

## 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<sub>x</sub> and SO<sub>x</sub> 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.

**Sensor:** Sensors are electronic or electrochemical devices that detect and measure physical or chemical phenomena and convert them into electrical signals.

#### **Examples:**

- **pH Sensor (glass electrode):** Detects H<sup>+</sup> ion concentration in solutions.
- **Conductivity Sensor:** Measures the ionic conductivity of an electrolyte.
- **Gas Sensor:** Detects CO<sub>2</sub>, H<sub>2</sub>S, or O<sub>2</sub> levels in chemical or environmental systems.

**Transducer:** A transducer is a device that converts a non-electrical physical or chemical quantity into an electrical signal.

#### **Examples in Chemistry:**

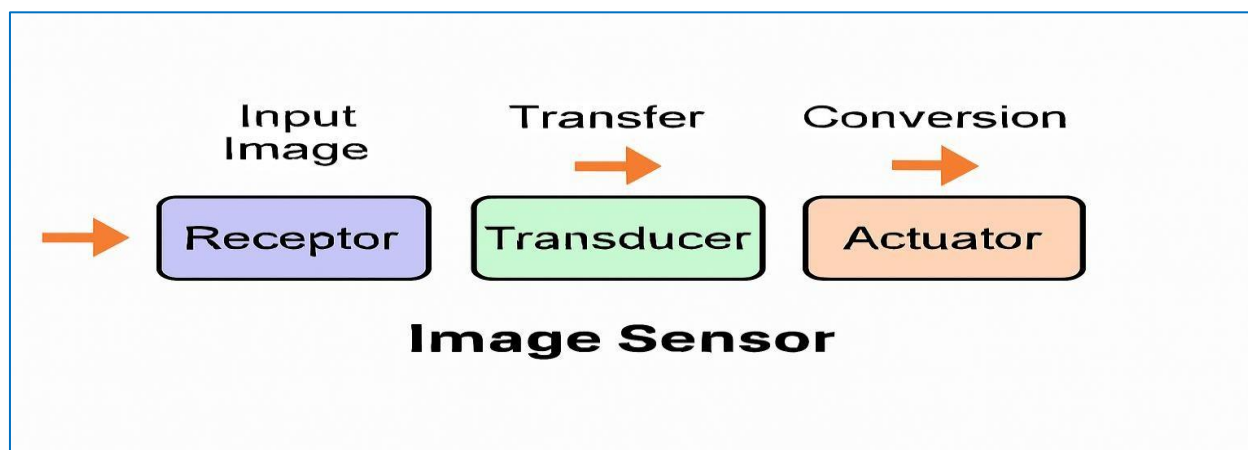
- **Electrochemical Oxygen Sensor:** Converts dissolved oxygen concentration into an electrical current.

**Actuator:** An actuator is a device that receives an electrical signal and produces a physical or chemical action. It is often used for control in experiments.

#### • **Examples in Chemistry/Electrochemistry:**

- **Electrolysis Cell:** Converts electrical current into chemical products (H<sub>2</sub> and O<sub>2</sub> gases).

**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.



### 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, amperometric, or conductometric sensors. They offer high sensitivity, selectivity, and fast response.

**Examples:** pH electrodes, glucose sensors, and oxygen sensors. **Applications:** environmental monitoring, biomedical diagnostics, food quality control, and industrial process monitoring.

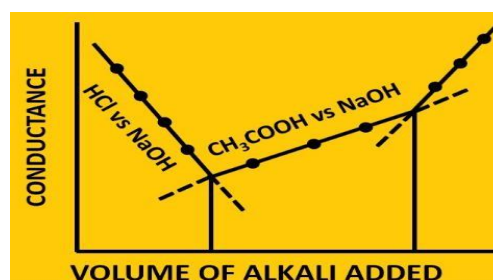
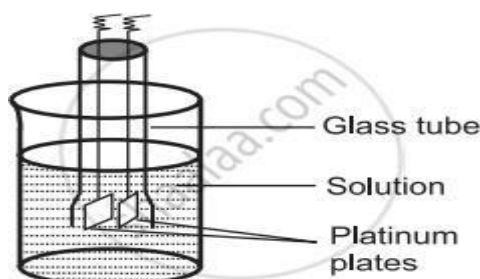
### Conductometric Sensors: Principle, Construction, and Application in Acid Mixture Estimation

