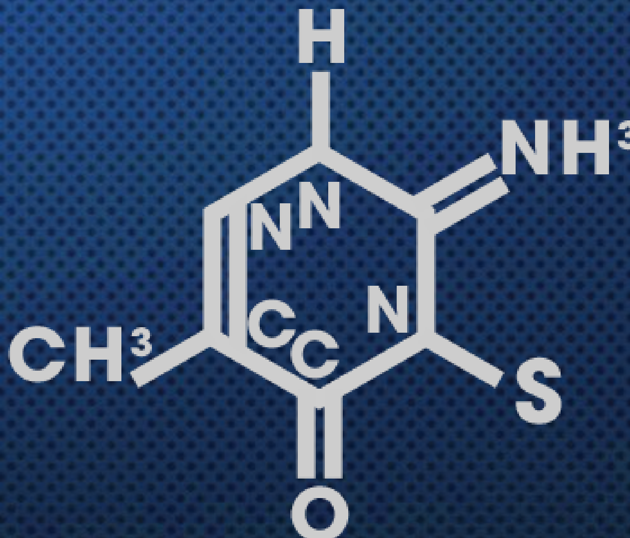
Corrosion &
Corrosion Control



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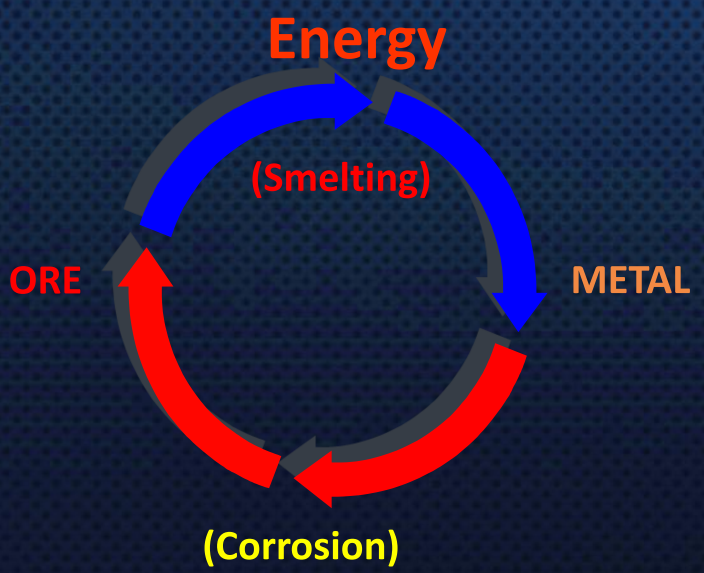
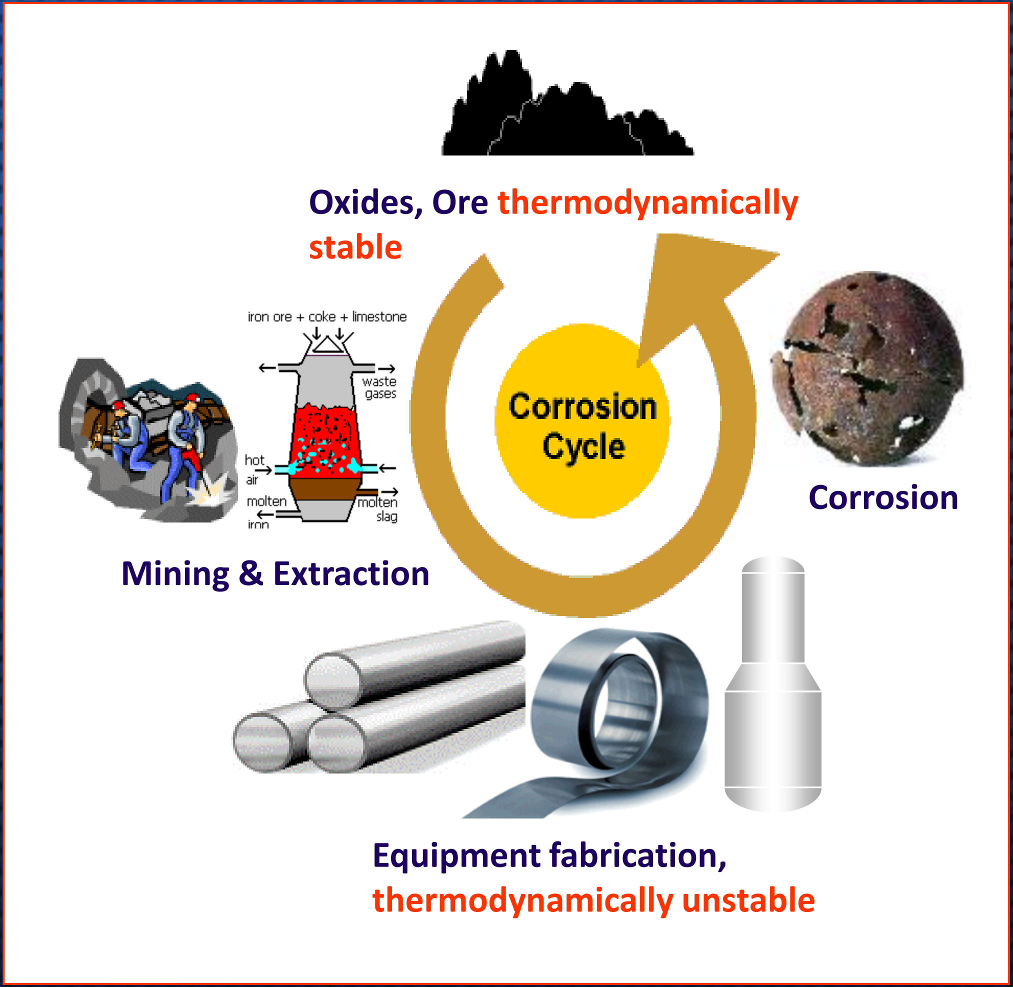
I. Basics of Corrosion

What is Corrosion?

- **Corrosion is defined as the degradation of a material due to its reaction with the environment.**
- **In case of metallic corrosion, corrosion is related to the law of conservation of energy.**





Why we study Corrosion?

- In some countries corrosion damage reaches 5% of the total yearly GDP.
- Economic losses are attributed to; loss of production, replacement of equipment, maintenance of equipment, environmental pollution, etc.
- Recent studies revealed that 2/3 of such corrosion damage could have been avoided if a proper corrosion control technique was applied.
- Corrosion damage can extend far from economic losses, where it could cause loss of life in some circumstances. Loss of life was reported in many incidents and reason was directly attributed to corrosion.

Cost Of Corrosion

Corroded rotor leading to equipment failure

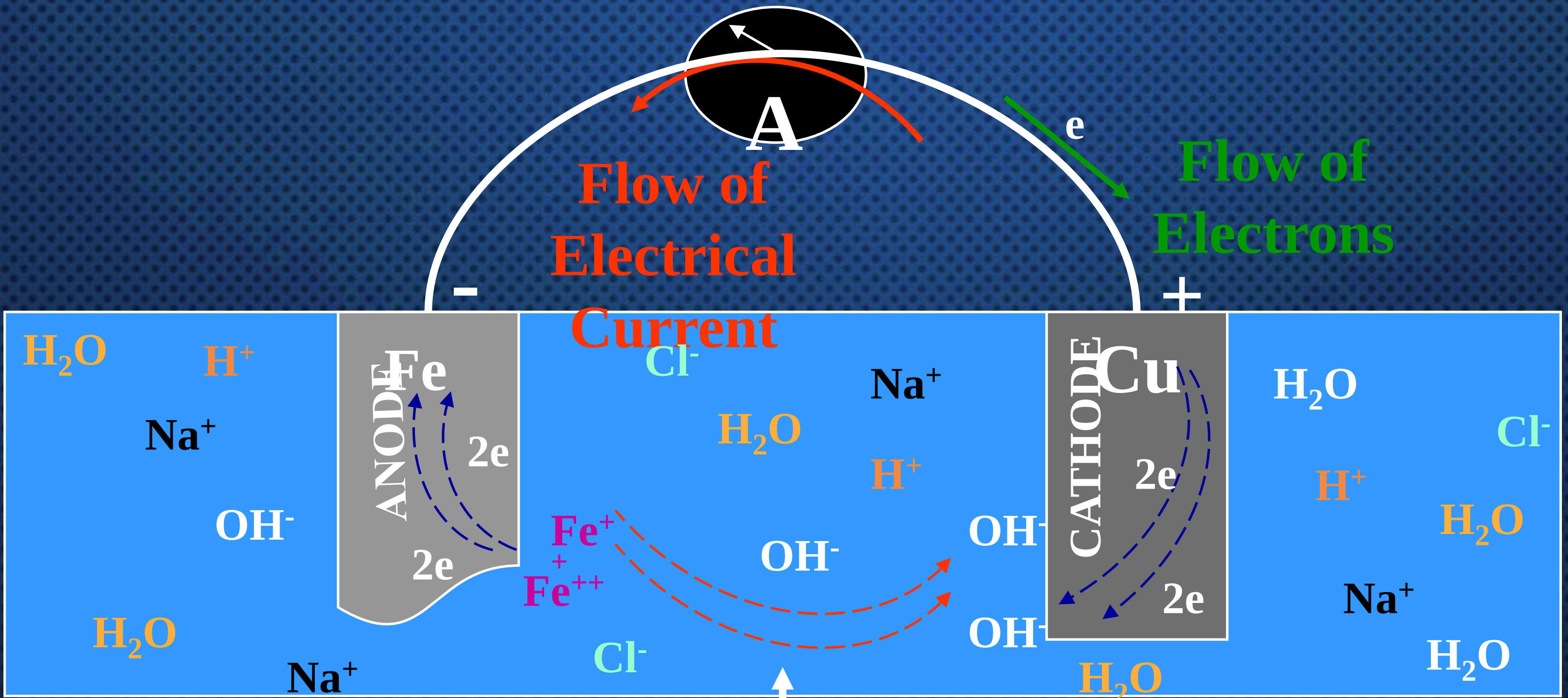
Leakage leading to environmental pollution

Catastrophic failure

Corrosion Mechanism

- In most cases corrosion is an electrochemical phenomenon.
- For corrosion to take place, the following are required:
  - An anode - at which the metal goes into solution (corrodes)
  - A cathode - at which electrons from the anode are consumed
  - An electrical continuity between anode and cathode (the internal conductor)
  - A common continuous electrolyte (the external conductor) across both anode and cathode.

Corrosion Mechanism



Electrolyte

Reaction at Anode

$2Fe \uparrow 2Fe^{++} + 4e$

Reaction at Cathode

$O_2 + 2H_2O + 4e \uparrow 4OH^-$

Corrosion Mechanism

- **At anode, metal dissolves producing electrons**

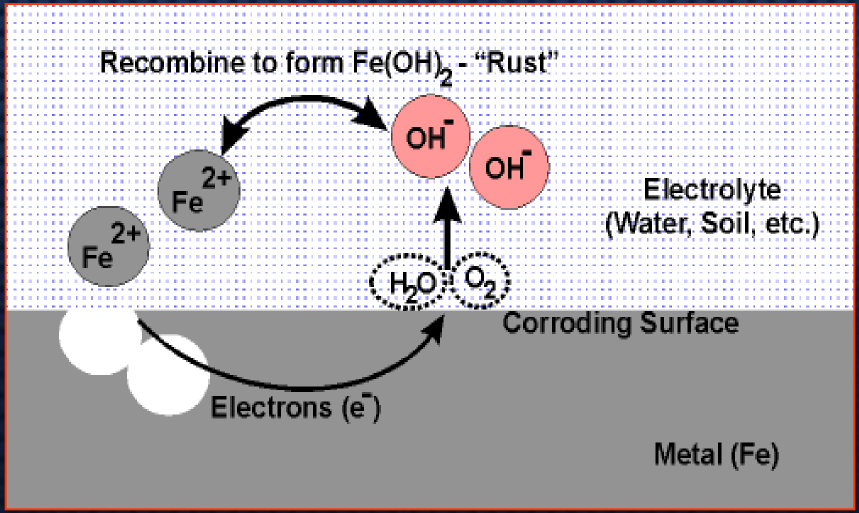
  $$4M = 4M^{++} + 8e$$

- **At cathode electrons are consumed**

  $$4H_2O + 2O_2 + 8e = 8OH^-$$

- **The faster that electrons are consumed at the cathode, the faster will the metal go into solution at the anode (corrode).**
- **This keeps the reaction in equilibrium.**
- **Overall reaction is:**

  $$4M + 4H_2O + 2O_2 = 4M(OH)_2$$



Standard EMF Series

Standard EMF series represents a ranking of metals in terms of its natural potential reference to a hydrogen electrode.

Element		Potential (Volts)
Magnesium	$Mg \rightarrow Mg^{++} + 2e$	-2.34
Aluminum	$Al \rightarrow Al^{+++} + 3e$	-1.67
Zinc	$Zn \rightarrow Zn^{++} + 2e$	-0.76
Iron	$Fe \rightarrow Fe^{++} + 2e$	-0.44
Nickel	$Ni \rightarrow Ni^{++} + 2e$	-0.25
Tin	$Su \rightarrow Su^{++} + 2e$	-0.14
Lead	$Pb \rightarrow Pb^{++} + 2e$	-0.13
Hydrogen	$2H \rightarrow 2H^{+} + 2e$	0.00
Copper	$Cu \rightarrow Cu^{++} + 2e$	0.34
Silver	$Ag \rightarrow Ag^{++} + 2e$	0.79
Platinum	$Pt \rightarrow Pt^{++} + 2e$	1.20
Gold	$Au \rightarrow Au^{+++} + 3e$	1.42

↑ Readiness to Corrode (Reconvert to Ore)

↓ Ease of Smelting

Standard Galvanic Series

Standard galvanic series represents a realistic ranking for metals. Ranking is made in seawater reference to a $Cu/CuSO_4$ electrode.

THE GALVANIC SERIES OF METALS IN SEA WATER

ACTIVE

- Magnesium
- Zinc
- Aluminum
- Iron
- Lead
- Tin
- Nickel (Active)
- Brass
- Copper
- Nickel (Passive)
- 410 Stainless
- Titanium
- 304 Stainless
- Silver
- Gold
- Platinum

NOBLE

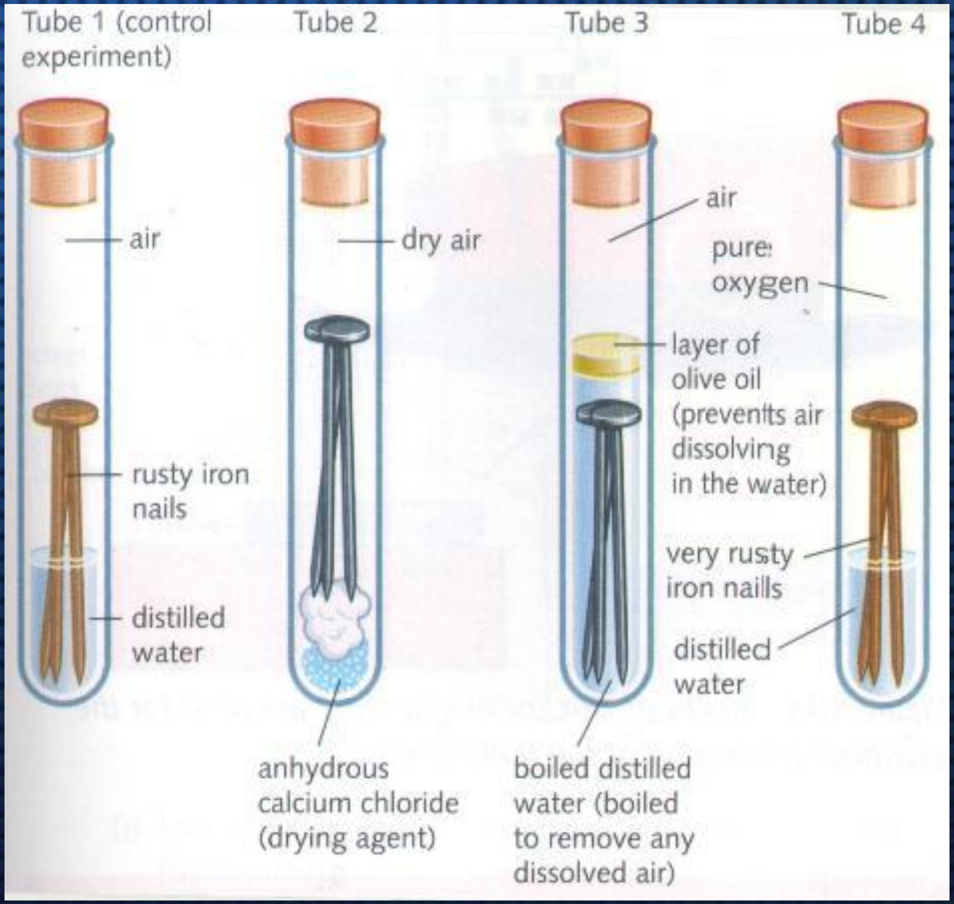
Couple Mildly Corrosive for Iron (Iron – Lead)

Couple Severely Corrosive for Iron (Iron – Copper)

Factors Affecting Corrosion

There are numerous factors that affect the corrosion process these are:

- pH of environment
- Concentration of corrosive species
- Stream Velocity
- Oxygen Content
- Temperature



Forms of Corrosion

There are two major forms of corrosion and these are:
<u>UNIFORM</u> and <u>LOCALIZED</u> corrosion forms

Forms of Corrosion

Uniform Corrosion

- Is called general corrosion
- Is of little engineering importance
- Can be easily controlled
- Can be easily monitored
- Is caused by natural environments and acids

Uniform Corrosion

Forms of Corrosion

Localized Corrosion

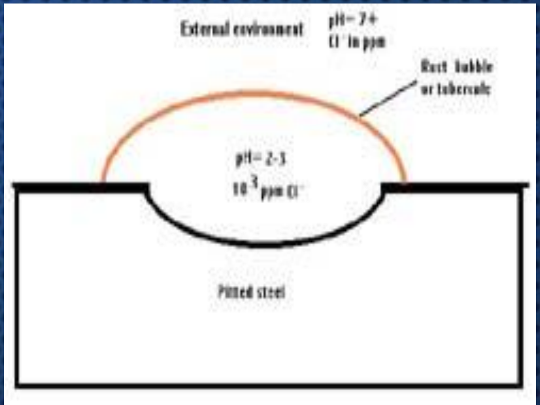
Takes place on specific locations:

- Is hard to predict
- Is hard to monitor
- Can lead to catastrophic failures
- Has numerous forms the most important are:
    - Pitting
    - Crevice
    - Stress Corrosion Cracking
    - Erosion Corrosion
    - Galvanic

Forms of Corrosion

Uniform Corrosion – Pitting Corrosion

**Pitting is another form of much localized corrosion attack in which small pits or holes form.
This type of corrosion is very dangerous where it is undetected and with very little material loss until failure occurs.**



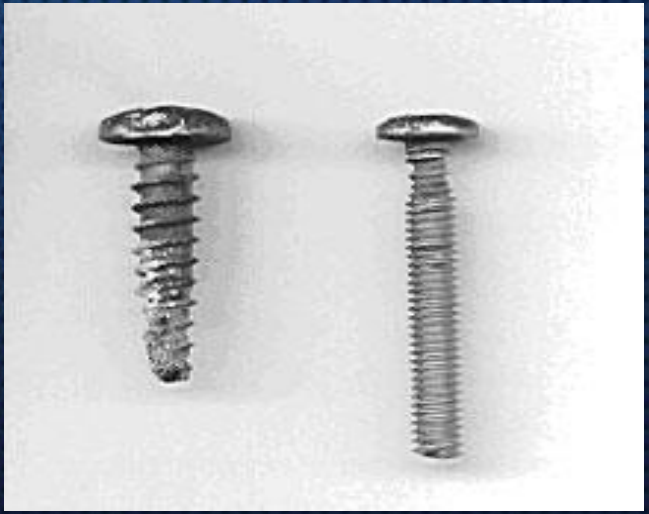
Pitting corrosion of SS

Forms of Corrosion

Uniform Corrosion – Crevice Corrosion

Crevice or contact corrosion is the corrosion produced at the region of contact of metals with metals or metals with nonmetals.

Stainless steels are susceptible to this kind of corrosion.



Crevice corrosion of SS

Forms of Corrosion

Uniform Corrosion – Galvanic Corrosion

- **Galvanic corrosion occurs when two metals or alloys having different compositions are electrically coupled while exposed to an electrolyte.**

- **Rate of galvanic attack depends on the relative anode to cathode surface areas that are exposed to the electrolyte**

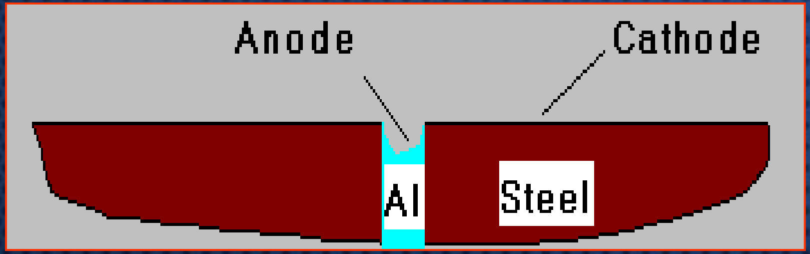
Galvanic corrosion of a helicopter rotor blade

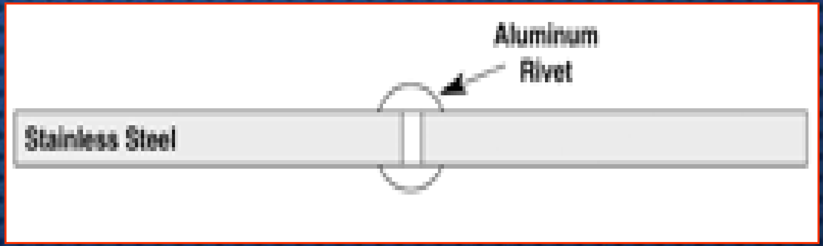
Forms of Corrosion

Uniform Corrosion – Galvanic Corrosion

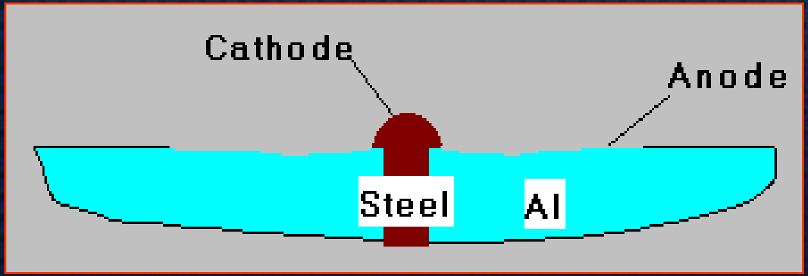
Surface Area Effect in Galvanic Corrosion

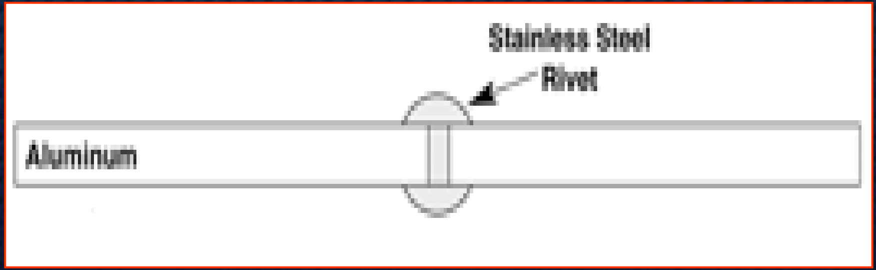
- **Small Anode Large cathode combination is NOT Acceptable**





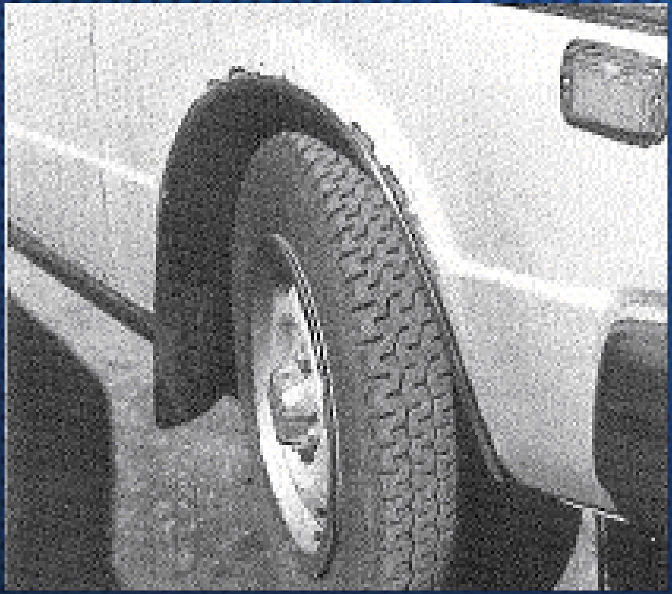
- **Small Cathode Large anode combination is Acceptable**



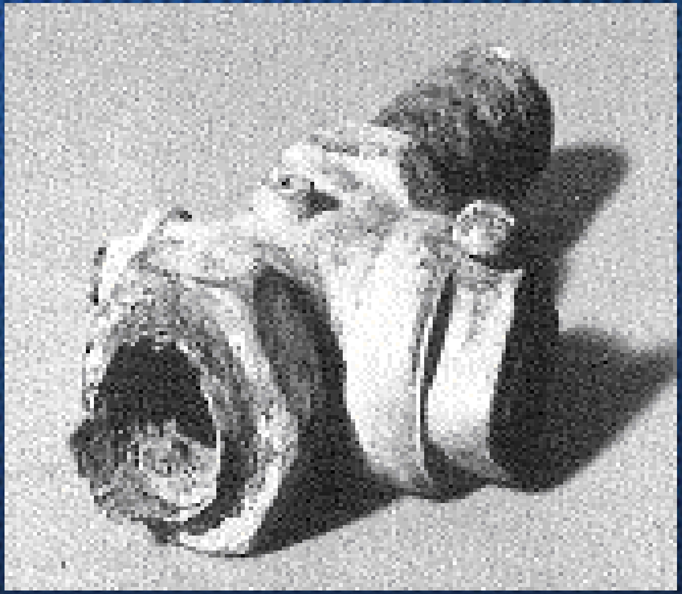


Forms of Corrosion

Uniform Corrosion – Galvanic Corrosion

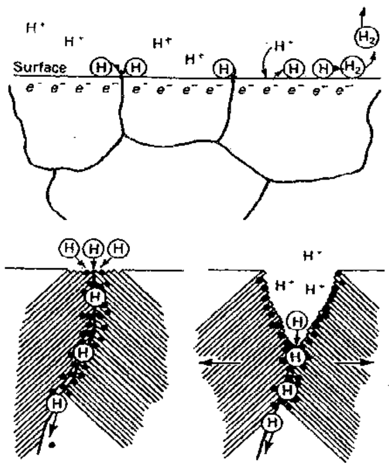


Galvanic corrosion of painted steel body in contact with SS wheel opening molding



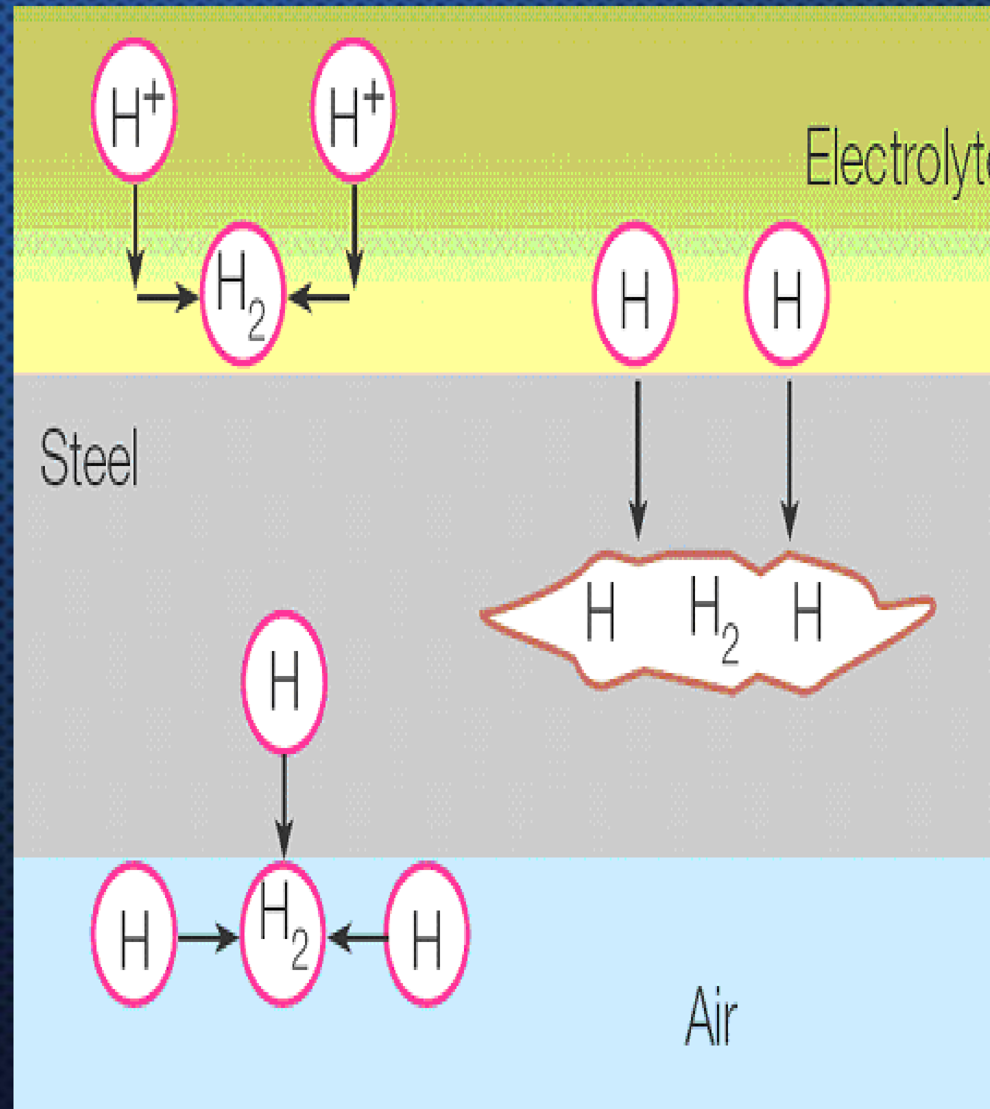
Galvanic corrosion of steel pipe at brass fitting in humid marine atmosphere

Hydrogen Blistering

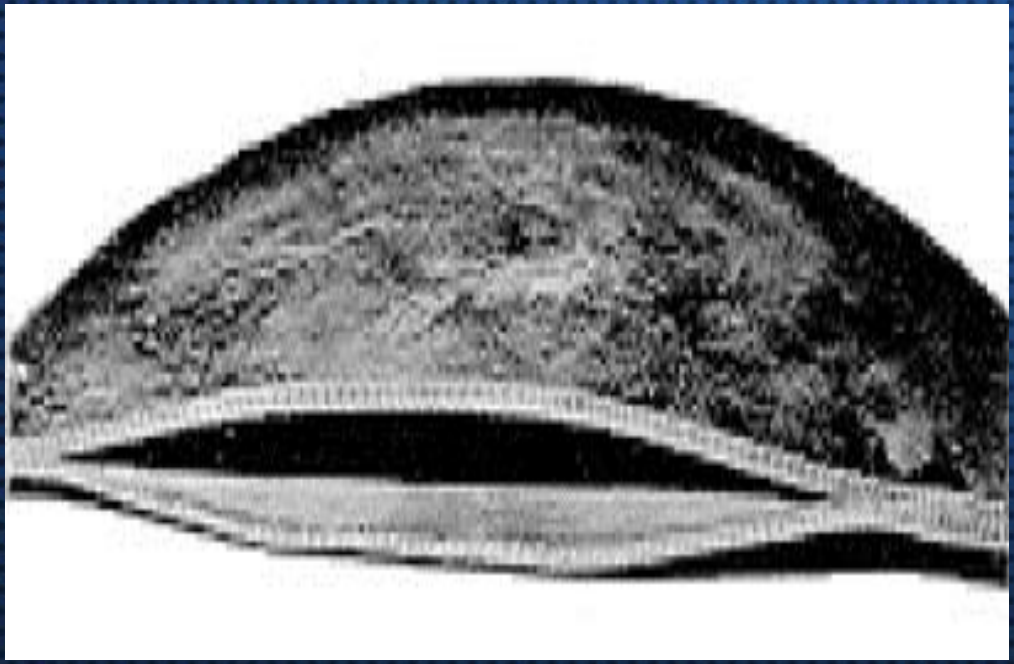


Schematic showing effect of some impurities on mechanism by which intergranular embrittlement of nickel is presumed to occur at cathodic potentials

