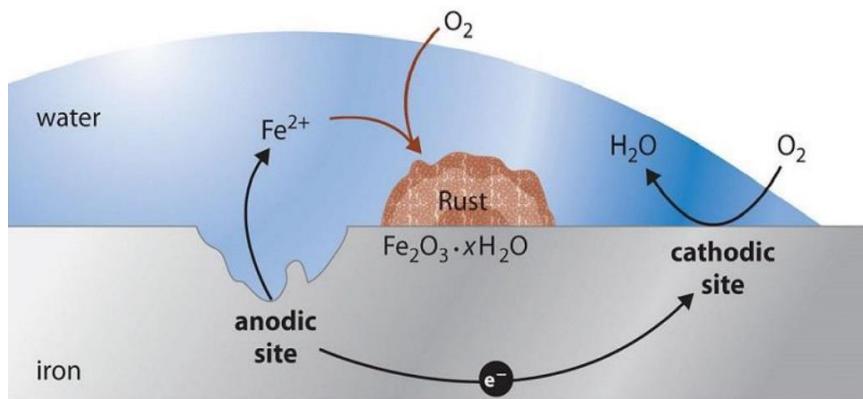
Mahamudul Hasan Pranto

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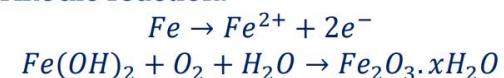
CORROSION is defined as the destruction or deterioration of a material because of reaction with its environment.

Corrosion is the destructive attack of a material (metal & nonmetal) by chemical or electrochemical reaction with its environment.

Some insist that the definition should be restricted to metals, but often the corrosion engineers must consider both **metals** and **nonmetals** for solution of a given problem. For purposes, we include ceramics, plastics, rubber, and other nonmetallic materials.



Anodic reaction:



Cathodic reaction:



Need: An Anode (where oxidation is taking place); A Cathode (where reduction is taking place); Conductive electrolyte; Electrical contact between the Anode and Cathode.

COST OF CORROSION

Estimates of the annual cost of corrosion in the United States vary between \$8 billion and \$126 billion. I believe \$30 billion is the most realistic figure. In any case, corrosion represents a tremendous economic loss and much can be done to reduce it. Studies of the cost of corrosion to Australia, Great Britain, Japan, and other countries have also been carried out. In each country studied, the cost of corrosion is approximately 3 – 4 % of the Gross National Product. Global economic loss is about \$3.5 Trillion which is equivalent to 3.4% of the Global GDP.

IMPORTANCE OF CORROSION

The **three main** reasons for the importance of corrosion are: **economics, safety, and conservation.**

 **Economics:**

To reduce the **economic impact** of corrosion, corrosion engineers, with the support of corrosion scientists, aim to reduce material losses, as well as the accompanying economic losses, that result from the corrosion of piping, tanks, metal components of machines, ships, bridges, marine structures, and so on.

Economic losses are divided into (1) **direct losses** and (2) **indirect losses**.

Direct losses include

- ✓ The costs of replacing corroded structures and machinery or their components, such as condenser tubes, mufflers, pipelines, and metal roofing, including necessary labor.
- ✓ Repainting structures where prevention of rusting is the prime objective and the capital costs plus maintenance of cathodic protection systems for underground pipelines. Example: Sizable direct losses are illustrated by the necessity to replace several millions domestic hot water tanks each year because of failure by corrosion and the need for replacement of millions of corroded automobile mufflers.
- ✓ The extra cost of using corrosion - resistant metals and alloys instead of carbon steel where the latter has adequate mechanical properties but not sufficient corrosion resistance.
- ✓ The costs of galvanizing or nickel plating of steel.
- ✓ The cost of adding corrosion inhibitors to water and of dehumidifying storage rooms for metal equipment.

The total direct cost of corrosion is estimated at \$276 billion per year or 3.1% of the Gross Domestic Product (GDP), according to a recent study. It has been estimated that about 25 – 30% of this total could be avoided if currently available corrosion technology were effectively applied.

Indirect losses are more difficult to assess, but a brief survey of typical losses of this kind compels the conclusion that they add several billion dollars to the direct losses already outlined. Examples of indirect losses are as follows:

- ✓ Shutdown: The replacement of a corroded tube in an oil refinery may cost a few hundred dollars, but shutdown of the unit while repairs are underway may cost \$ 50,000 or more per hour in lost production. Similarly, replacement of corroded boiler or condenser tubes in a large power plant may require \$ 1,000,000 or more per day for power purchased from interconnected electric systems to supply customers while the boiler is down.

- ✓ Loss of Product: Losses of oil, gas, or water occur through a corroded - pipe system until repairs are made. Antifreeze may be lost through a corroded auto radiator; or gas leaking from a corroded pipe may enter the basement of a building, causing an explosion.
- ✓ Loss of Efficiency: Heat transfer is decreased by accumulated corrosion product; pumping capacity is decreased by the clogging of pipeline with rust. This may cost \$40 million/year in US
- ✓ Contamination of Product: A small amount of copper picked up by slight corrosion of copper piping or of brass equipment that is otherwise durable may damage an entire batch of soap. Copper salts accelerate rancidity of soaps and shorten the time that they can be stored before use. Traces of metals may similarly alter the color of dyes. Lead equipment, otherwise durable, is not permitted in the preparation of foods and beverages because of the toxic properties imparted by very small quantities of lead salts. Similarly, soft water that passes through lead piping are not safe for drinking purposes. The poisonous effects of small amounts of lead have been known for a long time
- ✓ Overdesign: This factor is common in the design of reaction vessels, boiler tubes, buried pipelines, water tanks, and marine structures. A line of 8-inch diameter pipe 225 miles long was specified to have a wall thickness of 0.322 inch to allow corrosion from the soil side. With adequate corrosion protection, a wall thickness of only 0.225 inch could have been used, saving 3,700 tons of steel, as well as the increasing the internal capacity by 5%.

Safety:

Corrosion can compromise the **safety** of operating equipment by causing failure (with catastrophic consequences) of, for example, **pressure vessels**, **boilers**, **metallic containers** for toxic chemicals, **turbine blades** and **rotors**, **bridges**, **airplane components**, and **automotive steering mechanisms**. Safety is a critical consideration in the design of equipment for **nuclear power plants** and for disposal of nuclear wastes.

Conservation:

Loss of metal by corrosion is a waste not only of the metal, but also of the energy, the water, and the human effort that was used to produce and fabricate the metal structures in the first place. In addition, **rebuilding** corroded equipment requires further investment of all these resources — metal, energy, water, and human.

Metals	Reservation in years
Chromium	95
Iron	93
Nickel	53

Table: Time left before some metal resources would be exhausted (report conducted by US Bureau of Mines)

DIFFERENT TYPES OF CORROSION



Fig 1: Atmospheric Corrosion



Fig 2: Corrosion Fatigue



Fig 3: Uniform Corrosion



Fig 4: Pitting Corrosion



Fig 5: Selective Corrosion of Brass Pipe

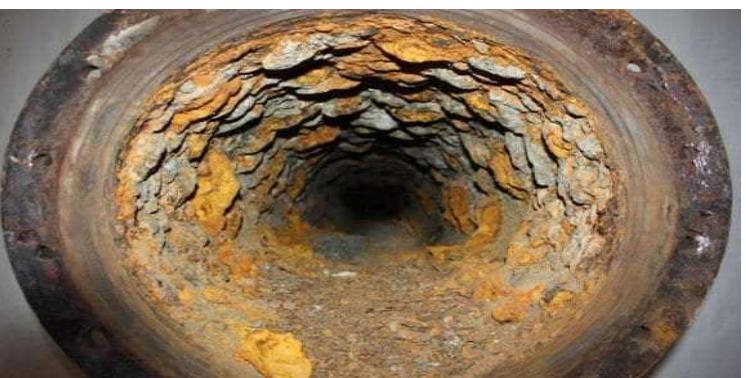


Fig 6: Erosion Corrosion



Fig 7: Stress Corrosion

Fig 8: Inter-granular Corrosion

Corrosion Engineering

Corrosion engineering is the application of science and art to prevent or control corrosion damage economically and safely.

In order to perform their function properly, expectations from the corrosion engineers:

1. Well versed in the practices and principles of corrosion; the chemical, metallurgical, physical, and mechanical properties of materials; corrosion testing; the nature of corrosive environments; the availability and fabrication of materials; computers; and design.
2. Having the usual attributes of engineers-a sense of human relations, integrity, the ability to think and analyze, an awareness of the importance of safety, common sense, a sense of organization, and, of prime importance, a solid feeling for economics.
3. Selecting the method that will maximize profits.
4. Ensuring maximum life of new equipment.
5. Preservation of existing equipment
6. Protecting or improving the quality of a product in order to maintain or improve a competitive position.
7. Avoiding costly interruptions of production.
8. Reducing or eliminating losses of valuable products by spillage or leaks.
9. Refitting of equipment withdrawn from service because of corrosion.
10. Reducing hazards to life and property that might be associated with corrosion:
 - ✓ Explosions of pressure vessels or piping systems.
 - ✓ Release of poisonous or explosive gases or vapors

CORROSION PRINCIPLES

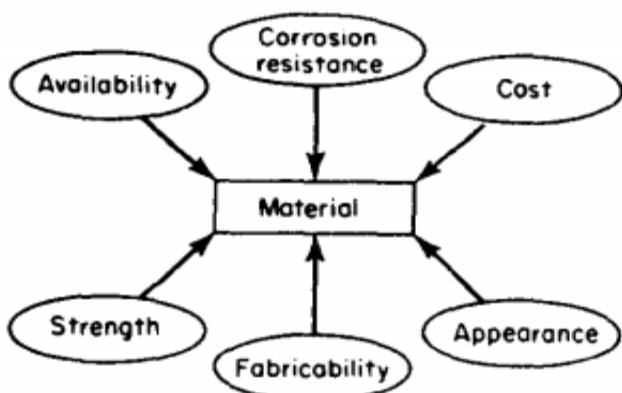


Figure 2-1 Factors affecting choice of an engineering material.

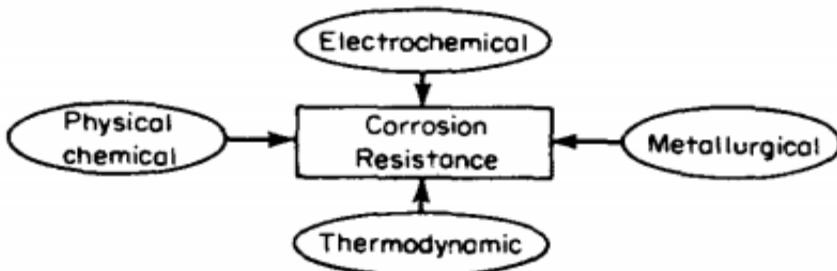


Figure 2-2 Factors affecting corrosion resistance of a metal.

Corrosion Rate Expressions

Metals and nonmetals will be compared on the basis of their corrosion resistance. To make such comparisons meaningful, the rate of attack for each material must be expressed quantitatively. Corrosion rates have been expressed in a variety of ways in the literature; such as **percent weight loss**, **milligrams per square centimeter per day**, and **grams per square inch per hour**. These do not express corrosion resistance in terms of penetration. From an engineering viewpoint, the rate of penetration, or the thinning of a structural piece, can be used to predict the life of a given component. The expression **mils per year** is *the most desirable way* of expressing **corrosion rates**. This expression is readily calculated from the weight loss of the metal specimen during the corrosion test by the formula given below:

$$\text{mpy} = \frac{534W}{DAT}$$

where **W** = weight loss, mg

D = density of specimen, g/cm³

A = area of specimen, sq. in.

T = exposure time, hr

$$\text{Corrosion rate (mdd)} = \frac{\text{weight of metal corroded in mg}}{\text{area in square dm} \times \text{exposure time in day}}$$

OR

$$\text{Corrosion rate (mm/y)} = \frac{8.76 \times 10^4 W}{ATD}$$

Where, W = weight of metal corroded in g, A = surface area in cm^2 , T = exposure time in hr, D = density of the metal in gm/ cm^3

Example: A steel coupon with an anode surface area of 1000 cm^2 is placed in an electrolyte. The corrosion current is measured to be 1 mA. What mass of steel will be lost in 6 hours? What is the corrosion rate in $\mu\text{g}/\text{cm}^2/\text{day}$? In mpy? Assume valence of 2.

$$m = Izt$$

$$I = 0.001 \text{ A}$$

$$z = \frac{a}{nF} = \frac{55.847 \text{ g}}{(2 \text{ mol e}^-)(96,500 \text{ A} \cdot \text{s/mol e}^-)} = 2.89 \times 10^{-4} \text{ g/A} \cdot \text{s}$$

$$t = (6 \text{ hr}) \left(\frac{60 \text{ min}}{1 \text{ hr}} \right) \left(\frac{60 \text{ s}}{1 \text{ min}} \right) = 21,600 \text{ s}$$

$$m = (0.001 \text{ A})(2.89 \times 10^{-4} \text{ g/A} \cdot \text{s})(21,600 \text{ s})$$

$$m = 6.255 \times 10^{-3} \text{ g}$$

To find the corrosion rate in $\mu\text{g}/\text{cm}^2/\text{day}$, first divide by anode area and time.

$$\text{rate} = \frac{m}{At} = \frac{6.255 \times 10^{-3} \text{ g}}{(1000 \text{ cm}^2)(21,600 \text{ s})} \left(\frac{10^6 \mu\text{g}}{1 \text{ g}} \right) \left(\frac{3600 \text{ s}}{1 \text{ hr}} \right) \left(\frac{24 \text{ hr}}{1 \text{ day}} \right) = 25.02 \mu\text{g}/\text{cm}^2/\text{day}$$

To find the corrosion rate in mpy, divide by the metal density.

$$\text{rate} = \frac{25.02 \mu\text{g}/\text{cm}^2/\text{day}}{\rho} = \frac{25.02 \mu\text{g}/\text{cm}^2/\text{day}}{7.20 \times 10^6 \mu\text{g}/\text{cm}^3} \left(\frac{365 \text{ days}}{1 \text{ yr}} \right) \left(\frac{1 \text{ mil}}{2.54 \times 10^{-3} \text{ cm}} \right)$$

rate = 0.499 mpy

The following table gives density, atomic mass, valence, and corrosion rate for various metals.