#### 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 acid mixture estimation, the neutralization of a strong acid (HCl) and a weak acid ( $\text{CH}_3\text{COOH}$ ) 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 foils of unit cross-sectional area separated by unit distance. The volume between electrodes =  $1 \text{ cm}^3$ . Conductance of unit volume is called specific conductance ( $\kappa$ ) and is given by:



$$\kappa = (1/R) \times (l/a)$$

where R = resistance, and l/a = cell constant.

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

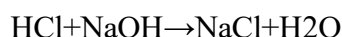
### Working:

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.

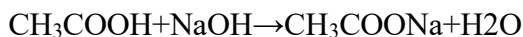
### Estimation of Acid Mixture

Example: Mixture of HCl and CH<sub>3</sub>COOH titrated with NaOH

- Initially, high conductance due to free H<sup>+</sup> ions from HCl.
- As NaOH is added, H<sup>+</sup> ions are neutralized, conductance decreases sharply due to Highly mobile **H<sup>+</sup> ions** are replaced by less mobile **Na<sup>+</sup> ions**,



- After HCl is neutralized, acetic acid starts neutralizing; conductance decreases more slowly due to partial dissociation.



- After all acids are neutralized, excess OH<sup>-</sup> ions increase conductance sharply.

### Colorimetric sensor-principle, instrumentation and its application in the estimation of copper in PCB.

#### 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:

$$A = \epsilon l c$$

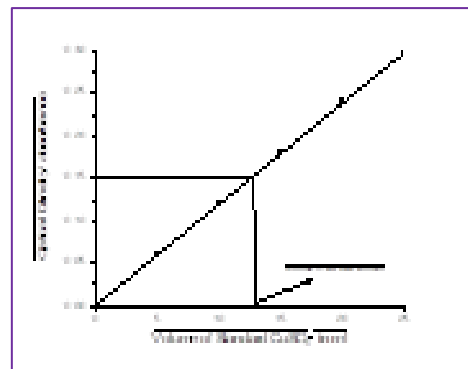
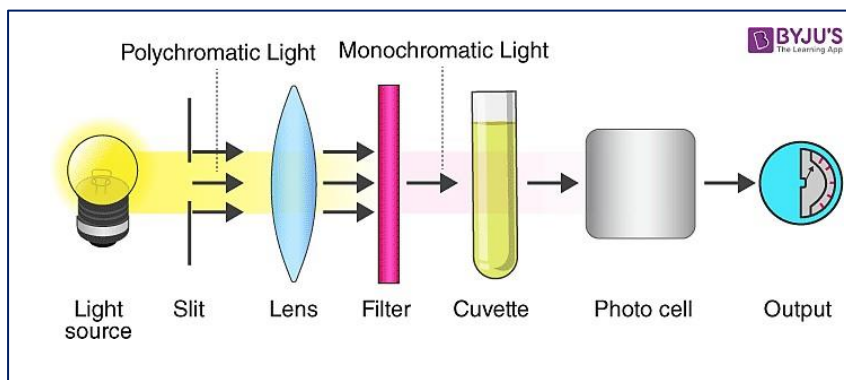
Where:

A = absorbance,  $\epsilon$  = molar absorptivity, l = path length, c = analyte concentration

#### For copper estimation in PCB using ammonia:

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.



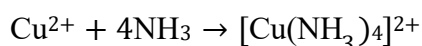
### Working:

Monochromatic light passes through the analyte solution. Part of the light is absorbed by the deep blue colored complex. Absorbance depends on **concentration** and **path length**. Detector converts light intensity into electrical signal → displayed as concentration.