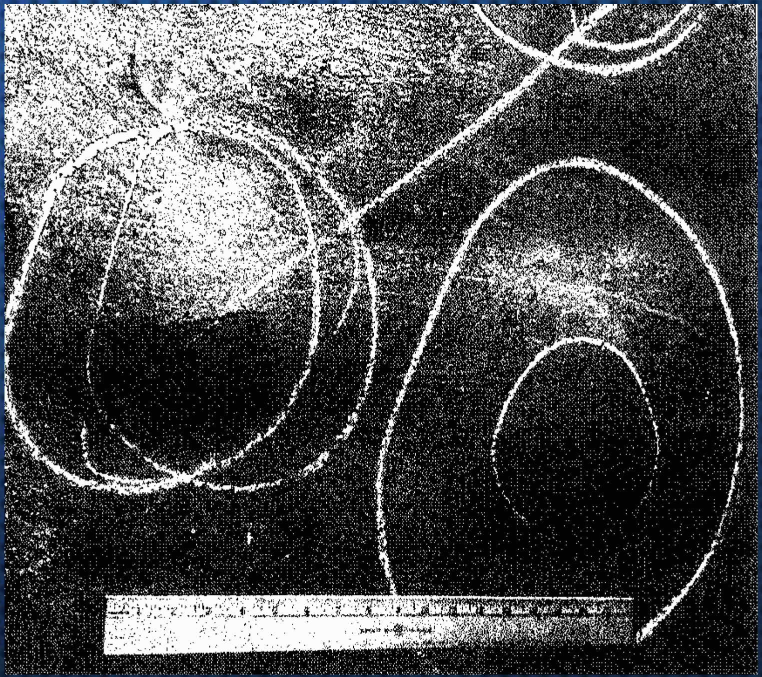
Grain Boundaries



Hydrogen Blistering



Cross-section of a carbon steel plate showing a large hydrogen blister

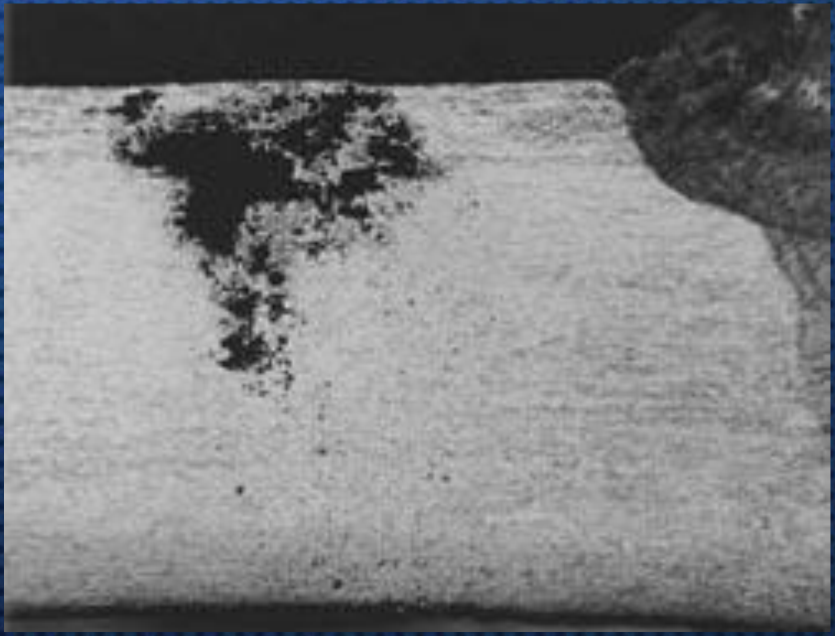


Hydrogen blistering of a carbon steel plate

Hydrogen Embrittlement

Intergranular Corrosion

- **Intergranular corrosion occurs preferentially along grain boundaries for some alloys and in specific environments**



Intergranular corrosion attack of stainless steel in the heat affected zone of welding

Erosion Corrosion

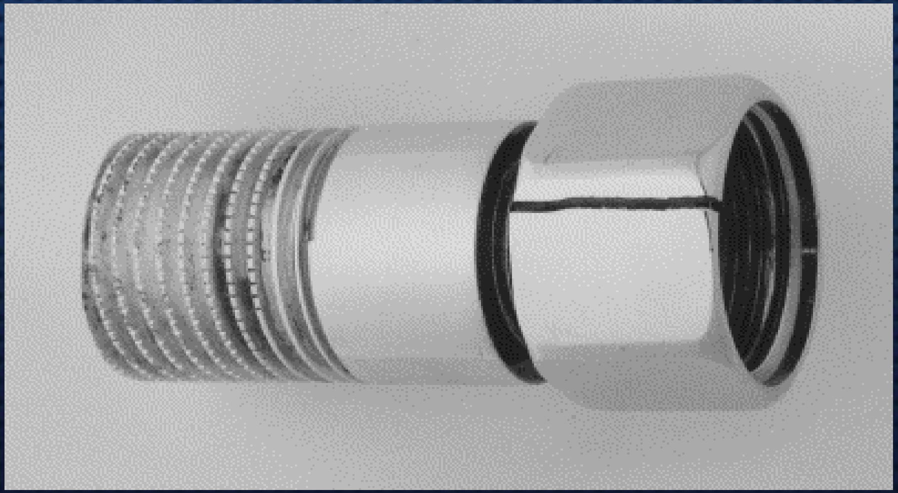
- **Erosion Corrosion arises from the combined action of chemical attack and mechanical abrasion or wear as a consequence of fluid motion.**

Erosion corrosion for: Check valve (left) and ship rotor blade (right)

Stress Corrosion Cracking

- Stress corrosion cracking (SCC) is caused by the simultaneous effects of tensile stress and a specific corrosive environment. Stresses may be due to applied loads, residual stresses from the manufacturing process, or a combination of both.

Stress corrosion cracking of stainless steel



Stress corrosion cracking of brass

II. Engineering Material

ENGINEERING MATERIALS

Materials are classified into two groups; metals and non metals

Metals are divided into ferrous and non-ferrous metals :

- Ferrous:

    e.g. Carbon Steel, Cast Iron, Stainless Steel

- Non-ferrous:

    e.g. Monel, Inconel, Hastelloy

Non metals contain several categories like:

- Polymer:

    e.g. PTFE, PF, PP, Epoxies

- Ceramics:

    e.g. Silicon Carbide

Materials Standards and Specifications

- **Materials International codes and standards aim at issuing standard procedures for testing of materials and at specifying the grades and properties of standard materials.**

International materials standards and codes

INTERNATIONAL MATERIAL STANDARD SPECIFICATION

GERMANY	D.I.N.
FRANCE	A.F. N O R.
ENGLAND	B.S.
JAPAN	J.I.S.
SWEDEN	S.I.S.
RUSSIA	G O S T
USA	A.S.T.M. A.P.I. A.N.S.I. A.W.S. A.W.W.A.

INTERNATIONAL CODES

GERMANY	T.Ü.V. D.I.N.
FRANCE	S.N.C.T.
USA	A.S.M.E. A.P.I. N.A.C.E. A.N.S.I. T.E.M.A.

Material Properties

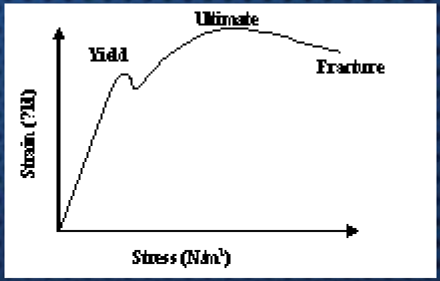
- **Physical Properties**
  - Density
  - Thermal Expansion
  - Thermal Conductivity

- **Mechanical Properties**
  - Strength (ultimate, yield)
  - Ductility
  - Elasticity
  - Hardness
  - Toughness (Impact resistance)
  - Wear Resistance
  - Creep resistance & rupture

Mechanical Properties of Material

- ## Yield Strength

  Material resistance to yield (start of plastic deformation)



- ## Ultimate Strength

  Maximum strength prior to fracture

- ## Fracture

  Material Failure

Mechanical Properties of Material

Hardness

Material resistance to notch formation, however, more hard materials are more susceptible to cracking during processing, forming, or welding

Hardness Test Methods

- Brinell Method (HB)
- Rockwell Methods (HRC, HRB)
- Vickers Method (HV)

Mechanical Properties of Material

Toughness

Toughness is defined as a materials capacity to absorb energy, which, is dependant upon strength as well as ductility

Test Methods

- Charpy V-notch
  - -Most applicable method
- Drop weight nil-ductility
  - -Used for brittle materials
- Crack tip opening displacement
  - -Used for measuring flaw size

Mechanical Properties of Material

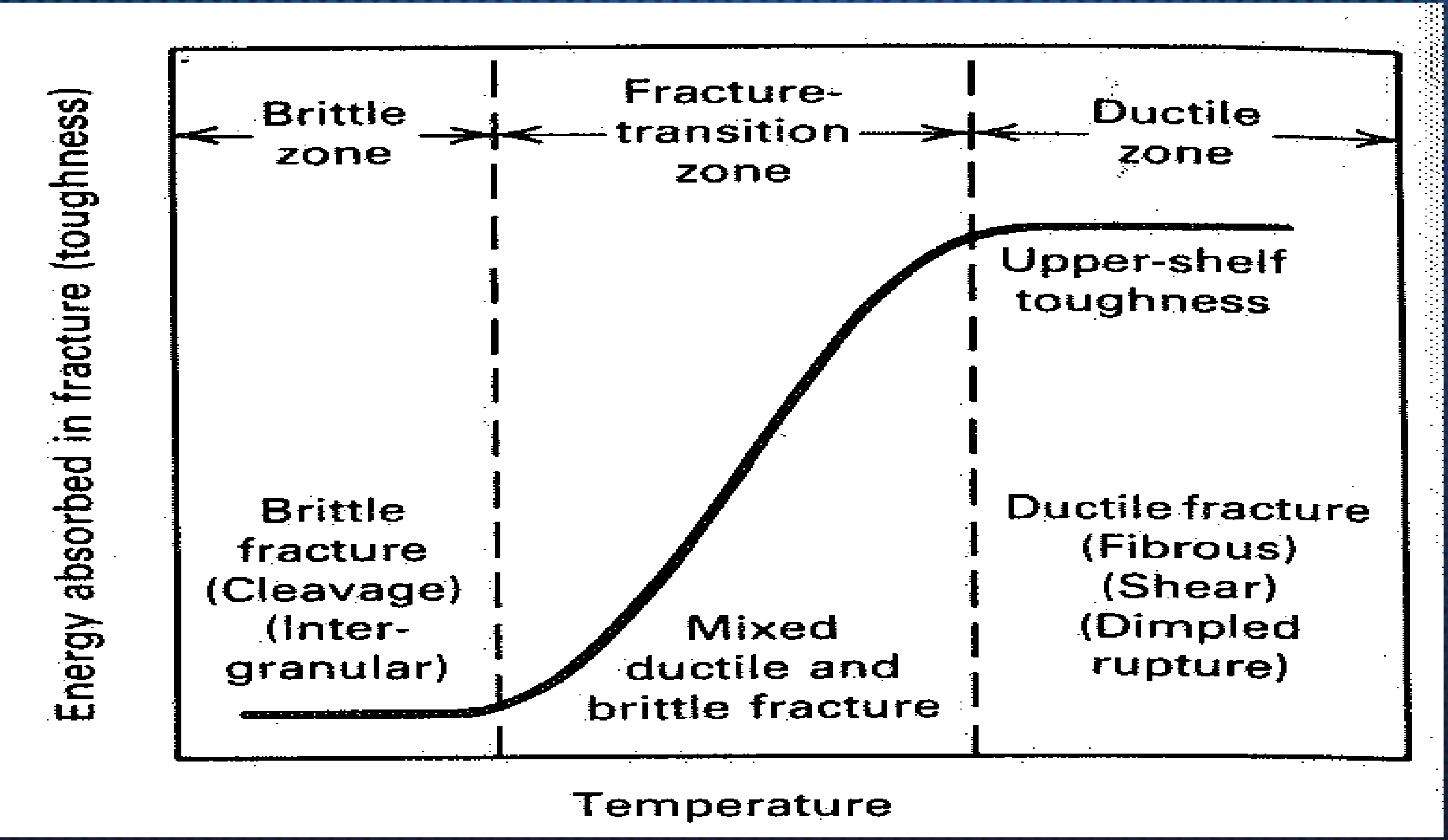
Factors affecting material toughness

- Chemical composition
- Materials processing
- Heat treatment

Ductile-to-Brittle Transition

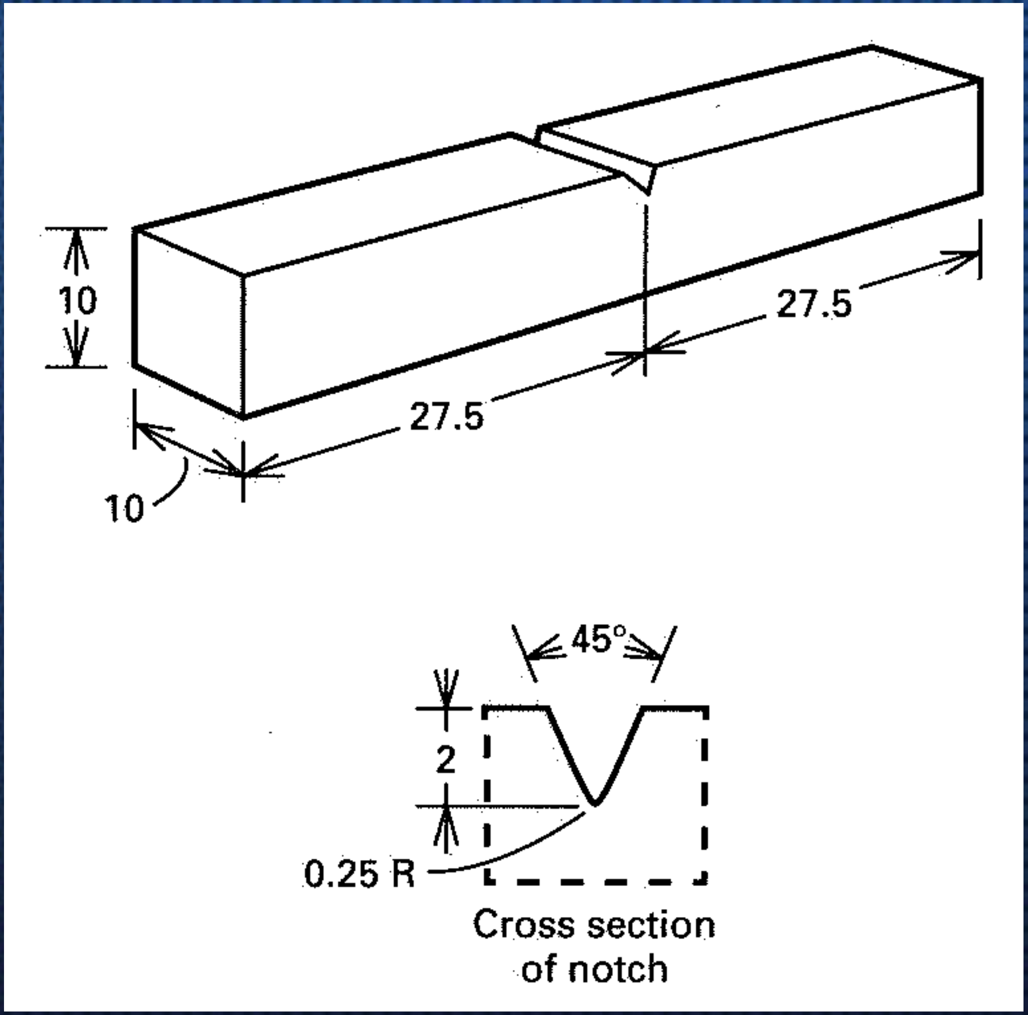
This characteristics is accompanying solid-state phase transformation changing fracture characteristics from ductile to brittle whenever metal temperature is decreased to lower levels (-29 deg. C for carbon steel materials)

Mechanical Properties of Material



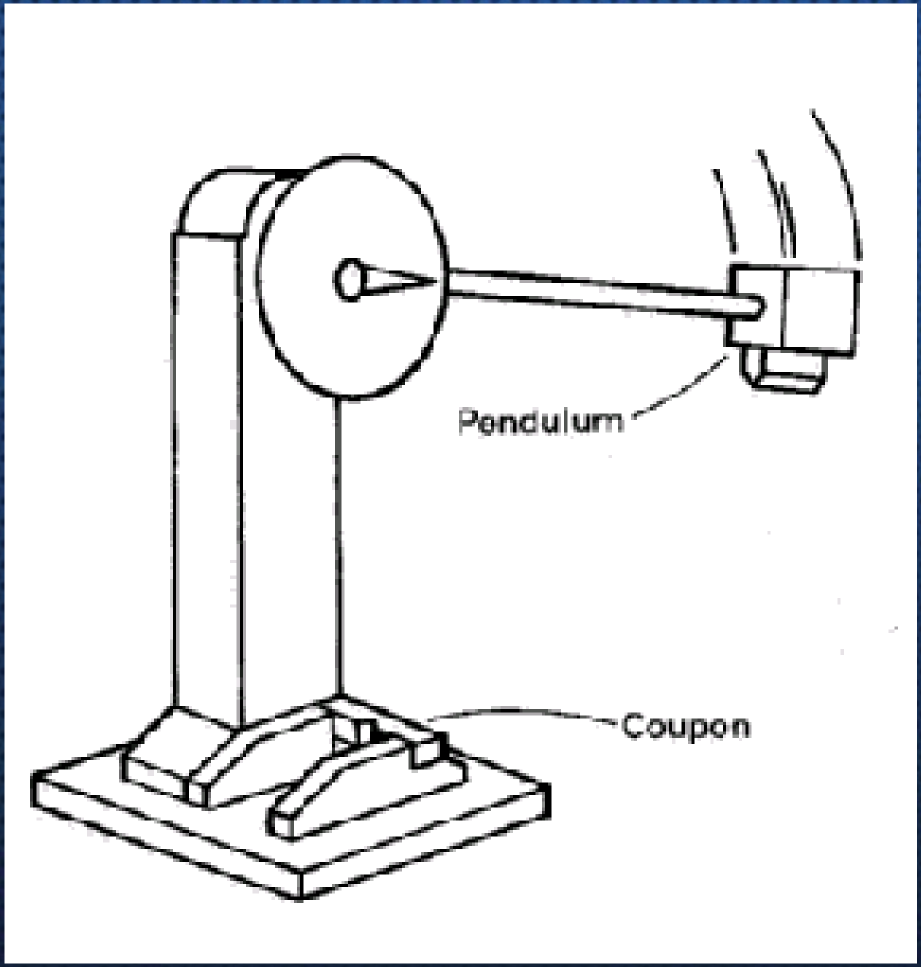
Ductile-to-Brittle Transition

Mechanical Properties of Material



V-Charpy Impact Test Specimen

Mechanical Properties of Material



V-Charpy Impact Test Set-up

Mechanical Properties of Material

Wear Resistance

Wear of metal is defined as plastic displacement of surface or near-surface material by contact with other metals, non-metallic solids, flowing liquids, solid particles contained in flowing liquids

Classification of Wear

- Metallic against non-metallic abrasive (erosion)
  - Erosion of impellers by sands contained in flowing liquid
  - Erosion of earth removing devices by abrasives in dry sand
- Metal against metal
  - Sliding
  - Rolling

  e.g. wear of shaft in bearing
- Liquid or vapor impingement on metal

  e.g. cavitation, turbulent, high-velocity flowing liquids

Mechanical Properties of Material

- **Creep**

  Creep is defined as a very slow plastic strain increased by time and temperature (time and temperature dependant) for stressed materials.

- **Rupture**

  Rupture is material failure due to creep

I. Families of Alloys

Materials Categories

For the sake of materials selection, materials fall in two categories;

1. Degradable materials (e.g. Carbon Steel)
2. Corrosion Resistant Alloys (CRA), such as stainless steels, nickel alloys, copper alloys and titanium alloys

6. Carbon Steel

- Is the most common material used today
- Known of is excellent mechanical properties
- High availability
- Economic
- Has poor corrosion resistance properties
- Usually requires corrosion control techniques

Carbon Steel Materials

Carbon Steels

Iron-Base alloys contain certain percentage of carbon as a main alloying element, however, some elements may be contained as residuals.

Classification of Carbon Steels (according to Carbon content)

- **Low-carbon steels**

  Contain upto 0.3% C

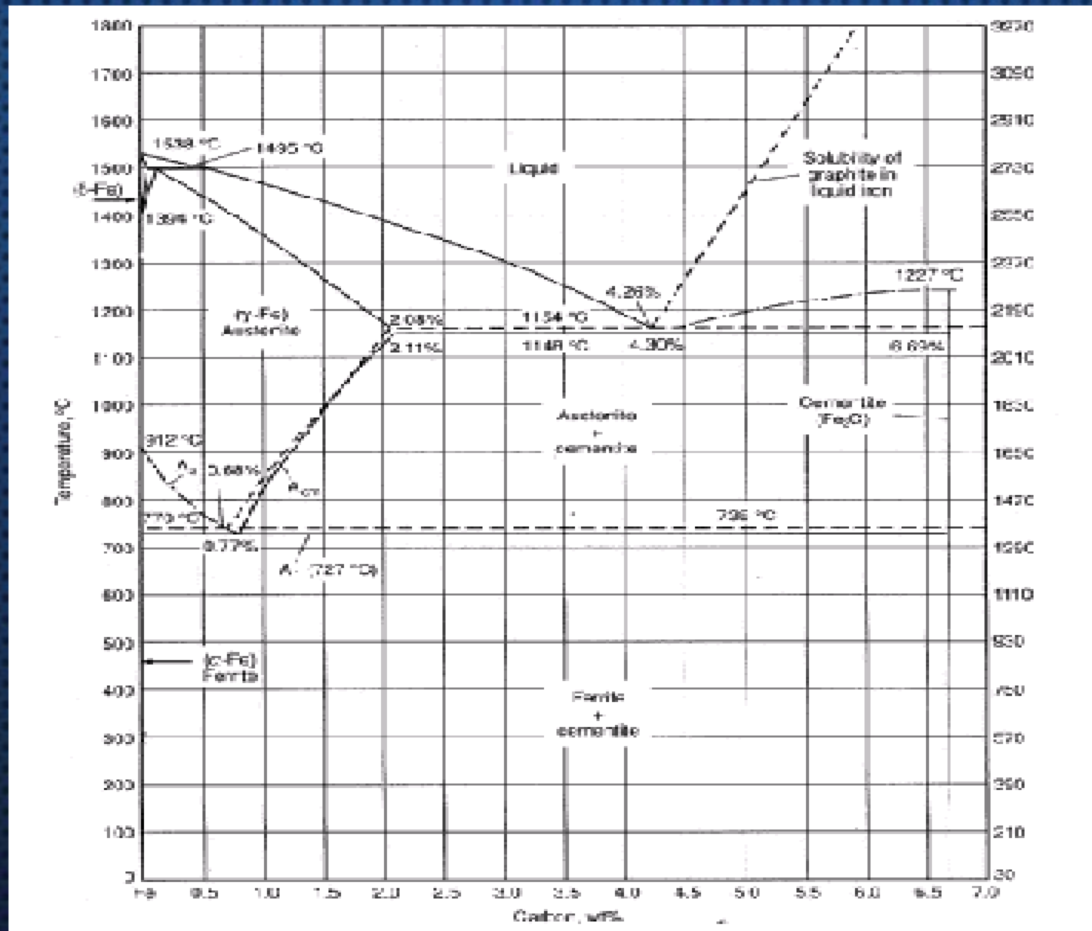
- **Medium-carbon steels**

  Contain 0.3 to 0.6% C

- **High-carbon steels**

  Contain 0.6 to 1.0 % C

Carbon Steel Materials



Iron-Carbon Diagram

Carbon Steel

- Is the most common material used today
- Known of is excellent mechanical properties
- High availability
- Economic
- Has poor corrosion resistance properties
- Usually requires corrosion control techniques

7. Stainless Steel

Experimental car made from a stainless steel body, photo taken after 30 years of manufacturing

7. Stainless Steel (Cont.)

- Stainless Steel is defined as a ferrous alloy containing a minimum of 11% of Cr content.
- Is known of its superior resistance against corrosion
- Is known of its good mechanical properties
- Is divided into five families according to their crystallographic structure

7. Stainless Steel (Cont.)

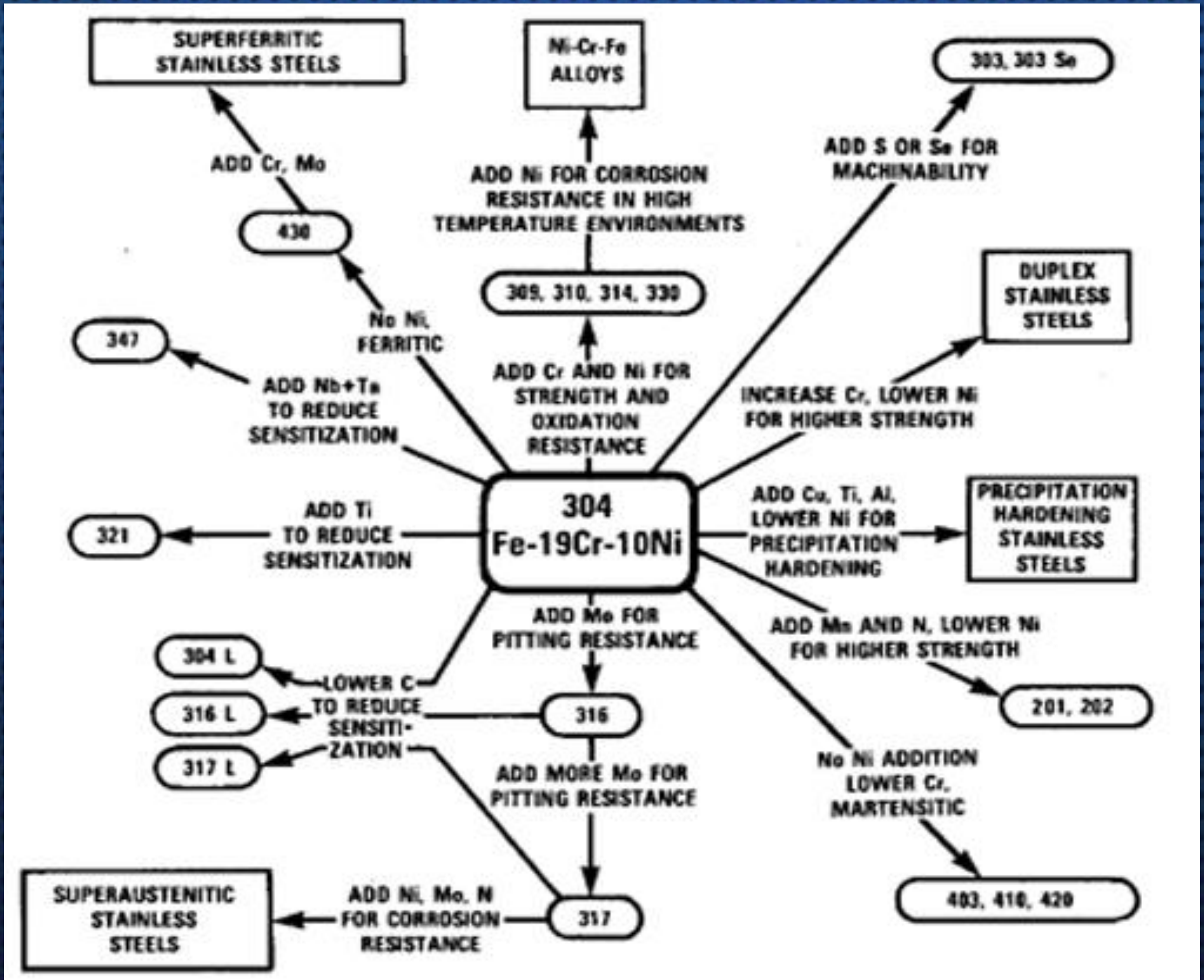
Stainless Steel families are:

- Austenitic Stainless Steel
- Ferritic Stainless Steel
- Martensitic Stainless Steel
- Super Stainless Steel
- Duplex Stainless Steel

7.1 Austenitic Stainless Steel

- Is of an austenite FCC (face centered cube structure)
- Non-Magnetic
- Non-hardenable by Heat-treatment
- Hardenable by cold-working
- Have high corrosion resistance properties
- High temperature strength
- Good weldability
- Contains a min. of 18%CR and 8%Ni as the main alloying elements
- Is recognized by the AISI (American Iron and Steel Institute) as the 3xx series, e.g. 304, 316, etc.

7.1 Austenitic Stainless Steel (Cont.)



Austenitic SS Grades

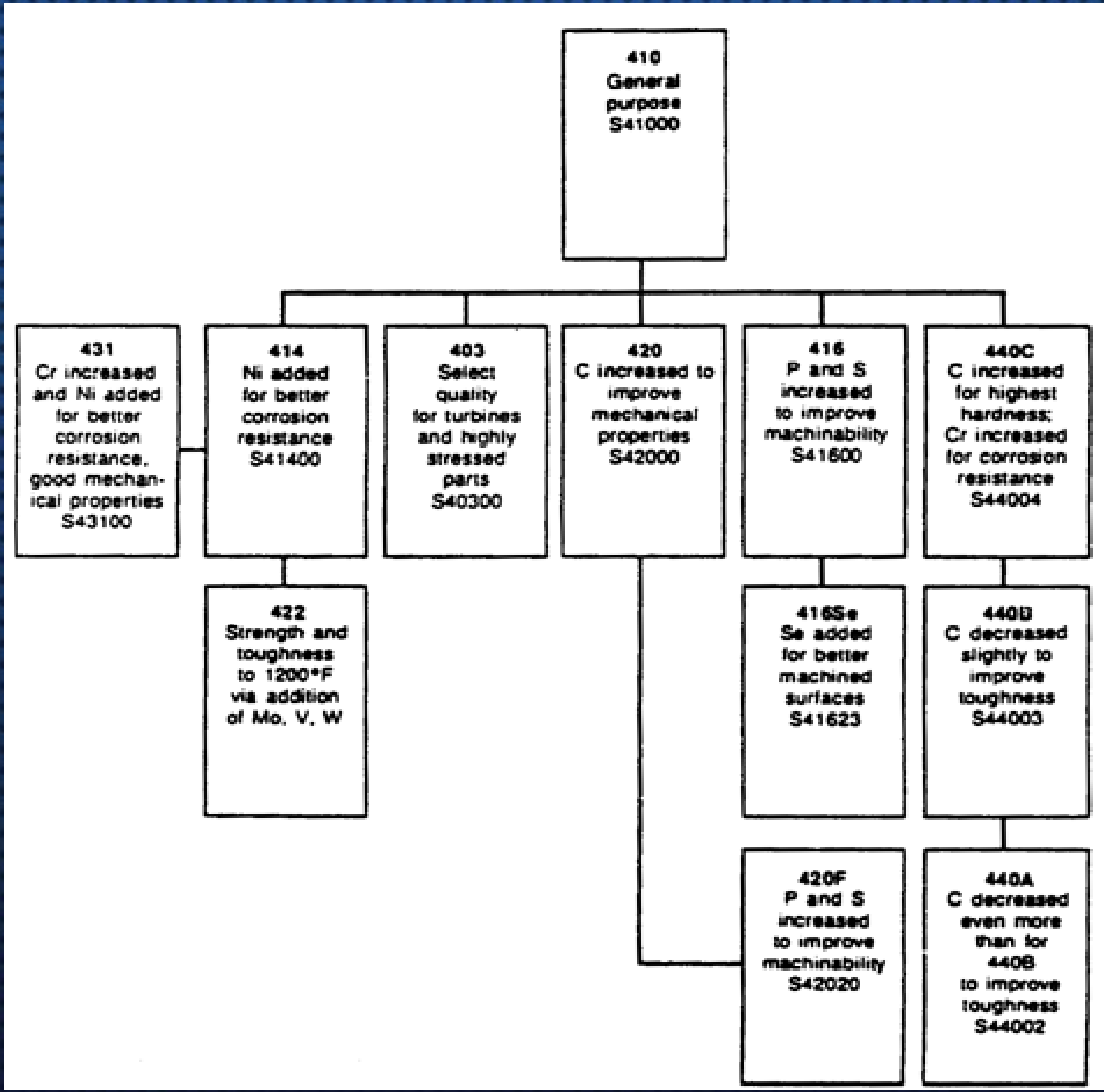
7.2 Ferritic Stainless Steel

- Is included within the AISI 400 series
- Cr is 11-30%
- Ferro-magnetic
- Not hardened by heat treatment
- Used for nitric acid services, water, food processing, automobile trims and architectural applications.
- Their impact resistance is poor
- Their weldability is poor
- The general-purpose grade of this stainless steel family is grade 430 which contains 17% Cr.
- Contains Cr and Mo as the major alloying elements

7.3 Martensitic Stainless Steel

- Martensitic SS are hardenable grades
- Resist high temperatures, used in turbine blades
- Have a fair corrosion resistance and are only used in mild environments
- The most common grade is grade 410
- These grades are difficult to weld
- Their low temperature impact resistance is also poor
- Contains mainly Cr as the major alloying element
- Is the cheapest stainless steel

7.3 Martensitic stainless steel(Cont.)



Martensitic SS Grades

7.4 Super Stainless Steel

- The most famous super stainless steel is the 6 moly SS
- Super stainless steel have been developed to cover some weakness in corrosion resistance
- Mainly developed to combat chloride stress corrosion cracking that occurs to all austenitic grades
- The other famous SS type is the AISI 904 which is considered to be a non ferrous alloy due to its high Ni content

7.5 Duplex Stainless Steel

- Approximately they have 50% Austenite and 50% Ferrite
- Ferrite forming alloys such as Mo and Cr are present as well as Ni
- Duplex contains Mo for more resistance Chloride pitting
- Ferrite/Austenite mixture is not a blessing where any of the two phases can be selectively attacked or even galvanically corroded
- Welding of duplex should be controlled and monitored closely where the austenite phase could turn to ferrite

8. NICKEL AND NICKEL ALLOYS

- Is a noble metal, this is why it is known of it superior resistance to corrosion
- Ni forms a protection layer of nickel oxide
- Ni and Ni alloys are being used extensively in industry
- Its relatively high cost relative to the carbon steel or to the conventional stainless steel grades, resembles the only problem

8. NICKEL AND NICKEL ALLOYS (Cont.)

Ni and its alloys are found as :

- **Ni (Alloys 200 &201)**
- **Ni-Cu alloys (Alloys 400,K500, Cupronickel alloys 90/10 &70/30)**
- **Nickel-Molybdenum alloys (Alloy B-2)**
- **Nickel-Chromium-Iron alloys (Alloys 600 & 800)**
- **Nickel-Chromium-Molybdenum alloys (C-276, C-4 & alloy 625)**

8.1 Ni (alloys 200 &201)

- Corrosion rates in waters contaminated or aerated is less than 0.1 mm/yr

- Not resistant to stagnant seawater

- Is resistant to all salt solutions at all concentrations

- Resistant to of oxidizing and reducing acids

8.2 Ni-Cu alloys (alloys 400, K-500, Cupro-Nickels 90/10 & 70-30)

- Alloy 400 (Monel) si 65% Ni, 30% Cu, is resistant to HCl, to alkaline and neutral salts.
- Most famous application of Monel, is its use in the overhead section in crude distillation units.
- Cupro-nickel alloys 90/10 & 70/30 were mainly developed to be used as piping for the marine atmospheres

8.3 Nickel-Molybdenum alloys (Alloy B-2)

- **Addition of molybdenum ensures good resistance to chloride pitting and to reducing acids in general. Also alloy B-2 is known of its immunity against stress corrosion cracking.**

8.4 Nickel-Chromium-Iron alloys

(Alloys 600 & 800)

- Due to the high Chromium content, these two alloys were developed to be used in corrosive gases at extremely high temperatures under oxidizing conditions.