THERMODYNAMIC PRINCIPLES

Change of Gibbs Free Energy-

The tendency for any chemical reaction to go, including the reaction of a metal with its environment, is measured by the Gibbs free - energy change, ΔG . The more negative the value of ΔG , the greater the tendency for the reaction to go. The free-energy change accompanying an electrochemical reaction can be calculated by the following equation:

$$\Delta G = -nFE$$

where ΔG is the free-energy change, n is the number of electrons involved in the reaction, F is the Faraday constant, and E equals the cell potential.

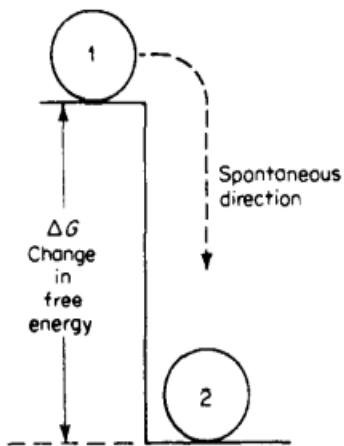
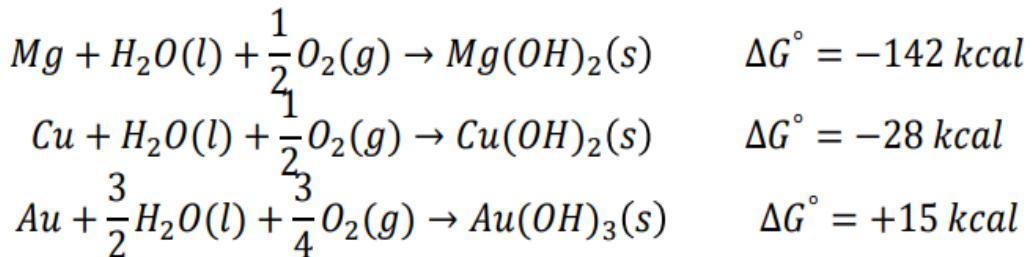


Figure 9-1 Mechanical analogy of free-energy change.

For example, consider the following reaction at 25 ° C:



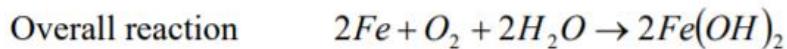
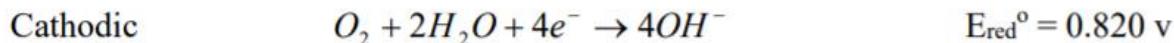
In case of Mg, the large negative value of ΔG° (reactants and products in standard states) indicates a pronounced tendency for magnesium to react with water and oxygen.

In case of Cu, the reaction tendency is less. Or we can say that the corrosion tendency of copper in aerated water is not as pronounced as that of magnesium.

In case of Au, the free energy is positive, indicating that the reaction has no tendency to go at all; and gold, correspondingly, does not corrode in aqueous media to form $Au(OH)_3$.

It should be emphasized that the tendency to corrode is not a measure of reaction rate. A large negative ΔG may or may not be accompanied by a high corrosion rate, but, when ΔG is positive, it can be stated with certainty that the reaction will not go at all under the particular conditions described. If ΔG is negative, the reaction rate may be rapid or slow, depending on various factors.

Example: Steel is placed in aerated seawater with a neutral pH. Is corrosion of the steel possible, why? (Assume valence of 2)



$$E = E_{ox}^{\circ} + E_{red}^{\circ}$$

$$E = 1.267 \text{ v}$$

$$\Delta G = -nFE$$

$$\Delta G = -(2 \text{ mol } e^-)(96,500 \text{ J/v } \cdot \text{mol } e^-)(1.267 \text{ v})$$

$$\Delta G = -244,531 \text{ J}$$

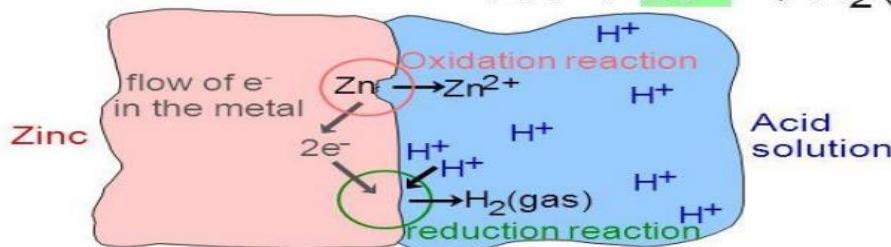
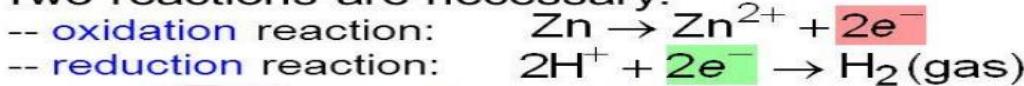
negative sign indicates corrosion reaction, as written, is possible

ELECTROCHEMICAL PRINCIPLES

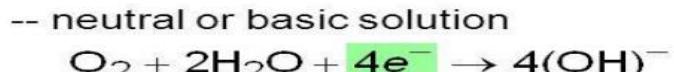
Electrochemical Corrosion

Corrosion of zinc in an acid solution

- Two reactions are necessary:



- Other reduction reactions in solutions with dissolved oxygen:



An **electrochemical** cell is a device that can generate electrical energy from the chemical reactions occurring in it, or use the electrical energy supplied to it to facilitate chemical reactions in it. These devices are capable of converting chemical energy into electrical energy, or vice versa.

Types of electrochemical cell

The necessary factors for corrosion to proceed are:

1. ANODE - the metal or site on the metal where oxidation occurs (loss of electrons). The anode has a more negative potential with respect to (wrt) the cathode and is termed less noble wrt the cathode.
2. CATHODE - the metal or site on the metal where reduction occurs (gain of electrons). The cathode has a more positive potential wrt the anode and is termed more noble wrt the anode.
3. ELECTROLYTE - the electrically conductive medium in which the anode and cathode reside.
4. ELECTRICAL CONNECTION - the anode and the cathode must be electrically connected.
5. POTENTIAL DIFFERENCE - a voltage difference must exist between the anode and the cathode.

There are **three** main types of cells that take part in corrosion reactions.

1. Dissimilar Electrode Cells (Thermo Galvanic cell)

Examples of dissimilar electrode cells include: the dry cell, a metal containing electrically conducting impurities on the surface as a separate phase, a copper pipe connected to an iron pipe, and a bronze propeller in contact with the steel hull of a ship. Dissimilar electrode cells also include cold - worked metal in contact with the same metal annealed, grain - boundary metal in contact with grains, and a single metal crystal of definite orientation in contact with another crystal of different orientation.

Galvanic cell

These cells may be formed in two dissimilar metals or in the same metal consisting of dissimilar sections. The dissimilarity may arise due to any of the following reasons:

- i. *Two dissimilar metals in contact: Iron pipe carrying water is anodic to Cu pipe*



- ii. *Different heat treatment:* Tempered steel is anodic to annealed steel.
- iii. *Scratches or abrasion:* Scratched area will be anodic to the remaining part.



- iv. *Differential strain:* Strained area is anodic to unstrained area. The head and point of a nail are anodic to the shank.



- v. *Grain boundaries:* Grain boundary is anodic to grain.



- vi. *Differential grain size:* Smaller grains are usually anodic to larger grains.

2. Concentration Cells.

These are cells with two identical electrodes, each in contact with a solution of different composition. There are **two** kinds of concentration cells.

The **first** is called a **salt concentration cell**. For example, if one copper electrode is exposed to a concentrated copper sulfate solution, and another to a dilute copper sulfate solution, on short - circuiting the electrodes, copper dissolves (i.e., $\text{Cu} \rightarrow \text{Cu}^{2+} + 2\text{e}^-$) from the electrode in contact with the dilute solution (anode) and plates out (i.e., $\text{Cu}^{2+} + 2\text{e}^- \rightarrow \text{Cu}$) on the other electrode (cathode). These reactions tend to bring the two solutions to the same concentration.

The **second** kind of concentration cell, which in practice is the more important, is called a **differential aeration cell**. This may include two iron electrodes in dilute sodium chloride solution, the electrolyte around one electrode being thoroughly

aerated (cathode), and the other unaerated (anode) by, for example, bubbling nitrogen through the solution. The difference in oxygen concentration produces a potential difference and causes current to flow. This type of cell accounts for the pronounced damage at crevices, which is called crevice corrosion. Crevices are common in many engineering designs — for example, at the interface of two pipes that are coupled together and at threaded connections. The oxygen concentration is lower within crevices, and the areas of lower oxygen concentration (inside the crevice) are anodic with respect to areas of higher oxygen concentration (outside crevices). Differential aeration cells can also cause pitting damage under rust and at the water line — that is, at the water – air interface. The amount of oxygen reaching the metal that is covered by rust or other insoluble reaction products is less than the amount that contacts other portions where the permeable coating is thinner or nonexistent. Differential aeration cells can also lead to localized corrosion at pits (crevice corrosion) in stainless steels, aluminum, nickel, and other passive metals that are exposed to aqueous environments, such as seawater.

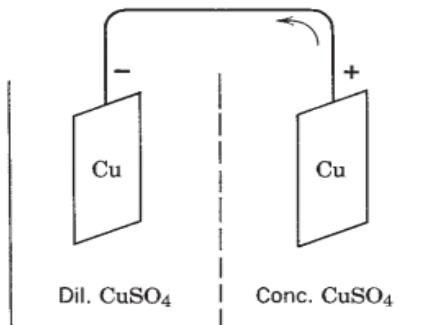


Figure 2.3. Salt concentration cell.

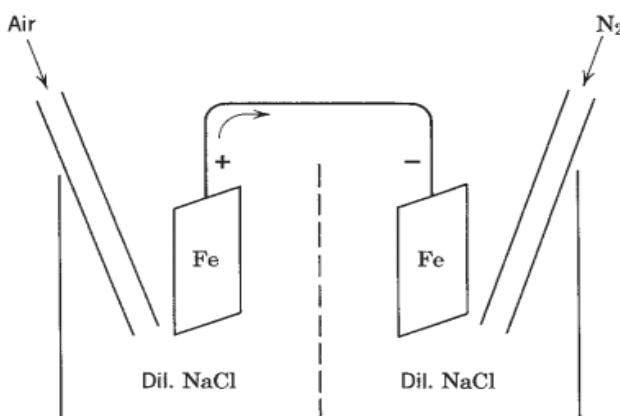


Figure 2.4. Differential aeration cell.

Two identical electrodes each in contact with a solution of differing composition. The factors contributing to these differences are:

I. Differential composition of the electrolyte –

- ✓ A section of pipe buried in clay soil is anodic to pipe section buried in loam soil.