### Estimation of Copper in PCB Using Ammonia Complex:

Draw out 5,10,15 & 20 cm<sup>3</sup> of given copper sulphate solution into four separate 50 cm<sup>3</sup> standard flasks. Add 5 cm<sup>3</sup> of NH<sub>3</sub> to each one of them and also into the test and blank solution, dilute up to the mark with distilled water and mix well. Measure the absorbance of each of these against blank solution (only ammonia and water) at 620 nm. Plot a graph of absorbance (OD) (ordinate) against concentration of copper (abscissa) and determine the concentration of copper in the e-waste solution.

- Copper ions (Cu<sup>2+</sup>) react with ammonia (NH<sub>3</sub>) to form a deep blue complex:



### 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, and automotive emission testing.

## Electrochemical gas sensors- principle, construction and its application in the detection of NO<sub>x</sub> and in air sample

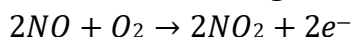
### Principle of Operation

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.

For NO<sub>x</sub> (NO and NO<sub>2</sub>) detection, the reactions are:

1. **Oxidation of NO at the working electrode:**



2. **Reduction of NO<sub>2</sub> (in some sensor types):**

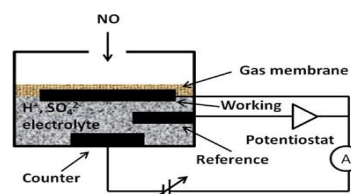
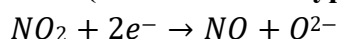


Fig: 1.14 NO<sub>x</sub> Gas Sensor

These electron transfers generate a current that can be calibrated to determine the **NO<sub>x</sub> concentration** in the air sample.

### Construction of the Sensor

- **Working Electrode (WE):** Metal oxide-coated electrode where NO<sub>x</sub> 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<sub>x</sub> gas and prevents electrolyte leakage.
- **Housing:** Encases the sensor and provides electrical connections.

### Working

NO<sub>x</sub> gas diffuses through the membrane to the working electrode. At the metal oxide-coated working electrode, NO<sub>x</sub> is **reduced to NO**, producing a flow of electrons. The **current generated** flows through the circuit and is measured to determine the NO<sub>x</sub> concentration.

### Applications

- **Environmental monitoring:** Air quality measurement in urban and industrial areas.
- **Automotive emission control:** Detecting NO<sub>x</sub> in exhaust gases.
- **Industrial safety:** Monitoring NO<sub>x</sub> levels in workplaces to prevent health hazards.

### Advantages:

- Real-time NO<sub>x</sub> detection
- High sensitivity and selectivity
- Compact, low-power operation suitable for continuous monitoring

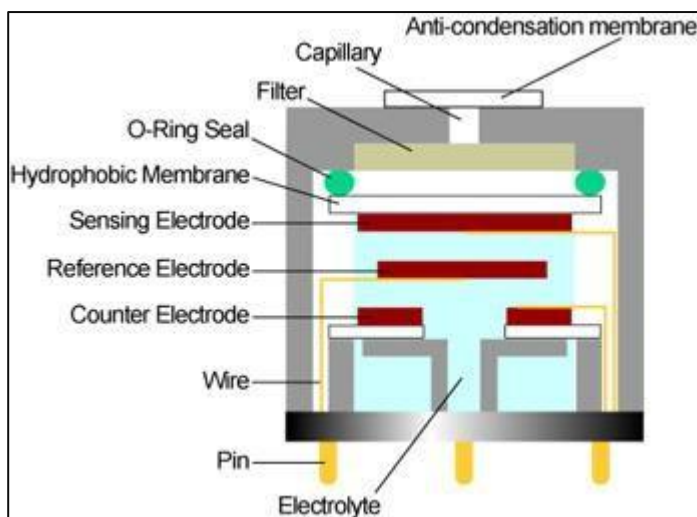
### Principle

Electrochemical gas sensors work on the principle of redox reactions occurring at the electrode–electrolyte interface. When a target gas (e.g., SO<sub>2</sub>) 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.

### SO<sub>x</sub> Electrochemical gas sensors- principle, construction and its application in the detection of NO<sub>x</sub> and in air sample

#### Construction

An electrochemical gas sensor typically consists of:



- **Working 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** allows controlled diffusion of the gas into the sensor, preventing interference.
- **Housing:** protects the components and ensures selective entry of the gas.

