

Module-4 Sensors and Corrosion Science

Sensors: Introduction, terminologies-Transducer, Actuators and Sensors. Conductometric sensor-principle, construction and its application in the estimation of acid mixture. Colorimetric sensor-principle, instrumentation and its application in the estimation of copper in PCB. Electrochemical gas sensors- principle, construction and its application in the detection of NO_x and SO_x in air sample. Biosensor-principle, construction and working for the detection of glucose in biofluids.

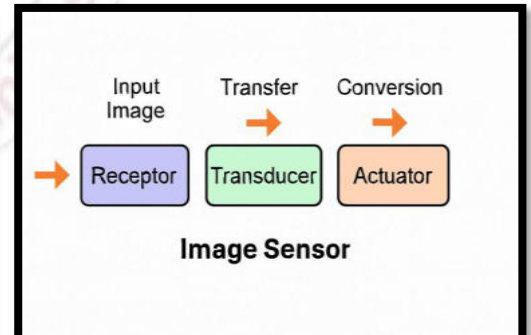
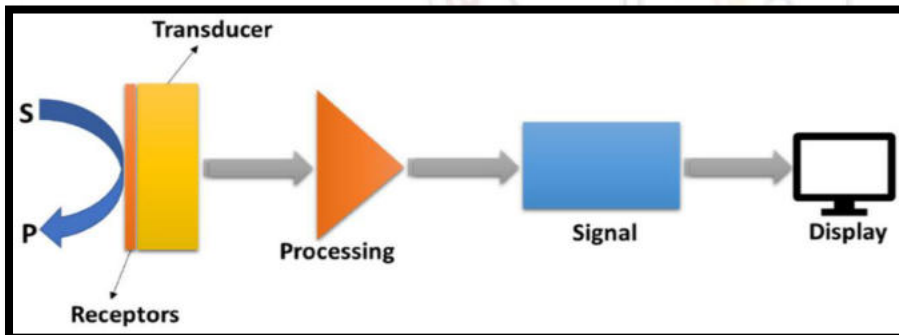
Corrosion: Introduction, electrochemical theory of corrosion, types of corrosion-differential metal and differential aeration corrosion-waterline and pitting corrosion. Corrosion control galvanization and anodization. Vapour corrosion inhibitors for protecting computer circuit boards, corrosion penetration rate (CPR)-definition and numerical problems.

Introduction:

- A **sensor** is a device that measures or detects a physical or chemical quantity such as temperature, pressure, humidity, ion concentration, light, sound, or motion. The sensor converts this quantity into an electrical signal that can be processed by computers or electronic systems.
- A sensor is often defined as a device that receives and responds to a signal or stimulus. Eyes, ears, and nose are all different types of sensors that help you navigate your surroundings on a day-to-day basis by detecting and processing light, sound, and smell/taste.

Examples:

- pH Sensor (glass electrode): Detects H⁺ ion concentration in solutions.
- Conductivity Sensor: Measures the ionic conductivity of an electrolyte.
- Gas Sensor: Detects CO₂, H₂S, or O₂ levels in chemical or environmental systems.



The key components are: **Receptor, Transducer and Actuator.**

- **Receptor:** It is a chemical element which is capable of interacting with analyte specifically and selectively. It produces signal corresponding to interaction in the form of change in potential, conductivity heat, pH etc.
- **Transducer:** A transducer is a device that converts energy from one form to another, typically transforming a signal in one form of energy into a signal in another.
 - Transducers are often used in automation, measurement, and control systems to convert physical quantities such as energy, force, torque, light, motion, and position into electrical signals, or vice versa. This process, known as transduction, enables the measurement, monitoring, and control of various physical phenomena.
 - In sound and vibration, transducers specifically convert mechanical energy (vibrations or sound waves) into electrical energy or vice versa. For example, microphones convert sound waves into electrical signals for recording and amplification, while loudspeakers convert electrical signals back into sound waves for audio playback.

- In a pH meter, the glass electrode acts as a transducer by converting hydrogen ion activity into an electrical voltage that represents p^H .

Example: Electrochemical Oxygen Sensor - Converts dissolved oxygen concentration into an electrical current.

- **Actuator:** An actuator is a device that receives an electrical signal (or other forms of input energy) and produces a physical or chemical action. It is often used for control in experiments. It is a component of a machine that is responsible for moving and controlling a mechanism or system.

Example: Electrolysis Cell - Converts electrical current into chemical products (H_2 and O_2 gases).

Electrochemical sensor:

An electrochemical sensor is a device that detects chemical substances by converting their concentration into an electrical signal through redox reactions. It typically consists of a working, reference, and counter electrode immersed in an electrolyte. The measured signal (current, voltage, or conductivity) corresponds to the analyte concentration. Based on the detection principle, they are classified as potentiometric, amperometry, or conductometric sensors. They offer high sensitivity, selectivity, and fast response.

Examples: pH electrodes, glucose sensors, and oxygen sensors.

Conductometric Sensors:

Principle, Construction, and its Application in Acid Mixture Estimation

Principle:

Conductometric sensors are electrochemical devices that measure the electrical conductivity of a solution, which depends on ion concentration and mobility. During titration, conductivity changes as ions are consumed or replaced. In this method, two inert metal electrodes are used. The ions or electrons produced during an electrochemical reaction may change the conductivity or resistivity of the solution. The conductivity of ionic solutions can be measured by using a conductometer. H^+ ions being the smallest ions shows the highest conductivity.

In acid mixture estimation, the neutralization of a strong acid (HCl) and a weak acid (CH_3COOH) with a strong base (NaOH) produces characteristic conductivity changes, allowing their individual quantification.

Construction:

The electrode system is a conductivity cell, made up of two platinum plates of unit cross-sectional area ($A=1\text{cm}^2$) separated by unit distance ($L=1\text{cm}$). The volume between electrodes = 1 cm^3 . When 'L' and 'A' are maintained constant, the ratio of L/A is constant. $\therefore$ Cell constant = L/A

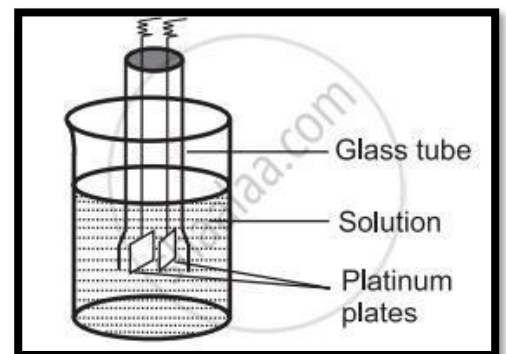
Electrolyte solutions obey Ohm's Law just as metallic conductors which is given by,

$$V=IR \rightarrow I \propto 1/R, \text{ where } R \text{ is Resistance, } V \text{ is potential, and } I \text{ is Current.}$$

Conductance of unit volume is called specific conductance (κ) and is given by:

$$\kappa = (1/R) \times (L/A), \text{ where } R = \text{resistance, and } L/A = \text{Cell constant}$$

An alternating current (AC) source is used to prevent polarization, and the output is measured by a conductometer.



Working:

The conductivity cell is dipped in the solution whose conductance is to be measured and connected to conductivity meter. When a potential difference is applied, an electric field is generated in the electrolyte. Cations migrate toward the cathode, and anions toward the anode. At electrodes, ions are neutralized or deposited, producing a chemical change, which is sensed and converted to an electrical signal by the transducer. The conductance of the ions in the solution is controlled by adding titrant and for each addition conductance is measured.