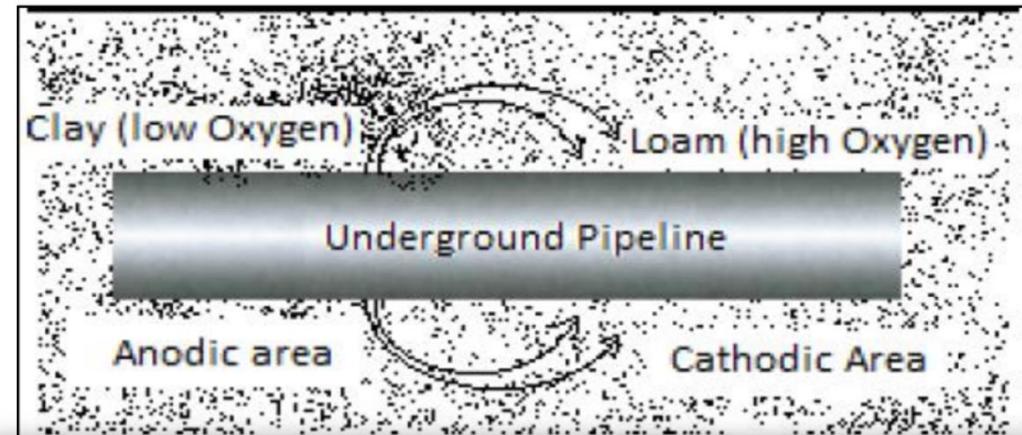


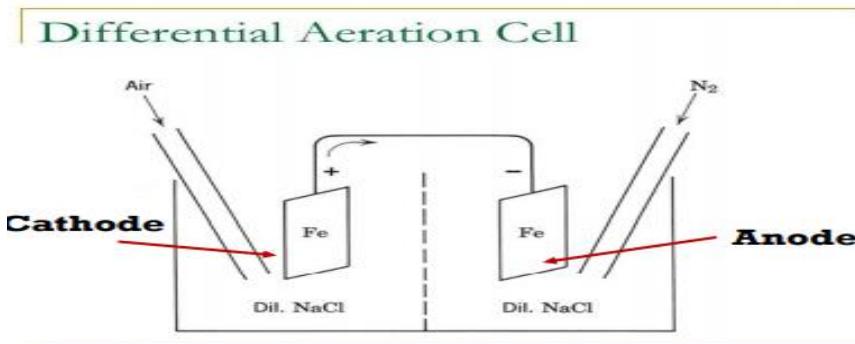
Figure 2.2: Buried pipeline exhibiting differential aeration corrosion [4]

II. Differential concentration of the electrolyte -

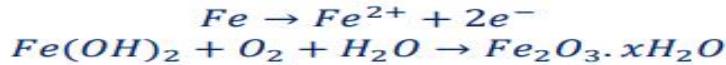
- ✓ These are also called **salt concentration cell**.
- ✓ Two identical electrodes each in contact with a solution of different concentration of the same solution.

III. Differential oxygen concentration –

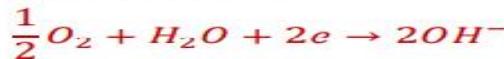
- ✓ Known as **differential aeration cells**



Anodic reaction:



Cathodic reaction:



- ✓ Two identical electrodes immersed in a electrolyte of same concentration.
 - ✓ Both the electrodes are in contact with different concentration of oxygen
 - ✓ The area in contact with lower oxygen concentration will be anodic and corroded
- Examples:
- ✓ Pitting damage under rust.

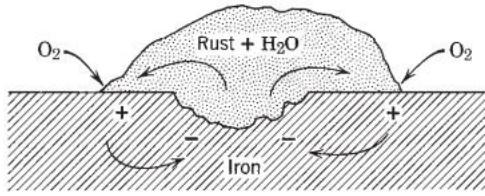


Figure 2.5. Differential aeration cell formed by rust on iron.

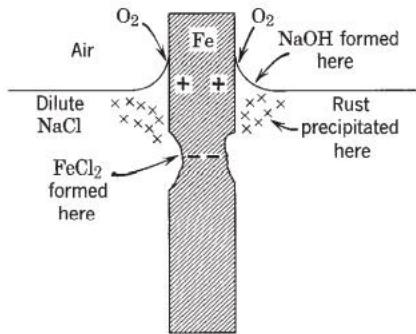
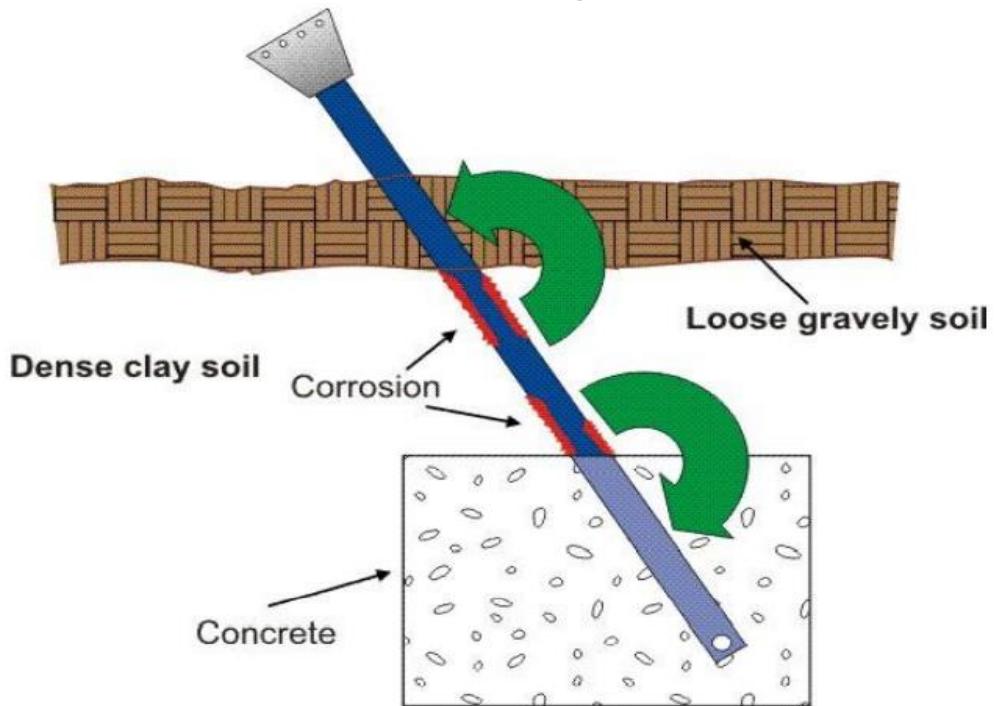


Figure 2.6. Water-line corrosion, showing differential aeration cell.

- ✓ Corrosion of hull of a ship under the water.
- ✓ Corrosion of a tower anchor shaft under the ground.



Differences in the porosity of the soil that can lead to an oxygen concentration corrosion cell.

The following **Figure** illustrates how soil stratification can produce an oxygen concentration cell on a tower anchor shaft. In this illustration, the upper soil layer is a loose somewhat gravelly soil below which there is a dense clay type soil.

The portion of the shaft in contact with the clay type soil acts as an anode to the portion of the shaft in contact with the looser gravelly soil, which is consequently

the cathode. Again, we have a corrosion cell where the shaft deteriorates in the anodic areas. Such differential aeration cells are also very common on buried pipes. For example, a pipe usually rests on undisturbed soil at the bottom of a ditch. Around the sides and on top of the pipe is relatively loose backfill which has been replaced in the ditch.

3. Differential Temperature Cells.

- ✓ Components of these cells are electrodes of the same metal, each of which is at a different temperature, immersed in an electrolyte of the same initial composition.
- ✓ These cells are found in heat exchangers, boilers, immersion heaters, and similar equipment.
- ✓ In copper sulfate solution, the copper electrode at the higher temperature is the cathode, and the copper electrode at the lower temperature is the anode. On short - circuiting the cell, copper deposits on the hot electrode and dissolves from the cold electrode.
Lead acts similarly, but for silver the polarity is reversed.
- ✓ For iron immersed in dilute aerated sodium chloride solutions, the hot electrode is anodic to colder metal of the same composition; but after several hours, depending on aeration, stirring rate, and whether the two metals are short - circuited, the polarity may reverse.
- ✓ Oil and gas well casings also experience similar cell attack. a) The hot pipe near the compressor is the anode. b) The cooler pipe down the line is the cathode. c) The soil is the electrolyte. d) The pipe itself is the connecting circuit.

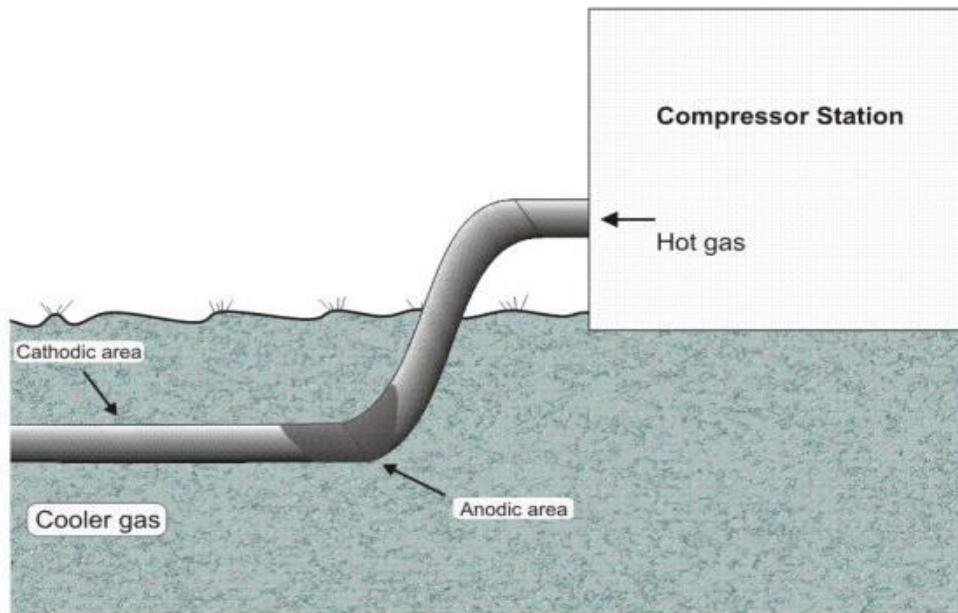
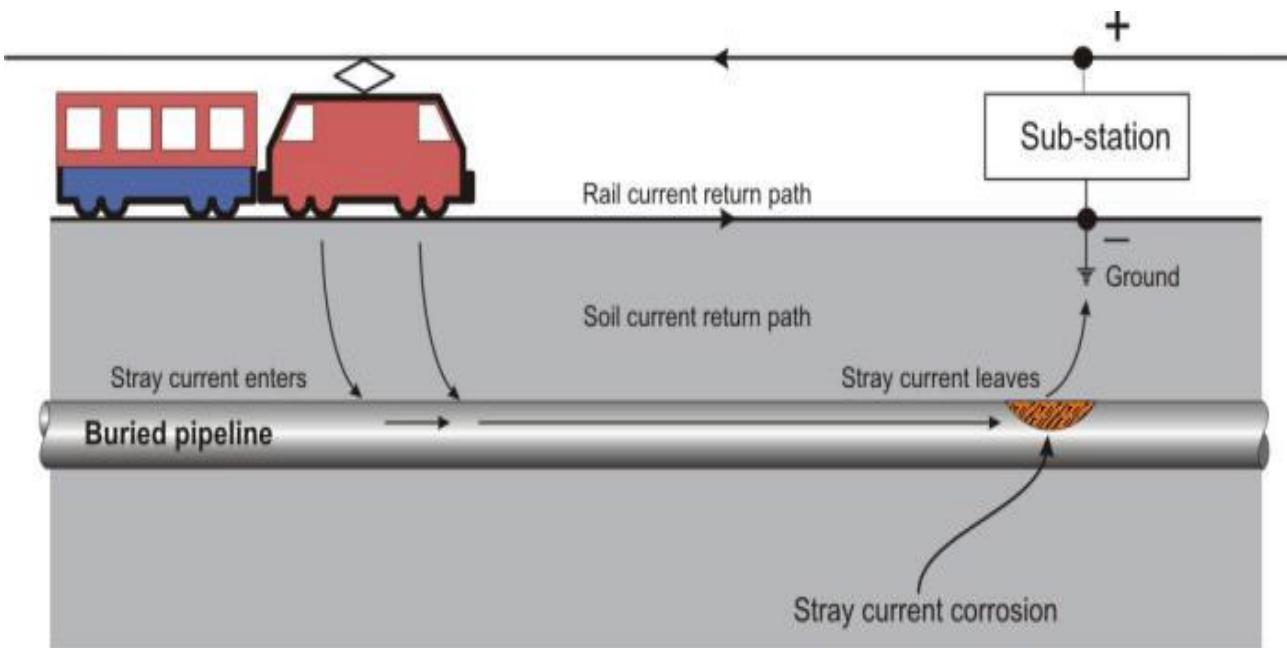


Figure: Concentration cell resulting from heat differential

Electrolytic cell



- ✓ Electrodes and electrolytes are homogeneous
- ✓ The presence of external energy can develop anodic and cathodic areas.
- ✓ If current enters a metallic structure at some points and leaves at other, then the area where the current leaves the metal surface becomes anodic and corrodes.



CLASSIFICATION OF CORROSION

Corrosion has been classified in many different ways. One method divides corrosion into **low-temperature** and **high-temperature** corrosion. Another separates corrosion into **direct combination (or oxidation)** and **electrochemical** corrosion. The preferred classification here is **(1) wet corrosion** and **(2) dry corrosion**.

Wet corrosion occurs when a liquid is present. This usually involves aqueous solutions or electrolytes and accounts for the greatest amount of corrosion by far. A common example is corrosion of steel by water.