#### Application in SO<sub>x</sub> Detection (e.g., SO<sub>2</sub> in Air Samples)

- **Detection principle:**
  - At the working electrode, SO<sub>2</sub> undergoes oxidation:  

$$\text{SO}_2 + 2\text{H}_2\text{O} \rightarrow \text{SO}_4^{2-} + 4\text{H}^+ + 2\text{e}^-$$

- At the counter electrode, oxygen reduction occurs to complete the electrochemical circuit:  

$$\text{O}_2 + 4\text{H}^+ + 4\text{e}^- \rightarrow 2\text{H}_2\text{O}$$
- The generated electrons produce a measurable current proportional to  $\text{SO}_2$  concentration.
- **Practical use:**
  - Widely employed in **air quality monitoring stations** to measure  $\text{SO}_2$  levels in urban and industrial environments.
  - Used in **occupational safety** to detect  $\text{SO}_2$  in confined spaces (factories, smelters, refineries).
  - Incorporated in **portable detectors** for environmental and health monitoring

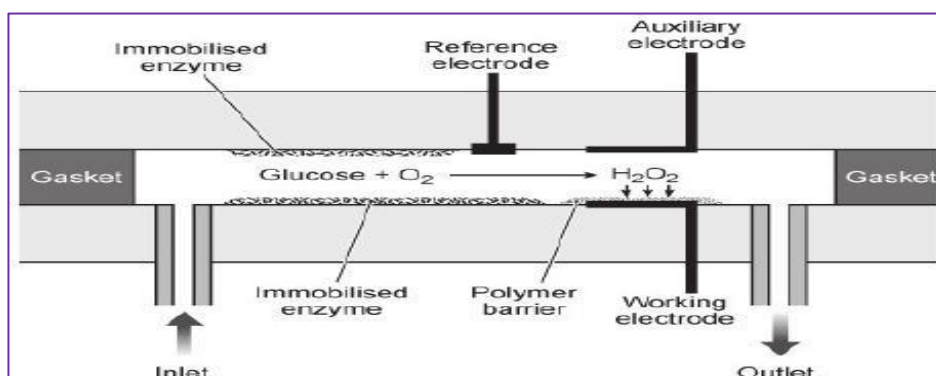
### Glucose Biosensor: Principle, Construction and Working

#### 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.

#### Construction:

- Biorecognition layer: Contains immobilized glucose oxidase enzyme, fixed using cross-linking agents (e.g., glutaraldehyde) or entrapped in polymeric matrices such as Nafion.
- Transducer element: A modified electrode made from materials like graphite rod, glassy carbon, or gold nanostructures, which converts the biochemical reaction into an electrical signal.
- Nanomaterial modifications: Incorporation of carbon nanotubes, gold nanoparticles, or Prussian blue to enhance electron transfer and provide larger surface area for enzyme attachment.
- Protective membrane: Covers the sensor to prevent enzyme leaching while permitting glucose diffusion toward the enzyme layer.

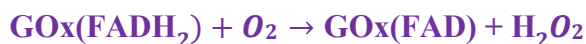


**Working:**

- 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(FADH<sub>2</sub>) 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:**

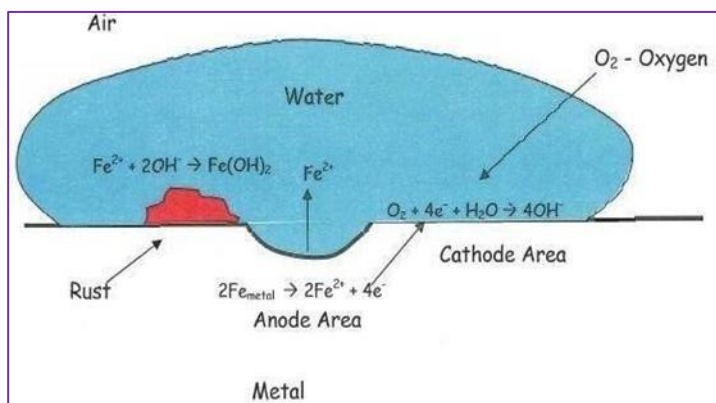
1. **Dry Corrosion:** Corrosion taking place in the absence of moisture that is direct chemical reaction taking place between metal and dry gases.
2. **Wet Corrosion:** Corrosion taking place in the presence of moisture or aqueous wet environment.