8.5 Nickel-Chromium-Molybdenum alloys

(C-276, C-4 & alloy 625)

- Nickel-Chromium-Molybdenum alloys combine the good resistance properties of the last two families they considered like the super-nickel alloys where they are resistant to nearly every single environment and hence their cost is considerably higher than the other Ni alloys.

9. TITANIUM AND TITANIUM ALLOYS

- Is widely used in aerospace, medical and petroleum industries
- Is known of its excellent corrosion resistance properties
- Used in seawater cooling, seawater valves and fittings, data logging systems, cathodic protection anodes, pumps and valves as well as underwater operations.

III. Corrosion Monitoring & Control

How we control Corrosion?

1. **Anodic** : by blocking the anodic reaction
2. **Cathodic** : by blocking the cathodic reaction
3. **Mixed** : by blocking both anodic & cathodic reactions

The army of corrosion control techniques is deployed to fulfill this goal

Corrosion Control Techniques

Corrosion control techniques are based on the mechanisms of the eight forms of corrosion: These techniques are:

1- Proper Materials Selection.

2- Improved design.

3- Environmental Process Control.

4- Utilization of Corrosion Inhibitors.

5- Application of Coatings and Paints.

6- Cathodic Protection.

I. MATERIALS SELECTION

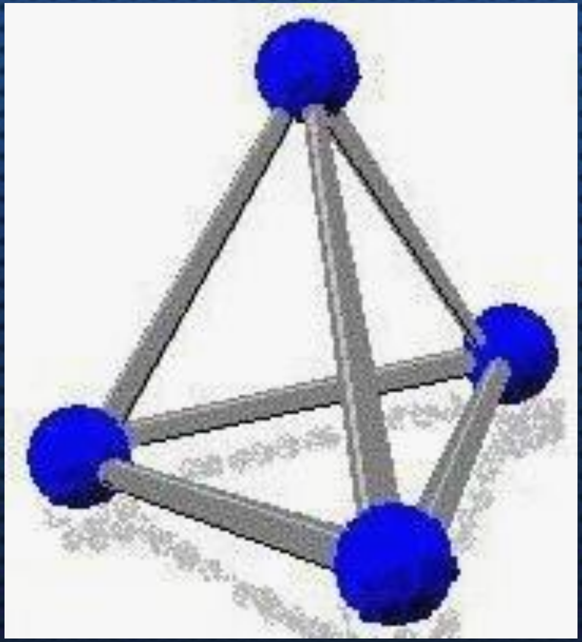
Corrosion Control Techniques

Materials Selection

Materials Selection Factors:

Corrosion Resistance

Mechanical Properties

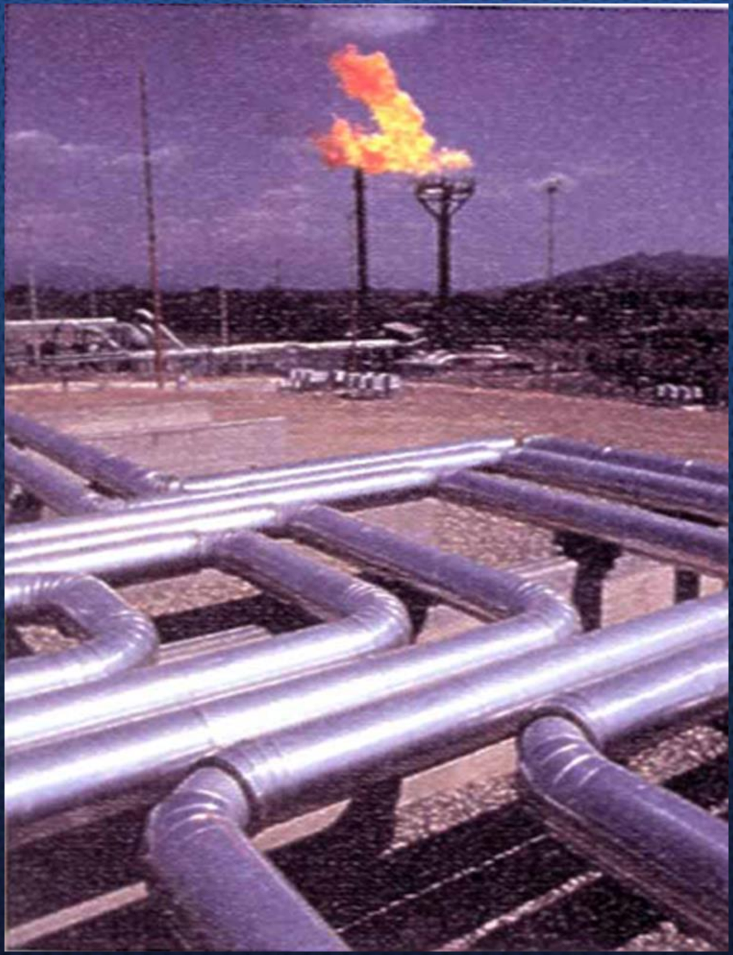


Cost Effectiveness

Availability

Corrosion Control Techniques

Materials Selection



INTRODUCTION

- Materials play an important role in our lives.
- Historical ages have been defined in conjunction with development of materials.

1- Materials Selection
Introduction

- ✓ Is considered as the first line of defense towards corrosion control.
- ✓ Is made to ensure proper resistance against the intended service environment.
- ✓ Materials are selected also against mechanical properties as well as cost viability.

Introduction (cont.)

- Materials selection is made either using a degradable material (carbon steel) with the addition of a “corrosion allowance” with or without the addition of a corrosion control technique (e.g. coating, cathodic protection, etc.)
- Or using a corrosion resistant alloy (a material that doesn’t readily corrode in the environment) such as the use of stainless steel or nickel alloys.
- The decision either to go for a CS or for CRA depends mainly on economics as well as other factors such as replacement capabilities, maintainability, criticality of service, etc.

Introduction (cont.)

Materials selection for corrosion control depends upon

1. Knowledge of materials properties and corrosion control
2. Knowledge of corrosion process, mechanism and theory
3. Knowledge of service (environment, its operating conditions)
4. Knowledge of materials behavior with the environment
5. Knowledge of lifetime required
6. Knowledge of economics
7. Knowledge of corrosion control techniques
8. Case histories in same application

Introduction (cont.)

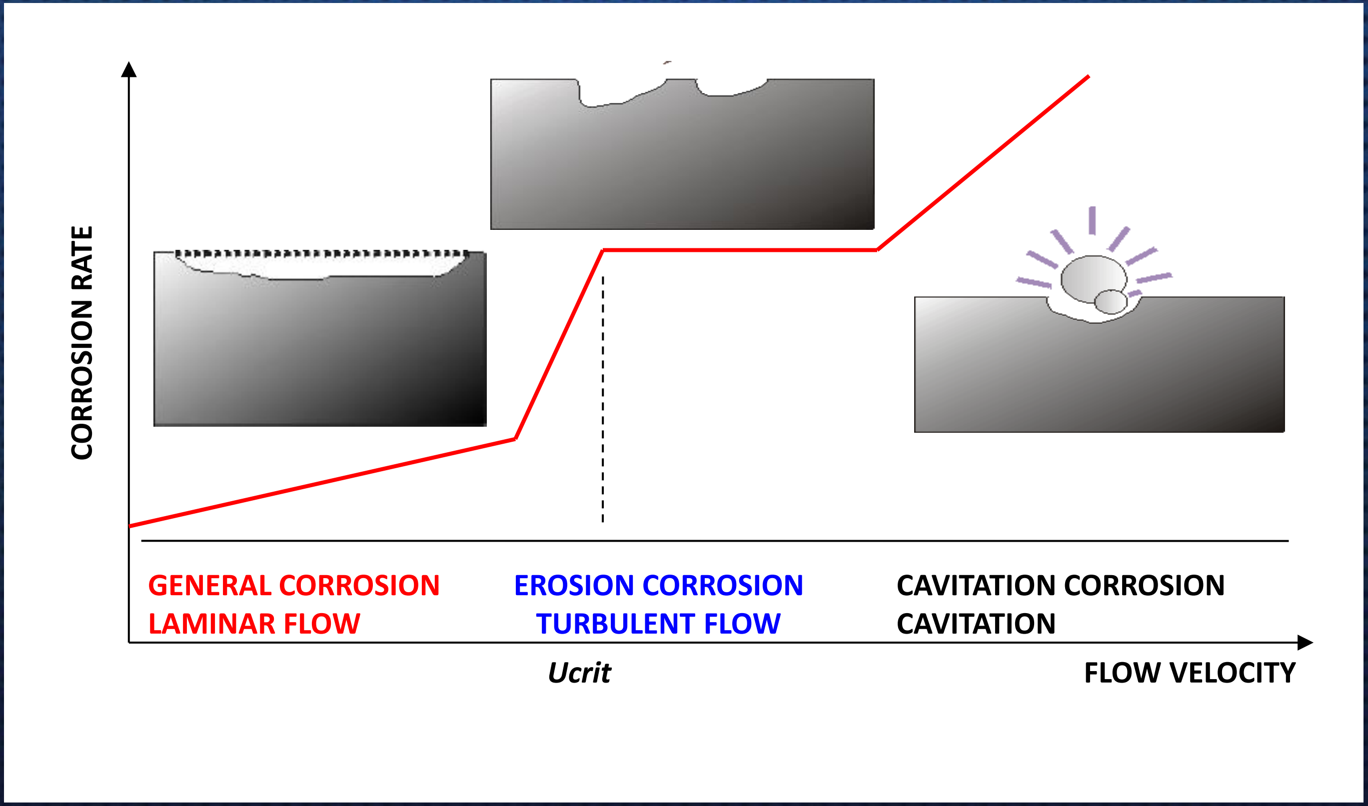
A. Information needs

- Process flow diagrams (PFD) showing design/ operating/ upset conditions of:
    - Temperature (min. & max.)
    - Pressure
- Stream chemical analyses showing the corrosive constituents and their concentrations:
    - H_2O
    - Dissolved gases (O_2, CO_2, H_2S)
    - Cl^-
    - TDS (total dissolved salts)
    - pH
    - TAN (total acid number) for crude oil
    - Total Sulfur Content

Introduction (cont.)

3. **Stream Velocity**

   Corrosion rate and corrosion type are function of flow velocity



Introduction (cont.)

B. <u>Issuance of materials selection diagram (MSD) and materials selection philosophy report (MSPR)</u>

<u>MSG</u> = PFD with designated material of construction for each equipment

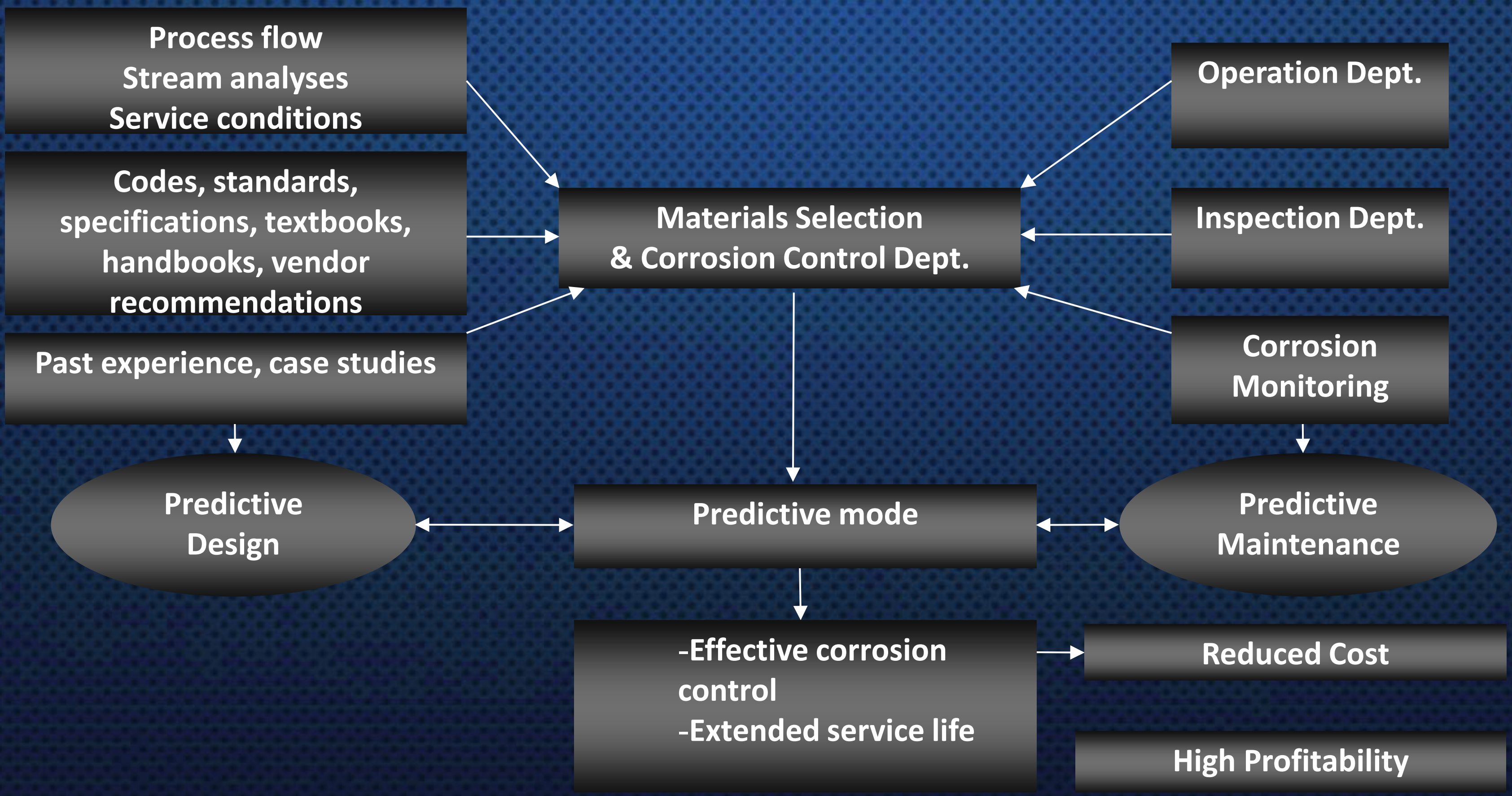
<u>MSPR</u> = highlights:

- expected corrosion mechanism
- predicted corrosion rates
- material of construction of each stream and equipment.

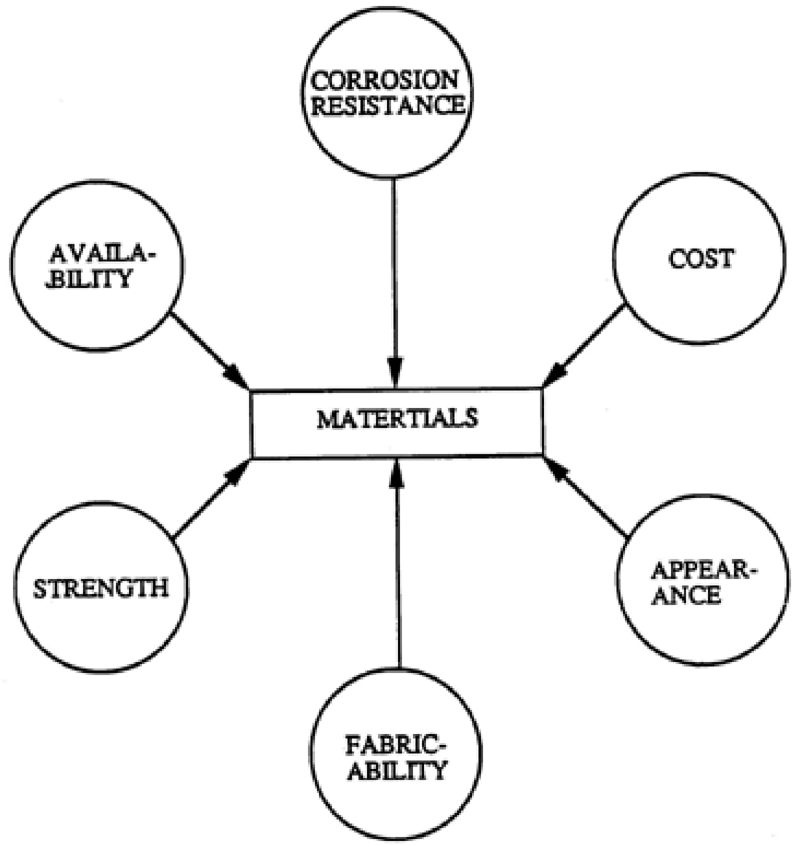
Effect of temperature on material selection

	Design Temperature, °F	Material	Plate	Pipe	Forgings	Fittings	Bolting
Cryogenic	−425 to −321	Stainless steel	SA-240-304, 304L, 347, 316, 316L	SA-312-304, 304L, 347, 316, 316L	SA-182-304, 304L, 347, 316, 316L	SA-403 304, 304L, 347, 316, 316L	SA-320-B8 with SA-194-8
	−320 to −151	9 nickel	SA-353	SA-333-8	SA-522-I	SA-420-WPL8	
Low temperature	−150 to −76	3½ nickel	SA-203-D	SA-333-3	SA-350-LF3	SA-420-WPL3	SA-320-L7 with SA-194-4
	−75 to −51	2½ nickel	SA-203-A				
	−50 to −21	Carbon steel	SA-516-55, 60 to SA-20	SA-333-6	SA-350-LF2	SA-420-WPL6	
	−20 to 4		SA-516-All	SA-333-1 or 6			SA-193-B7 with SA-194-2H
	5 to 32		SA-285-C	SA-53-B SA-106-B	SA-105 SA-181-60,70	SA-234-WPB	
Intermediate	33 to 60		SA-516-All SA-515-All SA-455-II				
	61 to 775						
Elevated Temperature	776 to 875	C-½Mo	SA-204-B	SA-335-P1	SA-182-F1	SA-234-WP1	
	876 to 1000	1Cr-½Mo	SA-387-12-1	SA-335-P12	SA-182-F12	SA-234-WP12	
		1¼Cr-½Mo	SA-387-11-2	SA-335-P11	SA-182-F11	SA-234-WP11	
	1001 to 1100	2¼Cr-1Mo	SA-387-22-1	SA-335-P22	SA-182-F22	SA-234-WP22	with SA-193-B5 SA-194-3
	1101 to 1500	Stainless steel	SA-240-347H	SA-312-347H	SA-182-347H	SA-403-347H	SA-193-B8 with SA-194-8
		Incoloy	SB-424	SB-423	SB-425	SB-366	
	Above 1500	Inconel	SB-443	SB-444	SB-446	SB-366	

MATERIALS SELECTION



Materials Selection (cont.)



MATERIAL SELECTION FACTORS

Materials Selection (cont.)

Materials selection for corrosion control requires knowledge of corrosion theory and dynamics as well as materials behavior in corrosive environments, factors are summarized as follows:

1. **Corrosion Theory**
2. **Corrosion Forms**
3. **Criticality of Service**
4. **Lifetime Required**
5. **Corrosion Control Techniques**
6. **Corrosion Resistance of Materials**

2. Corrosion Allowance

- Carbon steel is the classical material that is used in construction, its performance in any atmosphere shall be determined and hence we have to determine the quantity of metal to be lost by corrosion and then account for during design

Corrosion Allowance (Cont.)

$$CA= CR \times LT$$

- Where CA is the Corrosion allowance in mils (1/1000 inch) or in mm
  CR is the estimated corrosion rate in such an environment in mil/year or mm/year
  LT is the required lifetime in years.

- Calculating a corrosion rate is either uniform or considering the maximum localized corrosion rate (which is always harder to quantify)

Corrosion Allowance (Cont.)

CORROSION ALLOWANCE & DESIGN

CYLINDRICAL SHELLS	SPHERES & HEMISPHERICAL SHELLS	PIPES
$t = \frac{PR}{SE - 0.6P} + C.A.$	$t = \frac{PR}{2SE - 0.2P} + C.A.$	$t = \frac{PR}{SE - 0.6P} + C.A.$

P DESIGN PRESSURE IN Psi

R INSIDE RADIUS, INCH

S STRESS VALUE OF MATERIAL, Psi

E JOINT EFFICIENCY

CA CORROSION ALLOWANCE, INCH

t MINIMUM CORRODED THICKNESS

$$\text{LIFE TIME} = \frac{\text{Corrosion Allowance (mm)}}{\text{Corrosion Rate mm/year}} = \text{Years}$$

CA involvement in codes

3. Materials Selection in Selected Environments

- The following shall present the methodology of materials selection in some selected corrosive environments in the oil/gas industry

3.1. HIGH TEMPERATURE SULFUR CORROSION

- Crude oils and their fractions contain sulfur compounds including polysulfides, hydrogen sulfide, mercaptans, aliphatic sulfides, disulfides and thiophenes. At temperatures in the range 260°C to 540°C steels are significantly corroded by these compounds.

- Corrosion rates reduce above 540°C if a protective coking layer forms and is maintained.

- As a first approximation, corrosion rates for the various steels used in such applications (carbon steel, 1¼Cr to 9CrMo steels, 18/8 stainless steels) may be estimated using Modified McConomy Curves factored for sulfur content

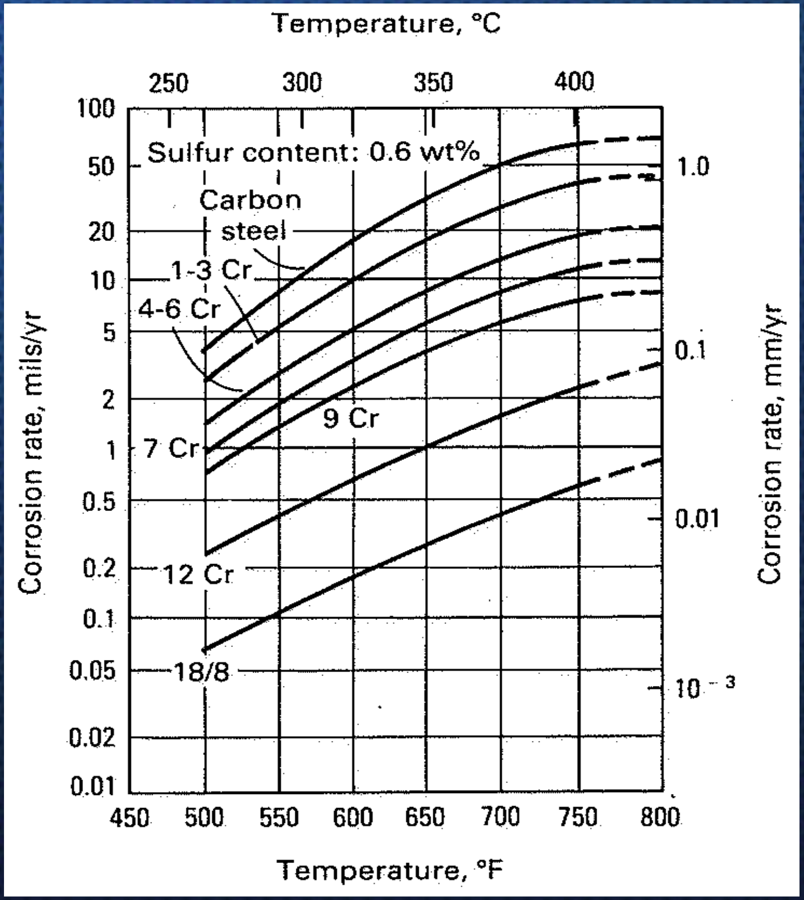
3.1. HIGH TEMPERATURE SULFUR CORROSION (CONT.)

- **Crude oils and their fractions contain sulfur compounds including polysulfides, hydrogen sulfide, mercaptans, aliphatic sulfides, disulfides and thiophenes. At temperatures in the range 260°C to 540°C steels are significantly corroded by these compounds.**

- **Sulfur corrosion depends on temperature and total sulfur content**

3.1. HIGH TEMPERATURE SULFUR CORROSION (CONT.)

Couper and Gorman curve for determination of corrosion rate for crudes containing sulfur



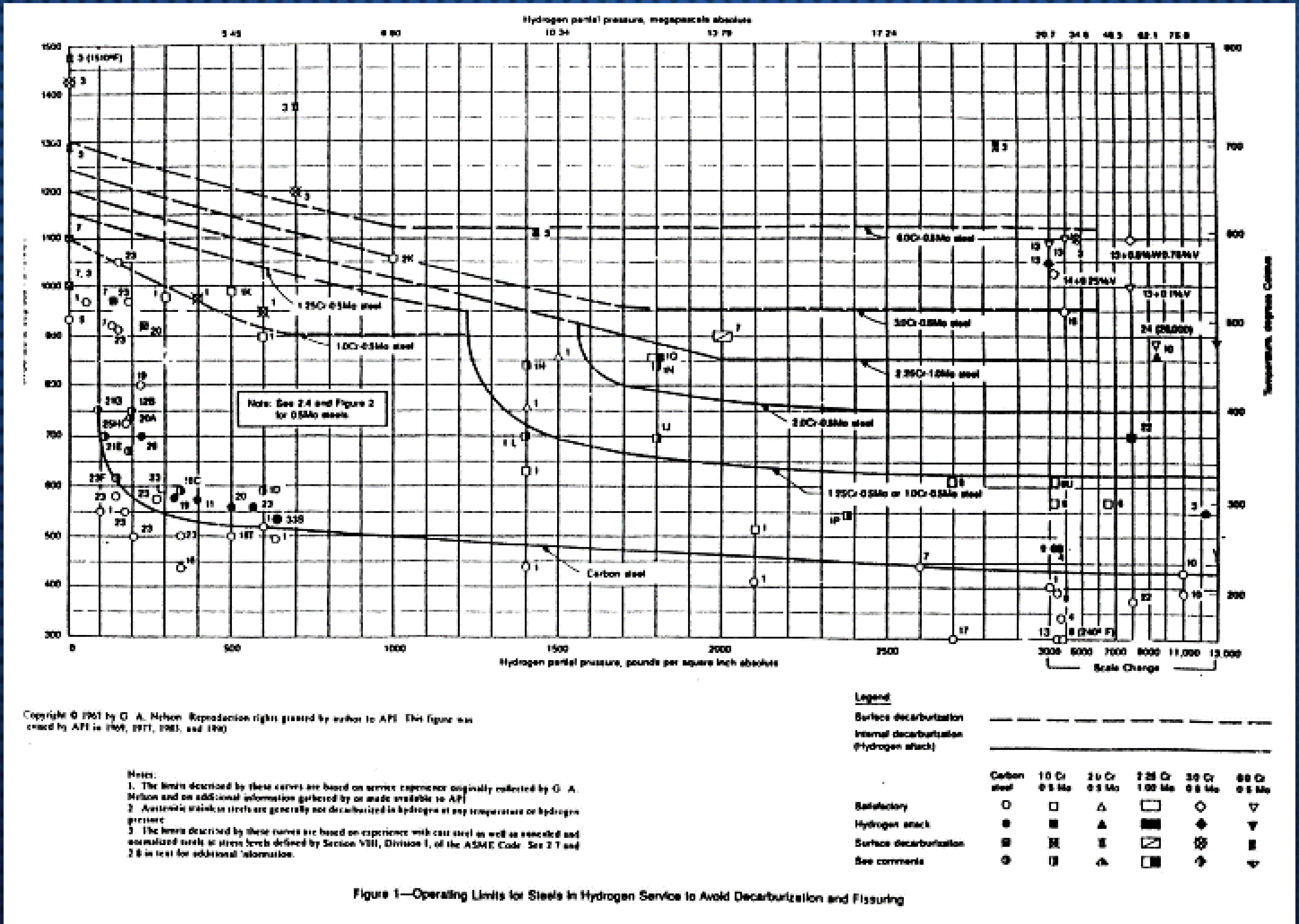
Rate of sulfur attack on steels depends on Cr content

3.2. HYDROGEN ATTACK

- Hydrogen service is defined as one in which the partial pressure of hydrogen exceeds 100 psig

- Hydrogen service damage of steels consists of internal fissuring and is avoided by selection of steels in accordance with API 941

3.2. HYDROGEN ATTACK(CONT.)



API 941 for Hydrogen Service

3.3. NAPHTHENIC ACID CORROSION

- Crude oils are considered to be "Naphthenic" in character and to give rise to corrosion at temperatures above about 230°C by organic acids when the Neutralization Number exceeds 0.5 mg KOH/g of crude oil.
- Carbon steel becomes not suitable in Naphthenic acid service.