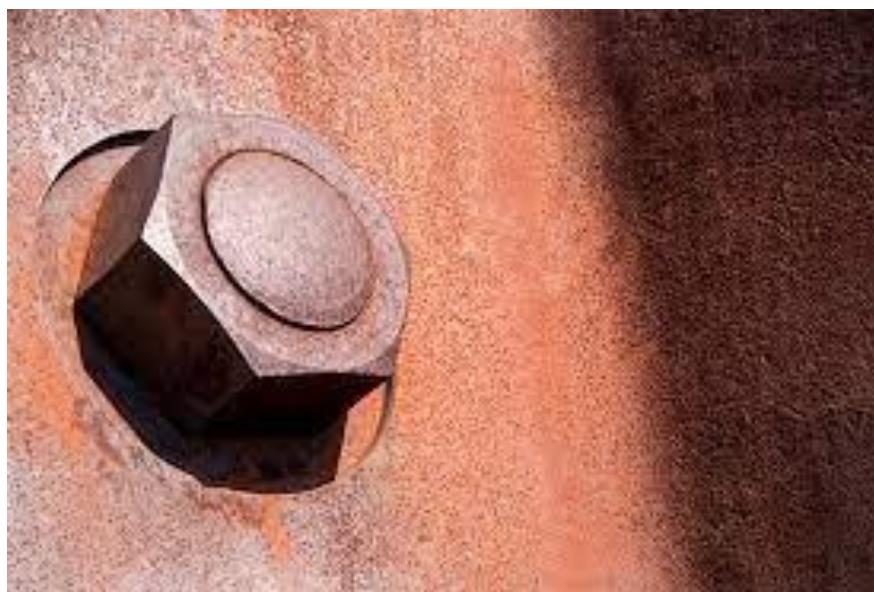
Dry corrosion occurs in the absence of a liquid phase or above the dew point of the environment. Vapors and gases are usually the corrodents. Dry corrosion is most often associated with high temperatures. An example is attack on steel by furnace gases.

The presence of even small amounts of moisture could change the corrosion picture completely. For example, dry chlorine is practically noncorrosive to ordinary steel, but moist chlorine, or chlorine dissolved in water, is extremely corrosive and attacks most of the common metals and alloys. The reverse is true for titanium-dry chlorine gas is more corrosive than wet chlorine.

Different types of corrosion damage

1. General corrosion or Uniform attack

It is normally characterized by a chemical or electrochemical reaction that proceeds uniformly over the entire exposed surface or over a large area.



- ✓ Metal surface is corroded uniformly.
- ✓ The initial corrosion rate is greater than subsequent rates.
- ✓ Rusting of iron, tarnishing of silver, fogging of nickel, high temperature oxidation of metal etc.
- ✓ Random creation and destruction of anodes and cathodes.
- ✓ Movement of anodes and cathodes.
- ✓ Near uniform thinning.
- ✓ Weight loss is a useful measure.
- ✓ Units –
 - mm/y (millimeter penetration per year)
 - gmd (grams per square meter per day)
 - ipy (inches penetration per year)
 - mpy (mils (1 mil = 0.001 inch) per year)
 - mdd (milligrams per square decimeter per day)

For handling chemical media whenever attack is uniform, metals are classified into three groups according to their corrosion rates and intended application. These classifications are as follows:

- A. $< 0.15 \text{ mm/y}$ ($< 0.005 \text{ ipy}$) — Metals in this category have good corrosion resistance to the extent that they are suitable for critical parts, for example, valve seats, pump shafts and impellors, springs.
- B. 0.15 to 1.5 mm/y (0.005 to 0.05 ipy) — Metals in this group are satisfactory if a higher rate of corrosion can be tolerated, for example, for tanks, piping, valve bodies, and bolt heads.
- C. $> 1.5 \text{ mm/y}$ ($> 0.05 \text{ ipy}$) — Usually not satisfactory.

2. Localized corrosion

Unlike general attack corrosion, localized corrosion specifically targets one area of the metal structure.

- ✓ Generates on the same surface
- ✓ Small area of the surface acts as anode compared to large cathode
- ✓ Localized corrosions are the following types
 - I. Pitting corrosion
 - II. Crevice corrosion
 - III. Film forming or under deposit corrosion
 - IV. Micro-bialy induced corrosion (MIC)

- **Pitting:** Pitting results when a small hole, or cavity, forms in the metal, usually as a result of de-passivation of a small area. This area becomes anodic, while part of the remaining metal becomes cathodic, producing a localized galvanic reaction. The deterioration of this small area penetrates the metal and can lead to failure. This form of corrosion is often difficult to detect due to the fact that it is usually relatively small and may be covered and hidden by corrosion-produced compounds.

- ✓ Extremely localized attack resulting in the formation of pits, holes, or cavities
- ✓ Very small fixed area of anode producing deep pits. Example-stainless steel immersed in sea water characteristically corrode with the formation of deep pits.
- ✓ Relatively larger area of anode creates shallow pits. Example-Iron buried in soil corrodes with the formation of shallow pits.
- ✓ Caused by break down or cracking of the protective film.
- ✓ Mostly occurs in Cl^- solutions containing oxygen or oxidizing salt.

Causes of pitting corrosion:

- ✓ Metal surfaces are not homogeneous
- ✓ External environment is not homogeneous
- ✓ Films are not perfectly uniform
- ✓ Crystallographic directions are not equal in the reactivity

The depth of pitting is expressed by the term Pitting factor. It is the ratio of deepest metal penetration to average metal penetration as determined by weight loss of the specimen.

A corrosion pit is a unique type of anodic reaction. It is an **autocatalytic process**. That is, the corrosion processes within a pit produce conditions which are both stimulating and necessary for the continuing activity of the pit. This is illustrated schematically in Fig. 3-19. Here a metal M is being pitted by an aerated sodium chloride solution. Rapid dissolution occurs within the pit, while oxygen reduction takes place on adjacent surfaces. This process is self-stimulating and self-propagating.

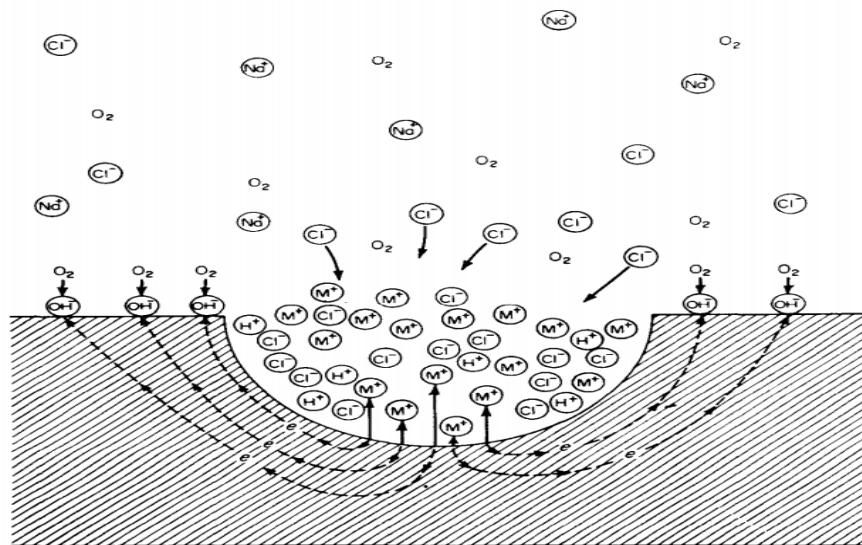
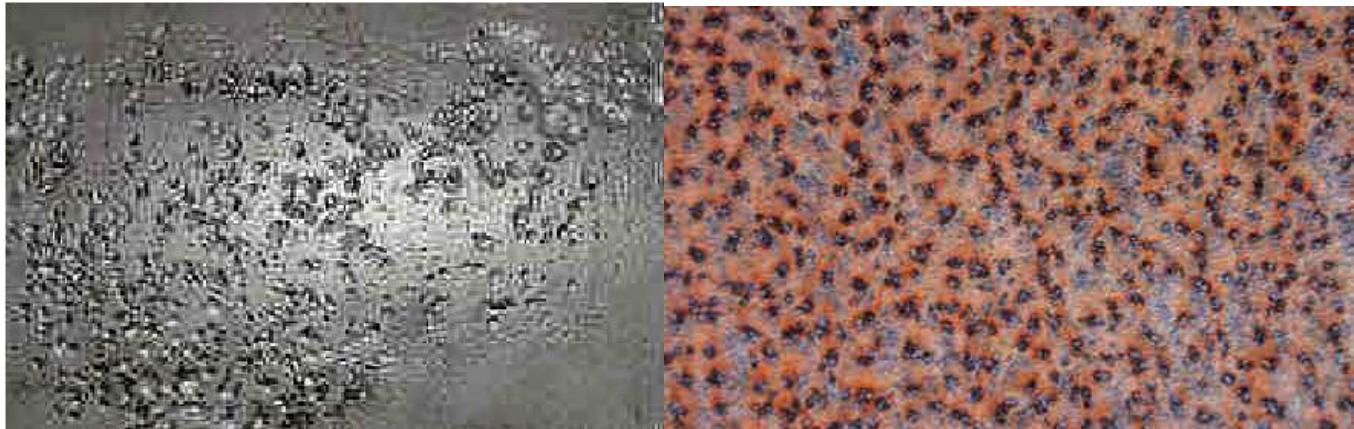
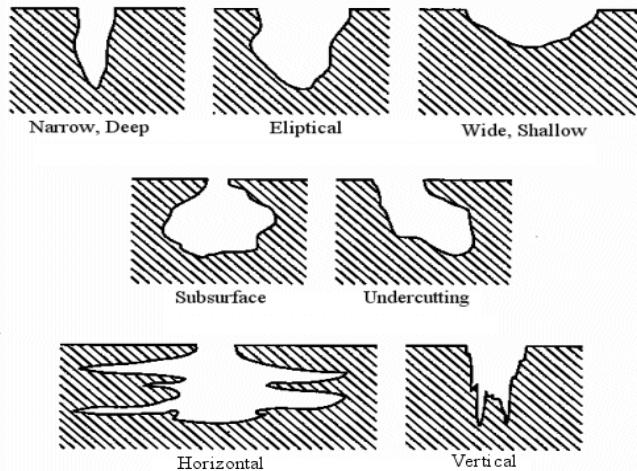


Figure 3-19 Autocatalytic processes occurring in a corrosion pit.

Table 3-7 Effects of alloying on pitting resistance of stainless steel alloys

Element	Effect on pitting resistance
Chromium	Increases
Nickel	Increases
Molybdenum	Increases
Silicon	Decreases ; increases when present with molybdenum
Titanium and columbium	Decreases resistance in FeCl_3 ; other mediums no effect
Sulfur and selenium	Decreases
Carbon	Decreases, especially in sensitized condition
Nitrogen	Increases

Source: N. D. Greene and M. G. Fontana, Corrosion 15:251 (1959).



- **Crevice corrosion:** Intensive localized corrosion frequently occurs within crevices and other shielded areas on metal surfaces exposed to corrosives. This type of attack is usually associated with small volumes of stagnant solution caused by holes, gasket surfaces, lap joints, surface deposits, and crevices under bolt and rivet heads. As a result, this form of corrosion is called crevice corrosion or, sometimes, deposit or gasket corrosion.

Examples of deposits that may produce crevice corrosion (or deposit attack) are sand, dirt, corrosion products, and other solids. The deposit acts as a shield and creates a stagnant condition thereunder. The deposit could also be a permeable corrosion product.

Contact between metal and nonmetallic surfaces can cause crevice corrosion as in the case of a gasket.

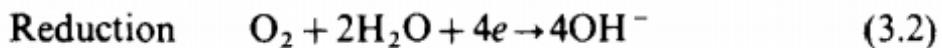
Wood, plastics, rubber, glass, concrete, asbestos, wax, and fabrics are examples of materials that can cause this type of corrosion.



First figure is a good example of crevice corrosion at a gasket-stainless steel interface. The inside of the pipe is negligibly corroded. Stainless steels are particularly susceptible to crevice attack. For example, a sheet of 18-8 stainless steel can be cut by placing a stretched rubber band around it and then immersing it in seawater. Crevice attack begins and progresses in the area where the metal and rubber are in contact. To function as a corrosion site, a crevice must be wide enough to permit liquid entry but sufficiently narrow to maintain a stagnant zone. For this reason, crevice corrosion usually occurs at openings a few thousandths of an inch or less in width. It rarely occurs within wide (e.g. 1/8 in.) grooves or slots. Fibrous gaskets, which have a wick action, form a completely stagnant solution in contact with the flange face; this condition forms an almost ideal crevice corrosion site.

Mechanism

To illustrate the basic mechanism of crevice corrosion, consider a riveted plate section of metal M (e.g., iron or steel) immersed in aerated seawater (pH 7) as shown in Fig. 3-9. The overall reaction involves the dissolution of metal M and the reduction of oxygen to hydroxide ions.



Initially, these reactions occur uniformly over the entire surface, including the interior of the crevice. Charge conservation is maintained in both the metal and solution. Every electron produced during the formation of a metal ion is immediately consumed by the oxygen reduction reaction. Also, one hydroxyl ion is produced for every metal ion in the solution. After a short interval, the oxygen within the crevice is depleted because of the restricted convection, so oxygen reduction ceases in this area. This, by itself, does not cause any change in corrosion behavior.