**Electrochemical Theory of Corrosion:**

- Corrosion occurs due to the formation of anodic and cathodic regions on the same or different metals in a conducting medium.

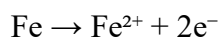


- At the anode, oxidation takes place, and the metal corrodes into ions by releasing electrons.
- At the cathode, reduction occurs by consuming the liberated electrons, keeping the cathodic region protected.
- Corrosion continues as long as anodic and cathodic reactions proceed simultaneously, influenced by impurities and oxygen concentration differences.



### At the Anodic Region:

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

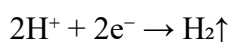


### At the Cathodic Region:

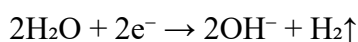
Chemical species in the cathode's surroundings undergo reduction by accepting electrons from the anodic region through the metal. Depending on the surrounding medium, four possible reduction reactions occur at the cathodic region:

#### 1) Hydrogen Liberation (Absence of Oxygen):

(a) In acidic medium without oxygen:

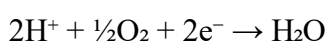


(b) In neutral or alkaline medium without oxygen, hydroxide ions form with simultaneous hydrogen liberation:

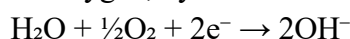


#### 2) Oxygen Absorption (Presence of Oxygen):

(a) In acidic medium with oxygen:

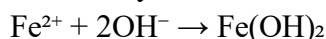


(b) In neutral or alkaline medium with oxygen, hydroxide ions form:

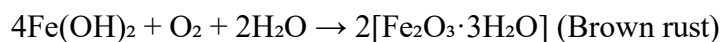


### Formation of Rust:

Corrosion of iron produces  $\text{Fe}^{2+}$  ions at the anode and  $\text{OH}^-$  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):

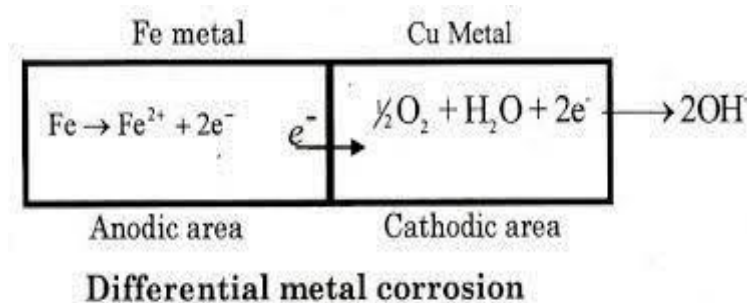


## Types of corrosion

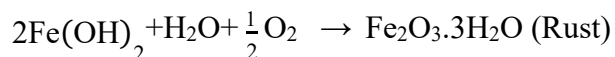
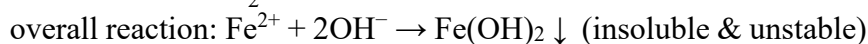
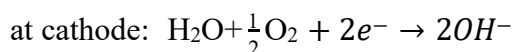
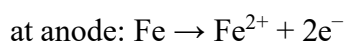
### Differential Metal Corrosion (galvanic corrosion):

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.



Fe has lower electrode potential when compared to copper. Hence iron undergoes oxidation and get corroded.



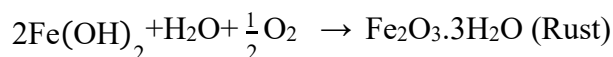
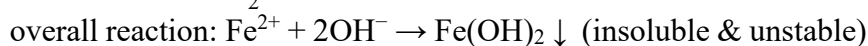
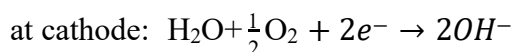
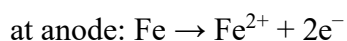
### Other examples:

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.