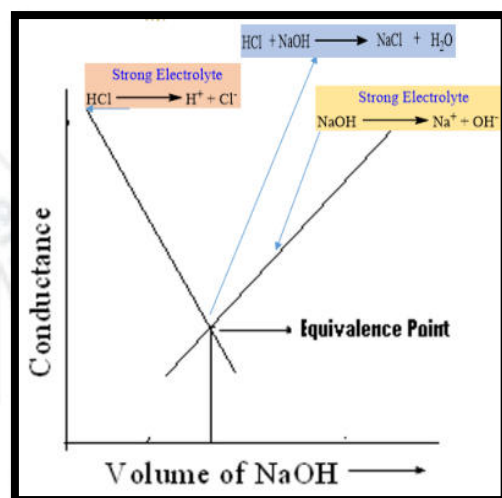
Estimation of Acid Mixture:

Strong Acid-Strong Base titration (HCl vs NaOH):

- When HCl is titrated against NaOH, H₂O and NaCl are formed.
- The initial conductivity will be very high due to the presence of small H⁺ ions.
- As NaOH is added, H⁺ ions are neutralized, conductance decreases sharply due to Highly mobile H⁺ ions are replaced by less mobile Na⁺ ions,

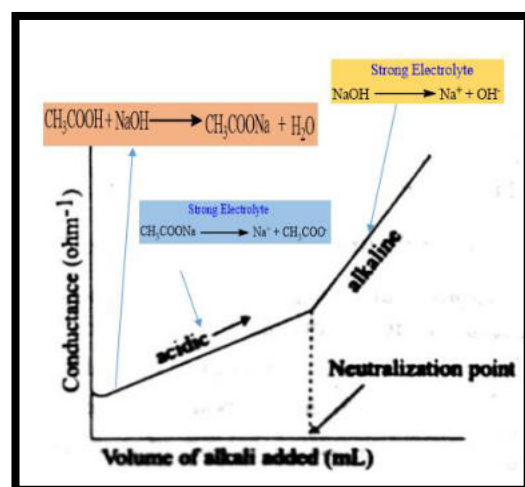


- On addition of NaOH the conductivity decreases due to the formation of H₂O and NaCl. This decrease in conductance is observed till all the acid is completely neutralized (Equivalence point).
- After the equivalence point, the NaOH added adds more OH⁻ ions to the solution thereby increasing the conductance.
- The plot of conductance Vs Volume of NaOH is as shown below.



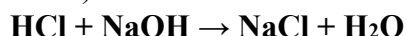
Weak Acid-Strong Base titration (CH₃COOH vs NaOH):

- When CH₃COOH is titrated against NaOH, H₂O and CH₃COONa are formed.
 - The initial conductivity will be very low due to the partial ionization of CH₃COOH ions.
 - After HCl is neutralized, acetic acid starts neutralizing; conductance decreases more slowly due to partial dissociation.
- $$\text{CH}_3\text{COOH} + \text{NaOH} \rightarrow \text{CH}_3\text{COONa} + \text{H}_2\text{O}$$
- On addition of NaOH the conductivity increases till equivalence point due to the presence of Sodium acetate which is a strong electrolyte.
 - After the equivalence point, the NaOH added adds more OH⁻ ions to the solution thereby increasing the conductance rapidly
 - The plot of conductance Vs Volume of NaOH (alkali) is as shown below.

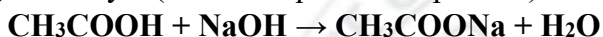


Mixture of strong acid and weak acid with a strong base (HCl+CH₃COOH v/s NaOH):

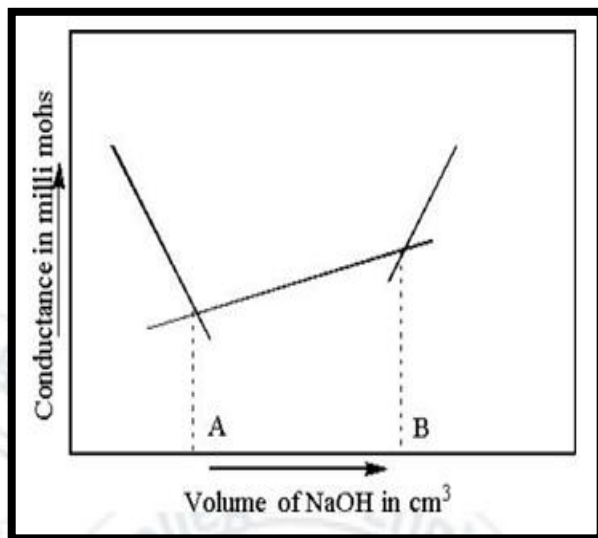
- In the titration of acid mixture containing strong and weak acid, the strong acid gets completely neutralized first and then the weak acid neutralization starts.
- The initial conductivity will be very high due to the presence of small H⁺ ions.
- On addition of NaOH the conductivity decreases due to the formation of H₂O and NaCl. This decrease in conductance is observed till all the acid is completely neutralized (First equivalence point A).



- Thereafter the conductivity slowly increases till equivalence point due to the presence of Sodium acetate which is a strong electrolyte (Second Equivalence point B).



- After the 2nd equivalence point, the NaOH added. After all acids are neutralized, excess OH⁻ ions increase conductance sharply.



Colorimetric Sensor:

Principle, Instrumentation and its Application in the Estimation of Copper in PCB

- Colorimetry is a quantitative analytical technique for measuring the transmittance and absorbance of light passing through a colored solution.
- Colorimeter is based on Beer-Lambert Law which states that “when a monochromatic light is passed through a coloured solution, the absorbance is directly proportional to the concentration of the solution when the path length is kept constant.”

$$A = \epsilon l c$$

Where, A = absorbance, ϵ = molar absorptivity, l = path length, c = analyte concentration

Principle of Colorimetric Sensor:

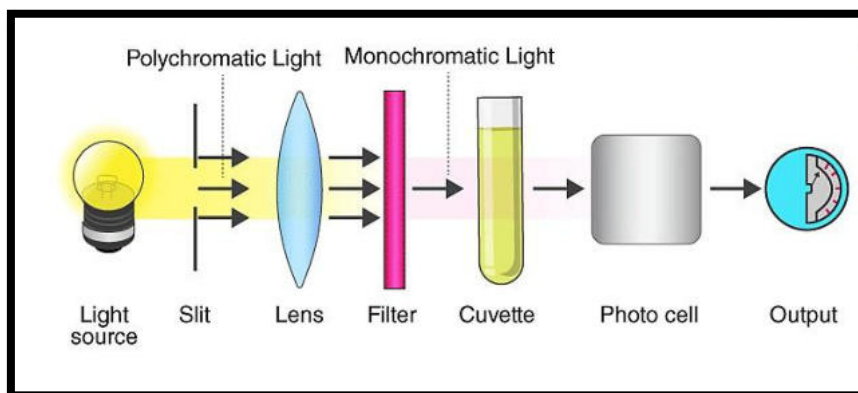
- Optical sensors work on the interaction of electromagnetic radiation (UV, visible, or IR) with a chemical species. Interaction can result in absorption, emission, scattering, or reflection of light.
- The intensity of light after interaction provides information about the analyte concentration.
- The intensity of the blue color is proportional to the copper concentration.
- Measurement is performed at ~620 nm using absorbance, following Beer-Lambert Law:

$$A = \epsilon l c$$

Where:

A = absorbance, ϵ = molar absorptivity, l = path length, c = analyte concentration

Instrumentation:



The key components are:

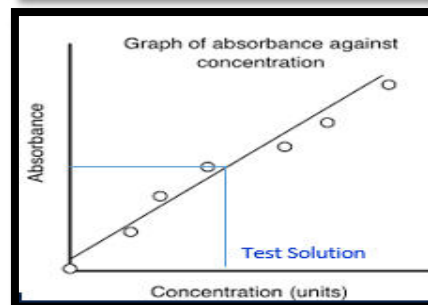
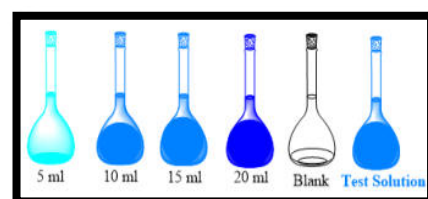
1. **Light Source:** Provides monochromatic or filtered light at the wavelength absorbed by the copper-ammonia complex (~620 nm). Examples: LED, tungsten lamp.
2. **Filters / Monochromator:** Selects the desired wavelength.
3. **Sample Holder / Cuvette:** Holds the solution of the copper-ammonia complex.
4. **Photocell / Detector:** Converts transmitted or absorbed light into an electrical signal.
5. **Signal Processor / Display:** Records and displays the signal as absorbance or concentration.

Working:

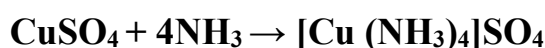
- Light from a light source is passed through the monochromator to obtain the radiations of desired wavelength ($\lambda_{\max}$), monochromatic light
- This monochromatic light is allowed to pass through the colored solution (Analyte) taken in the cuvette.
- Part of the light is absorbed by the deep blue coloured complex taken in the cuvette.
- Absorbance depends on **concentration** and **path length**.
- Detector converts light intensity into electrical signal and it is displayed as absorbance.

Procedure for Estimation of Copper in PCB:

- Draw out 5, 10, 15 & 20 cm³ of given copper sulphate solution into four separate 50 cm³ standard flasks.
- Add 5 cm³ of NH₃ to each one of them and also into the test and blank solution, dilute up to the mark with distilled water and mix well.
- After 10 minutes, measure the absorbance of each of these against blank solution (only ammonia and water) at 620 nm.
- Plot a graph of absorbance (OD) (Y-axis) against concentration of copper (X-axis) and determine the concentration of copper in the e-waste solution.



Copper sulphate (CuSO₄) reacts with ammonia to form deep blue coloured Cuprammonium sulphate complex having maximum absorbance at 620nm.



- Colorimetric sensors provide an effective and practical approach for the estimation of copper in PCBs.
- By forming stable-colored complexes with copper ions, these sensors enable accurate and reliable detection.
- They are particularly valuable in manufacturing, environmental monitoring, and recycling applications, making them an essential tool in the field of analytical chemistry and materials management.

Electrochemical Gas Sensors:

Electrochemical gas sensors are devices that detect specific gases by chemically reacting with the target gas and converting this reaction into an electrical signal. They are widely used in environmental monitoring, industrial safety, air quality control and automotive emission testing.

Electrochemical gas sensors are commonly used for the detection and monitoring of various gases, including sulfur oxides (SO_x) and nitrogen oxides (NO_x).

Electrochemical gas sensors- principle, construction and its application in the detection of NO_x in air sample:

Nitrogen oxides are a group of gases that include nitric oxide (NO) and nitrogen dioxide (NO₂). They are produced during combustion processes in engines, industrial activities, and from natural sources.

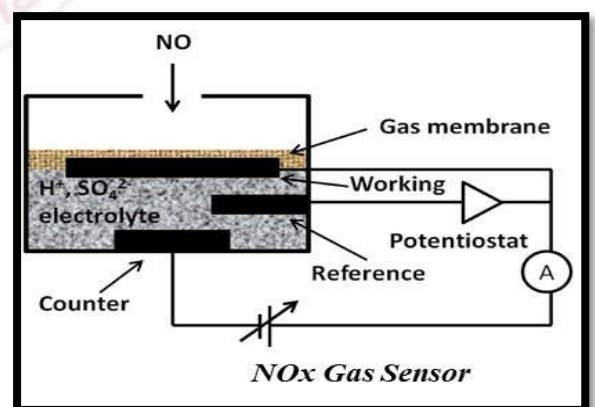
Principle:

The sensor works on the oxidation or reduction of the target gas at an electrode, which produces a current proportional to the gas concentration.

- The target gas diffuses through a gas-permeable membrane into the sensor.
- It reacts at the working electrode in the presence of an electrolyte, producing electrons.
- The measured current is directly proportional to the gas concentration in air.

Construction:

- **Working or Sensing Electrode (WE):** Metal oxide-coated electrode where NO_x reduction occurs.
- **Reference Electrode (RE):** Usually gold; maintains stable potential.
- **Counter Electrode (CE):** Completes the circuit.
- **Electrolyte:** Liquid or solid medium that facilitates ion transport between electrodes.
- **Gas-permeable Membrane:** Controls diffusion of NO_x gas and prevents electrolyte leakage.
- **Housing:** Encases the sensor and provides electrical connections.



Working:

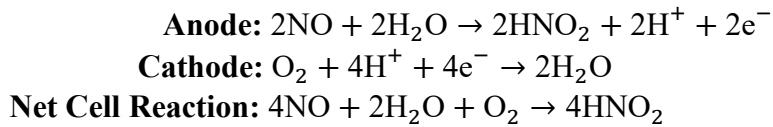
- When air containing NO_x interacts with the sensor, the NO_x gas oxidizes and reacts with the electrolyte at the sensing electrode, resulting in the production of an electric current proportional to the concentration of NO_x in the air.
- The sensor monitors the oxidation of NO as it occurs on the electrode surface.

- In many instances of electrochemical sensors, the electrode surface can be modified with catalysts, membranes, or other metals to make the electrode more sensitive and more selective toward the sample.

Application in NO_x Detection (e.g., NO in Air Samples)

Nitric oxide is typically detected via oxidation at the working electrode, where it loses electrons. The counter electrode reaction involves the reduction of oxygen from the air sample.

Reaction:



Electrochemical gas sensors - principle, construction and its application in the detection of SO_x in air sample:

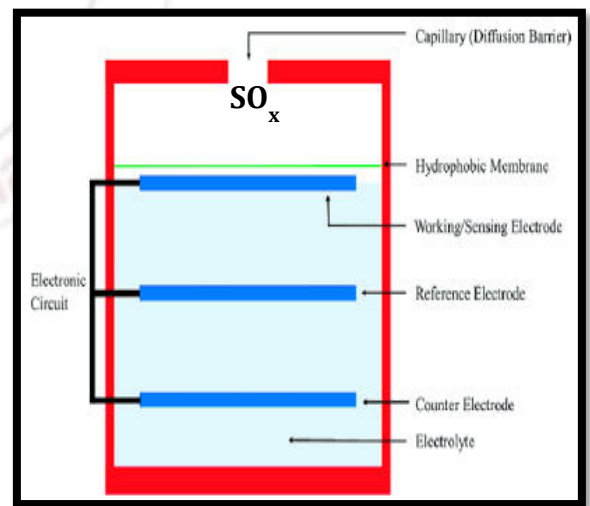
Sulfur oxides are a group of gases that include sulfur dioxide (SO₂) and sulfur trioxide (SO₃). They are primarily generated from industrial processes and the combustion of fossil fuels.