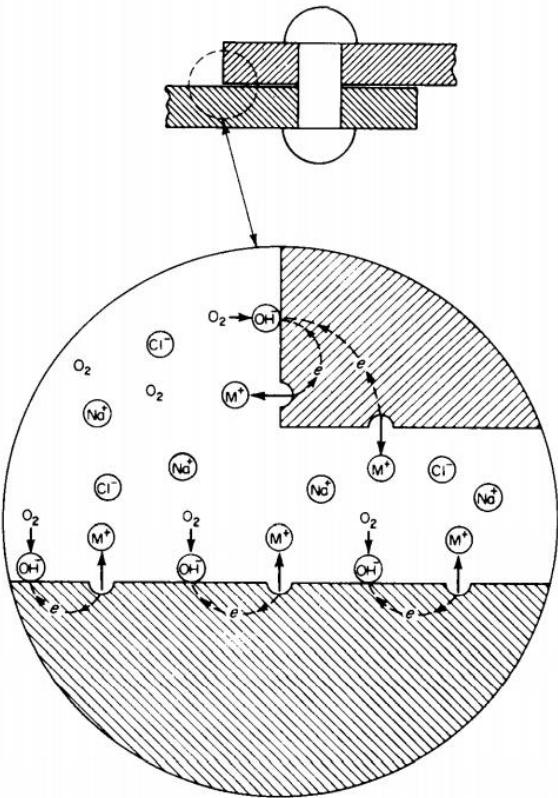


Figure 3-9 Crevice corrosion—initial stage.

and potassium), metal salts, including chlorides and sulfates, hydrolyze in water:

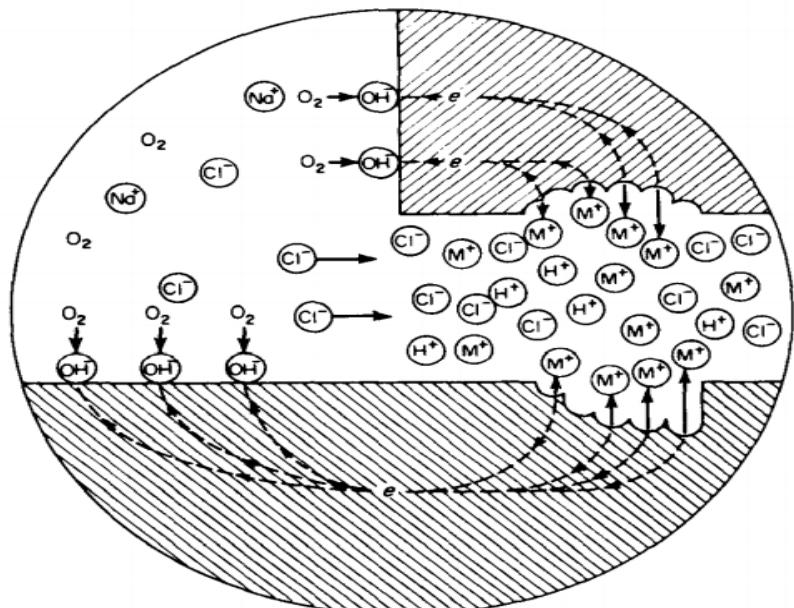
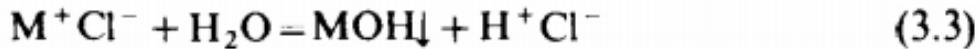


Figure 3-10 Crevice corrosion—later stage.

Since the area within a crevice is usually very small compared with the external area, the overall rate of oxygen reduction remains almost unchanged. Therefore, the rate of corrosion within and without the crevice remains equal. Oxygen depletion has an important indirect influence, which becomes more pronounced with increasing exposure. After oxygen is depleted, no further oxygen reduction occurs, although the dissolution: If metal M continues as shown in Fig. 3-10. This tends to produce an excess of positive charge in the solution (M^+), which is necessarily balanced by the migration of chloride ions into the crevice.^t This results in an increased concentration of metal chloride within the crevice. Except for the alkali metals (e.g., sodium

- **Filiform corrosion:** Occurring under painted or plated surfaces when water breaches the coating, filiform corrosion begins at small defects in the coating and spreads to cause structural weakness. Filiform corrosion (filamentary corrosion occurring on metal surfaces) is a special type of crevice corrosion. In most instances it occurs under protective films, and for this reason it is often referred to as under film corrosion. This type of corrosion is quite common; the most frequent example is the attack of enameled or lacquered surfaces of food and beverage cans that have been exposed to the atmosphere.
- **Microbiologically Induced Corrosion (MIC)** is the deterioration of a metal by corrosion processes that occurs directly or indirectly because of the metabolic activity of microorganisms in cold water systems. This type of corrosion results in severe pitting of metals, leading to rapid failures.

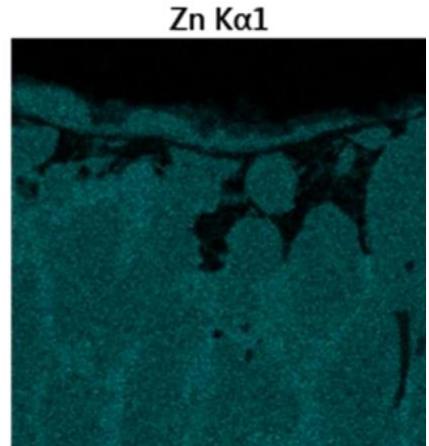
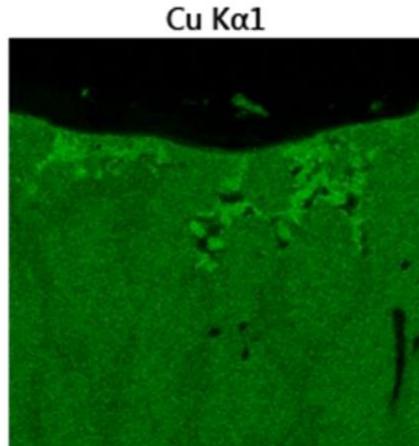
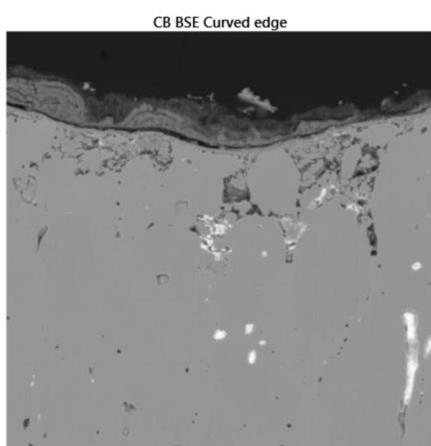
3. De-Alloying:

De-alloying, or selective leaching, is the selective corrosion of a specific element in an alloy. The most common type of de-alloying is de-zincification of unstabilized brass. The result of corrosion in such cases is a deteriorated and porous copper.

- ✓ One constituent of an alloy is preferentially removed from the alloy leaving an altered residual structure.
- ✓ Common examples are dezincification, parting, graphitization etc.



When the **dealloying** takes place, the alloy metal loses its reactive element and retains the more stable corrosion-resistant element in a porous state. Selective leaching, also called dealloying, demetalification, parting and selective corrosion, is a corrosion type in some solid solution alloys, when in suitable conditions a component of the alloys is preferentially leached from the material.



Dezincification: Mechanism

Two theories have been proposed for dezincification. One states that zinc is dissolved, leaving vacant sites in the brass lattice structure. This theory is not proven. A strong argument against it is that dezincification to appreciable depths would be impossible or extremely slow because of difficulty of diffusion of solution and ions through a labyrinth of small vacant sites. The commonly accepted mechanism consists of three steps, as follows: (1) the brass dissolves, (2) the zinc ions stay in solution, and (3) the copper plates back on. Zinc is quite reactive, whereas copper is more noble. Zinc can corrode slowly in pure water by the cathodic ion reduction of H₂O into hydrogen gas and hydroxide ions. For this reason dezincification can proceed in the absence of oxygen. Oxygen also enters into the cathodic reaction and hence increases the rate of attack when it is present. Analyses of dezincified areas show 90 to 95% copper with some of it present as copper oxide. The amount of copper oxide is related to oxygen content of the environment. The porous nature of the deposit permits easy contact between the solution and the brass.

4. Environmental Cracking:

Environmental cracking is a corrosion process that can result from a combination of environmental conditions affecting the metal. Chemical, temperature and stress-related conditions can result in the following types of environmental corrosion:

- **Stress Corrosion Cracking (SCC)**



Stress - corrosion cracking (S.C.C.) is a type of cracking that occurs when a material that is susceptible to S.C.C. is simultaneously stressed in tension and exposed to an environment that causes S.C.C.

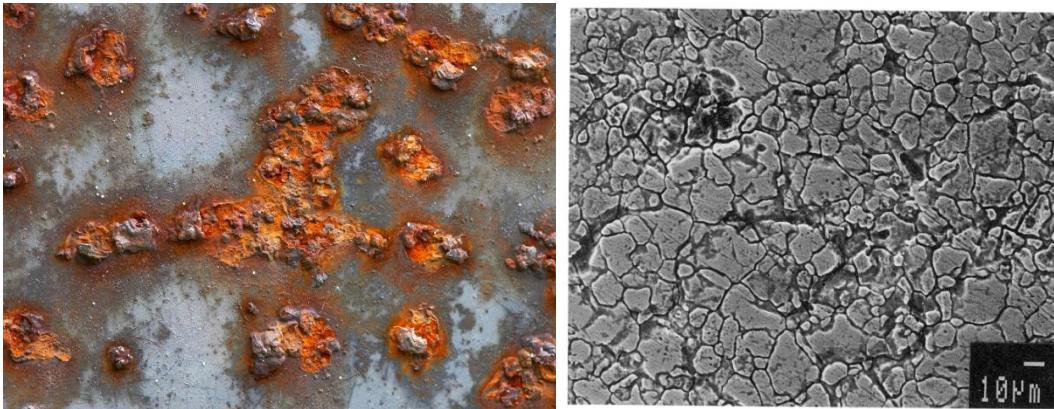
- ✓ If a metal is subject to a constant tensile stress and exposed to a specific corrosive environment, cracks immediately or after a given time, which is called stress corrosion cracking.
- ✓ It is the cracking induced from the combined influence of tensile stress and a corrosive environment.
- ✓ The stress may be residual stress in the metal as from cold working, or heat-treatment or may be externally applied stress.

- ✓ Practically all structural metals, e.g., steels, brass, SS, duralumin, nickel alloys and others are subjected to SCC in some environment.
- Corrosion fatigue.
- Hydrogen-induced cracking.
- Liquid metal embrittlement.

5. Intergranular corrosion

Intergranular corrosion is a chemical or electrochemical attack on the grain boundaries of a metal. It often occurs due to impurities in the metal, which tend to be present in higher contents near grain boundaries. These boundaries can be more vulnerable to corrosion than the bulk of the metal.

- ✓ Grain boundary acts as anode compare to the large grain.
- ✓ The attack is often rapid, penetrating deeply into the metal, and sometime causes catastrophic failures.
- ✓ Improperly heat treated 18-8 stainless steel, duralumin, etc.



iron is low, have been shown to segregate in the grain boundaries and cause intergranular corrosion. It has been shown that based on surface tension considerations the zinc content of a brass is higher at the grain boundaries. Depletion of chromium in the grain-boundary regions results in intergranular corrosion of stainless steels.

6. Erosion corrosion

Erosion corrosion is the acceleration or increase in rate of deterioration or attack on a metal because of relative movement between a corrosive fluid and the metal surface.