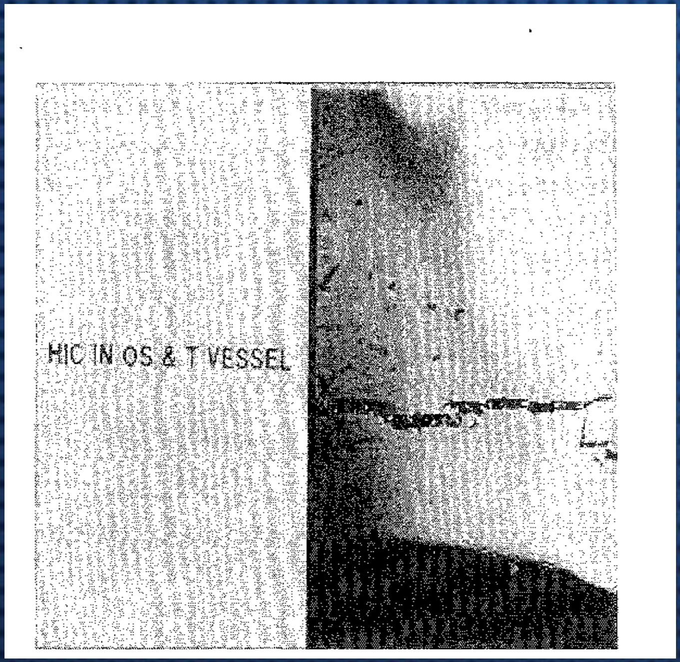
3.4. Wet Hydrogen Sulfide Attack

- Wet H_2S service is one in which liquid water with sufficient dissolved hydrogen sulfide is present to cause sulfide stress corrosion cracking (SSCC) and/ or hydrogen induced cracking (HIC) of vulnerable materials.
- The tendency for SSCC to occur in materials is a function of material type, condition, applied tensile stress and the amount of H_2S present in the water phase.
- The threshold conditions above which precautions have to be taken to avoid SSCC are defined in NACE MR0175

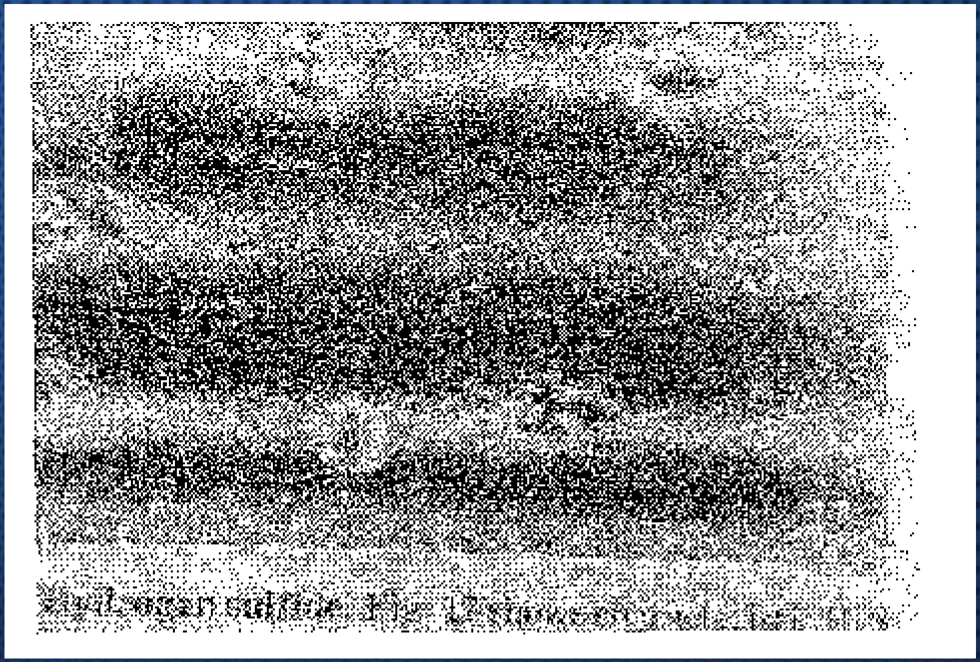
3.4. Wet Hydrogen Sulfide Attack

- H_2S is soluble in water
- Its aqueous solution behaves as a week acid
- CS shall:
  - contain Ni < 1% and S < 0.02
  - be normalized and thermally stress relieved
  - Have hardness < 22 HRC
  - have reasonable corrosion allowance
- Use of austenitic stainless steel and CRA

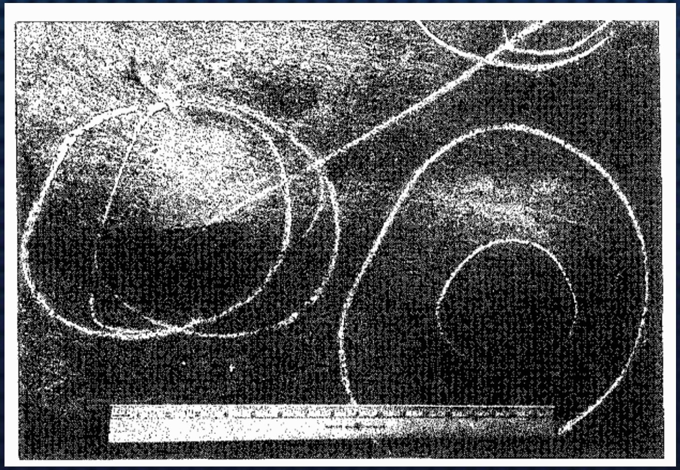
3.4. Wet Hydrogen Sulfide Attack



SCC

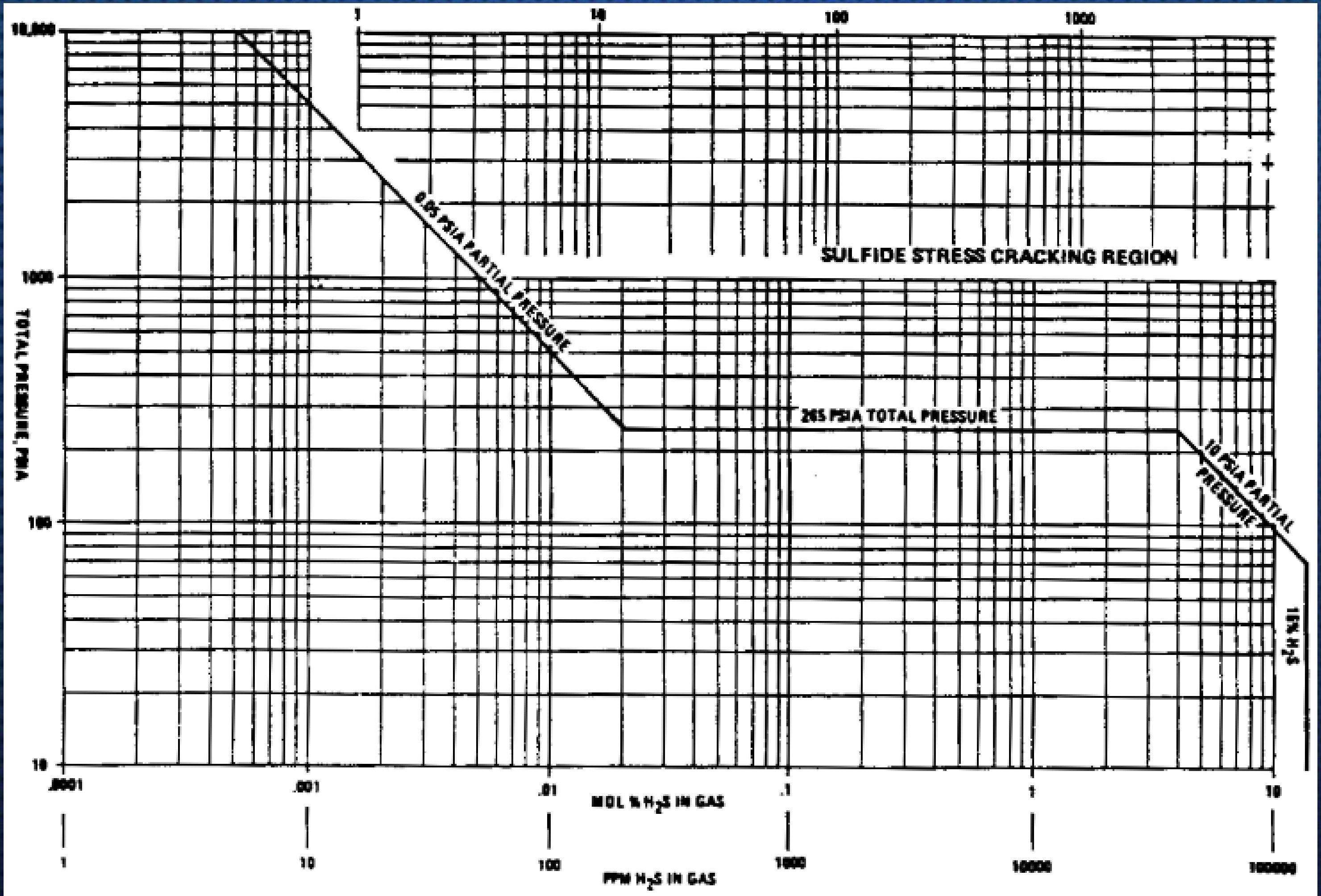


Pitting



Hydrogen embrittlement

3.4. Wet Hydrogen Sulfide Attack



NACE MR-01-75 in multiphase systems

3.5. POLYTHIONIC ACID CORROSION

- Is a mixture of sulfurous acids formed by the interaction of sulfides, moisture, and oxygen, and occurring when equipment is shutdown
- Austenitic stainless steels operating in sulphurous service in excess of 400° C can suffer a very severe and rapid form of intergranular stress corrosion on shutdown caused by polythionic acids (PTA) which form when moisture condenses and combines with high temperature sulfide scales in the presence of oxygen.
- Two strategies to avoid PTA are available. The most resistant grades of stainless steel, type 347 and 321, can be selected or the equipment can be provided with an alkaline wash on shutdown, as outlined in NACE RP0170

3.6. AMINE SERVICE

- Amine service is one containing aqueous solutions of monoethalomine (MEA), or diethanolamine (DEA), or methyldiethanolamine (MDEA), or di-isopropanolamine (DIPA), usually in about 30 % concentrations. DEA is to be used mainly in hydrogen sulfide removal units.

- Some precautions shall be made for the use of materials in amine units where amine solutions are capable of causing stress corrosion cracking of welded or cold-formed steel parts

3.6. AMINE SERVICE (CONT.)

item	requirements
Carbon and carbon manganese steel equipment (vessels, exchangers, filters etc.), paperwork and instrumentation (wetted parts).	*Fully killed steel (i.e. contains > 0.1% Is)* *"Requirements for Wet H_2S Service" apply in the case of Rich Amine Service.* *Cold formed items, including exchanger tubing bends shall be stress relieved.* *Post weld heat treat irrespective of thickness and operating temperature, including attachment and repair welds.*
Screwed connections	*Not permitted*
Copper or copper based alloys	*oNot permitted*
Aluminum or aluminum based alloys	*NNot permitted in Rich Amine Service*

Requirements For Materials In Amine Service

3.7. CAUSTIC SERVICE

- Depending on concentration and temperature, sodium hydroxide solutions can cause stress corrosion cracking of weldments and cold-formed items in carbon steels.

- Care should be made on using carbon steel for caustic service

3.8. WET CO_2 CORROSION

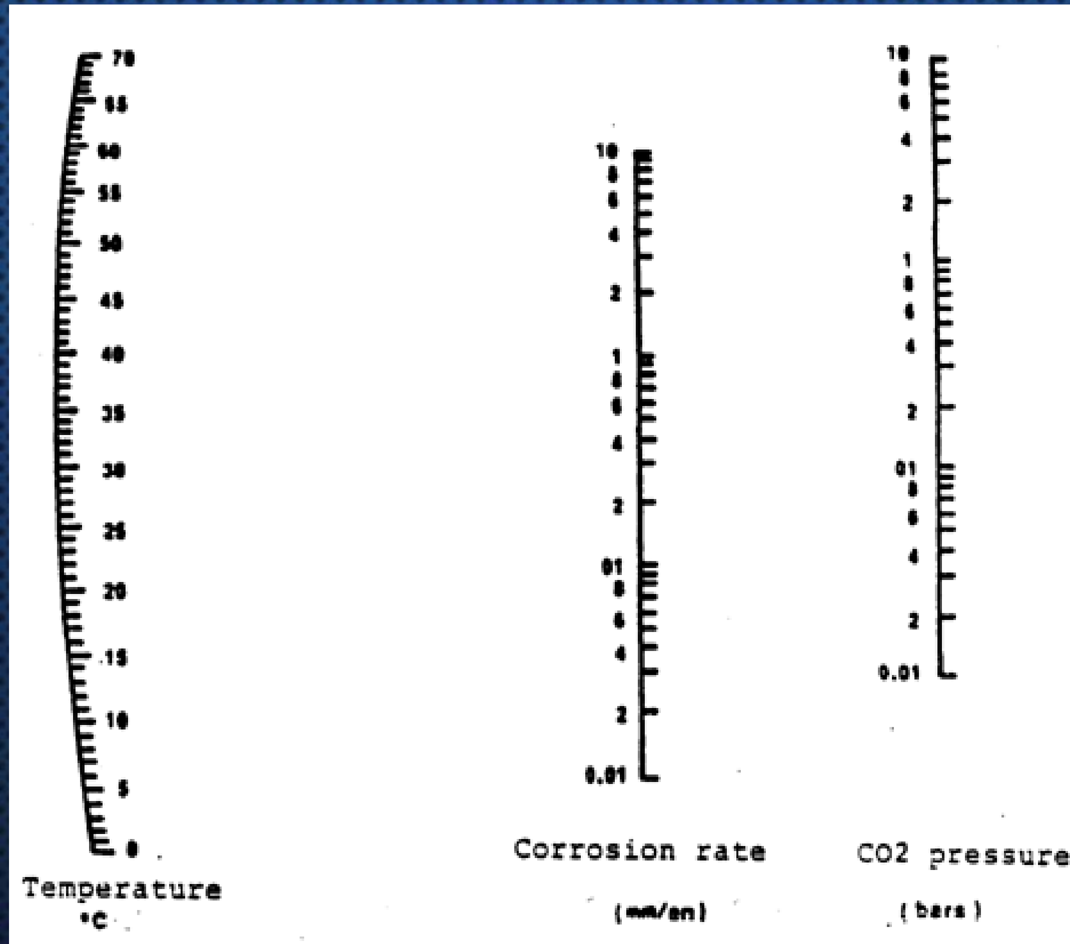
- This corrosion mechanism, less commonly encountered in refineries than upstream oilfield and gas plant operations, is caused by carbonic acid.

- Carbonic acid is corrosive to carbon and low alloy steels, corrosivity being dependent on a range of factors including CO_2 partial pressure, temperature, and liquid phase composition and flow velocity. Corrosion rates have been calculated using de Waard et al formulae

CARBON DIOXIDE CORROSION

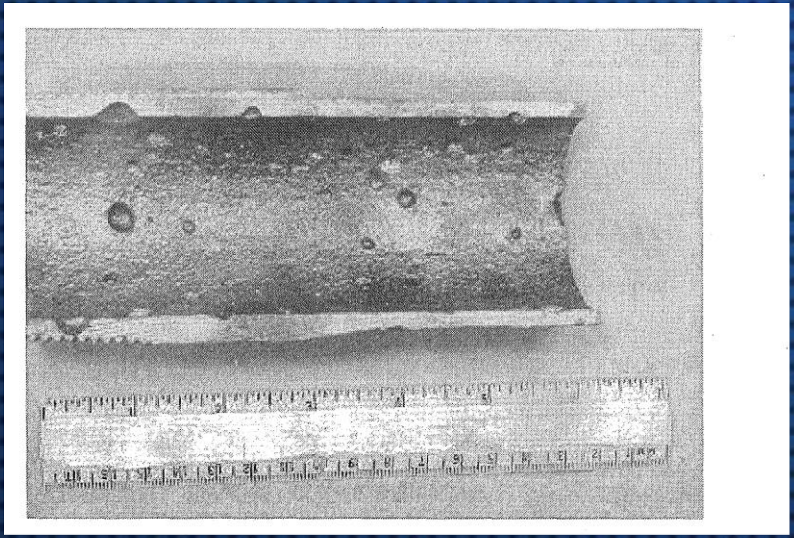
- CO_2 Gas is soluble in water
- CO_2 Solubility increases with temperature and pressure
- CO_2 Dissolves in water forming carbonic acid which attacks carbon steel
- With CS, use of filming and neutralizing inhibitors + suitable corrosion allowance
- Use of austenitic stainless steel if water contains less than 400ppm Cl- and temperature less than 50 Deg C
- The best alternative is the use of duplex stainless steels or higher corrosion resistant alloys (CRA)

3.8. WET CO_2 CORROSION (CONT.)

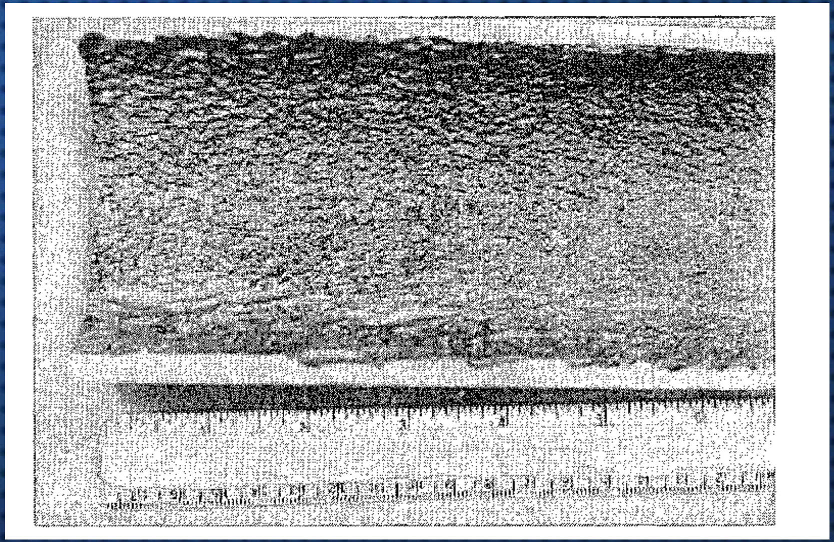


Nomogram for CA of CS in CO_2 Service,
De-Waard and Milliams

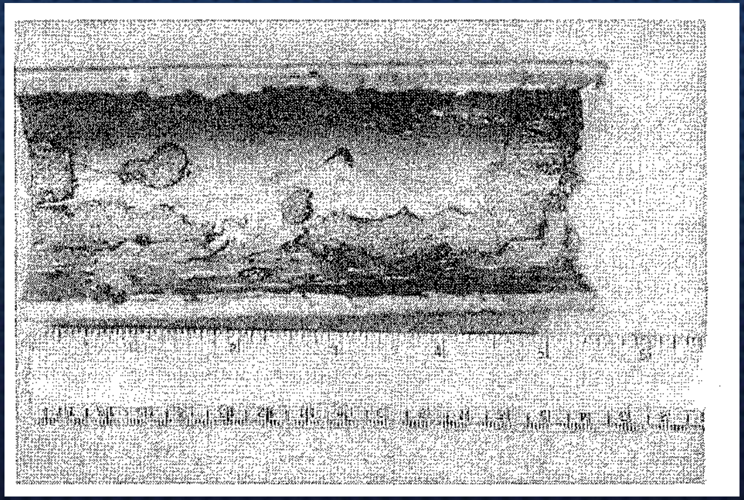
FORMS OF CO_2 CORROSION (CONT')



CO2 Pitting Corrosion



Uniform



Pitting with scales in turbulent zones

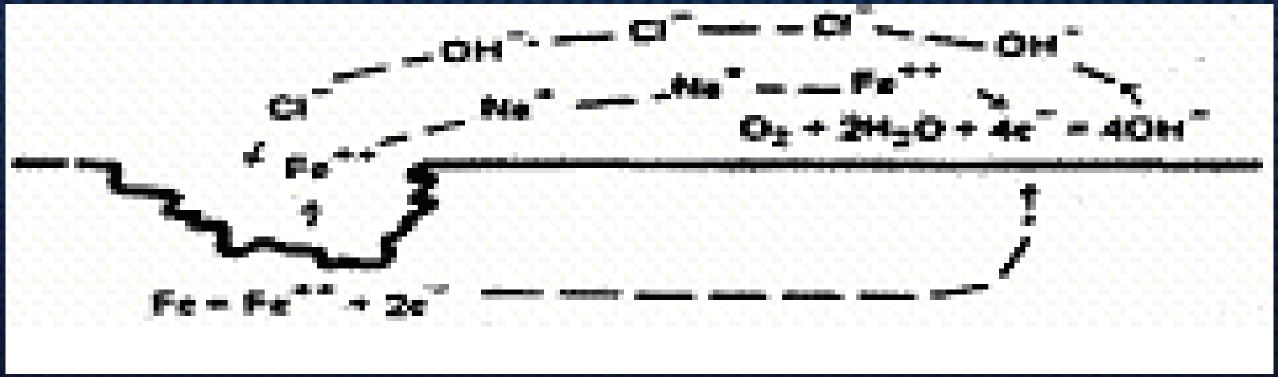
3.9. CHLORIDES CORROSION

- Austenitic stainless steels and high alloys may be prone to pitting, crevice or stress corrosion cracking in chlorides environment

- The standard 300 series austenitic stainless steels are potentially at risk of stress corrosion cracking in chloride containing environments at temperatures above about 60°C. It is common to apply external coatings, or foil wrapping under insulation, to such pipework in marine environments to prevent access of chlorides from rainwater and concentration at the metal surface.

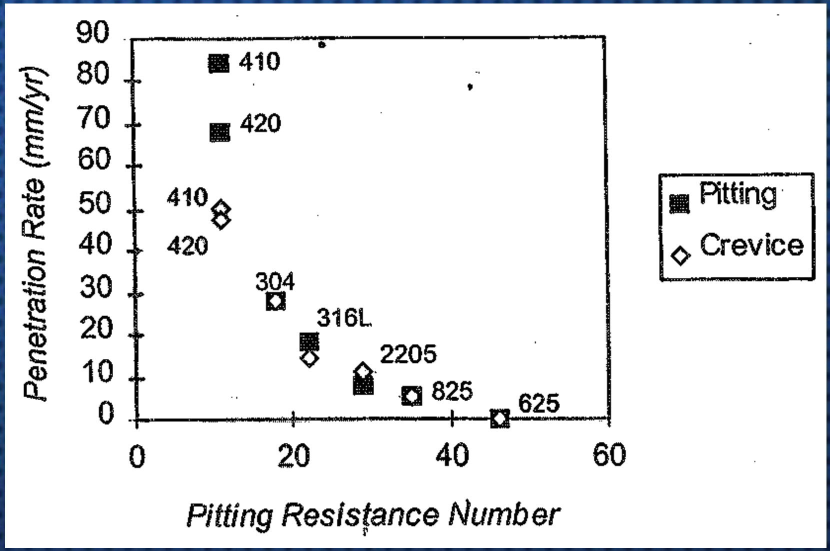
3.9. Chlorides Corrosion

- Formation water is the main source of salts
- Salts accelerates corrosion
- Austenitic stainless steel shall not be used at high levels of salinity
- CRA with a PREN>40 or a non-metallic material shall be used for handling high salinity water.

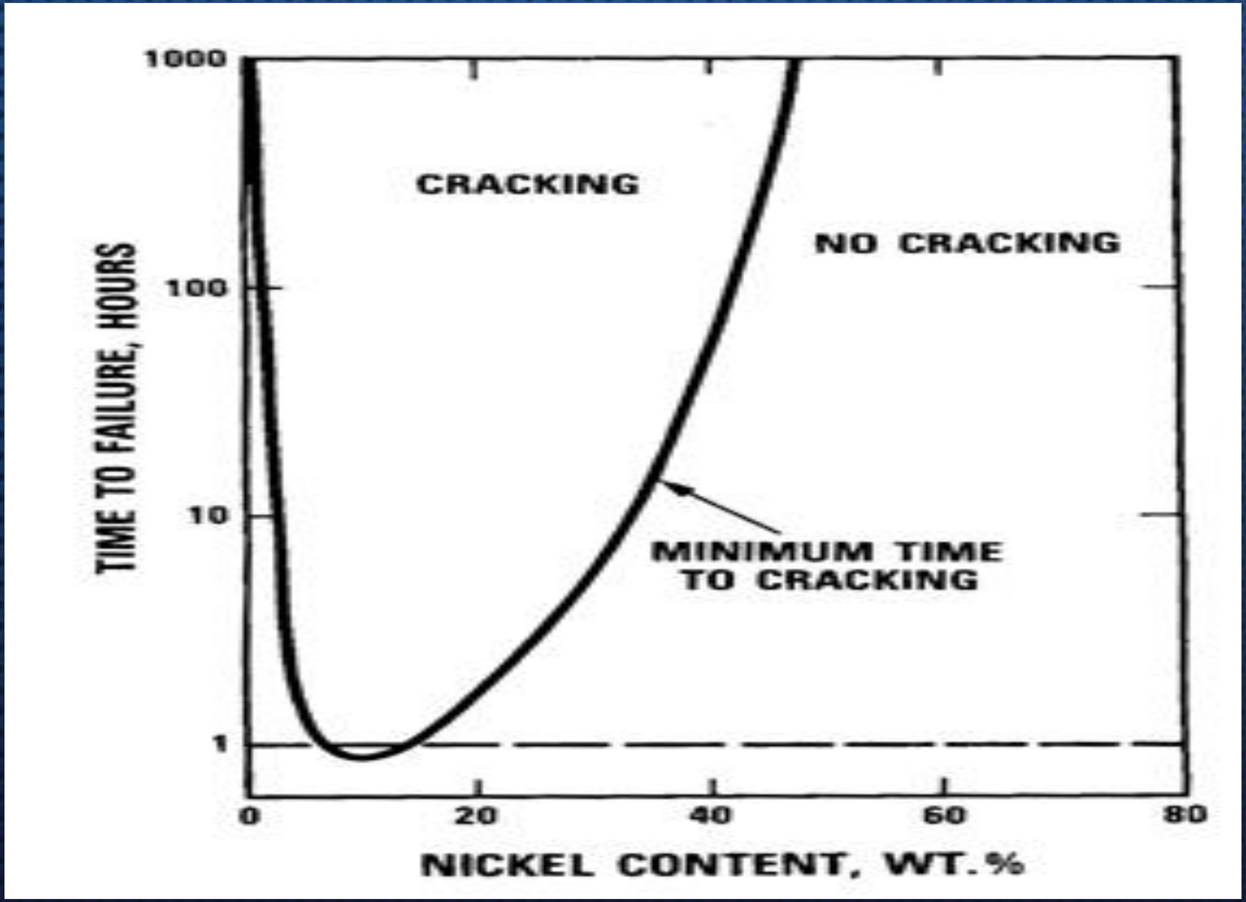


CHLORIDES PITTING

Reduction in pitting and crevice attack with increasing Pitting resistance Number



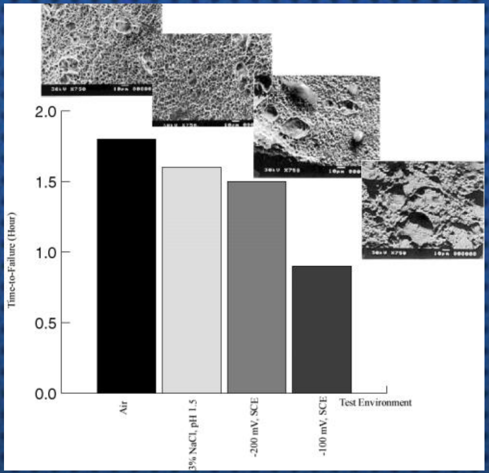
3.9. CHLORIDE PITTING, CREVICE AND STRESS CORROSION OF STAINLESS AND HIGH ALLOY MATERIALS(CONT.)



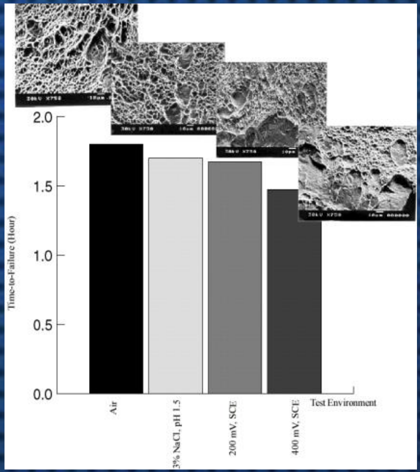
Effect of Ni content on SCC of high alloys- Copson

CHLORIDES SCC

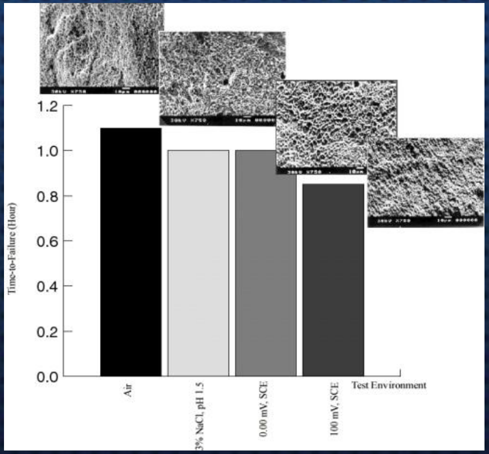
- Time-to-failure has been selected as a SCC criterion
- All tested specimens showed a decrease in time-to-failure on tensile testing in solution at open circuit potential and at applied potentials and even with increasing potentials in the noble direction.
- Opposite graphs show the reduction in time-to-failure with a correlation to the fractographs of outer zones of fractured surfaces.