Principle:

Electrochemical gas sensors work on the principle of redox reactions occurring at the electrode– electrolyte interface. When a target gas (e.g., SO₂) diffuses into the sensor, it undergoes oxidation or reduction at the **working electrode**. This reaction generates a current proportional to the gas concentration, which can be measured and correlated with its amount in the air sample.

Construction:

- Working or Sensing electrode (WE):** coated with a catalyst where the analyte gas undergoes oxidation/reduction.
- Counter electrode (CE):** balances the current by completing the circuit.
- Reference electrode (RE):** maintains a stable potential for accurate measurement.
- Electrolyte:** ionic medium that facilitates charge transfer (commonly acidic or alkaline solution).
- Gas diffusion membrane (Hydrophobic membrane):** allows controlled diffusion of the gas into the sensor, preventing interference.
- Housing:** protects the components and ensures selective entry of the gas.



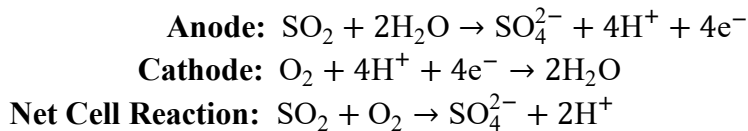
Working:

- The electrochemical sensor for SO_x detection typically consists of an electrode and an electrolyte.
- When air containing SO_x comes into contact with the sensor, the SO_x gas undergoes oxidation and reacts with the electrolyte at the sensing electrode.
- This reaction produces an electrical current proportional to the concentration of SO_x in the air.
- In many instances of electrochemical sensors, the electrode surface can be modified with catalysts, membranes, or other metals to make the electrode more sensitive and more selective toward the sample.

Application in SO_x Detection (e.g., SO₂ in Air Samples)

In a typical ambient-temperature electrochemical sensor using a liquid or solid polymer electrolyte (such as sulfuric acid or Nafion), SO₂ undergoes oxidation at the working electrode (anode), while an equal and opposite reduction reaction involving ambient oxygen occurs at the counter electrode (cathode). The generated electrons produce a measurable current proportional to SO₂ concentration.

Reaction:



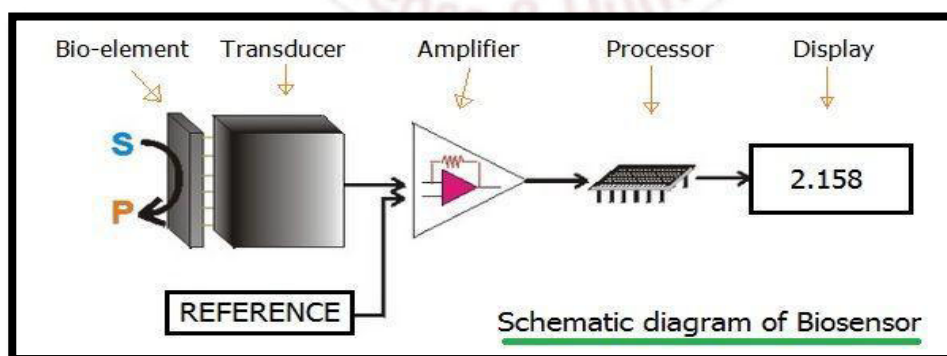
Biosensor - principle, construction and working for the detection of glucose in biofluids:

- Biosensors are **analytical devices** that combine a **biological recognition element** with a **transducer** to detect & quantify target analytes.
- The biological recognition element can be an **enzyme, antibody, nucleic acid, or other biological molecule** that specifically interacts with the target analyte.
- The **transducer** converts the **biological response into an electrical signal** that can be quantified and interpreted.

Principle:

Glucose biosensors are analytical devices that measure glucose concentration in biofluids such as blood, urine, and saliva. They function by combining a biological recognition element with a transducer to generate an electrical signal proportional to glucose concentration. Glucose oxidase (GOx) (along with coenzyme flavin adenine dinucleotide (FAD)), is an enzyme commonly used in biosensors to detect glucose levels in biological fluids, such as blood and urine. The enzyme catalyses glucose oxidation to Gluconic acid and hydrogen peroxide (H₂O₂), which a transducer can easily detect and quantify.

Construction:



- **Bio-element:** Glucose oxidase (GOx) enzyme immobilized on the sensor surface to specifically react with glucose.
- **Transducer:** An electrode system (working and reference electrodes) that converts the chemical reaction into a measurable electrical current.
- **Amplifier:** Circuitry that boosts the weak electrical signal from the transducer.
- **Processor:** An integrated circuit that converts the amplified signal into a concentration value.
- **Display:** A screen that shows the final glucose concentration result (e.g., 2.158 in the diagram).

Working:

The operation of a first-generation glucose biosensor involves the following steps:

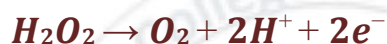
- A small volume of biofluid (such as blood or urine) is introduced onto the biosensor surface.
- Glucose molecules in the sample are specifically oxidized by the enzyme glucose oxidase (GOx). During this step, the coenzyme flavin adenine dinucleotide (FAD) present in GOx is reduced:



- The reduced enzyme GOx (FADH₂) is then re-oxidized by molecular oxygen, producing hydrogen peroxide:



- At the working electrode, the hydrogen peroxide undergoes electrochemical oxidation, releasing protons and electrons:



- The released electrons generate a measurable current, which is directly proportional to the glucose concentration in the original sample.

CORROSION

Introduction: Corrosion is a process of destruction or deterioration of metal by the environment through chemical or electrochemical reactions.

Most of the metals and alloys undergo corrosion except the noble metals. Corrosion is like “**Cancer**” for the metals.

Eg: Rusting of Iron - it is due to formation of hydrated ferric oxide.

Types of corrosion:

1. **Dry Corrosion:** Corrosion taking place in the absence of moisture that is direct chemical reaction taking place between metal and dry gases.
2. **Wet Corrosion:** Corrosion taking place in the presence of moisture or aqueous wet environment.

Why do metals undergo corrosion?

→ Metals are originally in the form of ore (oxidized state), which is the most stable form. Pure metals are extracted from ore, the pure metal thus obtained is less stable (more reactive), thus pure metals always naturally tend to revert to stable form (corrosion).

Electrochemical Theory of Corrosion:

- According to this theory, Corrosion occurs due to the formation of anodic and cathodic regions on the same or different metals in a conducting medium.
- At the anode, oxidation takes place, and the metal corrodes into ions by releasing electrons.
- At the cathode, reduction occurs by consuming the liberated electrons, keeping the cathodic region protected.
- Corrosion continues as long as anodic and cathodic reactions proceed simultaneously, influenced by impurities and oxygen concentration differences.