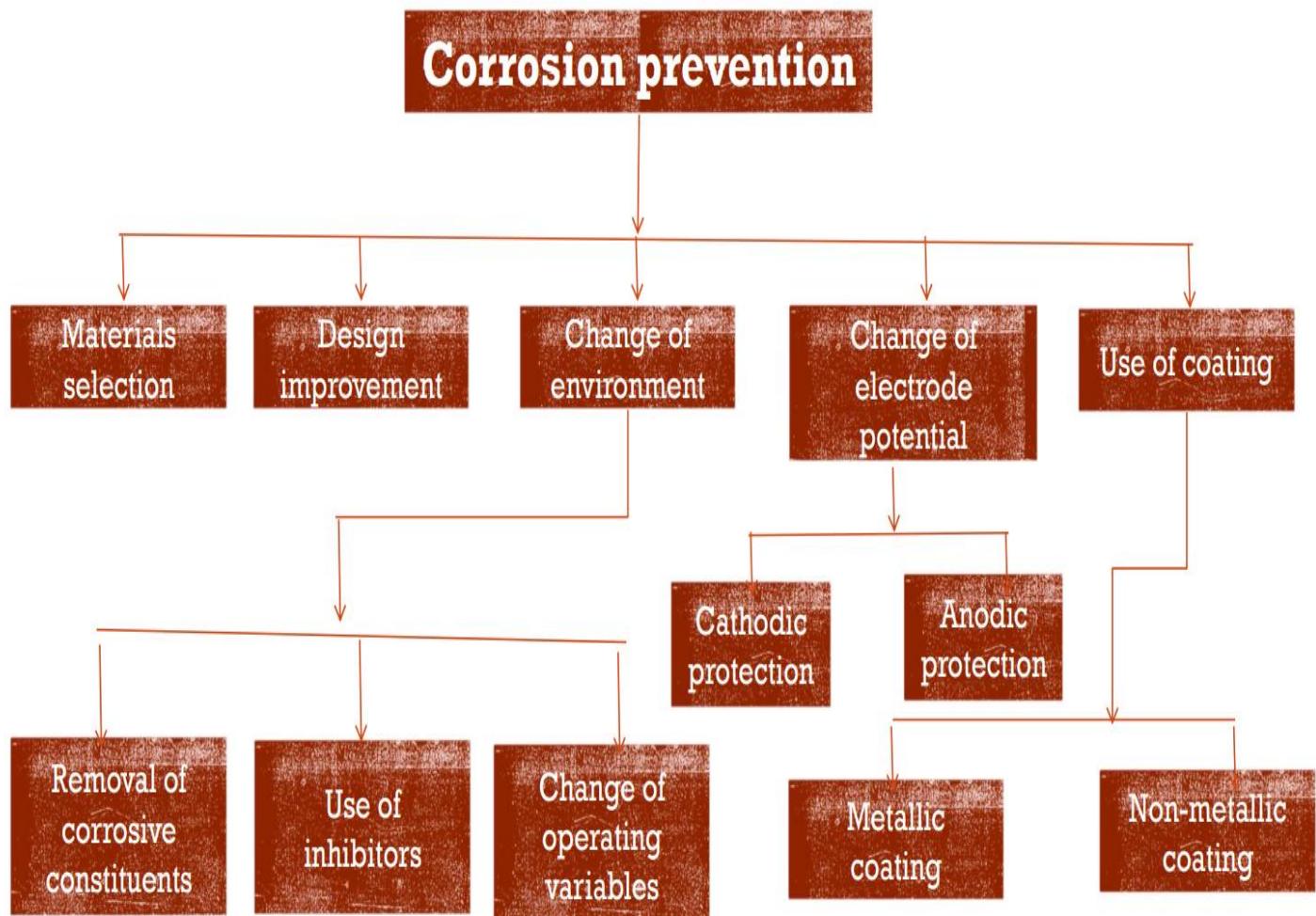


Generally this movement is quite rapid, and mechanical wear effects or abrasion are involved. Metal is removed from the surface as dissolved ions, or it forms solid corrosion products that are mechanically swept from the metal surface. Sometimes movement of the environment decreases corrosion, particularly when localized attack occurs under stagnant conditions, but this is not erosion corrosion because deterioration is not increased. Erosion corrosion is

characterized in appearance by grooves, gullies, waves, rounded holes, and valleys and usually exhibits a directional pattern. Figure 3-38 shows a typical wavy appearance of an erosion-corrosion failure. This pump impeller was taken out of service after three weeks of operation. Figure 3-39 is a sketch representing erosion corrosion of a heat-exchanger tube handling water. In many cases, failures because of erosion corrosion occur in a relatively short time, and they are unexpected largely because evaluation corrosion tests were run under static conditions or because the erosion effects were not considered.

- Destruction of materials by physical means like wear, abrasion etc.
- No chemical reaction will take place

Surface Films: The nature and properties of the protective films that form on some metals or alloys are very important from the standpoint of resistance to erosion corrosion. The ability of these films to protect the metal depends on the speed or ease with which they form when originally exposed to the environment, their resistance to mechanical damage or wear, and their rate of re-forming when destroyed or damaged.



1. Materials selection

a. Metals and alloys

S1. No.	Metals and alloys	Resistant to environment
1	Stainless steel	Nitric acid
2	Nickel and nickel alloys	Caustic
3	Monel metal	Hydrofluoric acid
4	Hastelloys	Hot hydrochloric acids
5	Lead	Dilute sulphuric acid
6	Aluminium	Non staining atmospheric exposure
7	Tin	Distilled water
8	Titanium	Hot strong oxidizing solution
9	Tantalum	Ultimate resistance
10	Steel	Concentrated sulfuric acid

b. Metal purification

- ✓ Pure metals are more corrosion resistance than impure one. But, they are usually expensive and are soft and weak.
- ✓ Good example is aluminum (99.5% pure)
- ✓ Arc-melted zirconium is more corrosion resistant than induction-melted zirconium as the later is impure.

c. Nonmetallics

- ✓ Five classes of nonmetallic materials are rubber, plastics, ceramics, carbon and graphite and wood.
- ✓ Rubber and plastics are more resistant to chloride ions and hydrochloric acids, less resistance to strong sulfuric acids, nitric acids, solvents and have relatively low temperature limitations.
- ✓ Ceramics have excellent corrosion resistant and very high temperature resistance, but brittle.
- ✓ Carbon shows good corrosion resistant and electricity and heat conductivity, but fragile.
- ✓ Wood is attacked by aggressive environments.

2. Design

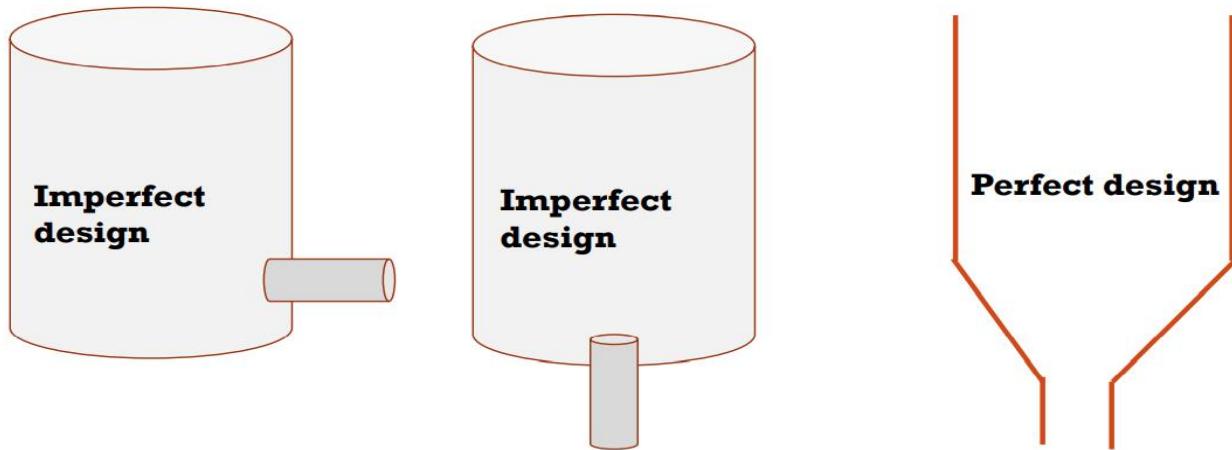
Some of the design rules that should be followed are listed below. It would be helpful if the designer had a good background in corrosion but unfortunately this is usually not the case.

1. Weld rather than rivet tanks and other containers. Riveted joints provide sites for crevice corrosion.
2. Design tanks and other containers for easy draining and easy cleaning. Tank bottoms should be sloped toward drain holes so that liquids cannot collect after the tank is emptied. Concentrated sulfuric acid is only negligibly corrosive toward steel. However, if a steel sulfuric acid tank is incompletely drained and the remaining liquid is exposed to the air, the acid tends to absorb moisture, resulting in dilution, and rapid attack occurs.
3. Design systems for the easy replacement of components that are expected to fail rapidly in service. Frequently, pumps in chemical plants are designed so that they can be readily removed from a piping system.
4. Avoid excessive mechanical stresses and stress concentrations in components exposed to corrosive mediums. Mechanical or residual stresses are one of the requirements for stress-corrosion cracking. This rule should be followed especially when using materials susceptible to stress-corrosion cracking.
5. Avoid electrical contact between dissimilar metals to prevent galvanic corrosion. If possible, use similar materials throughout the entire structure, or insulate different materials from one another.
6. Avoid sharp bends in piping systems when high velocities and/or solids in suspension are involved (erosion corrosion).
7. Provide thicker structures to take care of impingement effects.
8. Make sure materials are properly selected.
9. List complete specifications for all materials of construction and provide instructions to be sure the specs are followed all the way through to final inspection. Specify quality control procedures if relevant.
10. Properly design against excessive vibration, not only for rotating parts but also, for example, for heat exchanger tubes.
11. Select plant site upwind from other "polluting" plants or atmosphere if relevant and/or feasible.
12. The most general rule for design is: avoid heterogeneity. Dissimilar metals, vapor spaces, uneven heat and stress distributions, and other differences between points in the system lead to corrosion damage. Hence, in design, attempt to make all conditions as uniform as possible throughout the entire system.

- i. Welding rather than riveting tanks and other containers. Riveted joints provide sites for crevice corrosion.



- ii. Designing tanks and other containers for easy draining and easy cleaning.



3.Alteration of environment

Altering the environment provides a versatile means for reducing corrosion. Typical changes in the medium that are often employed are (1) **lowering temperature**, (2) **decreasing velocity**, (3) **removing oxygen or oxidizers**, and (4) **changing concentration**, (5) **Use of corrosion inhibitors**

Lowering temperature

This usually causes a pronounced decrease in corrosion rate. However, under some conditions, temperature changes have little effect on corrosion rate. In other cases, increasing temperature decreases attack. This phenomenon occurs as hot, fresh or salt water is raised to the boiling point and is the result of the decrease in oxygen solubility with temperature. Boiling seawater is therefore less corrosive than hot seawater.

Decreasing velocity

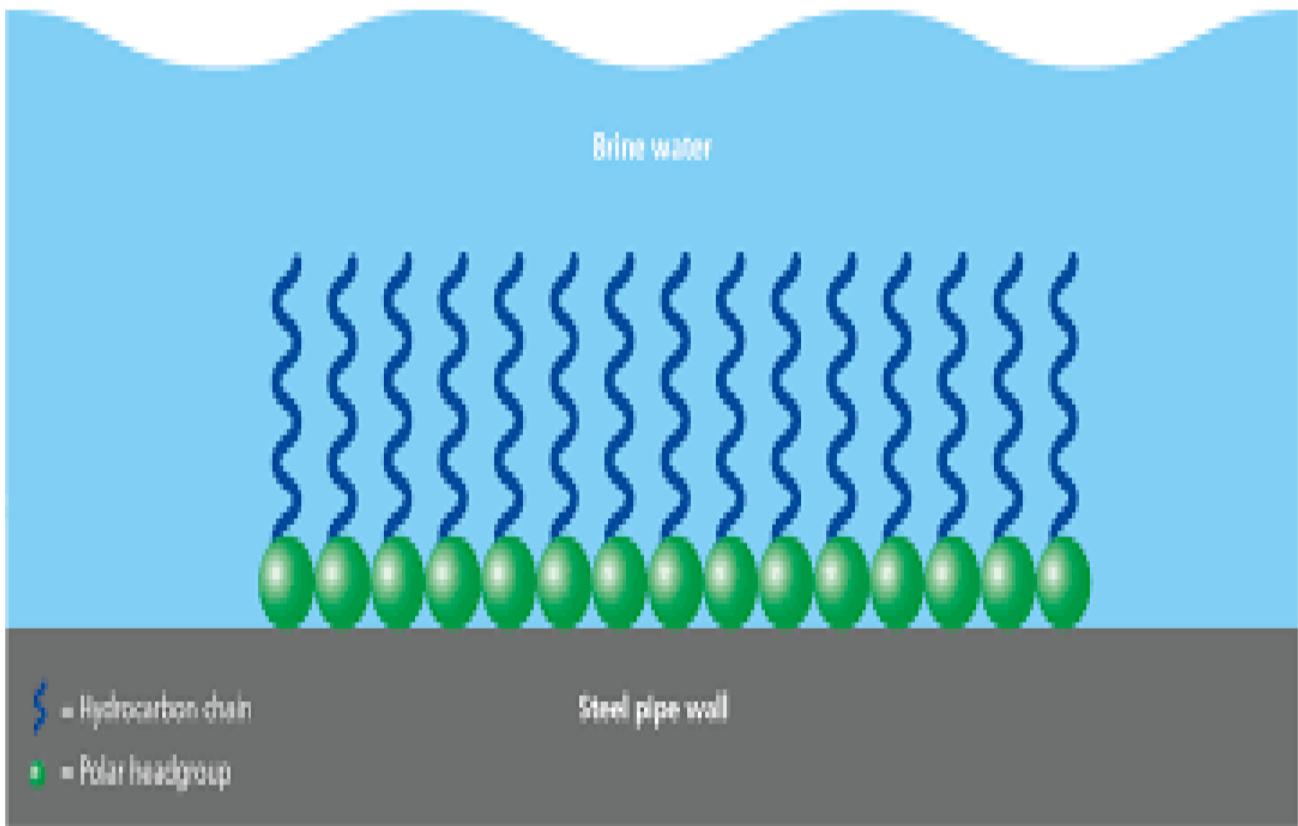
Velocity generally increases corrosive attack, although there are some important exceptions. Metals and alloys that passivate, such as stainless steels, generally have better resistance to flowing mediums than stagnant solutions. Very high velocities should be always avoided where possible, because of erosion-corrosion effects.