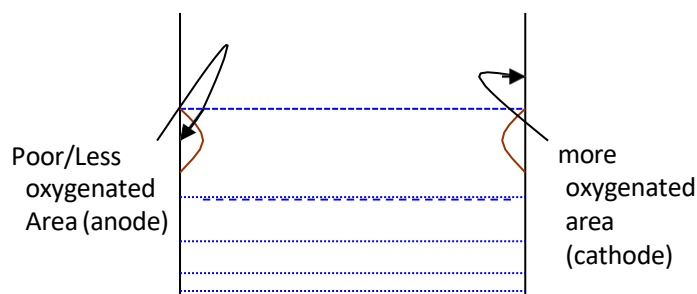
### Other examples:

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

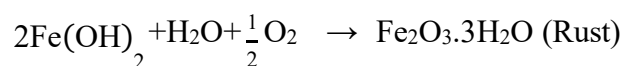
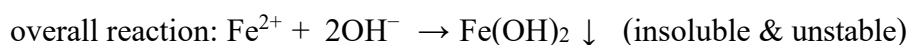
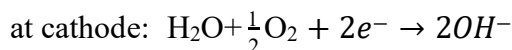
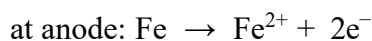
This differential aeration corrosion is divided into two types

### Water line corrosion:

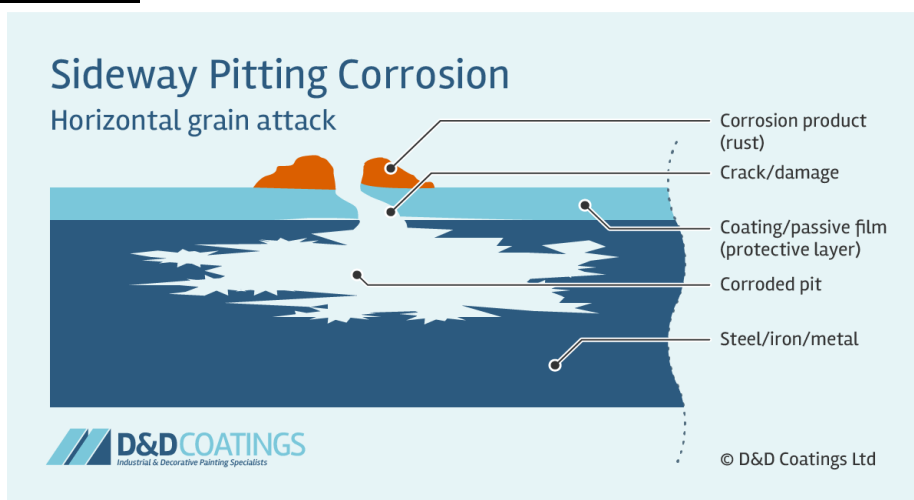
Eg: Water storage tank



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.



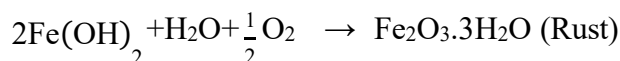
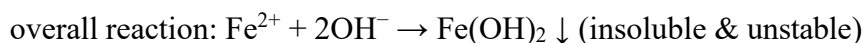
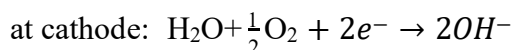
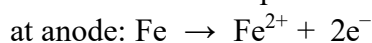
## Pitting Corrosion:



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.



## preventing the formation of galvanic cells.

**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

a) **Metal coating:** The process of covering base metal with a layer of protective metal is known as metal coating. They are divided into two types,

- i) **Anodic coatings:** It is produced by coating a metal surface with more active metals which acts as anodic to base metal.