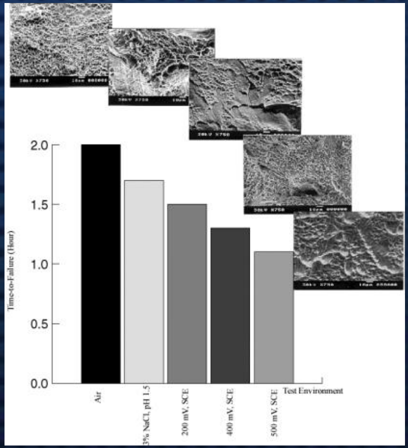
316L base-metal



6% Mo base-metal



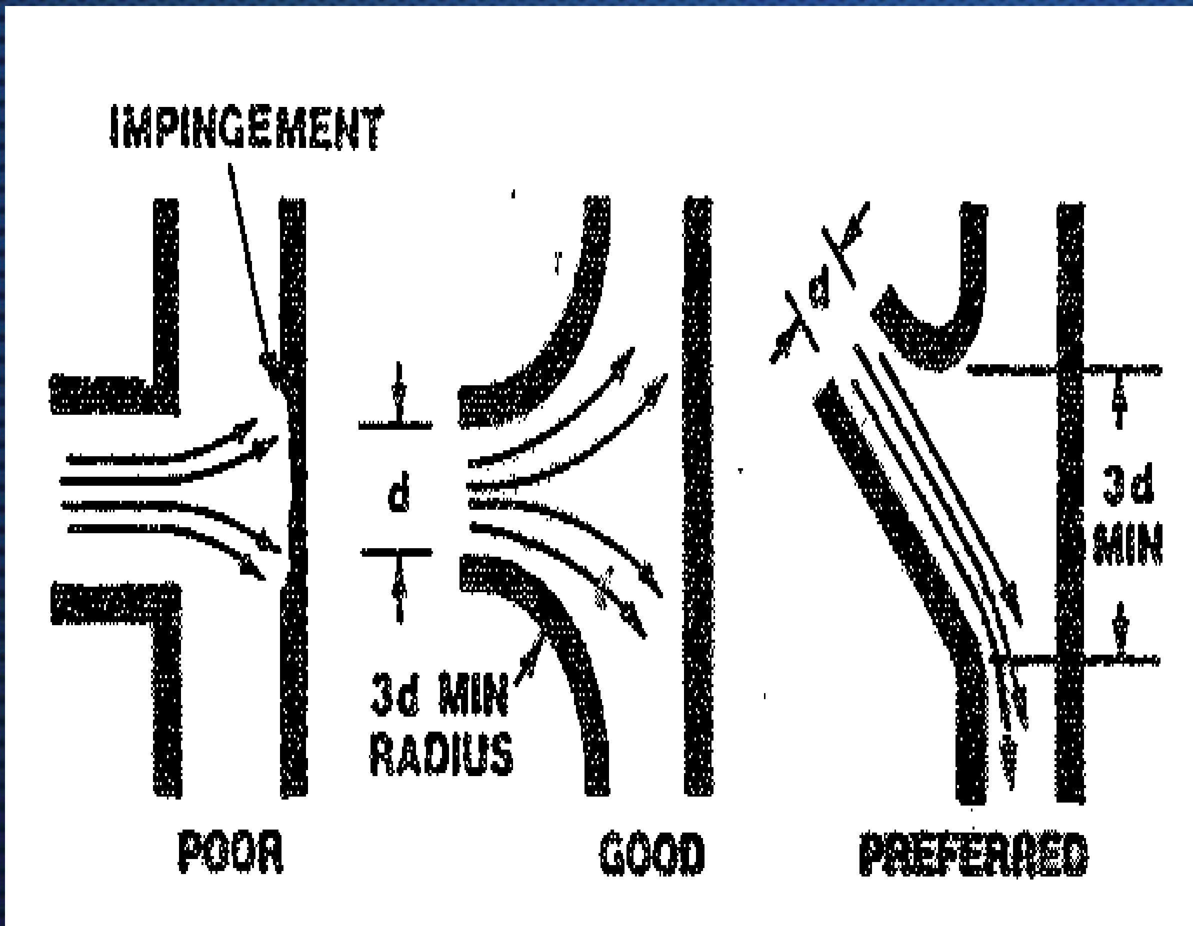
316L weldment

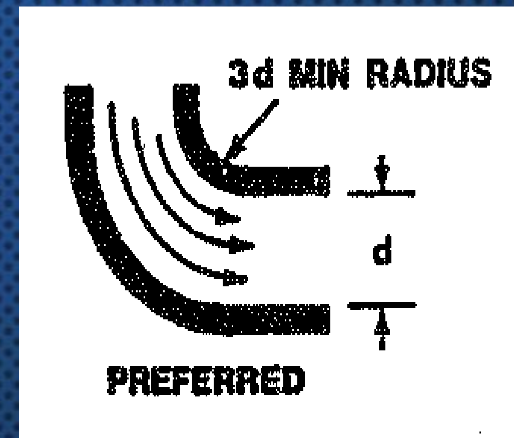


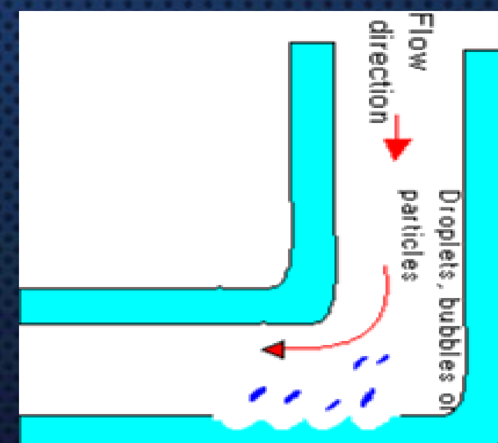
6% Mo weldment

II. Improved Design

Improved Design

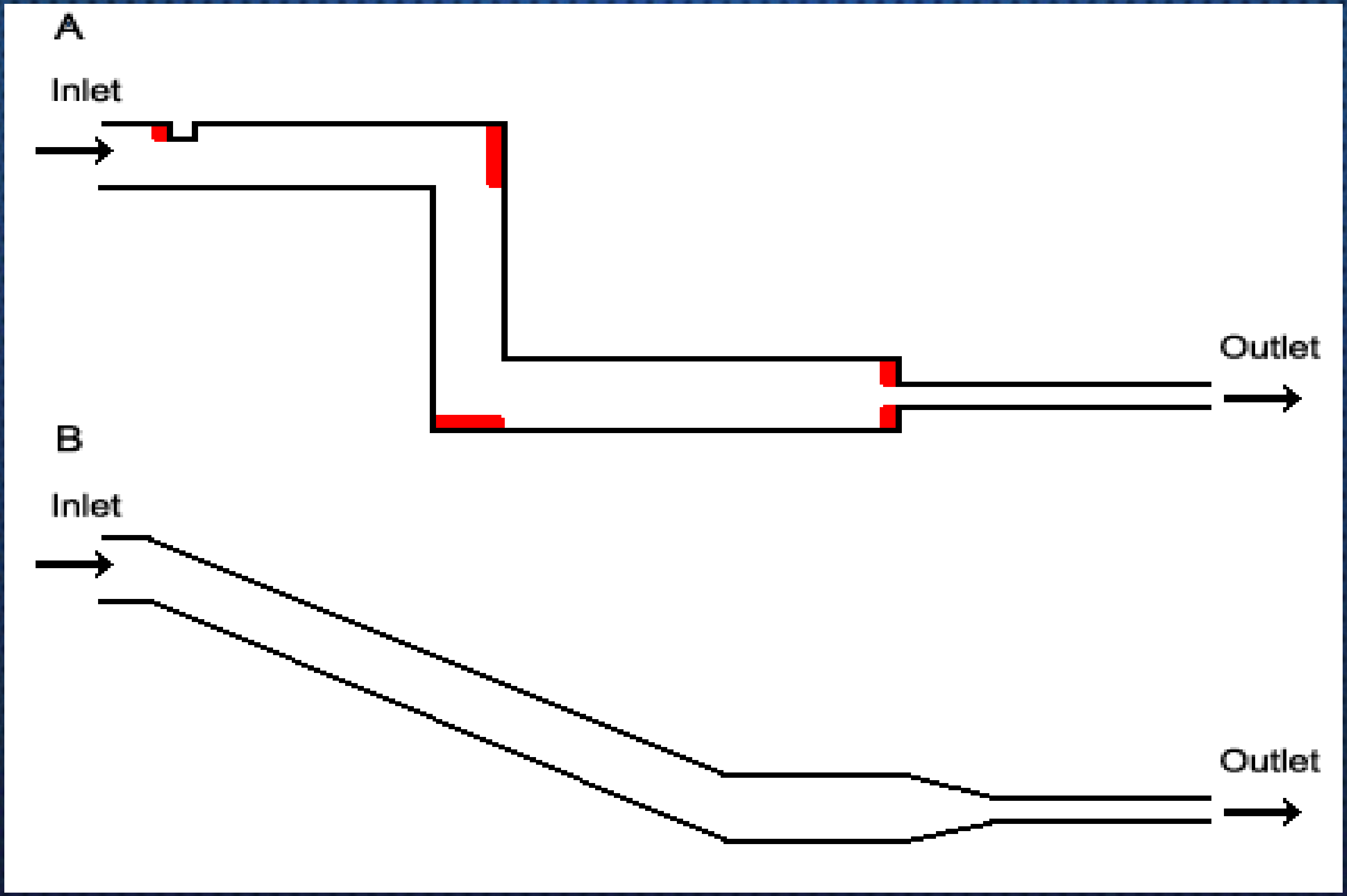






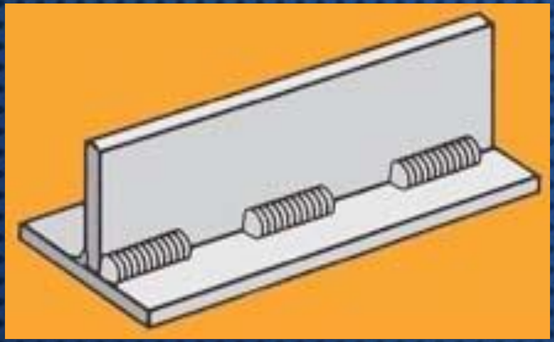
Examples of Impingement Corrosion

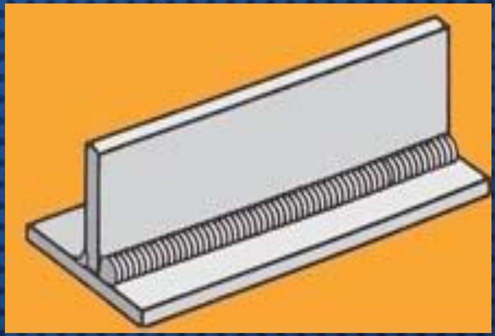
Improved Design



Examples of avoiding impingement corrosion by design

Improved Design

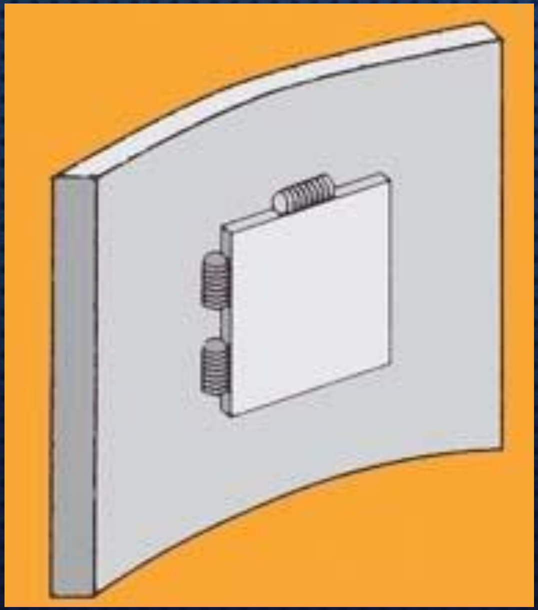


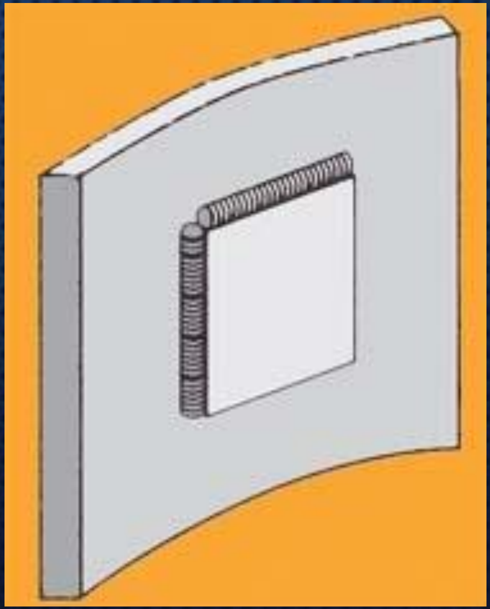


Bad

Examples of avoiding crevice corrosion by design

Good





Improved Design

- **Improved Design, e.g.:**
  - **Incorporation of corrosion allowance**

$$t_{(required)} = t_{min} + CA$$

Life time = corrosion allowance (mm) / corrosion rate (mm/year)

Improved Design

- Incorporation of corrosion allowance

CYLINDRICAL SHELLS	SPHERE SHELLS	PIPES
$T = \frac{PR}{SE-0.6} + C.A$	$T = \frac{PR}{2SE-0.2P} + C.A$	$T = \frac{PR}{SE-0.6P} + C.A$

P: design pressure in N/mm^2

R: inside radius, mm

S: stress value of material, N/mm^2

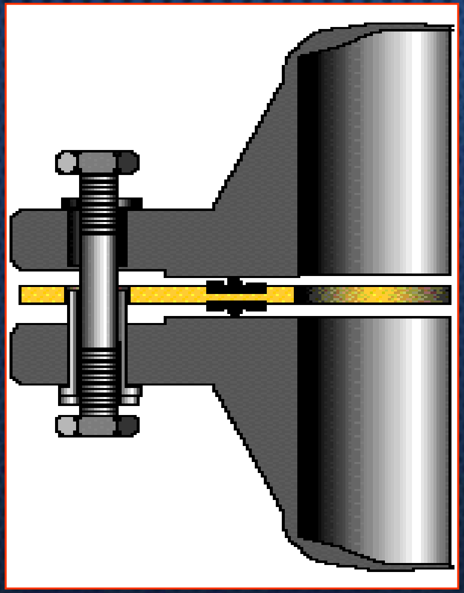
E: joint efficiency

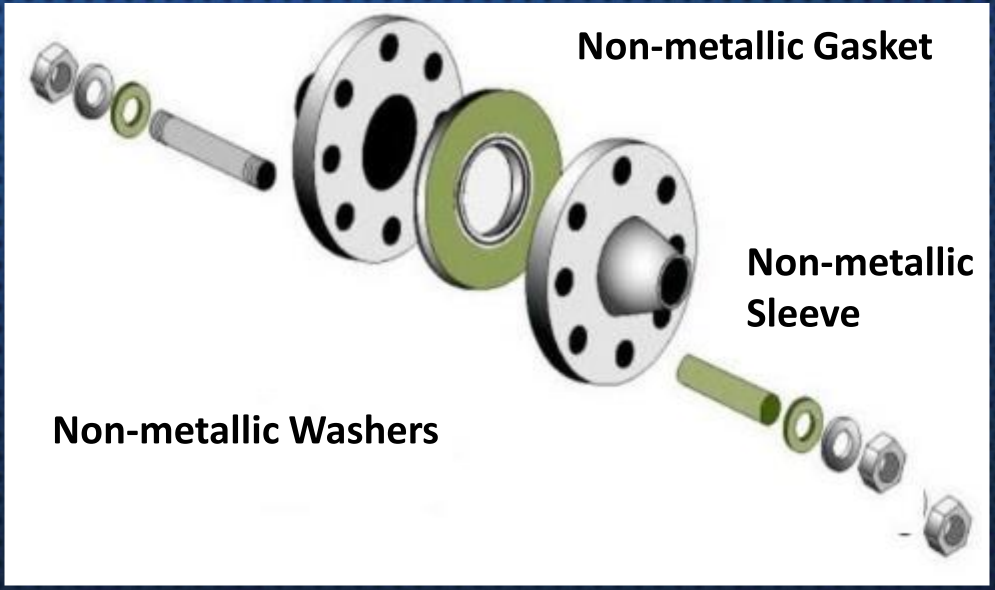
CA: corrosion allowance, mm

t : min. corroded thickness, mm

Improved Design

Avoiding contact between dissimilar metals using
Isolating Flange Kit





III. Corrosion Control Techniques

Chemical Treatment

Corrosion Control Techniques

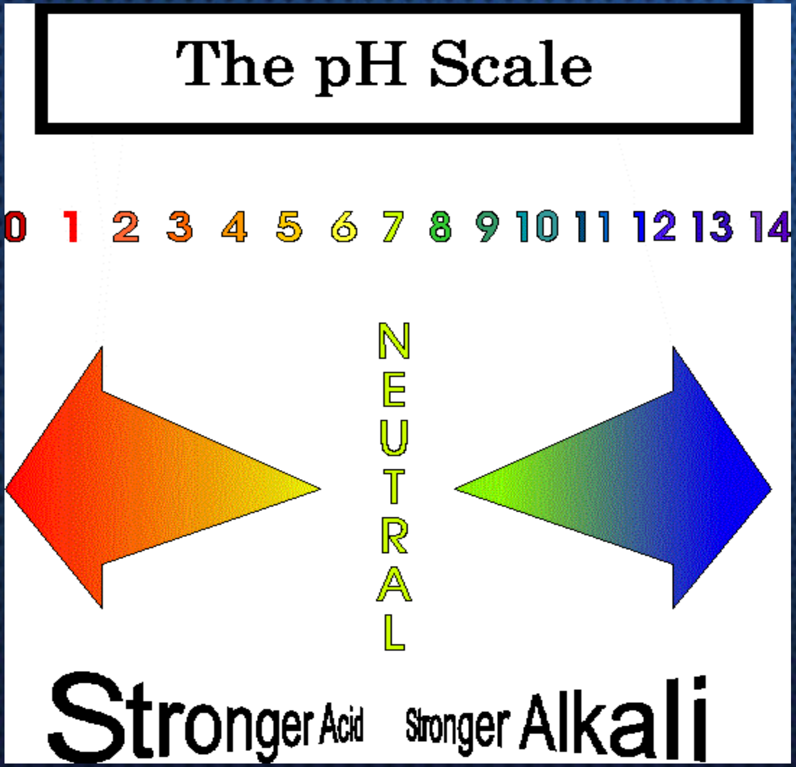
Chemical Treatment

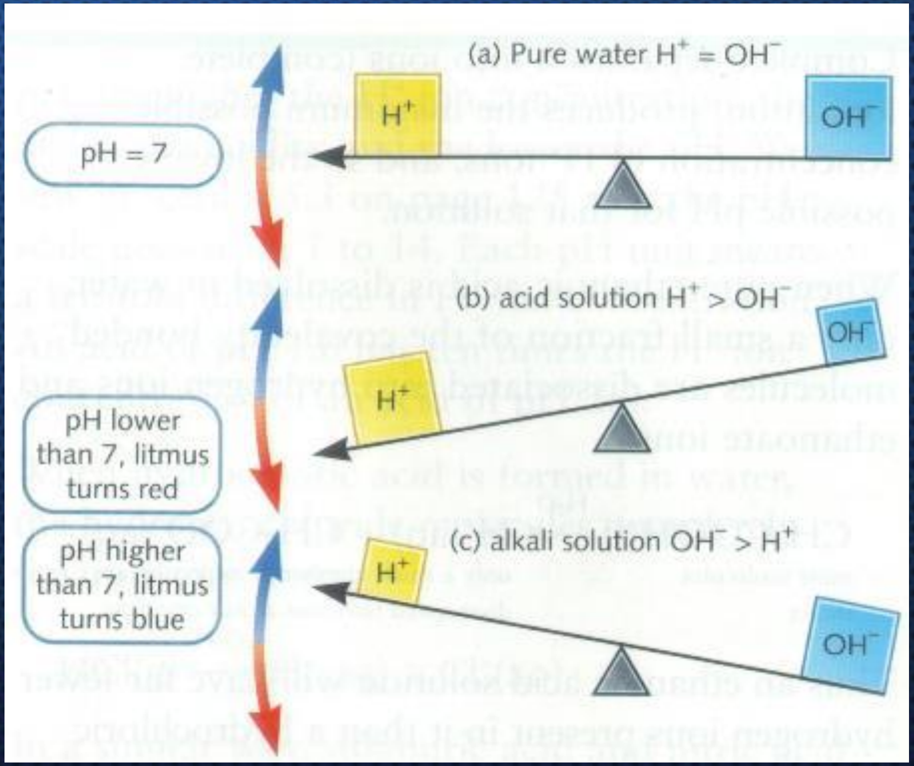
Chemical treatment involves injecting chemicals that Retard the corrosion of a metal.

Types of Treatment :

- Neutralization (pH control)
- Removal of dissolved gases (scavengers)
- Corrosion inhibitors
- Biocides

A. pH Control


The pH Scale
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
NEUTRAL
Stronger Acid
Stronger Alkali

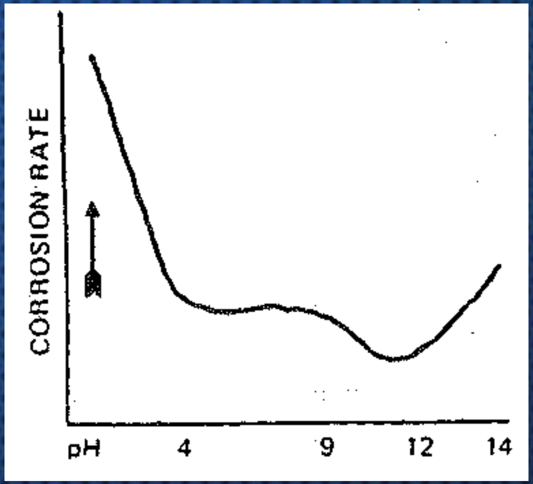

(a) Pure water $H^+ = OH^-$
H^+
OH^-
pH = 7
(b) acid solution $H^+ > OH^-$
H^+
OH^-
pH lower than 7, litmus turns red
(c) alkali solution $OH^- > H^+$
H^+
OH^-
pH higher than 7, litmus turns blue

A. pH Control

Steel corrosion rate related to hydrogen ion concentration in electrolyte

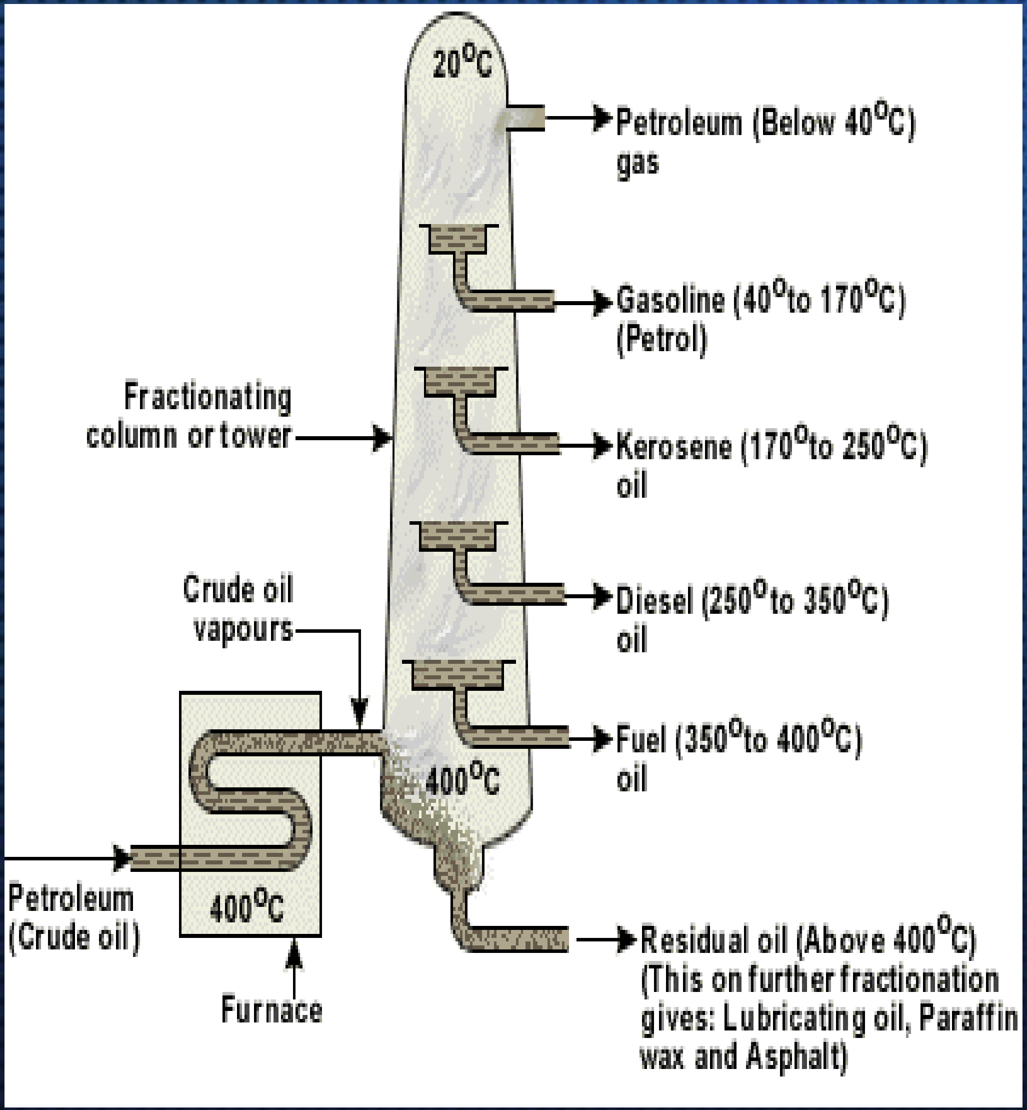
To avoid acid corrosion, the pH of the medium shall be raised up to about 7 by injection of

- Caustic Soda NaOH
- Ammonia NH_3



- Periodical check on pH by means of pH probes

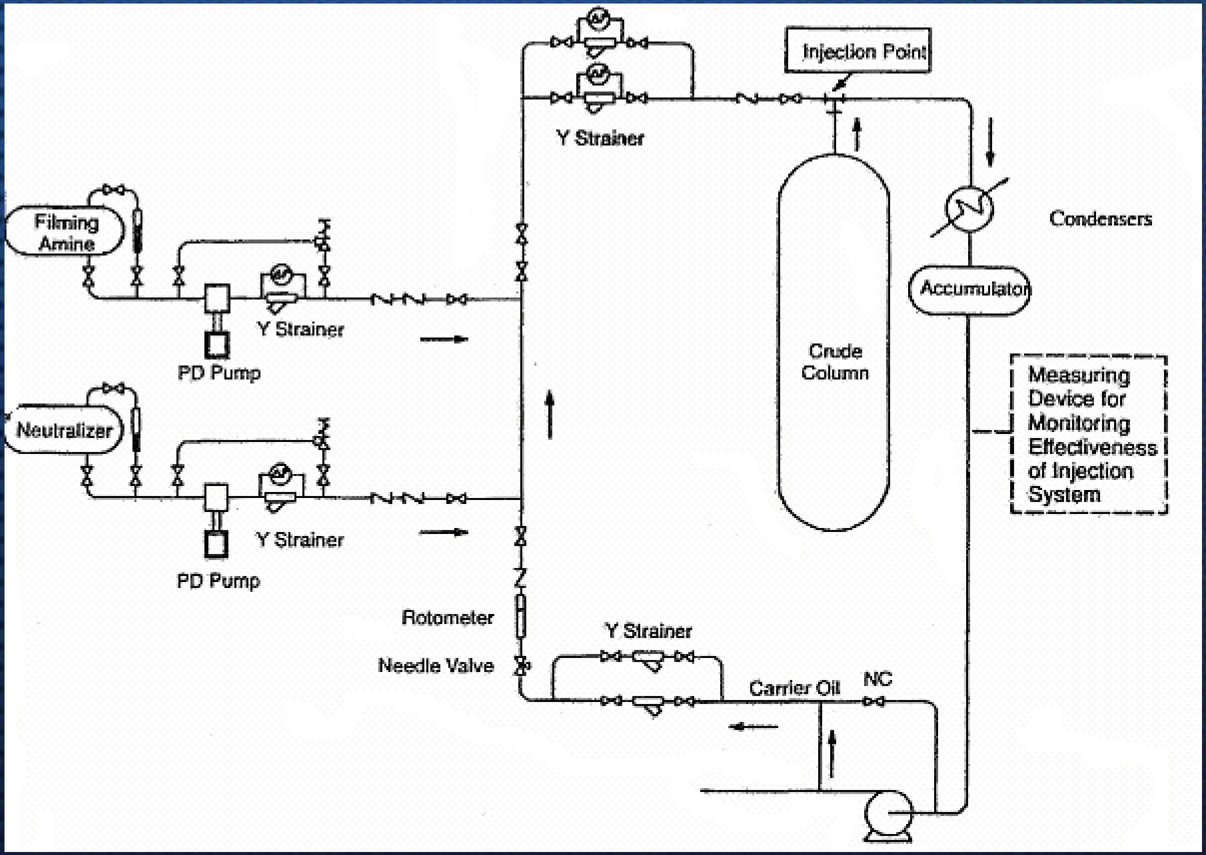
Crude Oil Fractional Distillation



Corrosion Control Techniques

Chemical Treatment

Chemical injection system for a crude distillation column overhead



B. Removal of Dissolved Gases

- Dissolved oxygen can be removed by injection of oxygen scavengers
- Mechanical deaerator can also be used to remove all dissolved gases: O_2, CO_2, H_2S
- Amine units can be used to remove CO_2 & H_2S
- Periodical checks on dissolved O_2 concentration by means of O_2 probes

C. Corrosion Inhibitors

NACE definition :

> ***" Chemicals which reduce the corrosion rate when added to a normally corrosive medium in small concentrations."***

Inhibitors selection is based on:

- **Metal**
- **Environmental chemical composition**
- **Service condition (e.g. temperature, flow rate)**

Application of Corrosion Inhibitors

- Oil refineries
- Petrochemical plants
- Oil and gas production
- Desalination plants
- Cooling water installations
- storage facilities
- Hydro tests

A Cooling Tower Unit

Classification of Inhibitors

- Inhibitors for Acid media

  pH < 5

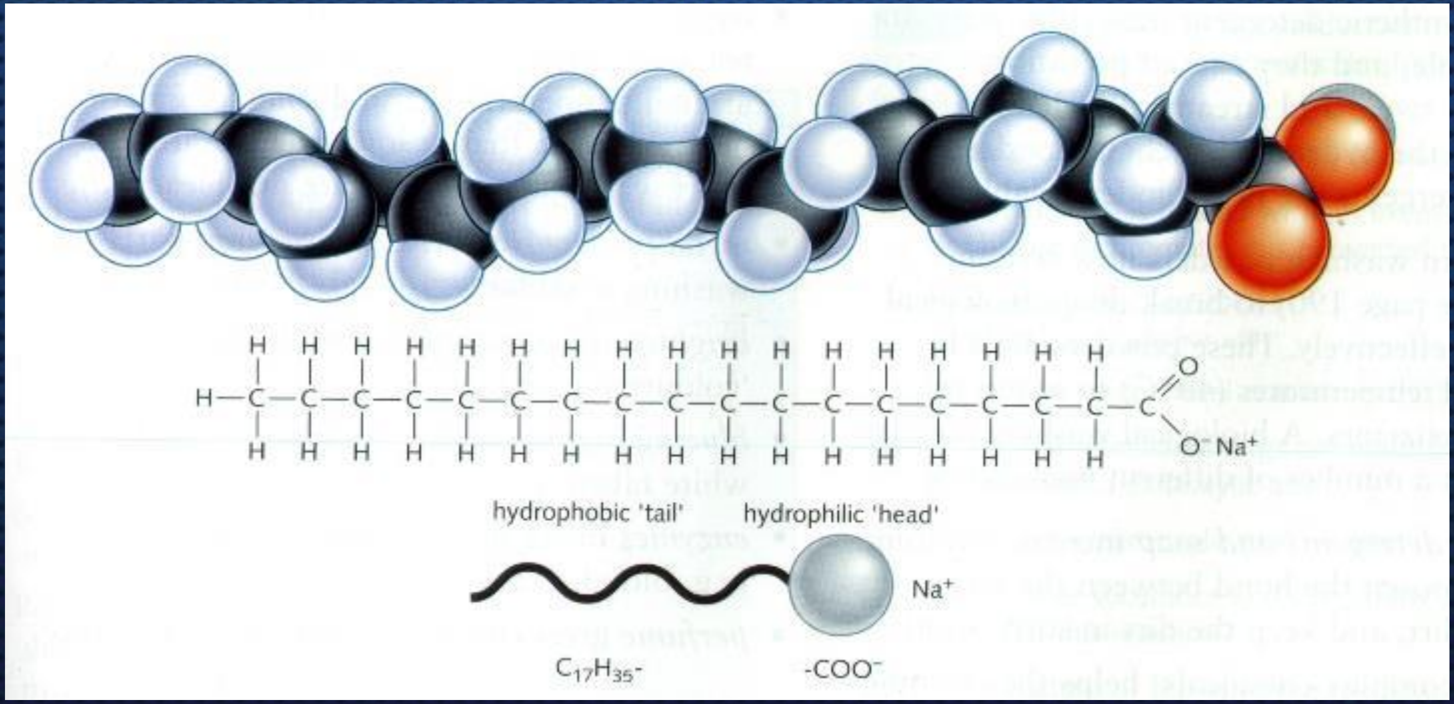
- Inhibitors for Near-Neutral media

  pH 5 – 10

- Above pH 10, the alkalinity (OH^- ions) of the medium is self-inhibiting

A. Inhibitors for Acid Media

Usually organic compounds with long hydrocarbon chains with polar (charged) head



B. Inhibitors for Near Neutral Media

Usually are inorganic compounds

- Anodic
- Cathodic, or
- Mixed (Mixtures of both anodic and cathodic inhibitors)

C. Inhibitors for Near Neutral Media

In case of Absence of the inhibitor: usually are categorized as:

Safe or Dangerous

- **Safe** → **General Corrosion**
- **Dangerous** → **Localized Corrosion**

Mixed Inhibitors

- Mixtures of both anodic and cathodic inhibitors
- Block both anodes and cathode
- Compatible mixture

Efficiency of Inhibitors

Expressed as :

Protective Power (Z)

Where,

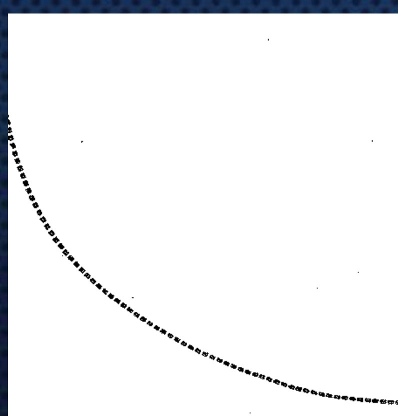
$$Z = [(R_O - R) / R_O] \times 100$$

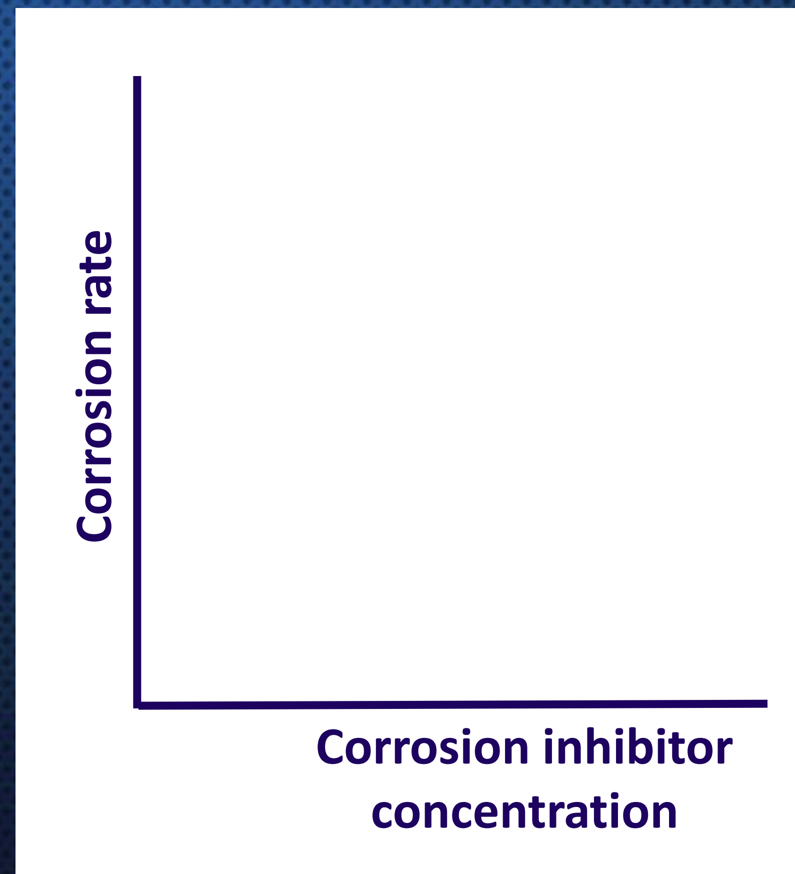
R_o: Corrosion rate in absence of inhibitor.

R : Corrosion rare in presence of inhibitor.