At the Anodic Region:

Iron liberates Fe^{2+} ions and electrons at the anodic region:

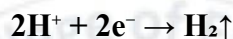


At the Cathodic Region:

Chemical species in the cathode's surroundings undergo reduction by accepting electrons from the anodic region through the metal. Depending on the surrounding medium, four possible reduction reactions occur at the cathodic region:

1) **Hydrogen Liberation** (Evolution of Hydrogen/Absence of Oxygen):

(a) In acidic medium without oxygen:

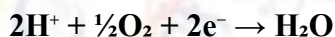


(b) In neutral or alkaline medium without oxygen, hydroxide ions form with simultaneous hydrogen liberation:

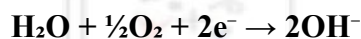


2) **Oxygen Absorption** (Presence of Oxygen):

(a) In acidic medium with oxygen:



(b) In neutral or alkaline medium with oxygen, hydroxide ions form:

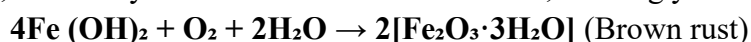


Formation of Rust:

Corrosion of iron produces Fe^{2+} ions at the anode and OH^- ions at the cathode. These ions diffuse toward each other to produce insoluble ferrous hydroxide:



In an oxidizing environment, ferrous hydroxide oxidizes to ferric oxide, forming yellow rust (hydrated ferric oxide):

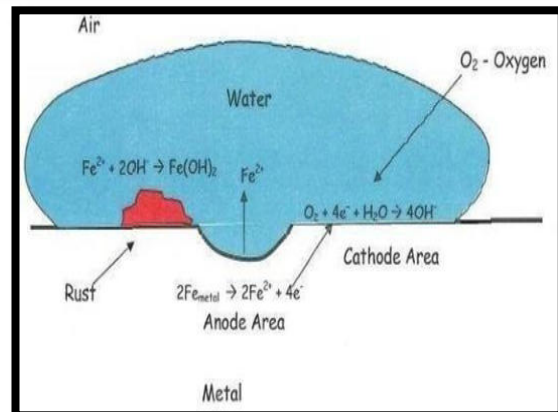


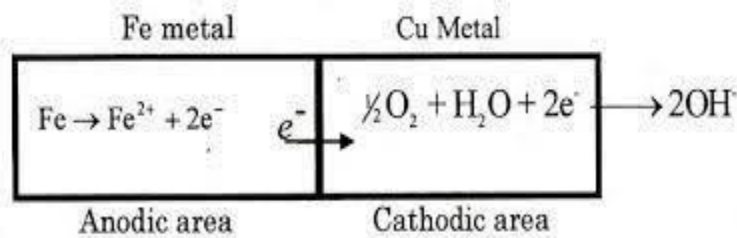
Types of corrosion

Differential Metal Corrosion (galvanic corrosion):

Differential metal corrosion occurs when two dissimilar metals are in contact with each other and are exposed to corrosive environment. The two metals differ in their electrode potential. The metal with lower electrode potential acts as anode, the metal with higher electrode potential acts as cathode. The potential difference between two metals is a driving force for corrosion. Here anode undergoes corrosion.

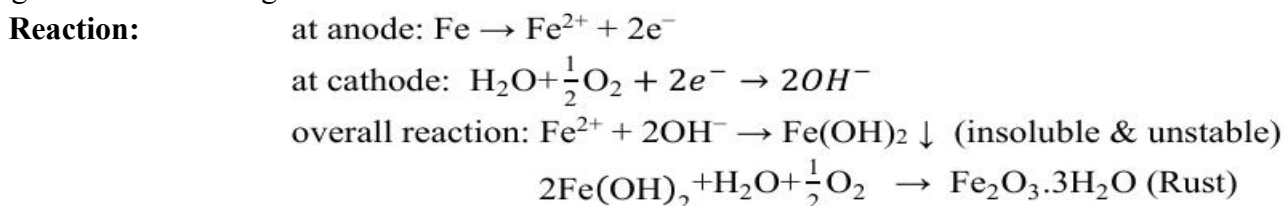
Eg: When iron is in contact with copper.





Differential metal corrosion

When Fe & Cu metals are in contact, Fe has lower electrode potential when compared to copper. Hence iron undergoes oxidation and gets corroded.



Other examples:

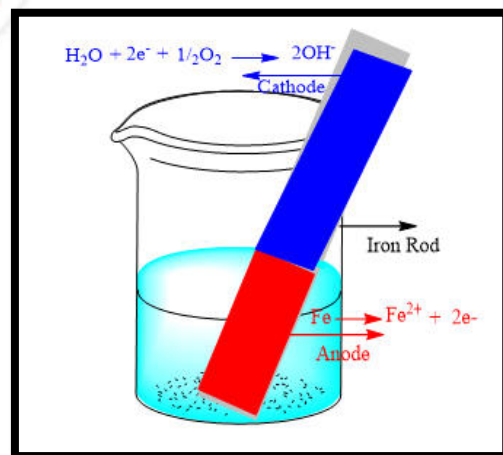
1. Steel screws in copper sheet
2. Steel screws with copper washer
3. Nut and bolts are made of different metals.

Differential aeration corrosion:

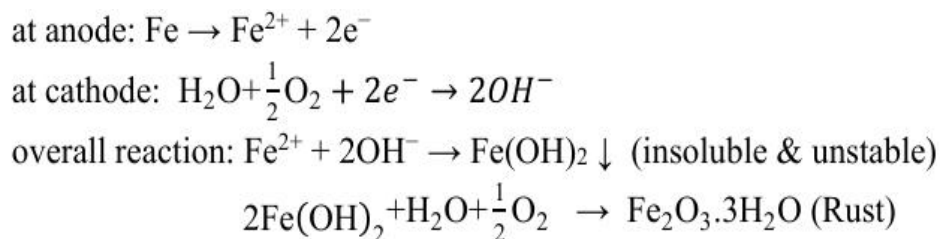
Differential aeration corrosion occurs when a metal surface is exposed to different oxygen concentration. Part of metal exposed to higher oxygen concentration acts as cathode and metal exposed to lower oxygen concentration acts as anode. The anodic region undergoes oxidation and gets corroded.

Eg: When iron rod partially dipped in water.

- Imagine that an iron rod is immersed half inside water
- Iron rod below water level is less oxygenated hence will act as anode and undergo oxidation.
- Iron rod above the water level is more oxygenated hence will act as cathode and undergo reduction.
- Once anode and cathode is formed, the corrosion of metal starts.



Reaction:



Other examples:

- Part of nail inside the wall undergoes corrosion.
- Partially buried pipeline in soil undergoes corrosion.
- Partially filled iron tank undergoes corrosion inside water.