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

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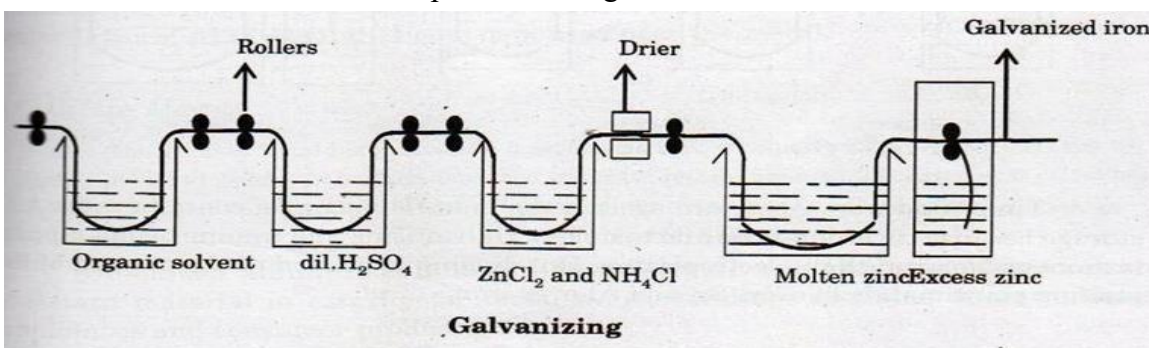
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- i) **Anodic coatings:** It is produced by coating a metal surface with more active metals which acts as anodic to base metal.

### **Eg: Galvanization of Iron**

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.



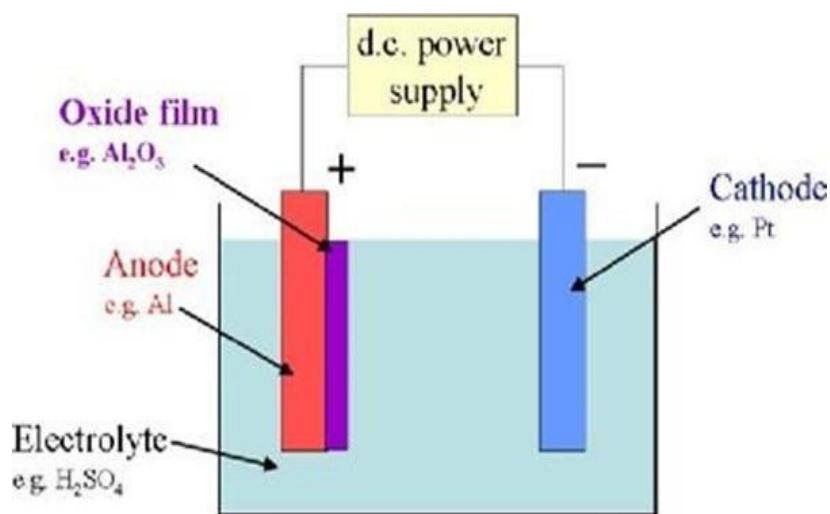
Galvanization process involves following steps:

- Metal surface is washed with organic solvents to remove organic matter.
- Rust and other deposits removed by washing with hot dil. H<sub>2</sub>SO<sub>4</sub> is called pickling process.
- Then it is well washed with water.
- It is air dried by-passing hot air.
- Then it is dipped in molten zinc, maintained at 430-450°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.

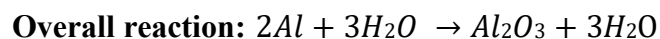
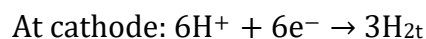
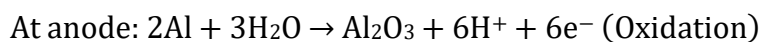
**Application:** Galvanized materials are used in fencing wire, buckets, bolts, nuts, nails, screw etc.

**Inorganic coating:** It is chemical conversion coating where metal surface is converted to a compound by chemical or electrochemical process which forms barrier. There are two types

### Anodizing (Anodizing of aluminium)



It is an electrochemical process which forms protective passive (non-reactive) oxide film on metal surface. Here aluminium metal is made as anode in a suitable oxidizing electrolyte like sulphuric acid, chromic acid, oxalic acid bath at a temperature of 30 - 40<sup>0</sup> C and moderate current density. A thin film of Al<sub>2</sub>O<sub>3</sub> 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.