Removal of oxygen or oxidizers & changing concentration

- i. Removal of moisture from air by dehumidification, e.g., using silica gel in small closed spaces
- ii. Lowering of relative humidity of air by increasing the temperature 6 to 7 °C above ambient in storage area.
- iii. Removal of oxygen from water by (a) saturation with inert gas, e.g., nitrogen, (b) evacuation, (c) addition of oxygen scavengers, e.g., hydrazine or sodium sulphite.
- iv. Removal of acid from water by neutralization, e.g., by addition of lime.
- v. Removal of chloride ions from the environment to prevent pitting and stress corrosion cracking.
- vi. Removal of solid particles from the environment by filtration.
- vii. Removal of salts from water by ion exchange.

Use of corrosion inhibitors

Corrosion inhibitors are chemical substances which reduce the corrosion rate of metal when added in small quantity. They reduce corrosion by either acting as a barrier by forming an adsorbed layer or retarding the cathodic and/or anodic reaction.



Classification of inhibitors

- I. Chemical passivators/oxidisers/oxidizing inhibitors – Chromates, dicromates, nitrite etc.
- II. Adsorption inhibitors – organic amines, azoles,
- III. Film forming inhibitors – Zn and Ca salts
- IV. Hydrogen-evolution poisons – arsenic and antimony ions
- V. Scavengers – sodium sulphite, hydrazine
- VI. Vapour phase inhibitors/volatile corrosion inhibitors – dicyclohexylamine chromate, dicyclohexylamine nitrite, benzotiazole, phenyl thiourea etc

Inhibitors have been classified differently by various authors. Some authors prefer to group inhibitors by their chemical functionality, as follows:

- Inorganic inhibitors. Usually crystalline salts such as sodium chromate, phosphate, or molybdate. Only the negative anions of these compounds are involved in reducing metal corrosion. When zinc is used instead of sodium, the zinc cation can add some beneficial effect. These zinc-added compounds are called mixed-charge inhibitors.
- Organic anionic. Sodium sulfonates, phosphonates, or mercaptobenzotriazole (MBT) are used commonly in cooling waters and antifreeze solutions.
- Organic cationic. In their concentrated forms, these are either liquids or waxlike solids. Their active portions are generally large aliphatic or aromatic compounds with positively charged amine groups.

TABLE 10.1 Some Corrosive Systems and the Inhibitors Used to Protect Them

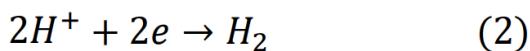
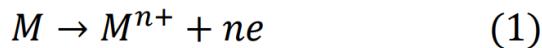
System	Inhibitor	Metals	Concentration
Acids			
HCl	Ethylaniline	Fe	0.5%
	MBT*	--	1%
	Pyridine + phenylhydrazine	--	0.5% + 0.5%
	Rosin amine + ethylene oxide	--	0.2%
H ₂ SO ₄	Phenylacridine	--	0.5%
H ₃ PO ₄	NaI	--	200 ppm
Others	Thiourea	--	1%
	Sulfonated castor oil	--	0.5–1.0%
	As ₂ O ₃	--	0.5%
	Na ₃ AsO ₄	--	0.5%
Water			
Potable	Ca(HCO ₃) ₂	Steel, cast iron	10 ppm
	Polyphosphate	Fe, Zn, Cu, Al	5–10 ppm
	Ca(OH) ₂	Fe, Zn, Cu	10 ppm
	Na ₂ SiO ₃	--	10–20 ppm
Cooling	Ca(HCO ₃) ₂	Steel, cast iron	10 ppm
	Na ₂ CrO ₄	Fe, Zn, Cu	0.1%
	NaNO ₂	Fe	0.05%
	NaH ₂ PO ₄	--	1%
	Morpholine	--	0.2%
Boilers	NaH ₂ PO ₄	Fe, Zn, Cu	10 ppm
	Polyphosphate	--	10 ppm
	Morpholine	Fe	Variable
	Hydrazine	--	O ₂ scavenger
	Ammonia	--	Neutralizer
	Octadecylamine	--	Variable
Engine coolants	Na ₂ CrO ₄	Fe, Pb, Cu, Zn	0.1–1%
	NaNO ₂	Fe	0.1–1%
	Borax	--	1%
Glycol/water	Borax + MBT*	All	1% + 0.1%
Oil field brines	Na ₂ SiO ₃	Fe	0.01%
	Quaternaries	--	10–25 ppm
	Imidazoline	--	10–25 ppm
Seawater	Na ₂ SiO ₃	Zn	10 ppm
	NaNO ₂	Fe	0.5%
	Ca(HCO ₃) ₂	All	pH dependent
	NaH ₂ PO ₄ + NaNO ₂	Fe	10 ppm + 0.5%

4. Change of metal potential

- Cathodic protection
- Anodic protection

A. Cathodic Protection –

Cathodic protection is achieved by supplying electrons to the metal structure to be protected.



Examination of Eq indicates that the addition of electrons to the structure will tend to suppress metal dissolution and increase the rate of hydrogen evolution. There are **two** ways to cathodically protect a structure: (1) by **an external power supply** or, (2) by **appropriate galvanic coupling**.

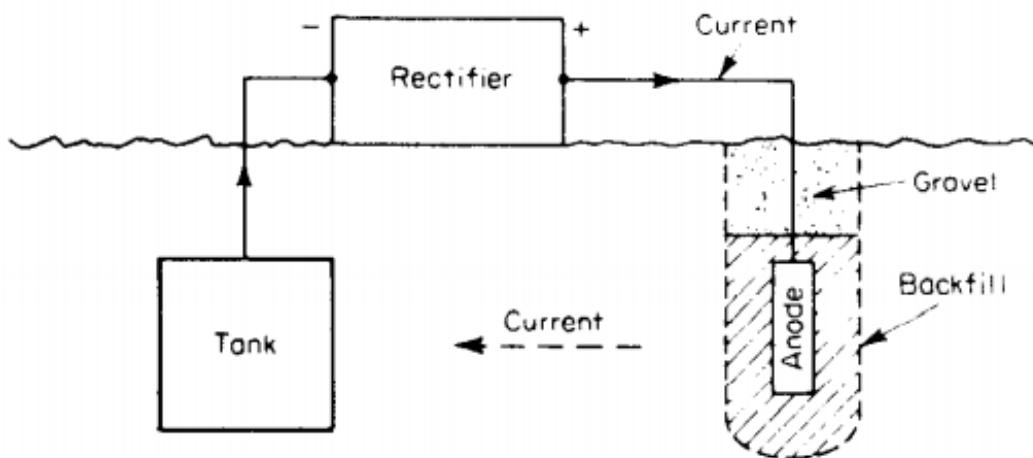


Figure 6-1 Cathodic protection of an underground tank using impressed currents.

Figure 6-1 illustrates cathodic protection by **impressed current**. Here, an external dc power supply is connected to an underground tank. The negative terminal of the power supply is connected to the tank, and the positive to an inert anode such as graphite or Duriron. The electric leads to the tank and the inert electrode are carefully insulated to prevent current leakage. The anode is usually surrounded by backfill consisting of coke breeze, gypsum, or bentonite, which improves electric contact between the anode and the surrounding soil. As shown in Fig. 6-1, current passes to the metallic structure, and corrosion is suppressed.

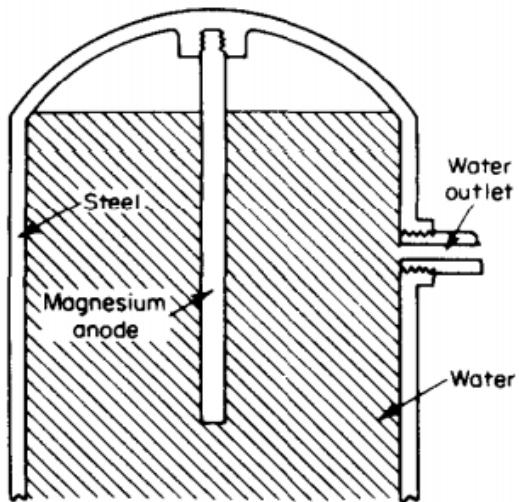
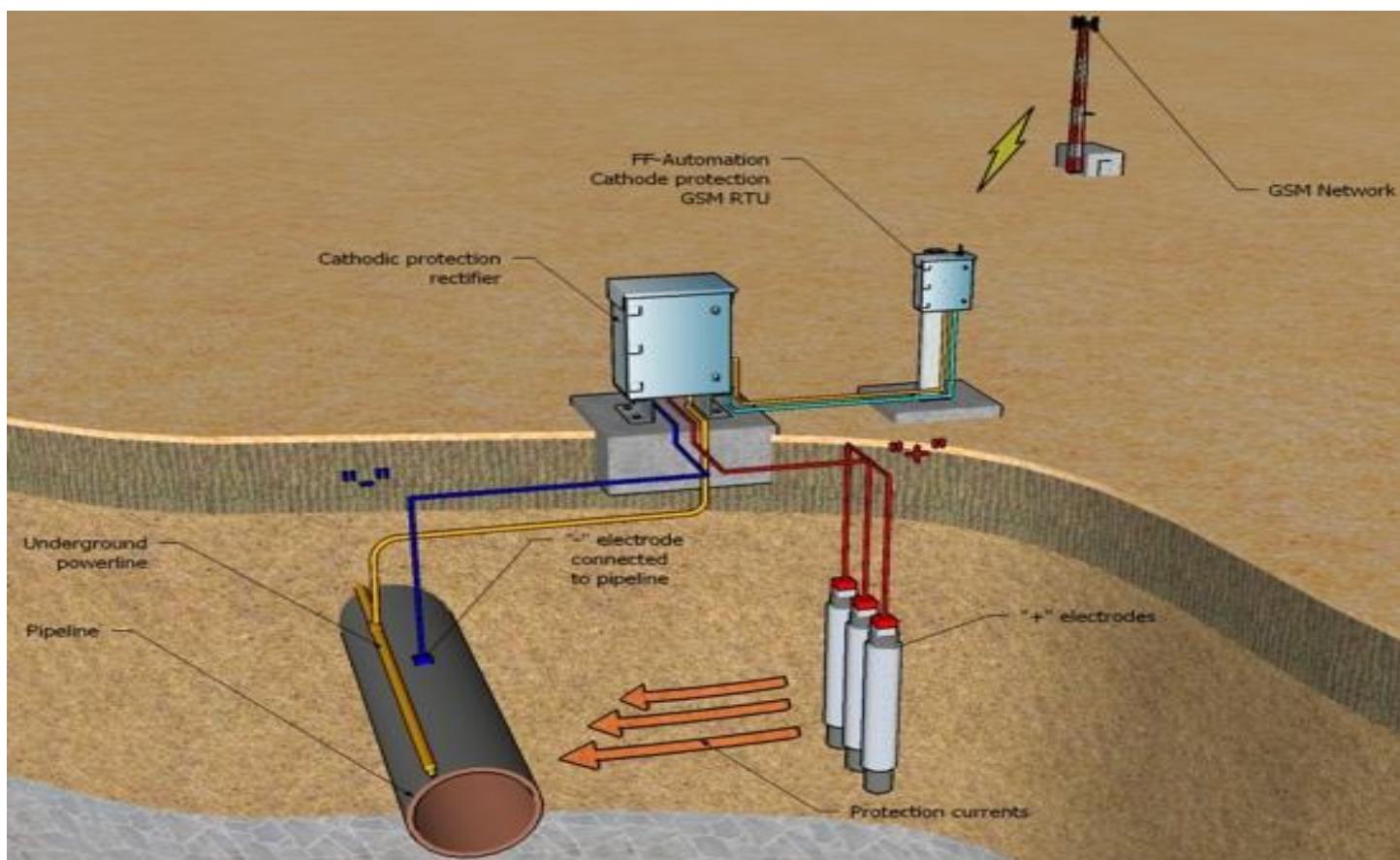


Figure 6-2 Cathodic protection of a domestic hot-water tank using a sacrificial anode.

Cathodic protection by galvanic coupling to magnesium is shown in Fig. 6-2. Magnesium is anodic with respect to steel, and corrodes preferentially when galvanically coupled. The anode in this case is called a **sacrificial anode** since it is consumed during the protection of the steel structure. Cathodic protection using sacrificial anodes can also be used to protect buried pipelines, as shown in Fig. below. The anodes are spaced along the pipe to ensure uniform current distribution.