Efficiency of Inhibitors

Curve showing drop in corrosion rate as a function of inhibitor concentration





D. Biocides

- ***Definition***

  A substance that is capable of killing a certain micro-organism or spectrum of Micro-organisms

- ***Biocidal activity***

  The concentration needed to kill the micro-organisms

  MKC VALUE = minimum killing concentration

Biocides role in corrosion control

- KILL MICRO-ORGANISMS THAT FEED ON THE CORROSION INHIBITORS
- KILL MICRO-ORGANISMS THAT PRODUCE CORROSIVE METABOLITES

Sulfate-reducing bacteria (SRB)

Control of Microbial Corrosion

USE OF BIOCIDES IN CLOSED SYSTEMS

- CAPABLE OF KILLING WIDE RANGE OF MICROBES

- BIODEGRADABLE, ENVIRONMENTALLY FRIENDLY

- NON-HARMFUL FOR HUMANS AND OTHER LIVING ORGANISMS

- COMPATIBLE WITH THE METAL, I.E. NON-CORROSIVE

- TWO DIFFERENT BIOCIDES TO BE USED ALTERNATIVELY

Chemical Injection

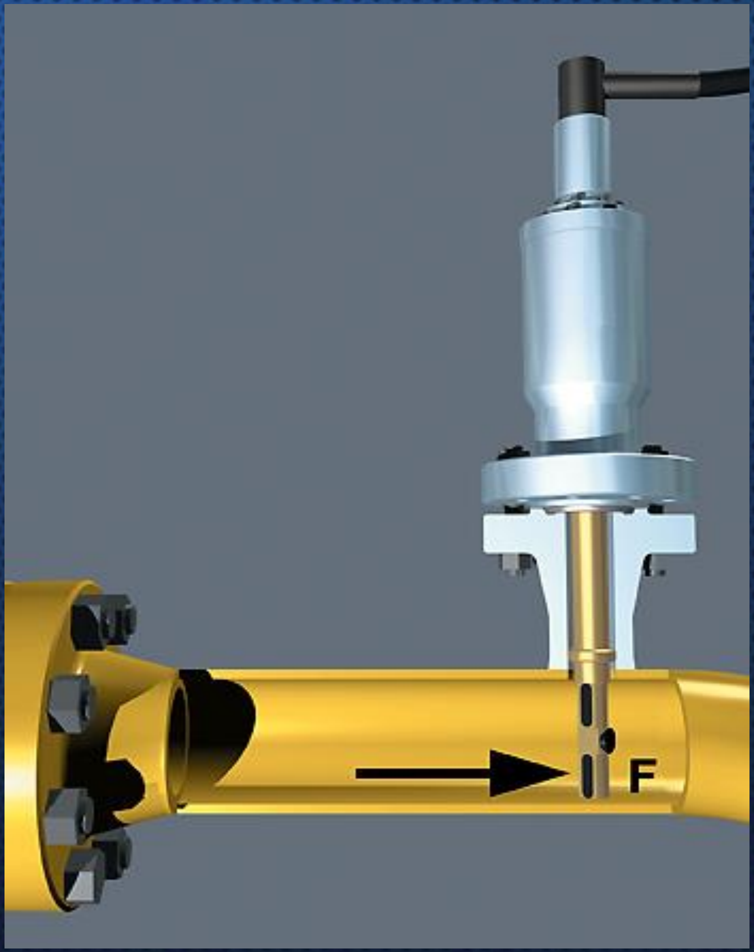
Chemical Injection Skid :

- Chemical Tanks
- Chemical Injection (Dosing) Pumps

Non-metallic Tanks

Stainless Steel Tanks

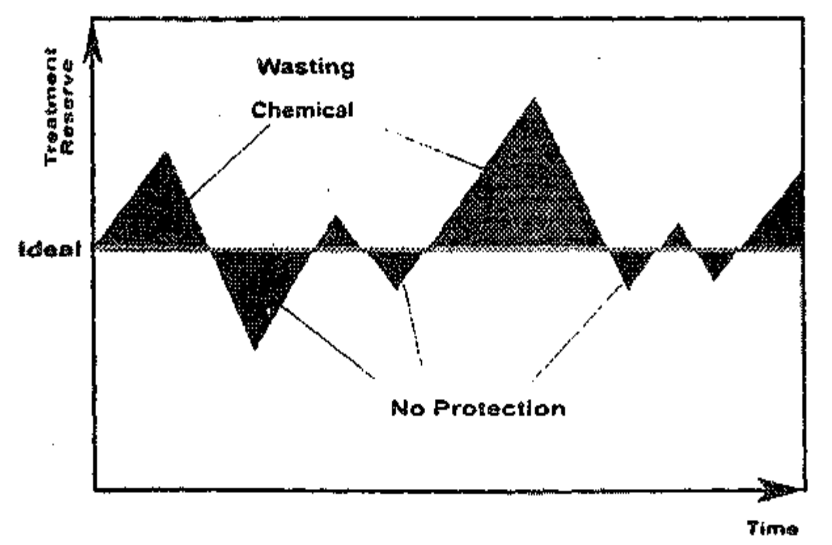
Chemical Injection Point

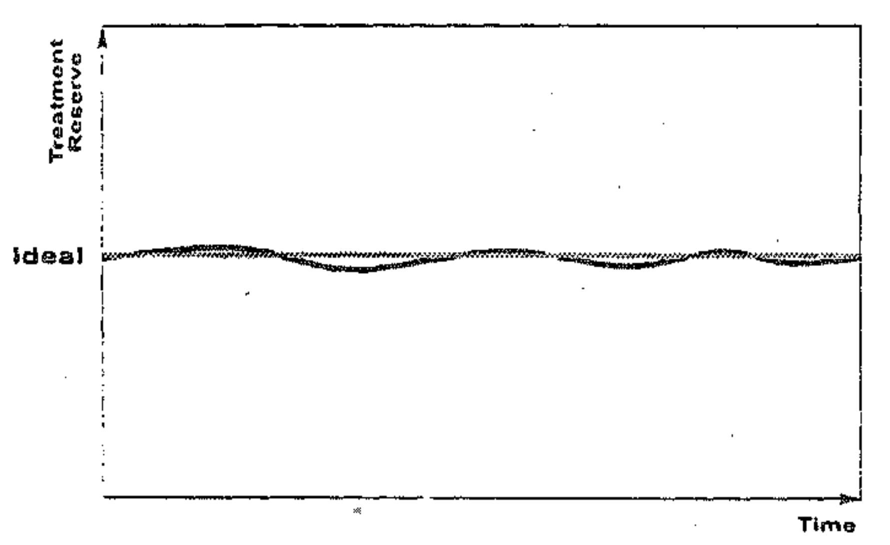


High Alloy Quell

Corrosion Control Techniques

Chemical Treatment





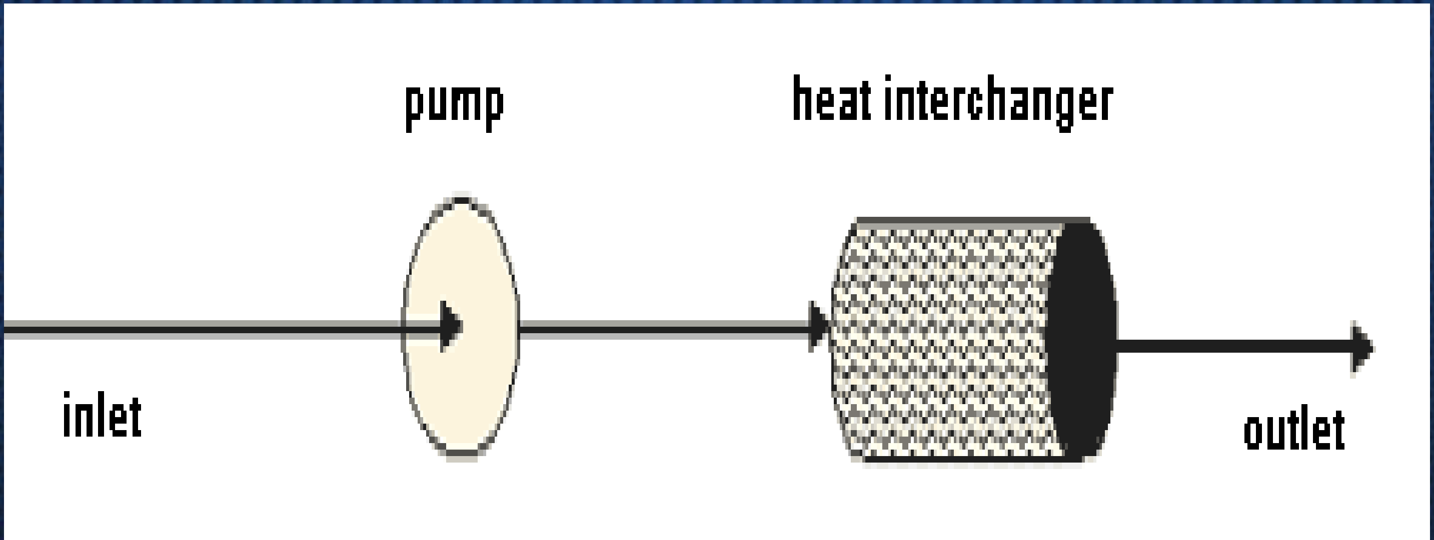
BAD CONTROL

GOOD CONTROL

Corrosion Control Techniques

Chemical Treatment

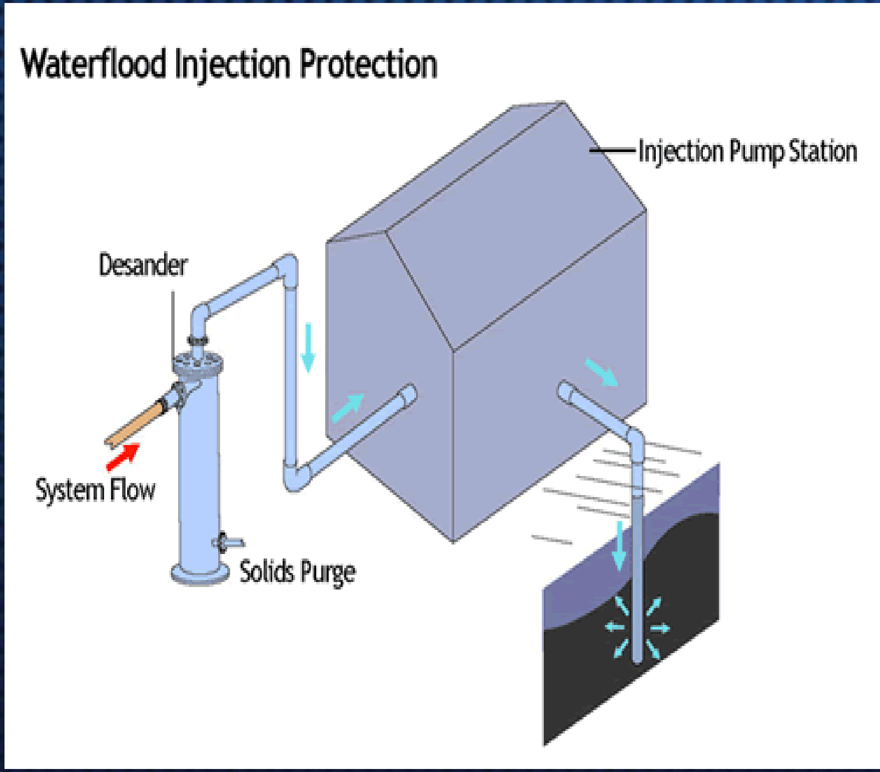
- Once – through Systems

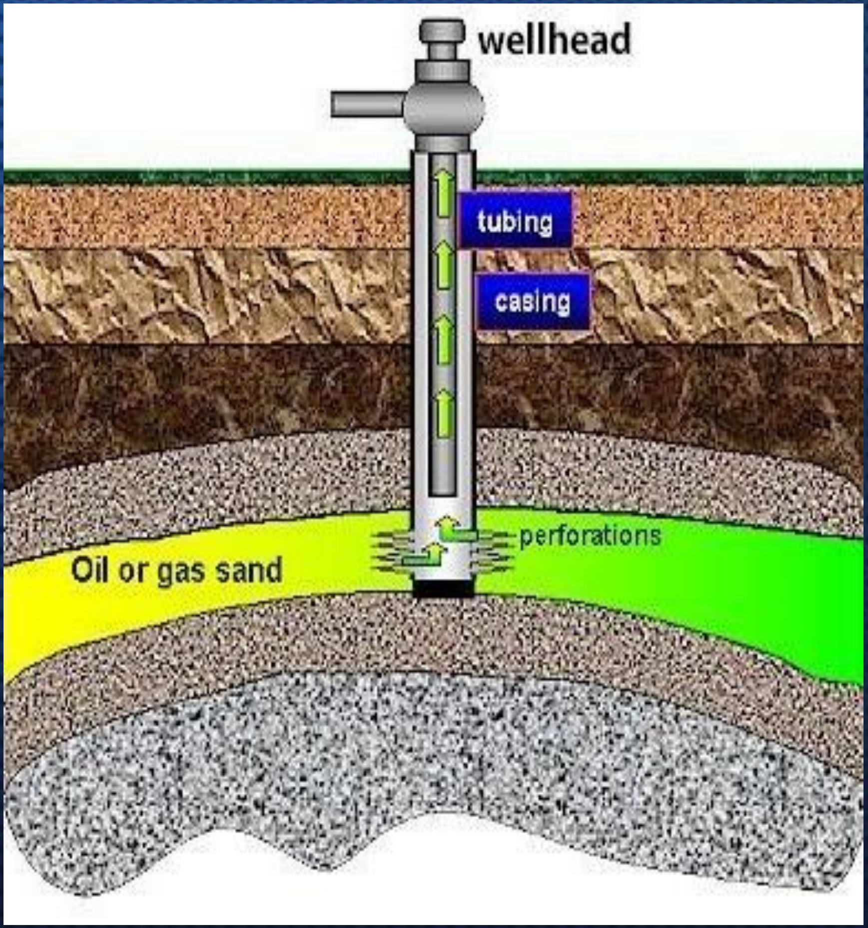


Corrosion Control Techniques

Chemical Treatment

- **Water Flooding & Wells**





Corrosion Control Techniques

Chemical Treatment

- **Corrosion Monitoring**

Definition :

“ the systematic measurement or evaluation of the corrosion rate and type of corrosion occurring on an equipment “ .

Corrosion Control Techniques

Chemical Treatment

Advantages of Corrosion Monitoring

- Avoids unplanned shutdowns
- Avoids loss of production resulting from unforeseen corrosion failure
- Effective scheduling of maintenance works
- Reduction of inspection activities

Corrosion Control Techniques

Chemical Treatment

- **The efficiency of corrosion inhibitors is checked by means of monitoring system.**
  - **Coupons**
  - **Electrical Probes**

Corrosion Control Techniques

Chemical Treatment

Corrosion Coupons

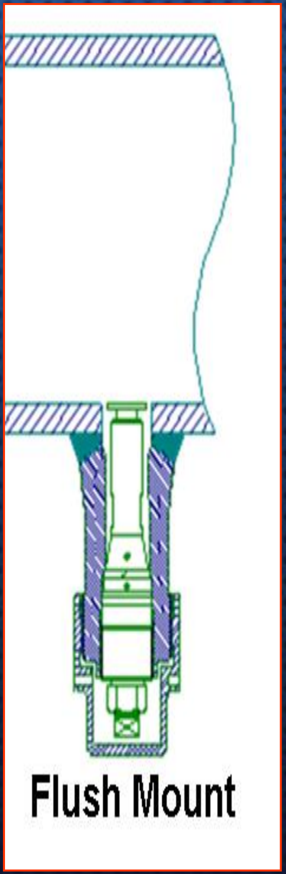
Cylindrical Coupons

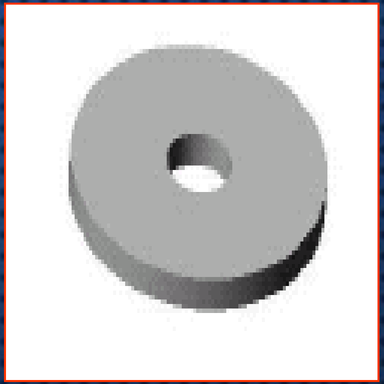
Strip Coupons

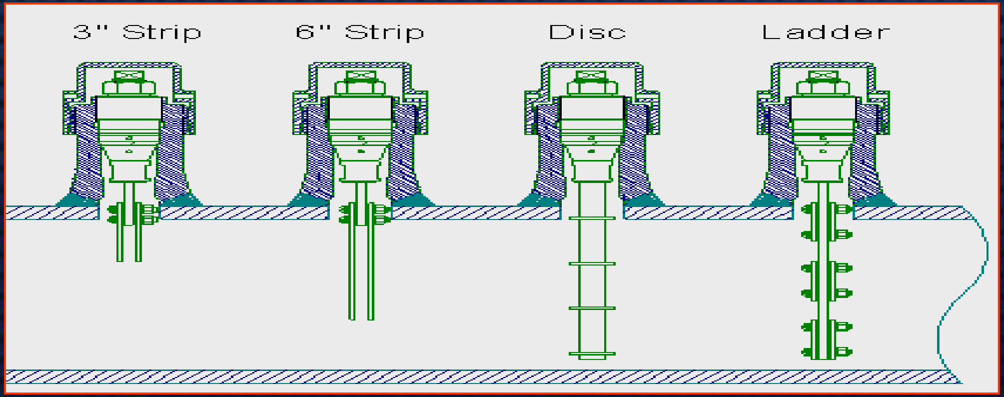
Corrosion Control Techniques

Chemical Treatment

Typical corrosion monitoring point







Corrosion Control Techniques

Chemical Treatment

Coupon Handling

Retrieving the coupon

Removal of corrosion product by soft wire mesh

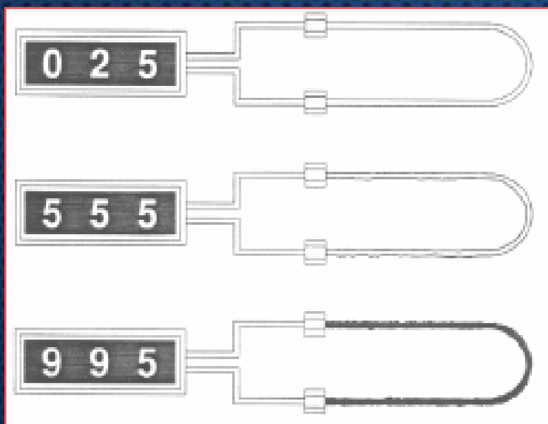
Removal of corrosion product by soaking in inhibited acid

The coupon is accurately weighed

Corrosion Control Techniques

Chemical Treatment

Electrical Resistance (ER) Probe- Corrosometer

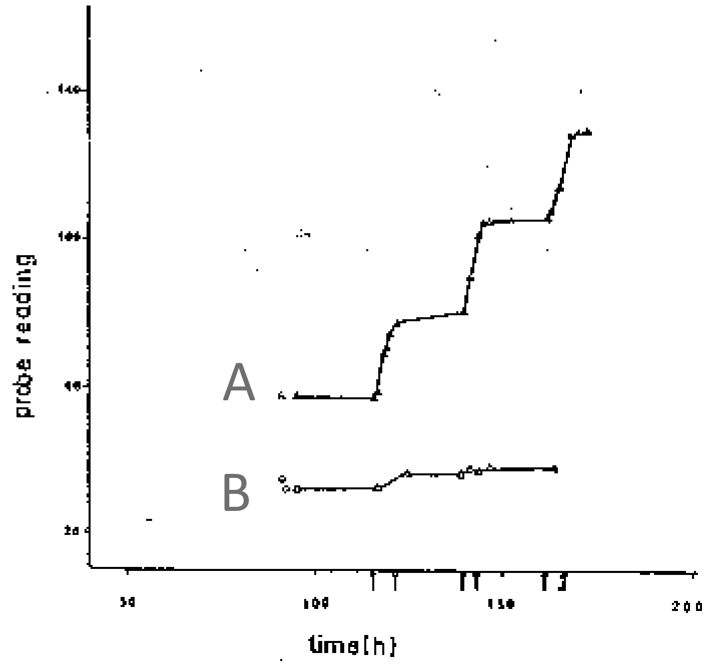


Corrosion Control Techniques

Chemical Treatment

Electrical resistance probe measurements for mild steel coupons

A. In corrosive media
B. In non-corrosive media



Electrical resistance probe measurements for mild steel foils exposed to SRB cultures purged with nitrogen (▲) and air (△); ↑ = sparge on/off

Corrosion Control Techniques

Chemical Treatment

Corrosion Monitoring Point

Usually includes:

- **Corrosion Coupon ; mainly for visual evaluation of corrosion type**
- **Electrochemical Probe ; for more accurate instantaneous corrosion rate determination, e.g. ER probe**

Corrosion Control Techniques

Chemical Treatment

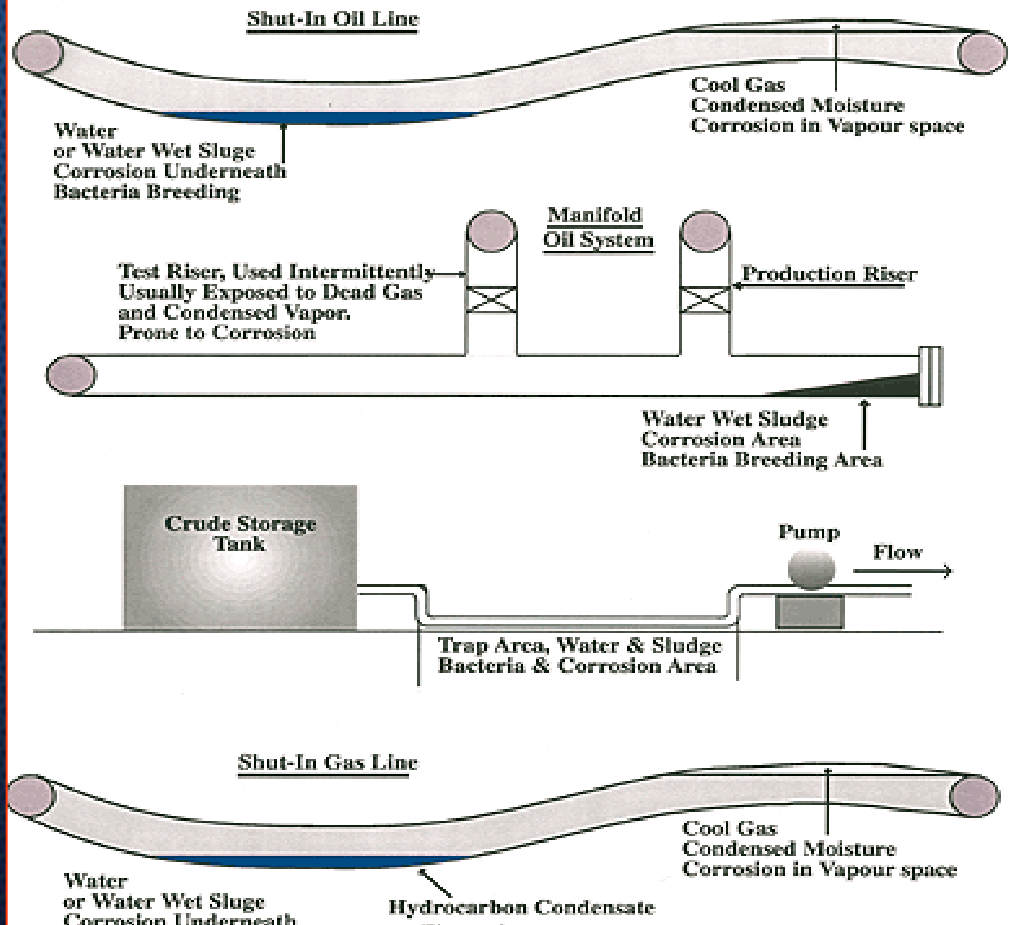


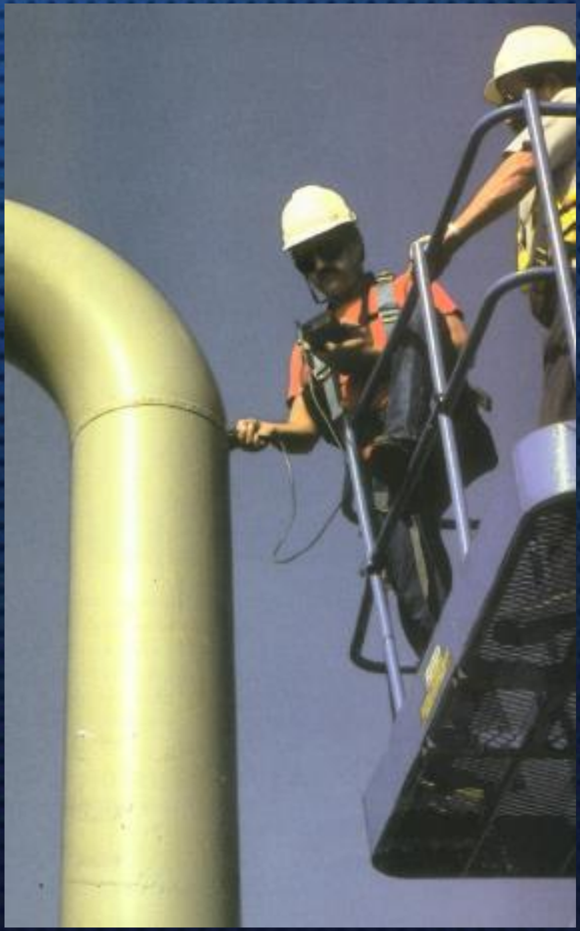
Figure 2
Typical Dead Gas and Liquid Traps
Shut - In or Intermittently Operated Systems

Corrosion Control Techniques

Chemical Treatment

- On-Line Wall Thickness (UT) Measurements

- Useful on-stream follow-up monitoring tool
- Base-line readings are taken at selected locations before and placing the equipment in service
- Types of UT :
  - A-scan (Spot) ,
  - B-scan (Linear) ,
  - C-scan (3D)

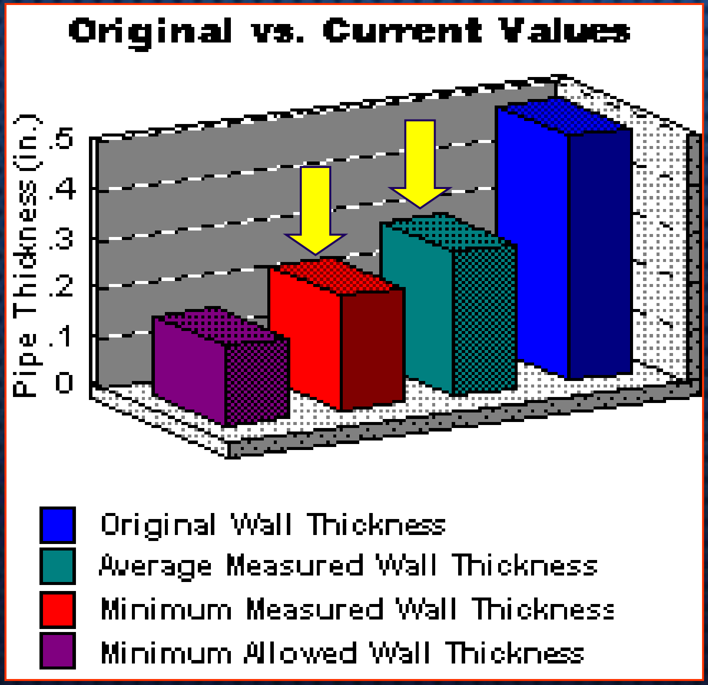


Corrosion Control Techniques

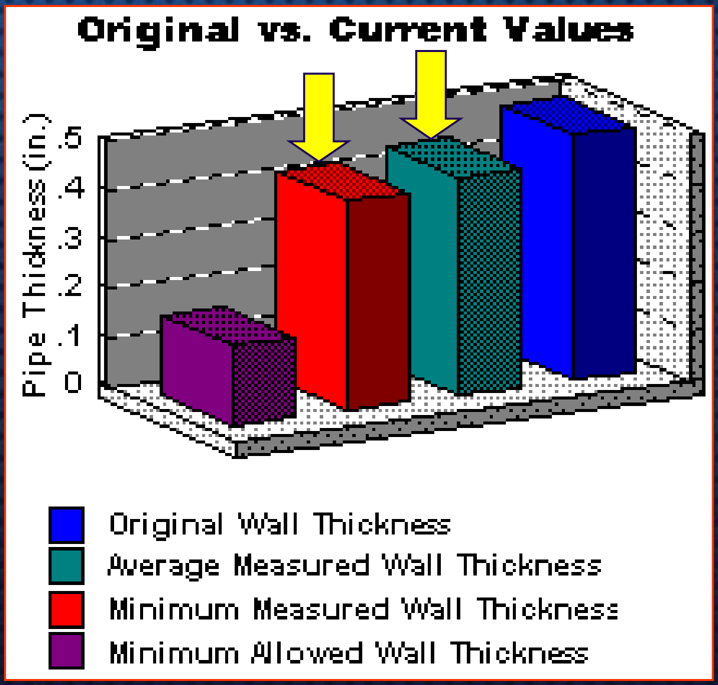
Chemical Treatment

- On-Line Wall Thickness (UT) Measurements

Without Inhibition



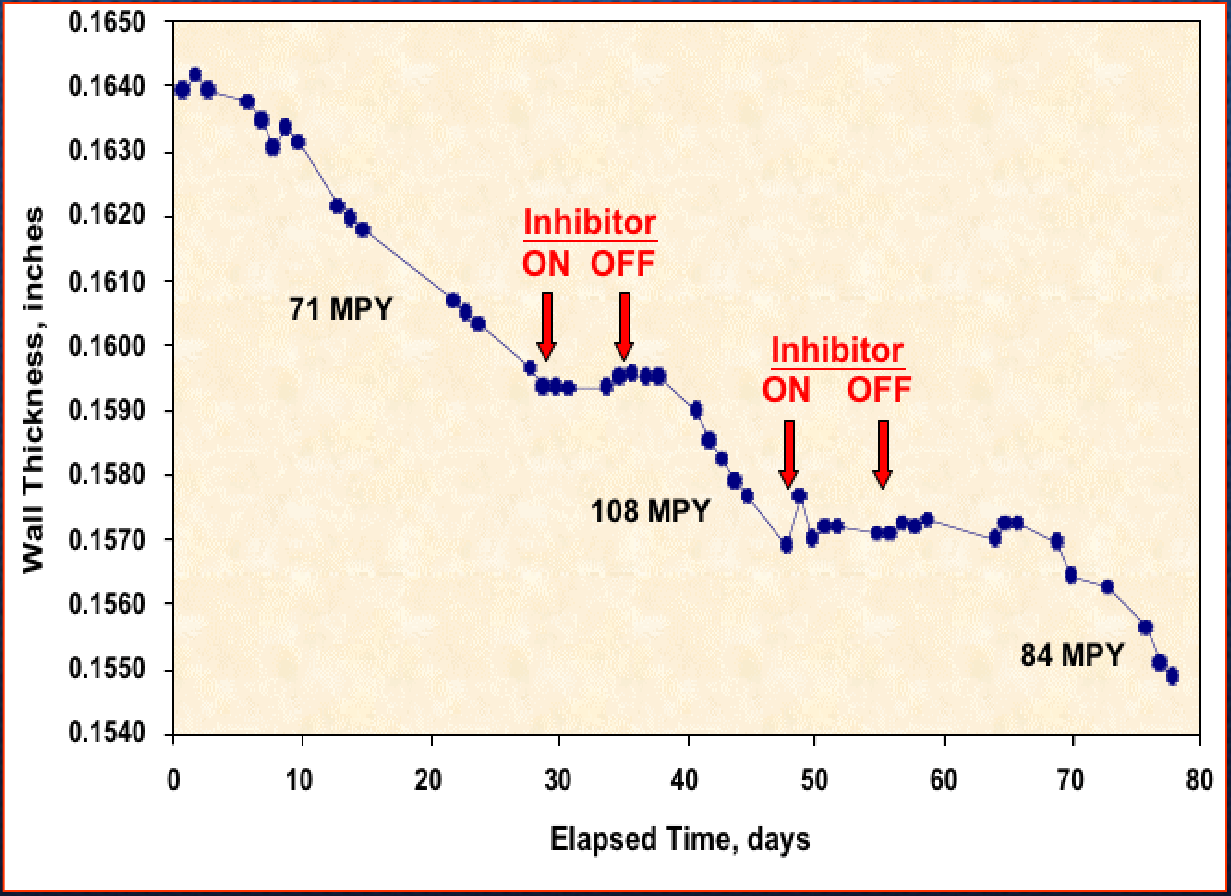
With Inhibition



Corrosion Control Techniques

Chemical Treatment

- On-Line Wall Thickness (UT) Measurements



IV. PROTECTIVE COATINGS

3. Protective Coatings

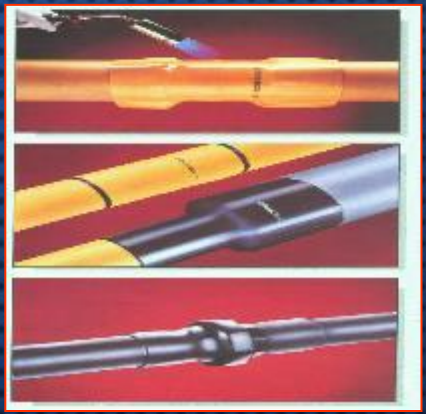
- **Definition of a COATING**

  A material that adheres to and covers the metal surface

- **The coating can be applied :**
  - **onto external surfaces; external coating**

  and / or
  - **onto internal surfaces; internal coating (Lining)**

Types of Coatings



- **Paints**

  Applied externally & internally

- **Wrapping**

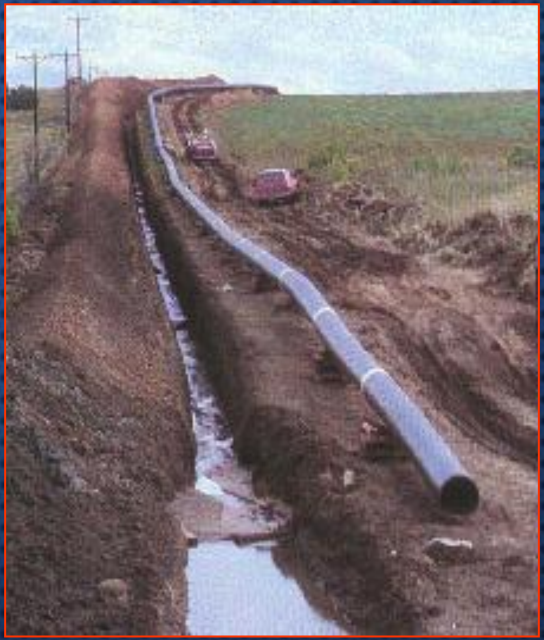
  Applied externally only

- **Heat-Shrinkable Sleeves**

  Applied externally only

Wrapping & Sleeves

- Used mainly for field joints

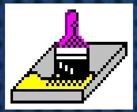


Wrapping & Sleeves

- Wrapping can be used for under- ground in-plant piping, e.g. open & closed drain piping network

Corrosion Control Techniques

3. Protective Coatings

 Paints

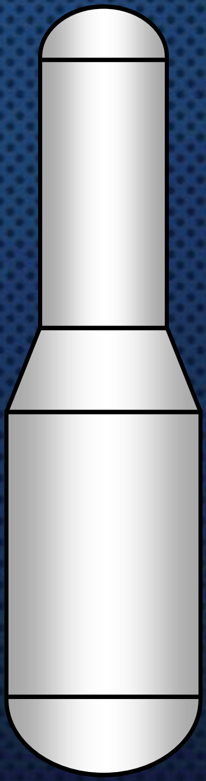
Definition :

" a liquid material, which can be applied on a surface, and which – after drying – forms a thin, cohesive, non-porous film with good adhesion to the surface".