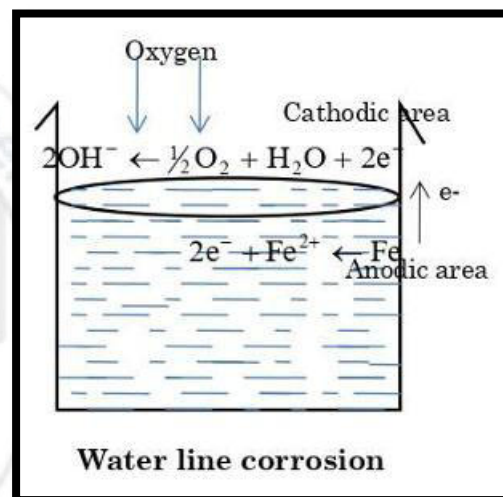
This differential aeration corrosion is divided into two types;

Water line corrosion:

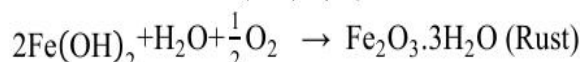
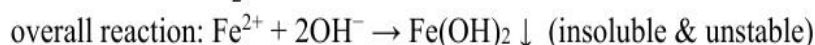
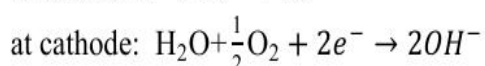
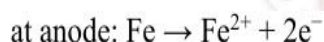
When a steel/Iron tank is partially filled with water for a long time, the inner portion of the tank below the water line is exposed only to dissolved oxygen whereas the portion above waterline is exposed to more oxygen. Thus, the portion below the water acts as anode and undergoes corrosion. The upper portion acts as cathode and it is unaffected.

Eg: Water storage tank

- Imagine a steel/iron tank, water is half filled inside the tank.
- The area below water is less oxygenated and it starts behaving as anode and starts undergoing oxidation.
- The area without water is more oxygenated and it starts behaving as cathode and starts undergoing reduction.
- Since the area of anode is very much larger than cathode, The rate of corrosion will be slow.
- The formed ions diffuse towards each other and meet at the surface of water.
- Hence forms a distinct brown line (corrosion product) at the surface of water.

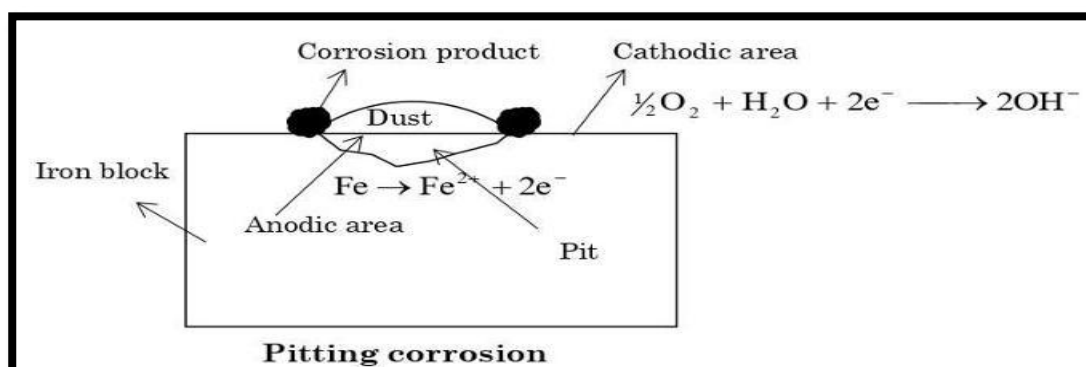


Reaction:



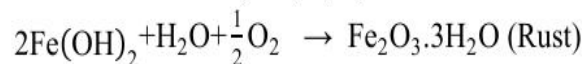
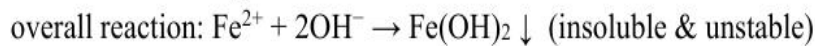
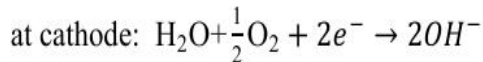
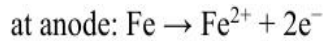
Pitting Corrosion:

“Pitting corrosion occurs when dust or oil particles get deposited on the metal surface”. Metal below the deposit is exposed to less oxygen and hence acts as anode and the remaining portion acts as cathode.



When a dust particle settles on an iron surface, the area beneath experiences reduced aeration, acting as the **anode**, while the exposed surface acts as the **cathode**. Corrosion initiates under the dust particle, leading to the formation of deep cavities or pits. Inside the pit, oxygen is depleted, and metal cations accumulate, creating a highly aggressive local environment that accelerates metal dissolution. The anodic reaction occurs within the pit.

Reaction:



Other examples:

- Less aerated part of the machinery
- Less aerated parts of barbed wires.
- Cracks in metals which are not well aerated.
- Pitting corrosion is also caused by the breakdown of the protective layer on a metal surface, like peeling of a small tin coating on iron give rise to small anodic area and large cathodic area. This results in acceleration of pitting corrosion at the exposed part.

CORROSION CONTROL

Once the mechanism of corrosion is understood, it becomes easy to find the ways to control corrosion. According to electrochemical theory, corrosion occurs due to oxidation and reduction reactions occurring at anodic and cathodic areas respectively. These two reactions occur simultaneously and are interdependent. Therefore, by decreasing the rate of any one reaction, it is possible to decrease the rate of other reaction and hence the rate of corrosion. Similarly, by preventing any one reaction, either anodic or cathodic, overall corrosion process can be prevented.

Corrosion can be controlled by protecting the surface of the metal or by preventing the formation of galvanic cells.

The following methods are commonly used to control corrosion.

Protective Coatings: Application of protective coating is one of the important methods of corrosion control. The protective coating protects the metal from corrosion by acting as a barrier between the metal and the corrosion environment. The principle types of coatings applied on the metal surface are

- a) Metal coating
- b) Inorganic coating
- c) Organic coating

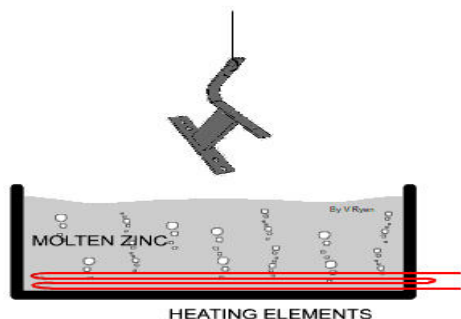
Galvanization:

Galvanization is a process that involves applying a protective zinc coating to steel or iron to prevent corrosion. This technique has been widely used for many years due to its effectiveness in increasing the lifespan and durability of metal structures.

Galvanization of iron can be attained by two different approaches

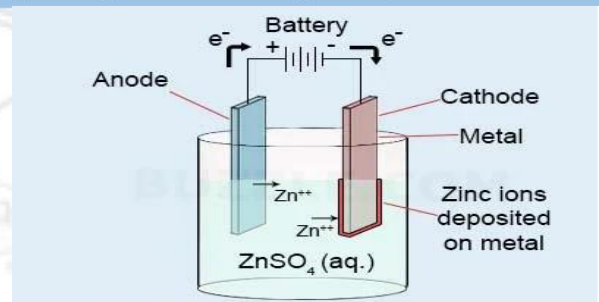
Hot-dip galvanization

Hot-dip galvanizing is a widely used technique that involves immersing the metal in a bath of molten zinc. The process creates a thick layer of zinc coating on the surface, providing excellent corrosion protection. Due to its durability, this method is commonly used for large structures and outdoor applications.