**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

- Concept of VCIs:**

Vapour Corrosion Inhibitors are chemical compounds such as **Carboxylates** (e.g., *benzoates*,

*sebacates*) – effective for steel and copper. that slowly vaporize and release protective molecules into the surrounding atmosphere.

- **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 speed or rate of deterioration depends on the environment conditions and the type of metal under study. The equation for **CPR** (Corrosion Penetration Rate) is:

$$CPR = \frac{KW}{\rho At}$$

Where:

- **CPR** = Corrosion Penetration Rate (measured in miles per year, mpy)

- 1 mpy = 0.001 inch per year
- **K** = A constant
- **W** = Total weight loss due to exposure to a corrosive environment
- **$\rho$**  = Density of the material
- **A** = Surface area of the exposed metal
- **t** = Time taken for the loss of metal (exposure time)

<b>CPR</b>	<b>mpy</b>	<b>mmpy</b>
<b>K</b>	534	87.6
<b>W</b>	mg	mg
<b><math>\rho</math></b>	$\text{g/cm}^3$	$\text{g/cm}^3$
<b>A</b>	$\text{In}^2$	$\text{cm}^2$
<b>T</b>	hrs	hrs

### Conversions:

1 Gram = 1000 Milligram or  $10^3$

1 Kg = 1000000 Milligram or  $10^6$

1 Day = 24 Hours

1 Month = 30 days =  $30 \times 24$  Hours

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

1 Square Centimeter = 0.155 square inch

1 square inch = 6.4516 sq cm

1. A thickness of brass sheet of area  $400 \text{ in}^2$  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  $8.73 \text{ g/cm}^3$ . 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 years =  $2 \times 365 \times 24 = 17,520$  hours



**Formula:**

$$PR = \frac{K \cdot W}{\rho \cdot A \cdot t}$$

**CPR in mpy:**

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

$K = 87.6$ Convert area from $\text{in}^2$ to $\text{cm}^2$ : $A = 400 \text{ in}^2 = 400 \times 6.4516 = 2580.64 \text{ cm}^2$ $W = 375,000 \text{ mg}$ , $\rho = 8.73 \text{ g/cm}^3$ , $t = 17,520 \text{ hrs}$	$\text{CPR}_{\text{mmpy}} = \frac{87.6 \times 375000}{8.73 \times 2580.64 \times 17520}$ $= \frac{32850000}{394248859.4} \approx 0.0833 \text{ mm/year}$
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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 inch<sup>2</sup> 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/cm<sup>3</sup>.

Given:

Area (A) = 20 in <sup>2</sup> Weight loss (W) = 1.2 kg = 1,200,000 mg CPR = 400 mpy Density of iron ( $\rho$ ) = 7.87 g/cm <sup>3</sup> 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 inch<sup>2</sup> 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/cm<sup>3</sup>, calculate CPR in mpy and mmpy.

where:

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

Weight loss: 375 g = 375,000 mg

Area: 400 in<sup>2</sup> = 400 × 6.4516 = 2,580.64 cm<sup>2</sup>

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

Density: 7.9 g/cm<sup>3</sup>

**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 cm<sup>2</sup> 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/cm<sup>3</sup>, 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.

**Given Data**

Area ( $A$ ): 450 cm<sup>2</sup> = 450 cm<sup>2</sup> ÷ 6.4516 = 69.8 in<sup>2</sup>

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

Density ( $\rho$ ): 7.9 g/cm<sup>3</sup>

Time ( $t$ ): 1 year

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

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

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

**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 cm<sup>2</sup> (or 62 in<sup>2</sup>) 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/cm<sup>3</sup>, 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.

**Given Data**

- Area ( $A$ ): 400 cm<sup>2</sup> (also given as 62 in<sup>2</sup>)
- Weight loss ( $W$ ): 375 g = 375,000 mg
- Density ( $\rho$ ): 7.9 g/cm<sup>3</sup>
- 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:**

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