Surface Preparation

Performed prior to coating application:

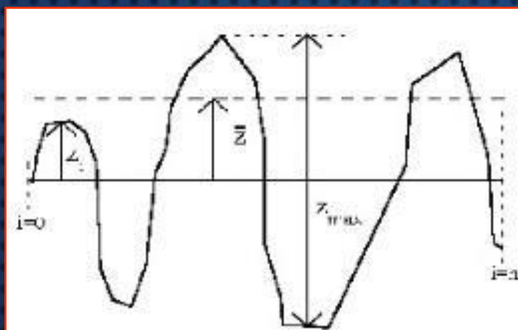
- **Criteria :**
  - Surface Cleanliness
  - Surface Roughness



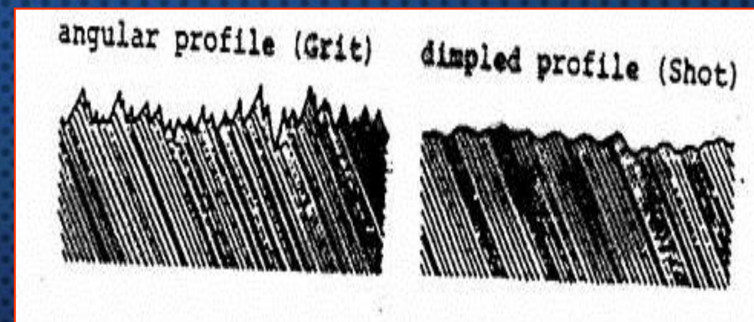
Surface Profile

THREE PARAMETERS ARE IMPORTANT

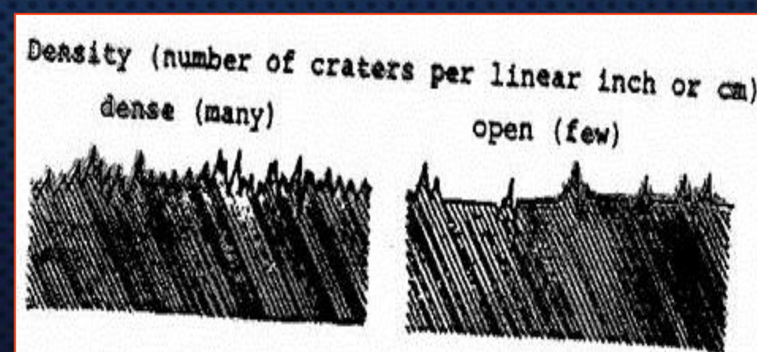
TO OBTAIN ACCEPTABLE SURFACE PROFILE :



1-Peak to valley depth



2-Shape of craters



3-Density

Surface Cleanliness International Standards

Surface Finish	USA Spec. SSPC	NACE	British Std. BS 4232	Swedish SIS 05 5900	Japanese Std. SPSS
White Metal	SSPC-SP 5	NACE 1	1st quality	SA 3	
Near White Metal	SSPC-SP 10	NACE 2	2 nd quality	SA2 1/2	JA Sh2 or JA Sd2
Commercial Blast	SSPC-SP 6	NACE 3	3 rd quality	SA 2	JA Sh1 or JA Sd1
Brush Off Blast	SSPC-SP 7	NACE 4	-	SA 1	-

Surface Cleanliness

Removal of scales, rust, dirt, grease, etc…

Done by :

- Water jetting
- Abrasive blasting (provides surface roughness)
  - Sand blasting
  - Grit blasting

Water Jetting

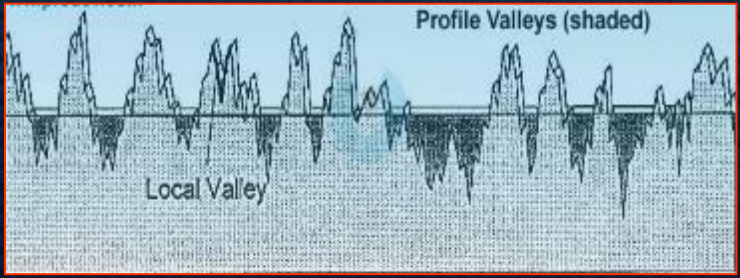
Abrasive Blasting

- **Sand blasting**
- ***not recommended as it causes air pollution by increasing the amount of suspended solids***
- **Provides reasonable surface roughness**

SAND BLASTING

Grit Blasting

- By using metal shots with sharp edges
- Recommended as it does not cause air pollution
- Provides excellent surface roughness (profile)
- Recyclable



Chemical Composition of Paints

- **Primary Components :**
  - Resin (binder / vehicle / base)
  - Hardener (curing agent)
  - Solvent (thinner)

- **Secondary Components :**
  - Color Pigments
  - Cementing Particles
  - Corrosion Inhibitors

Painting Application

- Paint Application Methods
- Paint Application Conditions
- Paint Application Defects
- Paint Inspection

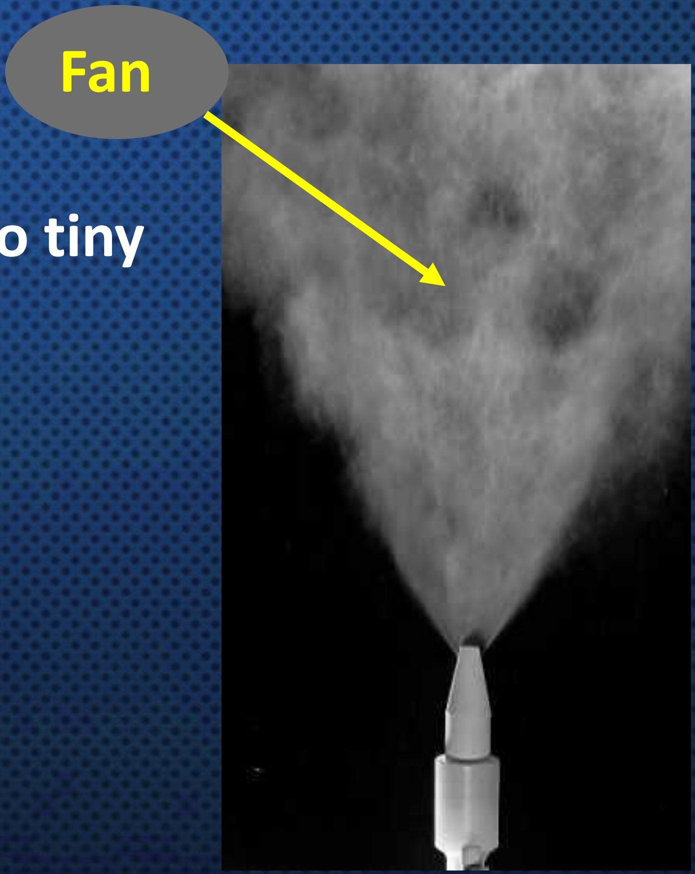
Paint Application Techniques

- **Brush:**
  - Very effective
  - Very slow
  - Used for small objects and touch-ups
- **Roller:**
  - Ineffective
  - Porous film
  - Slow
  - Used for gates and fences

Spray Application

- Atomization : converting a liquid into tiny minute droplets

- **SPRAYING = ATOMIZATION**



Spraying (cont.)

- **Spraying**
  - Fast
  - Very effective
  - Uniform film
  - Requires skillful operators
  - Most commonly used method
  - 20% approx. loss is expected

Air Spray

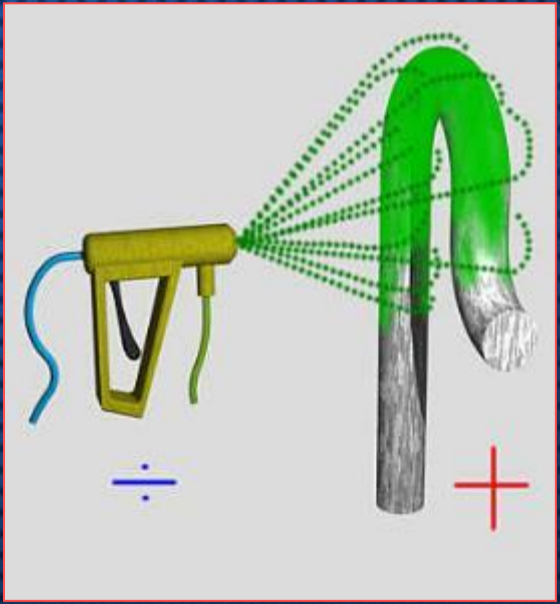
- Atomization of paint is assisted by air
- Requires air compressor + air filters
- Air quality is a must
- Not suitable for paints containing oxidizable metal particles , e.g. zinc-rich paints

Airless Spray

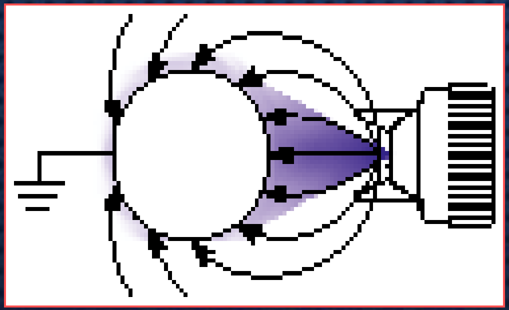
- Suitable for metal-containing paints
- Requires high pressure pumps
- Atomization is due to ΔP

Electrostatic Painting

- Needs DC power supply between
- spray gun & work piece
- Paint loss down to ~ 2%
- Excellent uniform appearance
- Most expensive



Electrostatic Spray



Painting System (Cycle)

The 3-layer paint system :

- **Primer** :1st layer
  - Provides corrosion protection
  - Provides adhesion to metal surface
- **Inter-coat** : 2nd layer
  - Provides mechanical strength to the system
- **Top (Finish)** : 3rd outmost layer
  - Provides UV resistance
  - Provides abrasion resistance
  - Provides the specified color code

3-Layer Paint System

Primer : Zinc-rich compounds
Inter-coat : High build / solids epoxy
Top (Finish) : Polyurethanes

- Recommended paint system For external steel surfaces at ambient temp. up to $94^{0}C$
- For higher temperatures, special painting systems to be specified
- For internal surfaces, No need for neither top coat Nor color code. Use extra thicker inter-coat instead

Pipeline Coating System

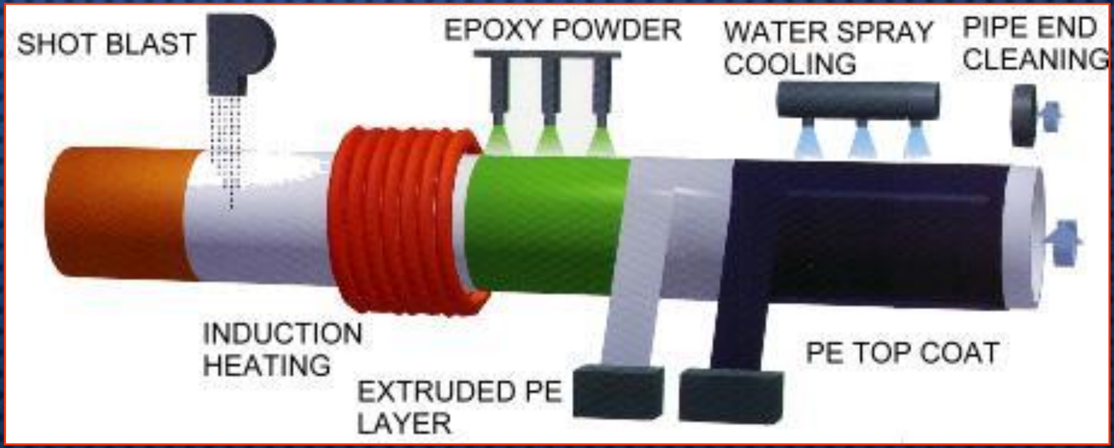
3-Layer System

- Polyethylene

Or

- Polypropylene

2-3 mm Thick



Keys of Coating Success

- Surface Preparation
- Materials
- Coating Application
- Inspection

Corrosion Control Techniques

3. Protective Coatings

Conditions of Successful Painting Application :

1. Adequate lighting 500-1000 lumen / m^2

2. Proper ventilation for confined or closed areas to ensure paint drying

3. Skin temperature between 3-45°C

Dew Point Measurement

DATASET

MEASURES

T_a – air temperature

T_s – surface temperature

RH – relative humidity

CALCULATES

T_d – dew point temperature

Δ – the difference between surface and dew point temperatures

Key to Successful Painting

1. No rain
2. No dust
3. Relative humidity does not exceed 85%
4. No wind
5. Atmosphere temperature should be between 10-50 °C
6. Good accessibility for the work piece

Key to Successful Painting

6. Paint inspection
    - integrity of cans
    - Shelf-life
    - Pot life
    - Induction time
    - Color code (top coat)

7. Paint system / cycle
    - Primer
    - Inter-coat
    - Top coat or finish

Key to Successful Painting

8. Paint technical data sheet
   - Generic type
   - Curing time
   - DFT (dry film thickness) limits

9. Paint application data sheet
   - Mixing ratio
   - Safety regulations during application

10. Paint safety data sheet

11. Operator skills (Workmanship)

Painting Data Sheet

Steel

Company	PAINTING SPECIFICATION	0000-000-100-2						
		Rev	0	1	2			
		YEAR	2003					

PAINTING SYSTEMS			
PAINTING SYSTEM NO. 2			
SERVICE			
Material	Carbon steels & low alloys (<9%Cr)	C. Temp.	
Environment	Onshore, above ground	From	To
Items	External surfaces of piping vessels, heat exchangers, towers, columns, etc.	Ambient	93

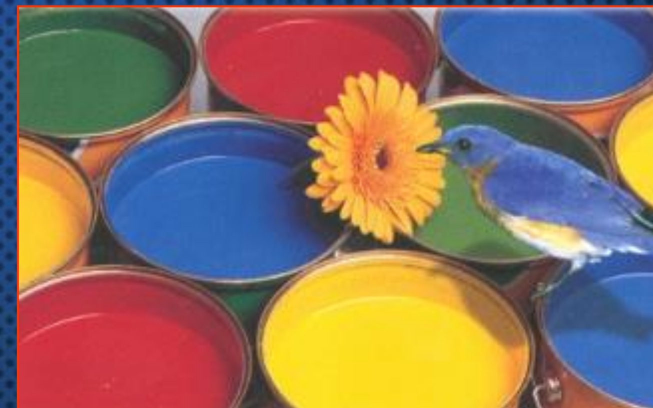
PAINTING CYCLE

Preparation/painting	Requirements	DFT (Microns)
Surface preparation	SA2.5	
Primer	Inorganic zinc silicate	75
Inter-coat	Polyamide MIO epoxy sealant	125
Top-coat	Polyurethane	50

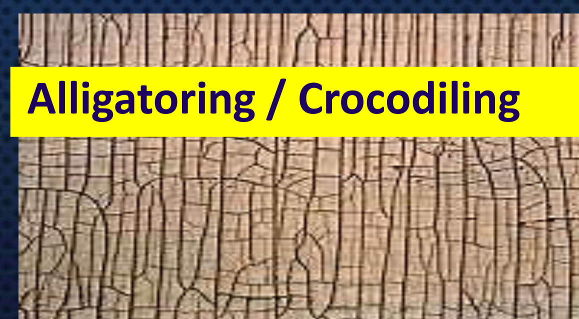
Coating Properties

In order to perform effectively, a corrosion resistant painting must be characterized by some essential properties.

- Water resistance
- Chemical resistance
- Proper adhesion
- Coherent
- Abrasion resistance
- Ability to expand and contract
- Weather resistance
- Non-porous
- Pleasing appearance



Environmentally Friendly



Rigid non-flexible paint

Paint Inspection

- **Surface cleanliness**
- **Surface roughness**
- **Conditions of paint application & equipment**
- **Coating defects & holidays**
- **Coating adhesion**
- **Coating dry film thickness**

Surface Cleanliness Inspection

- **Visual inspection for surface solid particles, e.g. dust**

Magnifying Lenses

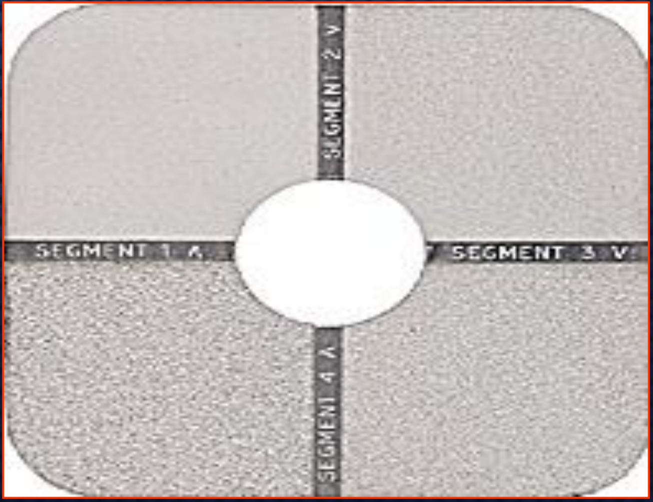
Torch

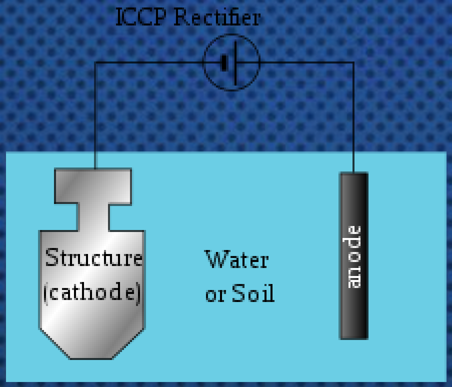
Masking Tape

Surface Cleanliness Inspection

- **SA 2.5 : Near-white, for external surfaces**
- **SA 3 : White, for internal surfaces**

Comparator

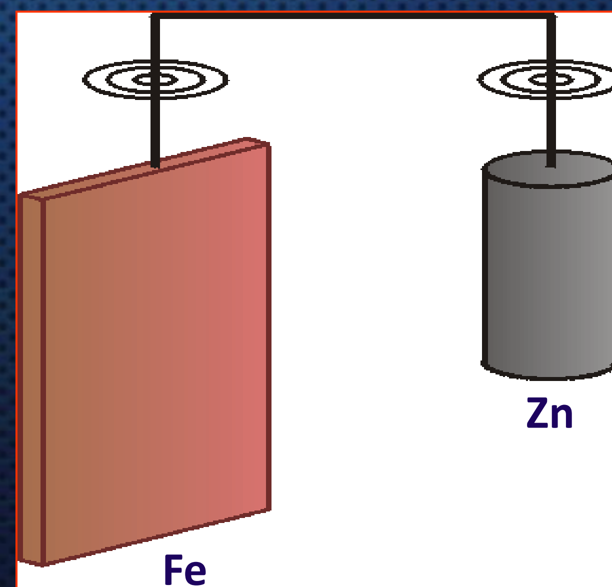




V. CATHODIC PROTECTION

Corrosion Control by Cathodic Protection

- Cathodic protection is defined as the means of using galvanic series as well as polarization principles to protect the structure against corrosion.
- Cathodic protection has been discovered as galvanic corrosion occurred on using copper rivets in ship hulls.



Application of Cathodic Protection

In industry cathodic protection is applied to:

- Ship hulls
- Offshore jackets
- Offshore jetty piles
- Offshore sheet piles
- Offshore pipelines
- Buried piping and pipelines
- On-grade storage tank bottoms
- Buried tanks
- Water tank interiors (as well as water portion of crude storage tanks)
- Any other electrolyte immersed structure

On-Shore Applications of CP Systems

PLANT AREAS

Underground pipelines
Tank bottoms
Earthing conductors
Power cables

PIPELINES

Oil pipelines
Gas pipelines
Water pipelines
Service lines

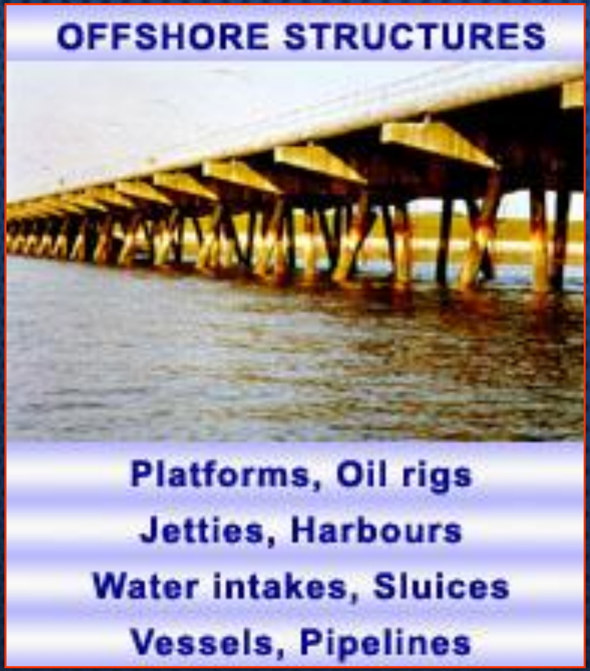
PRODUCTION WELL CASINGS

Oil well casings
Gas well casings
Water well casings

INTERNAL PROTECTION

Storage tanks
Heat exchangers
Coolers, Turbines
Condensers, Pipelines

Off-Shore Applications of Cathodic Protection



CP Codes and References

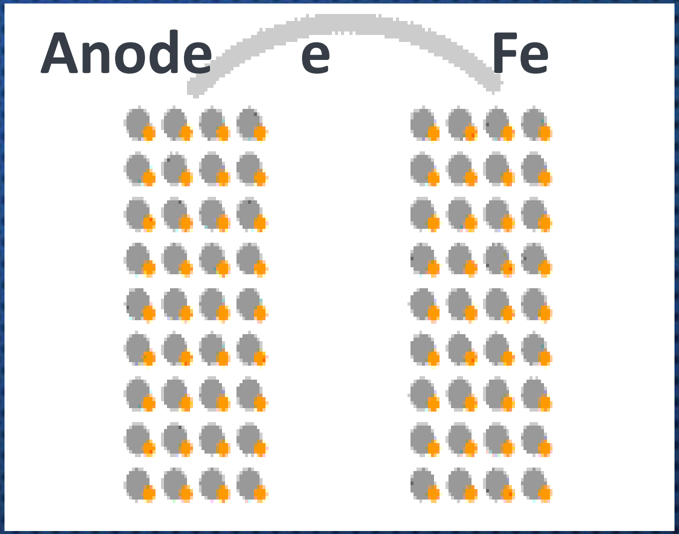
There are numerous codes and references that shall be referred to when dealing with cathodic protection among these are:

- NACE RP 0169
- NACE RP 0176
- NACE RP 177
- NACE RP 575
- BS 7361 PART I
- DNV RP B 401
- API 651
- J. Morgan, "Cathodic Protection"
- A.W. Peabody, "Control of Pipeline Corrosion"

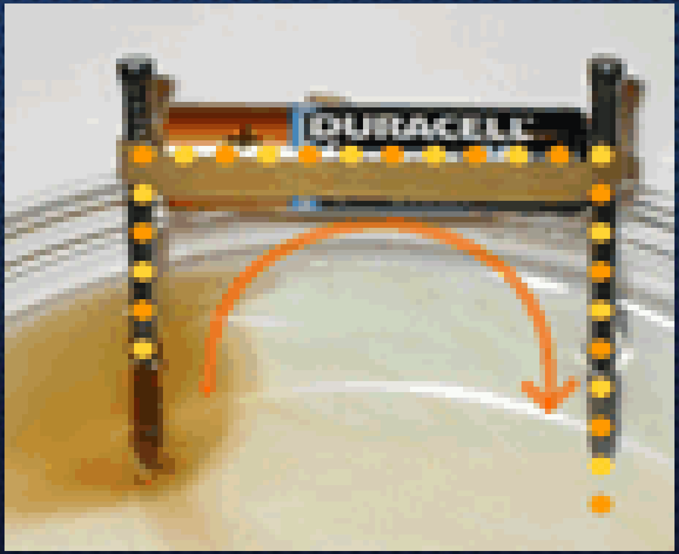
CP Techniques

There are two cathodic protection techniques these are:

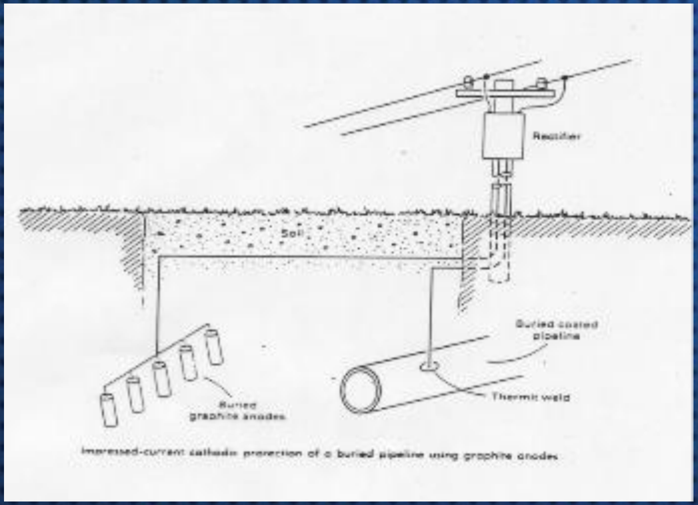
-Sacrificial (Galvanic): Involves the use of a more active metal as a source of protection current (anode)



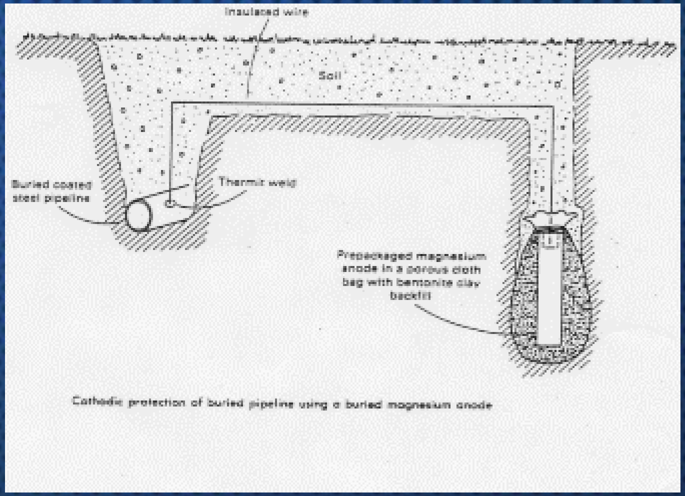
-Impressed current: Involves the enforcement of protection current by the use of a DC power source connected to anodes (positive terminal) and to cathode (negative terminal)



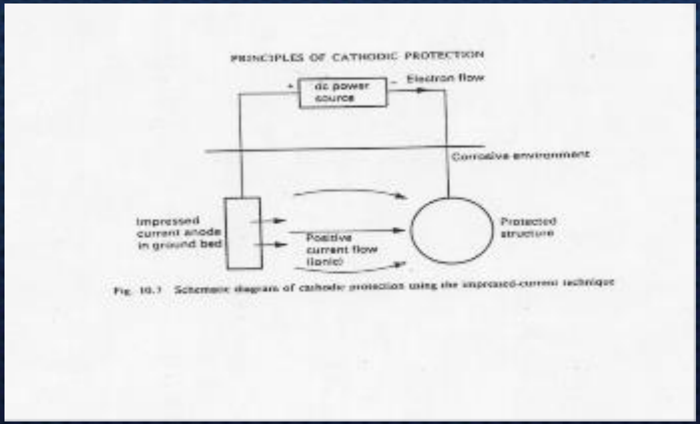
CP Techniques



Impressed-current cathodic protection of a buried pipeline using graphite anodes



Cathodic protection of buried pipeline using a buried magnesium anode



Schematic diagram of cathodic protection using the impressed-current technique

ICCP

Sacrificial

Sacrificial and Impressed Current CP

Sacrificial	Impressed current
No need for external power source	Requires an external power source
Easy to design and install	Requires skillful design and installation
uncontrollable	Can be controlled
Used only for limited surface areas and well coated structures	Can be used for uncoated surfaces and used for any surfaces
Has no detrimental effects	Can cause serious problems if not handled carefully
Is limited to low resistivity	can be used at any resistivity
Low maintenance	High maintenance

Cathodic Protection Criteria

There are several criteria for determining whether a structure has adequate cathodic protection. Once a testing method is adopted, it should continue to be used. The following methods are discussed:

- Potential- instant off
- Potential- shift criteria

Instant off Potential

Material	Potential in mV (VS. $Cu/CuSO_4$)
Steels, cast irons, alloy steels and stainless steels	
• Anaerobic Conditions	-950
• Aerobic Conditions	-850
Copper	-500
Lead	-600
Aluminum	-950

100mV Potential Shift

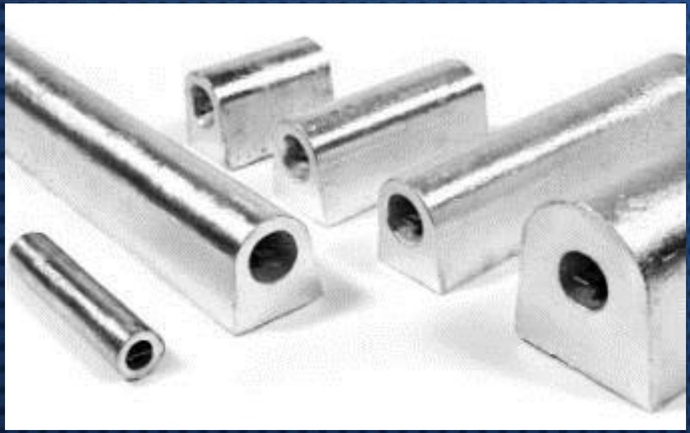
- When the potential shift is 100mV or more then the structure is said to be cathodically protected.
- Method involves the registry of structure's natural potential and then recording potential shift.
- Method difficulty remains in isolating all sources of current.

Sacrificial Anodes

For soil applications, anodes used are either magnesium or zinc.

- **Zinc use in soil is restricted above soil resistivity of 1000 Ω.cm**
- **Magnesium come in two types, standard and high potential.**

High Potential Mg Anodes

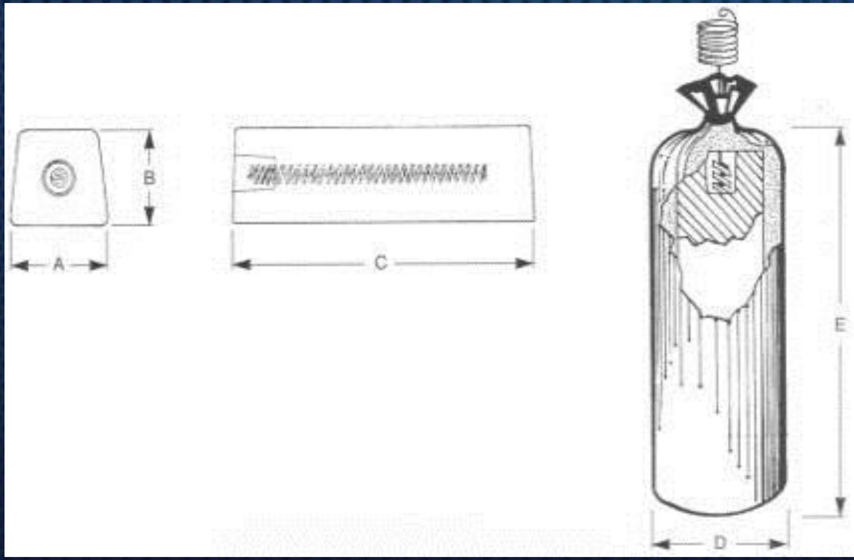


High potential magnesium anodes are used for higher resistivity applications

Element	ASTM B843 Industry Standard for M1C High Potential Anodes
Aluminum	0.01% max
Manganese	0.50 - 1.3%
Silicon	0.05% max
Copper	0.02% max
Nickel	0.001% max
Iron	0.03% max
Others, each	0.05

Standard Mg Anodes

Standard Mg anodes use is restricted above a resistivity of 3000 Ω.cm



Typical Chemical Analysis	
Aluminum	5.3 - 6.7%
Zinc	2.5 - 3.5%
Manganese	0.15 - 0.7%
Silicon	0.10% max
Copper	0.20% max
Nickel	0.002% max
Iron	0.003% max
Others	0.30% max
Magnesium	Remainder

Electrochemical Properties of Mg

Properties	High Potential Mg	Standard Mg
Specific gravity	1.77	1.80
Open Circuit Potential (V, Cu/$CuSO_4$)	-1.75	-1.55
Efficiency (%)	50	50
Effective Current Capacity (A.hr/kg)	1,100	1,100

Zinc Anodes

Zinc anodes are used either for soil cathodic protection at low resistivities or in sea water applications. Zinc has a limited output capacity.