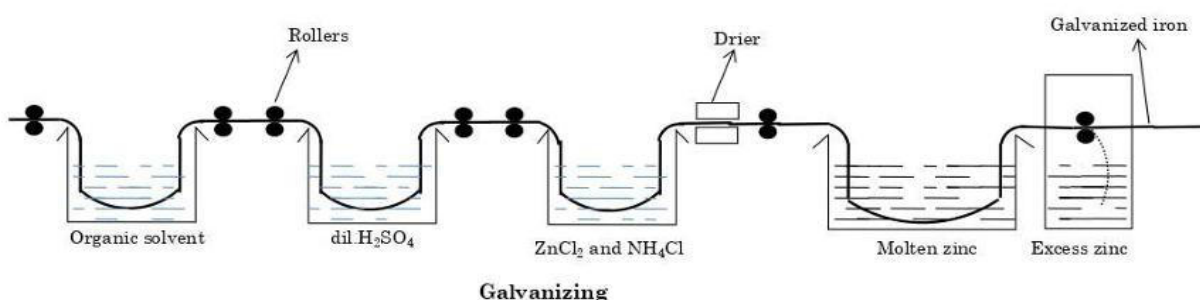
Electrogalvanizing

Electrogalvanizing on the other hand, involves applying a thin layer of zinc to the metal surface through an electroplating process. This technique offers precise control over the thickness of the coating and is often utilized for smaller components or products that require a smooth finish. Here metal which is being coated that is iron is connected to cathode (negative terminal) where as zinc is connected to positive terminal. On passing current zinc gets deposited over iron.



Galvanization of Iron (Hot-dip galvanizing):

Galvanization is a process of coating base metal like iron or its alloy surface with anodic and active Zn metal. One of the important characteristics of anodic coating is even if coating is ruptured, base metal does not undergo corrosion because base metal exposed to environment will be cathodic in nature with respect to coating metal.



Galvanization process involves following steps:

- Metal surface is washed with organic solvents to remove organic matter, dust or grease.
- Rust and other deposits removed by washing with hot dil. H_2SO_4 is called pickling process.
- Then it is well washed with distilled water.
- It is air dried by-passing hot air.
- Then it is dipped in molten zinc, maintained at $430\text{--}450^\circ\text{C}$ and covered with flux of ammonium chloride and zinc chloride to increase adhesion property.
- Excess of zinc on surface is removed by passing a pair of hot rollers, which removes excess of zinc and produces thin coating.

Application: Galvanized materials are used in fencing wire, buckets, bolts, nuts, nails, screw etc.

Anodizing:

- Anodizing is an electrochemical process that converts the metal surface into a decorative, durable, corrosion-resistant, anodic oxide finish.
- It is an electrochemical process which forms protective passive (non-reactive) oxide film on metal surface.
- In simple words, Anodizing is an electrolytic passivation process used to increase the thickness of the natural oxide layer on the surface of metal parts.
- Aluminum is ideally suited to anodizing, although other nonferrous metals, such as magnesium and titanium also can be anodized.
- Metals like Al, Zn and Mg are made to develop protective metal oxide coating artificially on their surfaces.

Anodizing of aluminium:

- In anodized coating, the base metal is made up of anode and inert metal like lead (less active than Aluminium) is made cathode.
- Anodizing is accomplished by immersing the aluminum into an acid electrolyte bath and passing an electric current through the medium.
- A cathode is mounted to the inside of the anodizing tank.
- The aluminum acts as an anode, so that oxygen ions are released from the electrolyte to combine with the aluminum to form Aluminium oxide on the surface of Aluminium.
- A thin film of Al_2O_3 is deposited on surface, this acts as protective layer preventing the corrosion.
- This film tends to be porous and provides good adherence for paint and dyes.

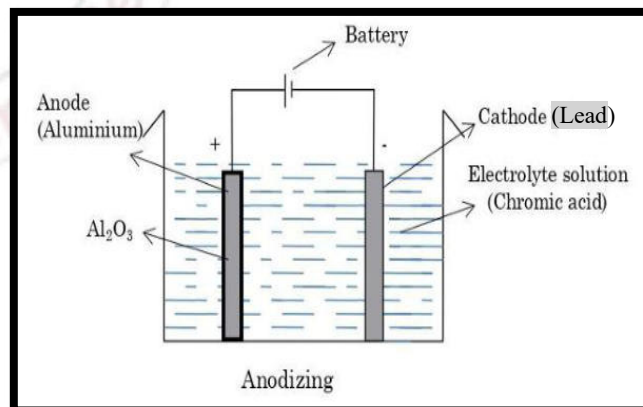
Reaction:

At anode: $2Al + 3H_2O \rightarrow Al_2O_3 + 6H^+ + 6e^-$ (Oxidation)

At cathode: $6H^+ + 6e^- \rightarrow 3H_2 \uparrow$

Overall reaction: $2Al + 3H_2O \rightarrow Al_2O_3 + 3H_2 \uparrow$

Uses: It is used as soap boxes, tiffin boxes, window frames etc. Anodic films are also used for number of cosmetic effects.



Vapour Corrosion Inhibitors (VCIs) for Protecting Computer Circuit Boards:

Introduction:

- Vapor-phase inhibitors are compounds with low vapor pressure (0.0002-0.4mm Hg). In a closed system, they volatilize and the vapor condenses on the metal surface to provide the protection.
- Vapour Corrosion Inhibitors are chemical compounds such as Carboxylates (e.g., benzoates, sebacates), nitrite, carbonate, and benzoate salts of dicyclohexamine, cyclohexamine, and hexamethylene imine – effective for steel and copper, that slowly vaporize and release protective molecules into the surrounding atmosphere.

Electronics corrosion always involves some type of damage to printed circuit boards (or PCBs). These are the foundational building block of most modern electronics.

PCB corrosion can occur for the following reasons:

- Exposure to moisture and humidity.
- Proximity to reactive metals and other materials.
- Electrolytic damage, occurring when surrounding ions are contaminated, impacting the voltage between two metal components.

Working Principle:

- **Adsorption on Metal Surfaces:**

The vaporized inhibitor molecules travel through the air and adsorb onto the exposed metal surfaces of the circuit board, such as copper tracks, connectors, and solder joints.

- **Formation of Protective Film:**

Once adsorbed, the molecules form a thin, invisible, and stable protective film. This layer prevents corrosive agents like moisture, oxygen, and acidic contaminants from reacting with the metal.

- **Neutralization of Aggressive Species:**

VCIs can neutralize or block the action of corrosive ions (e.g., chlorides or sulfates) present in the environment, reducing the electrochemical reactions that cause corrosion.

- **Self-Replenishing Mechanism:**

If the protective film is disturbed or partially removed, nearby vapor molecules continuously replenish the coating, ensuring long-term protection.

Advantages for Circuit Boards:

- Non-conductive and safe for electronic components.
- Protects even in enclosed spaces without direct application.
- Extends the service life of circuit boards stored or operated in humid or polluted environments.

Corrosion penetration rate (CPR)/ corrosion rate:

Corrosion penetration rate is defined in three ways;

- The speed at which any metal in a specific environment deteriorates due to chemical reaction in the metal when it is exposed to a corrosive environment.
- The amount of corrosion loss per year in thickness.
- The speed at which corrosion spreads to the inner portions of a material.