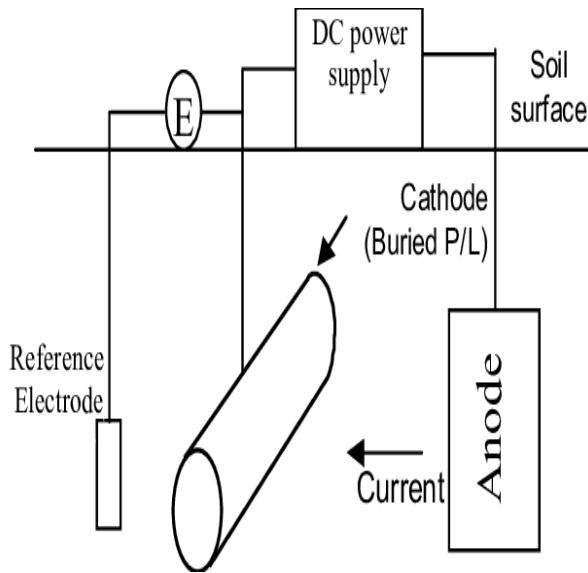


Table 6-2 Typical current requirements for cathodic protection of steel

Structure	Environment	Conditions	Current density, mA/ft ²
Tank	Hot H ₂ SO ₄	Static	50,000
Pipelines and storage tanks	Underground (soil)	Static	1-3
Pipelines	Fresh water	Flowing	5-10
Water heaters	Hot, fresh water	Slow flow	1-3
Pilings	Seawater	Tidal motion	6-8
Reinforcing rods	Concrete	Static	0.1-0.5

Advantages of Impressed current methods

- ✓ Larger driving force
- ✓ Larger flexibility of control
- ✓ Applicable to large object
- ✓ Uncoated parts can be protected

Limitations of impressed current methods

- ✓ Larger installation and maintenance cost
- ✓ Interference problem with parallel currents

Advantage of galvanic anode method

- ✓ Since no external power supply is needed, it can be used in remote areas
- ✓ Low installation and maintenance cost

Limitations of galvanic anode method

- ✓ Limited driving potential and current output
- ✓ Soil resistivity limitations
- ✓ Not applicable for large and uncoated object

Application of cathodic protection

- Pipelines
- Underground cables
- Chemical equipment
- Marine equipment

Table 6-3 Comparisons of sacrificial and impressed-current anodes for cathodic protection

Sacrificial anodes			
	Magnesium	Zinc	Aluminum-tin
Theoretical consumption, lb/ampere-year	9	23	6.5
Actual consumption, lb/ampere-year	18	25	16–20
Potential vs. Cu/CuSO ₄	—1.7	—1.15	—1.3

Impressed-current anodes		
Material	Typical applications	Typical loss, lb/ampere-year
Scrap steel	Soil, fresh- and sea-water	20
Aluminum	Soil, fresh- and sea-water	10–12
Graphite	Soil and fresh water	0.25–5.0
High-silicon iron and Si-Cr iron	Soil, fresh water, and seawater	0.25–1.0
Lead	Seawater	0.1–0.25
Platinized titanium	Seawater	nil

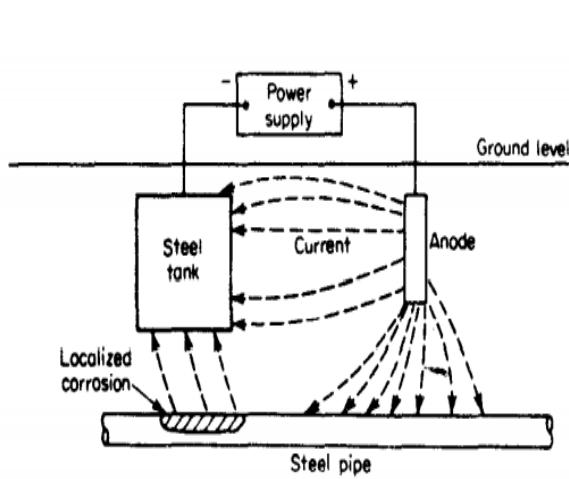


Figure 6-6 Stray currents resulting from cathodic protection.

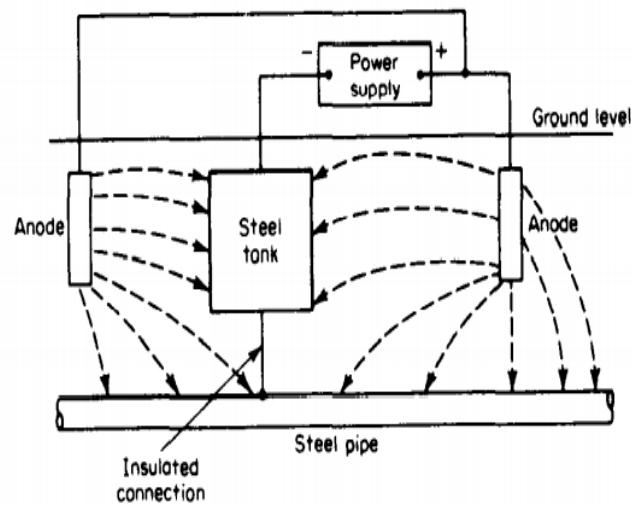


Figure 6-7 Prevention of stray-current corrosion by proper design.

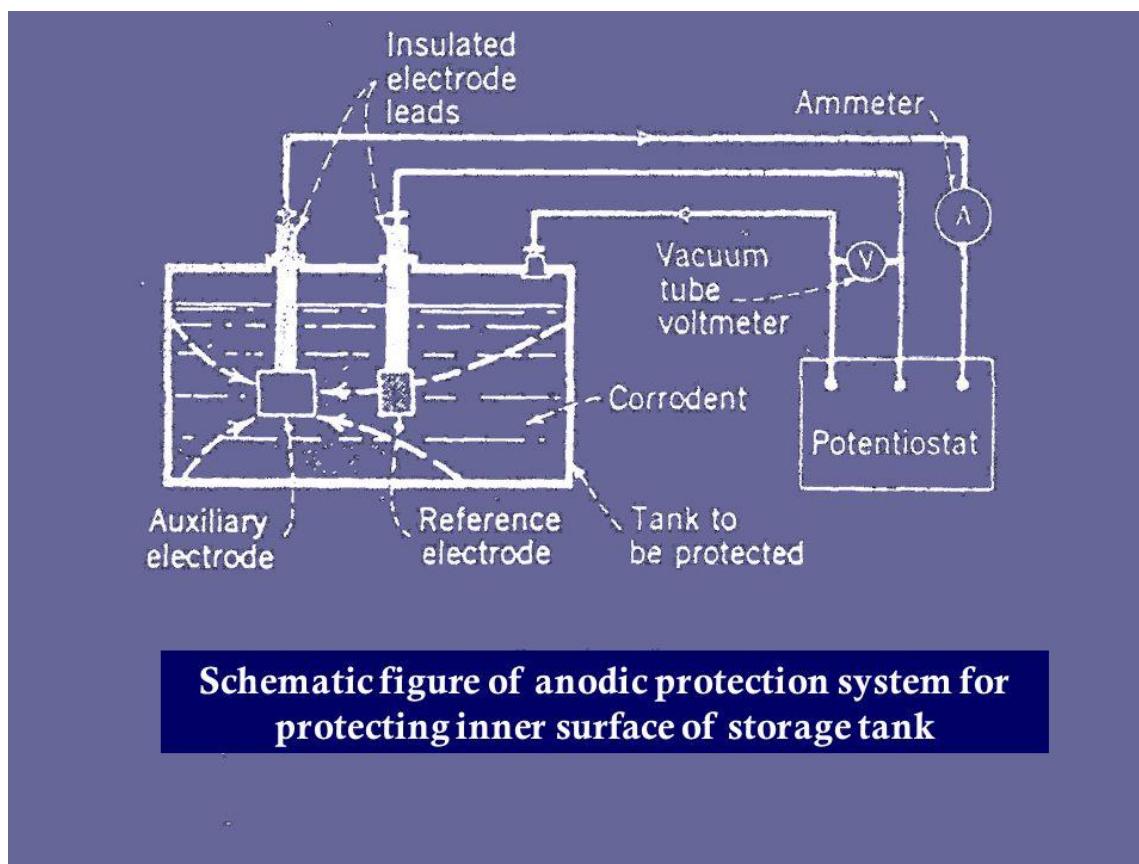
B. Anodic Protection

Anodic protection is based on the formation of a protective film on metals by externally applied anodic currents.

The metals having active-passive transition can be protected by this method such as nickel, iron, chromium, titanium, and their alloys. They do form protective films in moderate corrosive environment, and their films dissolve away in very strong corrosive environment.

If carefully controlled anodic currents are applied to these materials, they are passivated and the rate of metal dissolution is decreased.

To anodically protect a structure, a device called a **potentiostat** is required. A **potentiostat** is an electronic device that maintains a metal at a constant potential with respect to a reference electrode. The anodic protection of a steel tank containing sulfuric acid is illustrated in Fig. 6-8. The potentiostat has three terminals, one connected to the tank, another to an auxiliary cathode (a platinum or platinum-clad electrode), and the third to a reference electrode (e.g., calomel cell). In operation, the potentiostat maintains a constant potential between the tank and the reference electrode. The optimum potential for protection is determined by electrochemical measurements. Anodic protection can decrease corrosion rate substantially.



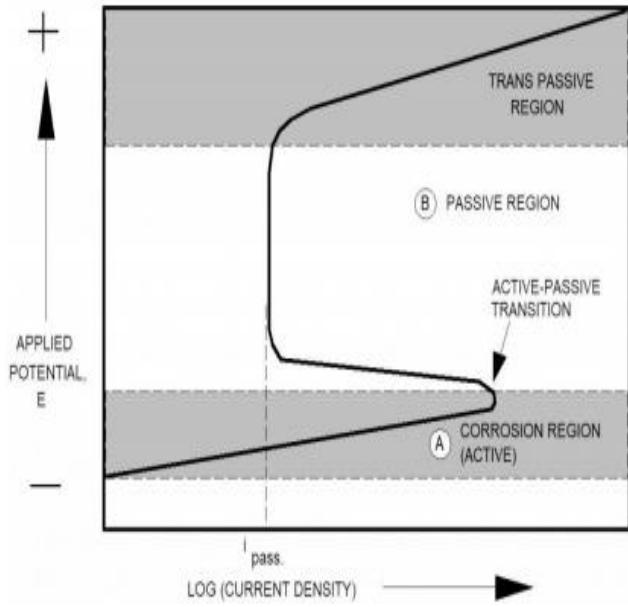


Table 6-5 Current requirements for anodic protection

Fluid and concentration	Temperature, °F	Metal	Current density, mA/ft ²	
			To passivate	To maintain
H_2SO_4	75	316SS	2100	11
	15%	304	390	67
	30%	304	500	22
	45%	304	165,000	830
	67%	304	4700	3.6
	67%	316	470	0.09
	67%	Carpenter 20	400	0.8
	93%	Mild steel	260	21
	Oleum	Mild steel	4400	11
H_3PO_4	75	Mild steel	38,000	19,000
	115%	304SS	0.03	0.00014
NaOH	75	304SS	4400	9.4

Advantage of anodic prevention

Anodic protection possesses **two unique** advantages. **First**, the applied current is usually equal to the corrosion rate of the protected system. Thus, anodic protection not only protects but offers a means for monitoring instantaneous corrosion rate. **Secondly**, operating conditions for anodic protection can be precisely established by laboratory polarization measurements. In contrast, the operating limits for cathodic protection are usually established by empirical trial-and-error tests.

- ✓ Applicable in extremely corrosive environment.
- ✓ Low current requirement.
- ✓ Cost independent of size of the article.
- ✓ Relatively high throwing power.
- ✓ Operating condition can be precisely established in the laboratory.

Limitations of anodic prevention

- ✓ Applicable for metals and alloys having active-passive transition.
- ✓ Cannot be applied in medium containing aggressive anions like chloride ion.
- ✓ If protection breaks down at any point, it is very difficult to re-established.

Application

- ✓ Carbon steel and stainless-steel equipment in contact with oleum, sulphuric acid, phosphoric acid, aqueous ammonia, sodium hydroxide etc.
- ✓ Chromium in contact with hydrofluoric acid.

Table 6-6 Comparison of anodic and cathodic protection

	Anodic protection	Cathodic protection
Applicability		
Metals	Active-passive metals only	All metals
Corrosives	Weak to aggressive	Weak to moderate
Relative cost		
Installation	High	Low
Operation	Very low	Mediums to high
Throwing power	Very high	Low
Significance of applied current	Often a direct measure of protected corrosion rate	Complex—does not indicate corrosion rate
Operating conditions	Can be accurately and rapidly determined by electrochemical measurements	Must usually be determined by empirical testing

5. Coating

a. Metallic coating

It can be classified into **two** categories:

1. **Cathodic coatings:** Base metal is coated with more noble metal. They prevent the corrosion by providing a physical barrier between the base metal and environment. Corrosion of the base metal occurs at any flaws or pinholes. Examples – coating of brass, chromium, copper or gold on steel.
2. **Anodic coatings:** Base metal is coated with more active metal. In addition to providing barrier layer, they prevent the corrosion by providing a galvanic coupling with the base metal. Examples – coating of zinc or aluminum on steel.

Methods of applying metallic coatings – electrodeposition, flame spraying, cladding, hot dipping, vapor deposition etc.

b. Non-metallic coatings

1. **Inorganic coatings** – vitreous enamel, oxide coating by anodizing, cement coating etc.
2. **Organic coatings** – paint, varnish, lacquers, enamel etc.

REFERENCES

- Mars G. Fontana, Corrosion Engineering
- Herbert H. Uhlig, R. Wniston Revie, Corrosion and Corrosion Control
- Pierre R. Roberge, Corrosion Engineering: Principles and Practice Book
- [ResearchGate](#)