Chemical Composition

Component	Composition (%, weight)
Fe	0.005 max.
Cd	0.025 ~ 0.07
Pb	0.006 max.
Cu	0.005 max.
Al	0.1 ~ 0.5
Zn	Remainder

ASTM B 418 Type I Properties

Properties	Zincano
Specific gravity	7.14
Open Circuit Potential (V, Ag/Agcl)	-1.05
Efficiency (%)	95
Effective Current Capacity (A.hr/kg)	780

Sacrificial Anode Backfill

This specially formulated anode backfill is used with either magnesium or zinc anodes. The standard anode mixture consists of:

- 75% gypsum,
- 20% bentonite
- 5% sodium sulfate

ALUMINUM ANODES

- **Typical chemical composition of aluminum anodes is shown**

Element	Percentage
Indium (In)	0.016 to 0.02%
Zinc (Zn)	4.75 to 5.75%
Silicon (Si)	0.08 to 0.12%
Copper (Cu)	0.003% Maximum
Iron (Fe)	0.12% Maximum
Cadmium (Cd)	0.002% Maximum
Others, each	0.02% Maximum
Others, total	0.05% Maximum
Aluminum	Remainder

ALUMINUM ANODES

- **Electrochemical properties of aluminum anodes can be seen in the table.**

Anode Capacity	1150 amp hours per pound (Minimum)
Potential (Calomel)	1.080 volts (Minimum)
Consumption Rate	7.6 pounds per amp year

- **Aluminum anodes are used for ship hulls, offshore pipelines, jackets, etc.**

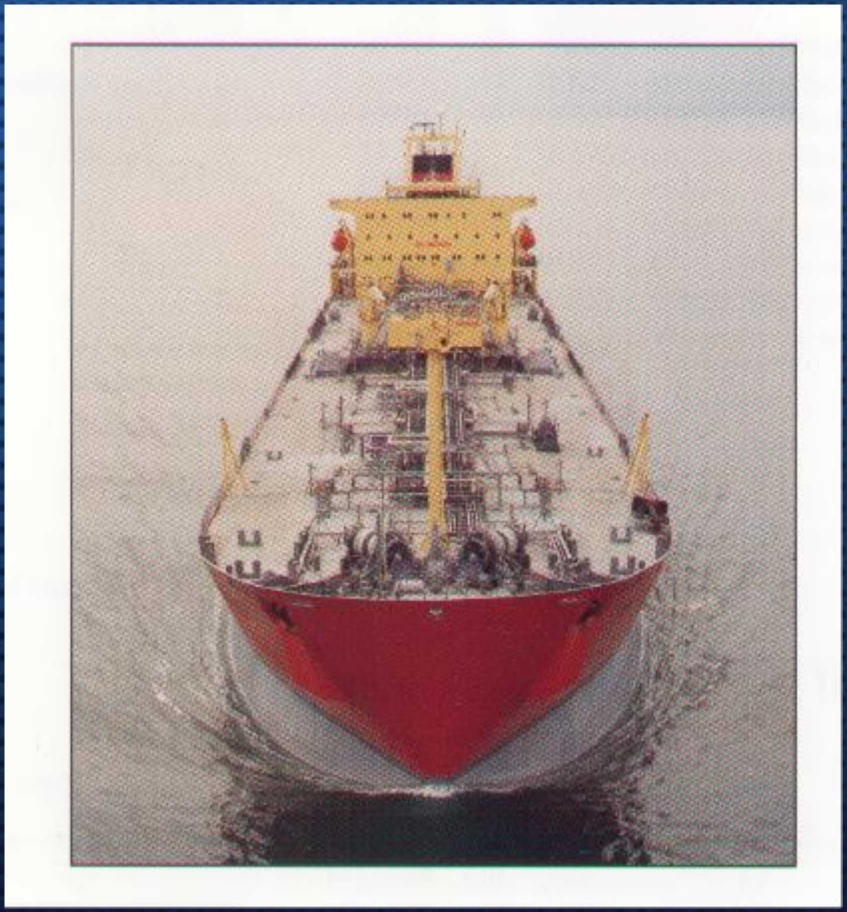
ALUMINUM ANODES

- **Aluminum anodes come in numerous shapes. Bracelet, slender or flush type are the aluminum anodes shapes used.**

ZINC ANODES FOR MARINE APPLICATIONS

- **Zinc anodes are used for marine applications and for fresh water applications, it is readily used for tank interiors as well as other marine applications.**

- **Zinc anodes are used primarily for the protection of ship hulls**



Zinc Anodes

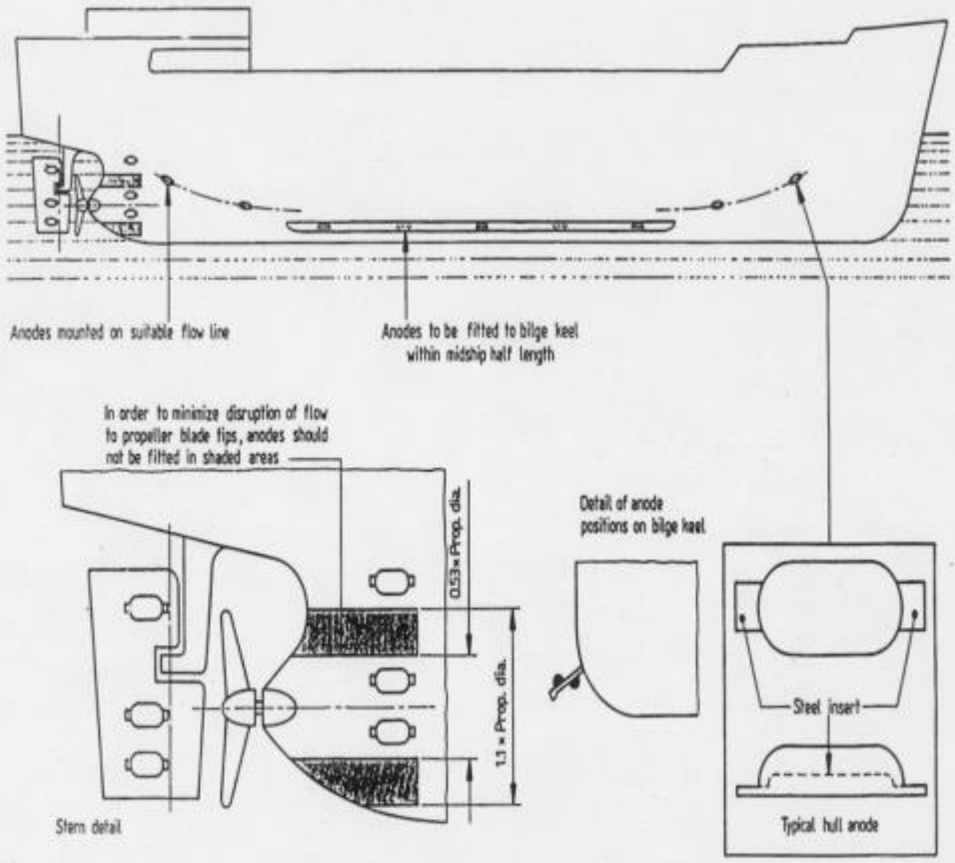


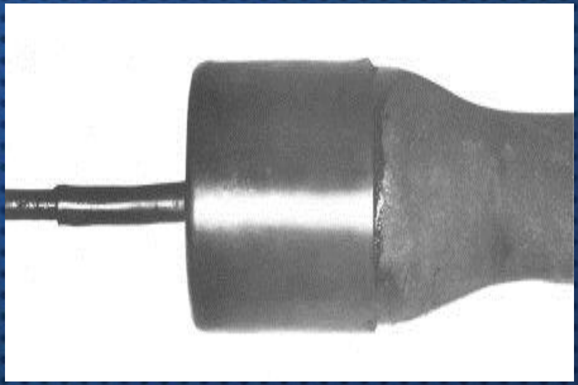
Figure 10. Typical sacrificial anode scheme for cathodic protection of a ship's hull

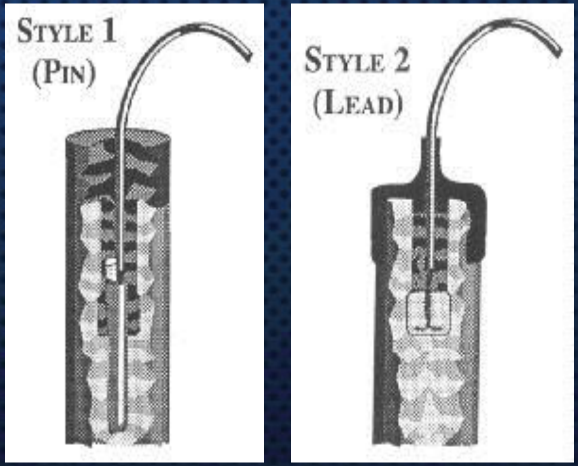
Impressed Current Anodes

- Impressed current anodes involves any material.
- The most common impressed current anode materials are:
  - FeSiCr
  - Graphite
  - Mixed metal oxide
  - Platinized
  - Elastomeric anodes

Fe Si Anodes

- Are the most common impressed current anodes
- Are used in soil, water or sea water
- Come in two grades; FeSi and FeSiCr for sea water applications
- Anode typical chemical composition as well as electrochemical properties are shown.
- Anodes could be a single head type or double head, solid or tubular.
- Cable connection to anode shall be handled with great care.
- There are numerous methods of cable connections to anode.





Fe Si Anodes

Composition, ASTM A518 Grade 3

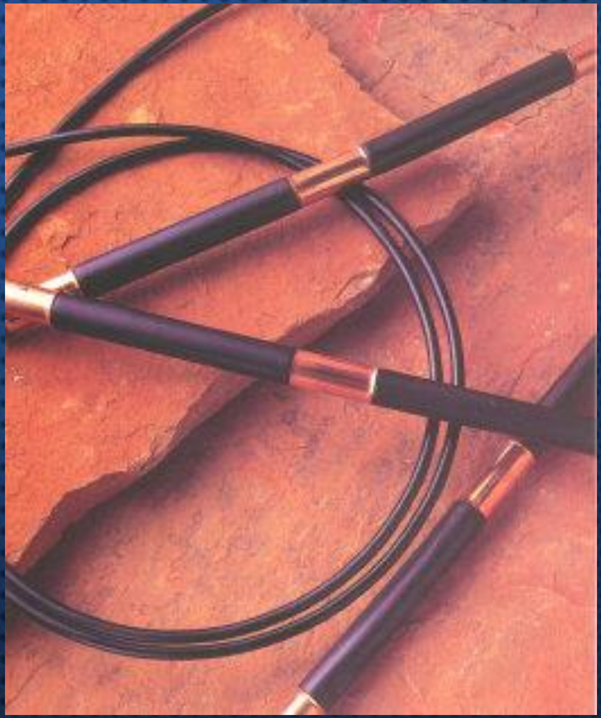
Silicon	14.20 - 14.75%
Chromium	3.25 - 5.00%
Manganese	1.50% max
Carbon	0.70 -1 .10%
Copper	0.50% max
Molybdenum	0.20% max

Electrochemical properties

Average soil resistitivity along groundbed, Ohm-cm	Maximum Amps per anode in a coke breeze column, 12" OD by 60"	Equivalent current density on surface of coke breeze column, Milliamps/sq ft
Less than 1000	2.00	127 (see note)
1000 - 1500	1.75	111 (see note)
1500 - 2000	1.50	96
2000 - 3000	1.25	80
Over 3000	1.00	64

MMO Anodes

- **Are termed non-consumable anodes**
- **They are used in extremely low resistivity soils and sea water applications.**
- **MMO anodes are platinum or titanium coated**
- **MMO anodes have the advantage of having a very light weight in comparison to its current output.**

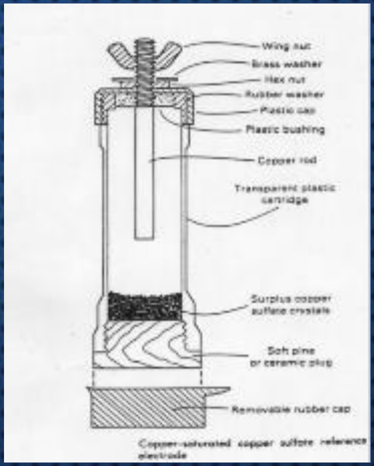


Potential Monitoring

- As previously mentioned, cathodic protection criteria is achieved when a metal reaches a certain potential against a reference electrode.
- Potential is measured using a high impedance multimeter utilizing a reference electrodes.

Potential Monitoring

- Reference electrodes could be portable or permanent.
- Reference electrodes shall be placed the closest to the structure being monitored.
- For soil applications Cu/CuSO4 reference electrodes are being used.
- For sea water applications either zinc or Ag/AgCl electrodes are used.



Test Stations

- Test stations are used as a mean for potential monitoring. It involves cable connection to the structure being monitored as well as other terminal for reference electrode.
- Test stations take many shapes and forms all of which serve the same purpose.

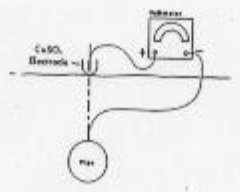


Fig. 2.2. Voltmeter Measurement of Pipe-to-Soil Potential. Connection to the pipe may be by means of a welded or soldered lead wire (as illustrated), by a contact bar, or by mechanical connection to a valve or fitting above the surface. The latter should be used with caution, as flanged fittings sometimes introduce extraneous potentials. If the soil is dry, a little water may be added to lower the contact resistance; it is usually adequate to dig a little below the surface.

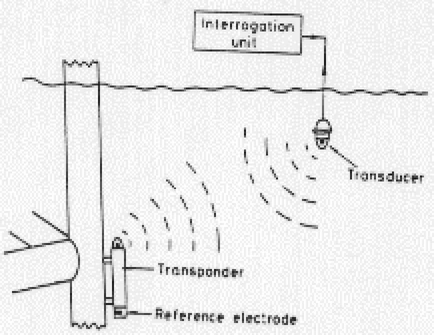
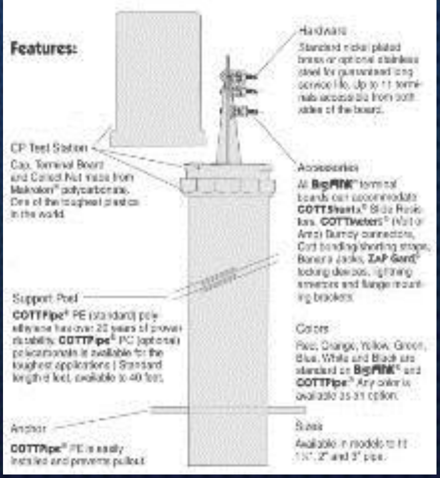
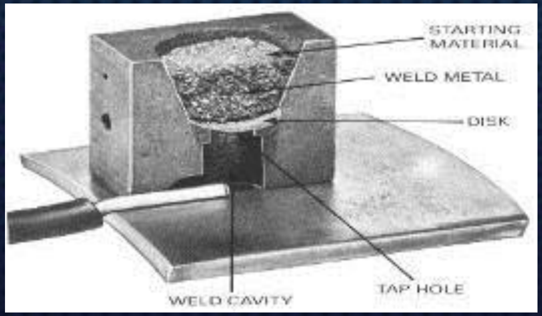


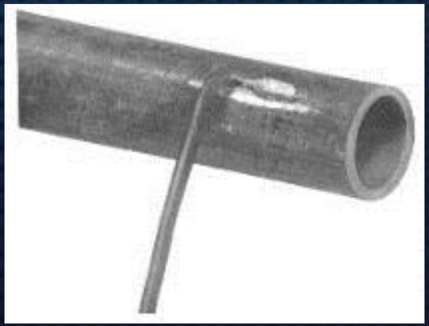
Fig. 14.8 – Transponder CP monitoring.



Cable Connections

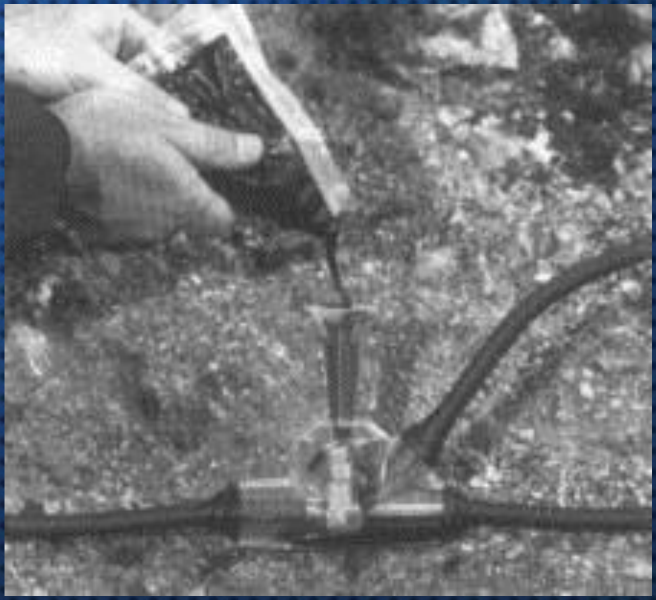
- In general cables are connected to structures either mechanically or by metallurgically (welding)
- Mechanical joining is made to ensure easy replacement of anodes, it involves bolting and joining through a mechanical coupling.
- Metallurgical joining involves coupling through welding. Arc welding of anode inserts is made. Cable connections is made through either CAD welding or through pin brazing.
- CAD welding is made using a crucible, flint gun and thermite weld powder.
- Pin brazing involves the use of pin brazing machine and requires more skilled labor.





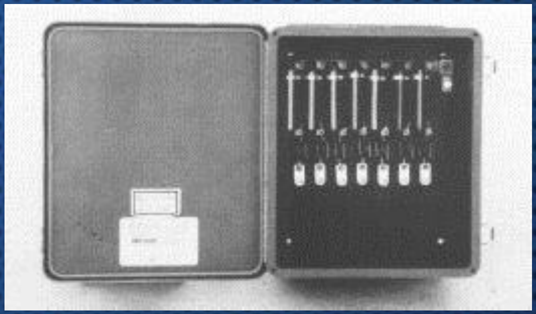
Cable to Cable Connection

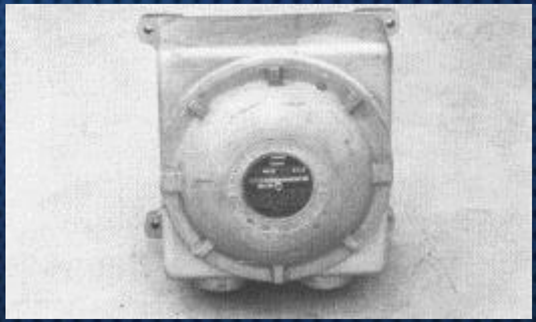
- In the case of impressed current anodes, cable to cable connection in the positive circuit is an extremely sensitive process, it requires a full isolation from the electrolyte.
- Impressed current cable to cable connections is made through splicing kits which involves full sealing with epoxy resin.
- Cable to cable connection in case of impressed current is not recommended for marine installations.



Cable to Cable Connection

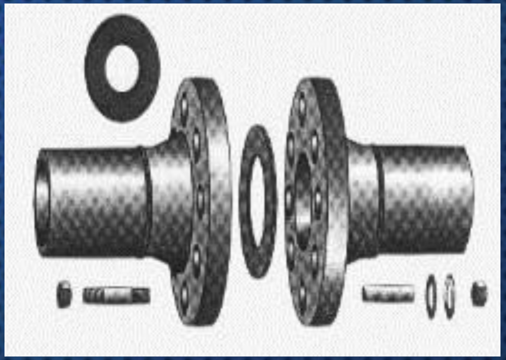
- The second method for connection of cable to cable is through a junction box
- Sometimes junction boxes are used to control current through variable resistors
- In the case of deep wells resistor cabinet is used to adjust anode outputs
- Negative output of T/Rs is sometimes connected to negative junction boxes to balance output current to protected structures





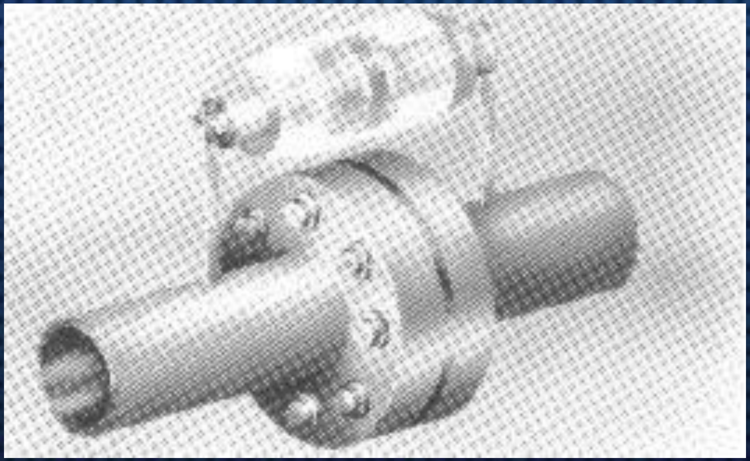
Electrical Isolation

- Structures to be protected shall be isolated from portions that doesn't require protection. Hence electrical isolation shall be made.
- In case of underground piping, electrical isolation is made through the use of either isolating flange kits or through the use of monolithic joints.
- Isolating flange kits have the disadvantages of maintainability, can leak at high pressures.
- Isolating flange kits shall not be used in offshore environments
- Isolating flange kits have the advantage of having a relatively low cost and is easy to install.
- Monolithic isolating joints can be used at under any operating pressure.



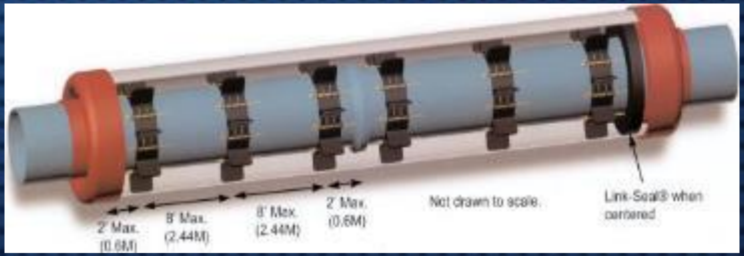
Electrical Isolation

- Isolating flange kits can be a source of hazard and thus a spark gap shall be used with the IFK in hazardous areas.



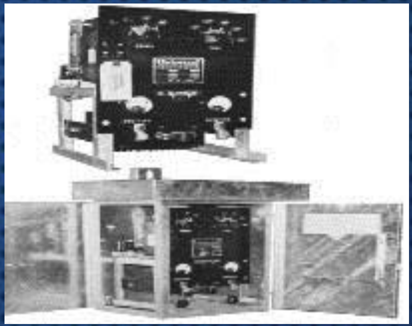
Pipeline Metallic Casing

- Pipeline inside casing is not cathodically protected
- It shall be electrically isolated from casing
- Pipeline inside casing shall be protected and full sealing of casing shall be made
- Casing insulation from pipe is made using casing spacers and end seals.



Impressed Current Power Source

- Any DC power source can be used for energizing the impressed current for protection.
- The most common DC power sources used are the transformer rectifiers, which are either air cooled or oil cooled. Control of rectifiers is selected according to purpose.
- Solar power stations are used where there is no power supply
- DC generators could be used where there is an ample diesel supply

Impressed Current Groundbed

- Impressed current anodes are placed together in a 'groundbed'
- Groundbeds are either shallow (horizontal or vertical) or are deep (depth >30m)
- Shallow horizontal or vertical groundbeds are used where there is a single structure to be protected with no obstacles in between
- Deep anode wells are used in the case of protecting a congested plant and in the case of high resistivity.

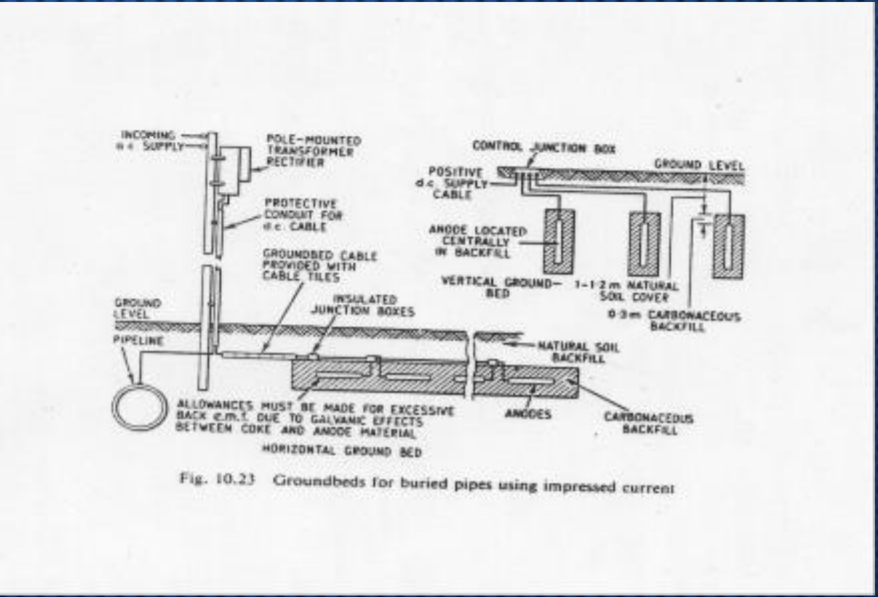


Fig. 10.23 Groundbeds for buried pipes using impressed current

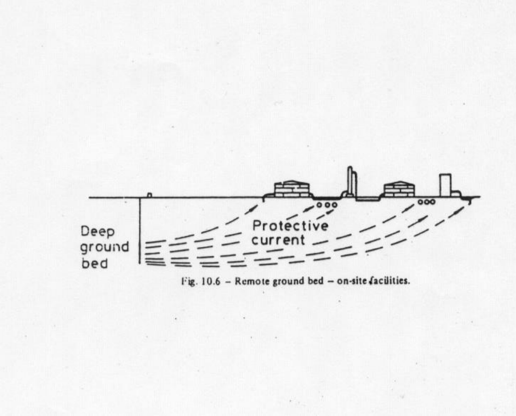
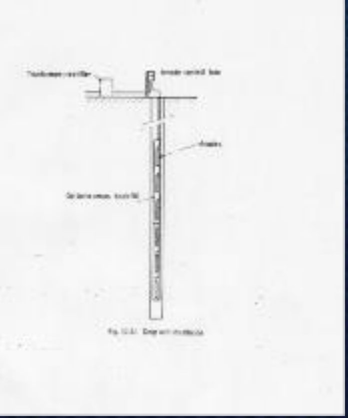
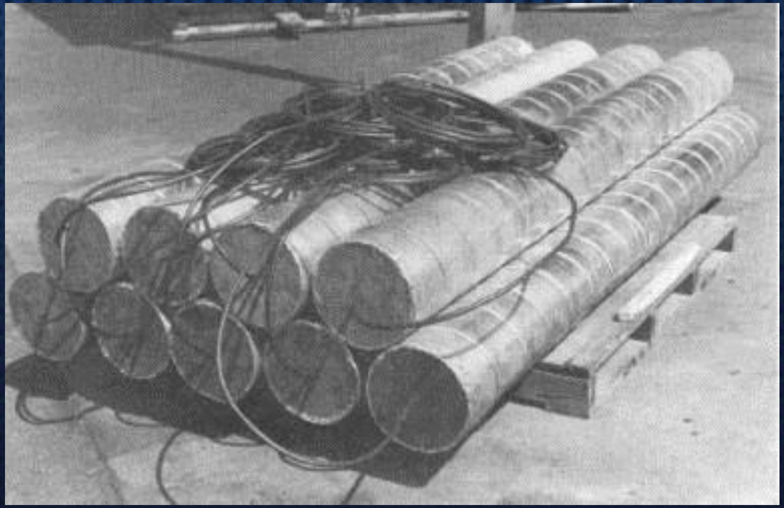


Fig. 10.6 – Remote ground bed – on-site facilities.



Carbonaceous Backfill

- Inorder to minimize the electrical resistance between groundbed anodes and earth, carbonaceous backfill is used.
- Coke breeze comes in many grades but the most important factor is the elctrical resistivity that shall be a minimum of 1 Ω.cm
- Impressed current anodes are some times cannistered with the backfill.
- Backfill shall be well tamped to eliminate air gaps and voids



Carbonaceous Backfill

Property	218-L	218-R	251	251-P	4518
• Resistivity, ohm-inch	0.02	0.02	0.01	0.01	0.01
• Resistivity, ohm-cm	0.05	0.05	0.03	0.02	0.03
• Carbon (L.O.I. method)	99.0	99.0	99.8%	99.8%	99.9%
• Moisture	0.10%	0.10%	0.07%	0.07%	0.02%
• Ash	0.35%	0.35%	0.12%	0.13%	0.10%
• VCM	0.30%	0.30%	0.02%	0.02%	0/22%
• Sulfur	3.75%	3.75%	5.8%	5.8%	4.3%
• Bulk Density (lbs/ft3)	46-50	48-53	64-72	64-72	62-66
• General Sizing + 4 Mesh + 8 Mesh - 8 Mesh	+4M < 10% +8M > 90% -8M < 10%	+4M 25% +8M > 70% -8M < 5%	+20M <5% +100M >70% -100M Balance		4M 10% +20M > 80% -20M 10%
• Applications			Use for Ground Beds & Deep Wells		

Cathodic Protection Surveys

- **Cathodic protection surveys are made for:**
  - **Gathering information regarding the electrolyte through resistivity and pH measurement**
  - **Gathering information with regards to any existing cathodic protection system**
  - **Information with regards to sources of corrosion hazard (sources of stray current)**
  - **Information with regards to power sources**
  - **Cathodic protection surveys could be made to existing underground facilities as means of evaluating the status quo of the structure survey includes:**
    - **DCVG survey**
    - **Line current survey**
    - **Potential Survey**
    - **Close interval survey**
    - **Interference survey**

Soil Resistivity Surveys

Table 2.3.3 Average resistivity of different environments[64]

Environment	ohm cm
Sea water	25
Brackish river water	1
Town water supply	1000- 1200
Alluvial soils	1000- 2000
Clays	1000- 5000
Mixed clays	4000-10000
Gravel	10000-25000
Sand	25000-50000
Porous rock	> 50000
Non-porous granite	>500000

Soil Resistivity

Up to 10 ohm.m : Severely Corrosive

10 ohm.m to 50 ohm.m : Corrosive

50 ohm.m to 100 ohm.m : Moderately Corrosive

100 ohm.m to 200 ohm.m : Slightly Corrosive

200 ohm.m and above : Non-Corrosive

Interference Surveys

- Interference survey is made to determine the detrimental effects caused by the interference of two cathodic protection systems
- Interference is eliminated in the case of pipelines through solid bonding or resistor bonding

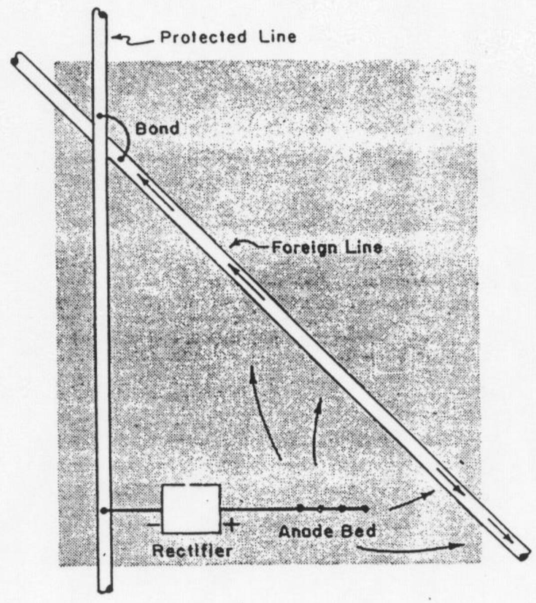


Fig. 10.6. An Obscure Case. Much of the current collected on the foreign line flows toward the crossing, where it can be safely handled with a simple bond. Some of it, however, flows in the opposite direction, and is discharged over a relatively large and remote area. Such a situation does not arise often, and probably does little damage in any case, because of the large discharge area. It can be avoided by proper anode bed placement, and can be remedied by the use of auxiliary drainage anodes.

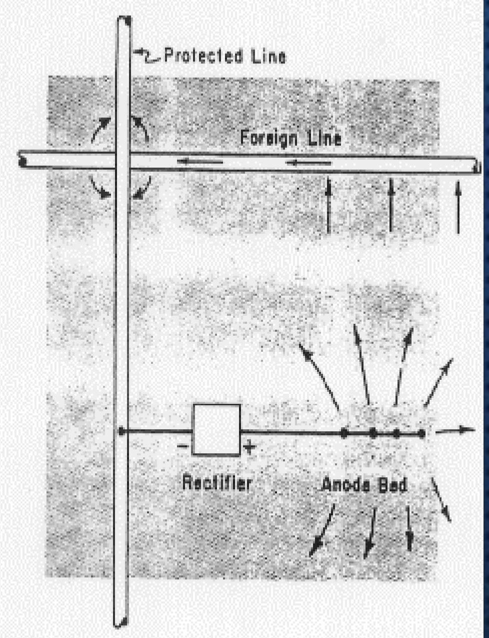
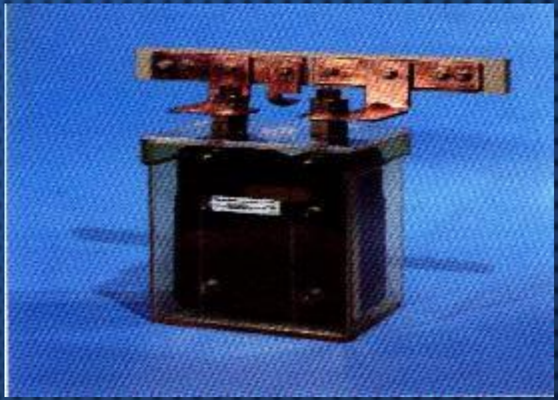


Fig. 10.1. Interference. Some of the current flowing from the anode bed to the protected line collects on the foreign line, flows along it toward the crossing (from both sides), and then discharges through the soil to the protected line. Damage is inflicted on the foreign line in the neighborhood of the crossing.

Stray Current

- Stray current is an unintentional or accidental source of current that is picked up by the underground pipes
- Sources of stray current are:
  - Electric tramways
  - High tension power cables
- Drainage of stray current to earth is essential or inclusion of the stray current source could be done.
- For protection against stray current from high tension lines, dual zinc electrodes or polarization cells are used



DCVG Surveys

- Used to determine the status of a buried pipeline
- Is made using reference electrodes, data logger and processor
- Can detect the location and severity of corrosion
- Can detect locations of coating deterioration