The equation for **CPR** (Corrosion Penetration Rate) is:

$$CPR = \frac{KW}{DAT}$$

Where:

CPR = Corrosion Penetration Rate
(measured in mils per year, mpy & millimeters per year, mmpy)

K = A constant

W = Total weight loss by the metal due to exposure to a corrosive environment

D = Density of the material

A = Surface area of the exposed metal

T = Time taken for the loss of metal (exposure time)

CORROSION PENETRATION RATIO

- The corrosion penetration rate (CPR) is the speed of deterioration of a metal when it is exposed to a corrosive environment.
- It is the measure of reduction in the thickness of metal per year.
- The unit of CPR is millimeter per year (mm/y) or mils per year (mpy).



$$CPR = \frac{K \times W}{D \times A \times T}$$

Parameter	Significance	Unit	
CPR	Corrosion Penetration Ratio	mm/y	mpy
K	A constant	87.6	534
W	Total weight lost by the metal	mg	mg
D	Density of metal	g/cm ³	g/cm ³
A	Surface area of the exposed metal	cm ²	inch ²
T	Time taken for the loss of metal	hour	hour

Problems on CPR:

- A thickness of brass sheet of area 400 inch² is exposed to air near the ocean. After two years period it was found to experience a weight loss of 375g due to corrosion. If the density of Brass is 8.73 g/cm³. Calculate the CPR in mm/year mpy.

Solution:

Given:

- Area $A = 400 \text{ in}^2$
- Weight loss $W = 375 \text{ g} = 375,000 \text{ mg}$
- Density of Brass $\rho = 8.73 \text{ g/cm}^3$
- Time $t = 2 \text{ years} = 2 \times 365 \times 24 = 17,520 \text{ hours}$

CPR in mpy:

$K = 534$ $W = 375,000 \text{ mg}$ $\rho = 8.73 \text{ g/cm}^3$ $A = 400 \text{ in}^2$ $t = 17,520 \text{ hrs}$	$CPR_{\text{mpy}} = \frac{534 \times 375000}{8.73 \times 400 \times 17520}$ $CPR_{\text{mpy}} = \frac{200250000}{61186560} \approx 3.27 \text{ mpy}$
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CPR in mm/year (mmpy)

$K = 87.6$ Convert area from in ² to cm ² : $A = 400 \text{ in}^2 = 400 \times 6.4516 = 2580.64 \text{ cm}^2$ $W = 375,000 \text{ mg}$, $\rho = 8.73 \text{ g/cm}^3$, $t = 17,520 \text{ hrs}$	$CPR_{\text{mmpy}} = \frac{87.6 \times 375000}{8.73 \times 2580.64 \times 17520}$ $= \frac{32850000}{394248859.4} \approx 0.0833 \text{ mm/year}$
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2. A metal iron plate was found in a vessel containing acidic media, it was estimated that the original area was 20 inch² that approximately 1.2 kg had corroded. Assuming a corrosion penetration rate of 400mpy for this iron in acidic, calculate time in years, density of iron 7.87g/ cm³.

Solution:

Area (A) = 20 in² Weight loss (W) = 1.2 kg = 1,200,000 mg CPR = 400 mpy Density of iron (ρ) = 7.87 g/cm³ K (for mpy) = 534 We are solving for time (t in hours), then convert to years	$\text{CPR} = \frac{K \cdot W}{\rho \cdot A \cdot t}$ Solve for time t: $t = \frac{K \cdot W}{\rho \cdot A \cdot \text{CPR}}$ $t = \frac{534 \cdot 1,200,000}{7.87 \cdot 20 \cdot 400} = \frac{640,800,000}{62,960} \approx 10,175.2 \text{ hours}$ Convert hours to years: $\text{Years} = \frac{10,175.2}{24 \cdot 365} = \frac{10,175.2}{8760} \approx 1.16 \text{ years}$
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3. A thick steel sheet of area 400 inch² is exposed to moist air. After 2 years of exposure, it was found to experience a weight loss of 375 g due to corrosion. If the density of steel is 7.9 g/cm³, calculate CPR in mpy and mmpy.

Solution:

Given: K is a constant (534 for mpy, 87.6 for mmpy)

Weight loss, w: 375 g = 375,000 mg

Area, A: 400 in² = 400 × 6.4516 = 2,580.64 cm²

Time, T: 2 years = 2 × 365 × 24 = 17,520 hours

Density, D: 7.9 g/cm³

Calculate CPR in mpy

$$\text{CPR}_{\text{mpy}} = \frac{534 \times 375,000}{7.9 \times 400 \times 17,520} = \frac{200,250,000}{55,286,400} = 3.62 \text{ mpy}$$

Calculate CPR in mmpy

$$\text{CPR}_{\text{mmpy}} = \frac{87.6 \times 375,000}{7.9 \times 2,580.64 \times 17,520} = \frac{32,850,000}{357,646,755.2} = 0.092 \text{ mmpy}$$

4. A steel plate with a surface area of 450 cm² is exposed to air in a coastal environment. After one year, the plate shows a weight loss of 385 grams due to corrosion. Given that the density of steel is 7.9 g/cm³, calculate the corrosion rate in both mils per year (mpy) and millimeters per year (mmpy).

Use $k = 534$ for mpy and $k = 87.6$ for mmpy in your calculations.

Solution:

Given:

Area (A): 450 cm² = 450 cm² ÷ 6.4516 = 69.8 in²

Weight loss (W): 385 g = 385 g = 385,000 mg

Density (ρ): 7.9 g/cm³

Time (t): 1 year

Constants: $K = 534$ for mpy, $K = 87.6$ for mmpy

Time in hours: 1 year = 365 × 24 = 8,760 hours

For mpy:

$$\text{CPR}_{\text{mpy}} = \frac{534 \times 385,000}{7.9 \times 69.8 \times 8,760} = \frac{205,890,000}{4,819,927.2} = 42.74 \text{ mpy}$$

For mmpy:

$$\text{CPR}_{\text{mmpy}} = \frac{87.6 \times 385,000}{7.9 \times 450 \times 8,760} = \frac{33,726,000}{31,099,800} = 1.085 \text{ mmpy}$$

5. A steel sheet with an area of 400 cm² (or 62 in²) is exposed to moist air. After one year, it is found to have lost 375 grams in weight due to corrosion. Given that the density of steel is 7.9 g/cm³, calculate the corrosion penetration rate (CPR) in both mils per year (mpy) and millimeters per year (mmpy). Use the constants $K = 534$ for mpy and $K = 87.6$ for mmpy in your calculations.

Solution:

Given Data:

- Area (A): 400 cm² (also given as 62 in²)
- Weight loss (W): 375 g = 375,000 mg
- Density (ρ): 7.9 g/cm³
- Time (t): 1 year = 365 × 24 = 8,760 hours
- Constants: $K = 534$ for mpy, $K = 87.6$ for mmpy

Apply the CPR Formula

$$\text{CPR} = \frac{K \times W}{\rho \times A \times t}$$

For mpy:

$$\text{CPR}_{\text{mpy}} = \frac{534 \times 375,000}{7.9 \times 62 \times 8,760} = \frac{200,250,000}{4,287,672} = 46.72 \text{ mpy}$$

For mmpy:

$$\text{CPR}_{\text{mmpy}} = \frac{87.6 \times 375,000}{7.9 \times 400 \times 8,760} = \frac{32,850,000}{27,676,800} = 1.19 \text{ mmpy}$$

NOTE:

Conversions:

1 Gram = 1000 Milligram or 10^3

1 Kg = 1000000 Milligram or 10^6

1 Day = 24 Hours

1 Month = 30 days = 30×24 Hours

1 Year = $1 \times 365 \times 24$ Hours

1 inch = 2.54 cm

1 m = 100 cm

