

ENGINEERING STANDARD
FOR
CORROSION CONSIDERATION
IN
MATERIAL SELECTION

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1. SCOPE

This Engineering Standard covers an outline for the corrosion consideration in selection of materials used in Oil, Gas and Petrochemical Industries.

The designers have to apply provisions of this Standard during the design stage of a system in order to avoid or minimize corrosion hazards technically, economically and safely during the designed life of such a systems.

2. REFERENCES

Throughout this standard the following standards and codes are referred to. The editions of these standards and codes that are in effect at the time of publication of this standard shall, to the extent specified herein, form a part of this Standard. The applicability of changes in standards and codes that occur after the date of this Standard shall be mutually agreed upon by the company and the Vendor/Consultant/Contractor.

API (AMERICAN PETROLEUM INSTITUTE)

- Guide for Inspection of Refinery Equipment (Chapter II Conditions Causing Deterioration of or Failure)
- API 5L "Line Pipe"
- API RP 14E "Recommended Practice for Design and Installation of Offshore Production Platform Piping systems"
- API Publication 941
"Recommended Practice for Calculation of Heater Tube Thickness in Petroleum Refinery"

ASME (AMERICAN SOCIETY OF MECHANICAL ENGINEERS)

- ASME VIII "Boiler and Pressure Vessel Codes"

ASTM (AMERICAN SOCIETY FOR TESTING AND MATERIALS)

- ASTM Corrosion Standard Test Method: G1 to G52
- B 117 "Salt Spray (Fog) Testing"
 - B 287 "Acetic Acid-Salt Spray (Fog) Testing"
 - G 1 "Recommended Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens"
 - G 2 "Recommended Practice for Aqueous Corrosion Testing of Samples of Zirconium and Zirconium Alloys"
 - G 3 "Recommended Practice for Conventions Applicable to Electrochemical Measurements in Corrosion Testing"
 - G 4 "Recommended Practice for Conducting Plant Corrosion Tests"
 - G 5 "Recommended Practice for Standard Reference Method for Making Potentiostatic and Potentiodynamic Anodic Polarization Measurements"
 - G 15 "Definition of Terms Relating to Corrosion and Corrosion Testing"
 - G 16 "Recommended Practice for Applying Statistics to Analysis of Corrosion Data"

- G 28 "Detecting Susceptibility to Intergranular Attack in Wrought Nickel-Rich, Chromium-Bearing Alloys"
- G 30 "Recommended Practice for Making and Using U-Bend Stress Corrosion Test Specimens"
- G 31 "Recommended Practice for Laboratory Immersion Corrosion Testing of Metals"
- G 32 "Vibratory Cavitation Erosion Test"
- G 33 "Recommended Practice for Recording Data from Atmospheric Corrosion Tests of Metallic-Coated Steel Specimens"
- G 34 "Test for Exfoliation Corrosion Susceptibility in 7××× Series Copper-Containing Aluminum Alloys (EXCO Test)"
- G 35 "Recommended Practice for Determining the Susceptibility of Stainless Steels and Related Nickel-Chromium-Iron Alloys to Stress Corrosion Cracking in Polythionic Acids"
- G 36 "Recommended Practice for Performing Stress Corrosion Cracking Tests in a Boiling Magnesium Chloride Solution"
- G 37 "Recommended Practice for Use of Mattsson's Solution of pH 7.2 to Evaluate the Stress Corrosion Cracking Susceptibility of Copper-Zinc Alloys"
- G 38 "Recommended Practices for Making and Using the C-Ring Stress Corrosion Cracking Test Specimen"
- G 39 "Preparation and Use of Bent-Beam Stress Corrosion Specimens"
- G 40 "Definition of Terms Relating to Erosion by Cavitation and Impingement"
- G 41 "Recommended Practice for Determining Cracking Susceptibility of Titanium Alloys Exposed Under Stress to a Hot Salt Environment"
- G 43 "Acidified Synthetic Sea Water (Fog) Testing"
- G 44 "Recommended Practice for Alternate Immersion Stress Corrosion Testing in 3.5% Sodium Chloride Solution"
- G 46 "Recommended Practice for Examination and Evaluation of Pitting Corrosion"
- G 47 "Recommended Practice for Determining Susceptibility to Stress Corrosion Cracking of High Strength 7××× Aluminum"
- G 48 "Test for Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys by the Use of Ferric Chloride Solution"
- G 49 "Recommended Practice for Preparation and Use of Direct Tension Stress Corrosion Test Specimens"
- G 50 "Recommended Practice for Conducting Atmospheric Corrosion Tests on Metals"
- G 51 "Test for pH of Soil"
- G 52 "Recommended Practice for Conducting Surface Sea Water Exposure Tests on Metals and Alloys"

BS (BRITISH STANDARDS)

BS 5500	"Unfired Fusion Welded Pressure Vessels"
BS 5903	"Corrosion Testing of Austenitic Stainless Steel"
BS 6682	"Bimetallic Corrosion Determination"
BS 7318 PP	"Materials Testing for Design"
BS 534	"Steel Pipes, Fittings and Specials for Water, Gas and Sewage"

IPS (IRANIAN PETROLEUM STANDARDS)

IPS-M-ME-130	"Pressure Storage & Spheres (for LPG)"
IPS-E-PI-221	"Piping Materials Selection (Petroleum Refinery & Petrochemical Plant)"
IPS-E-PI-140	"Onshore Transportation Pipelines"
IPS-E-TP-820	"Electrochemical Protection"
IPS-E-TP-780	"Chemical Control of Corrosive Environments"
IPS-E-TP-760	"Corrosion Consideration in Design"
IPS-E-TP-100	"Paints"
IPS-C-TP-274	"Coating"
IPS-E-TP-350	"Lining"

ISO (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION)

ISO 9000	"Quality Systems"
ISO 8993	Corrosion • Anodized aluminum and aluminum alloys - Rating system for the evaluation of pitting # - Chart method
ISO 8994	Corrosion • Anodized aluminum and aluminum alloys - Rating system for the evaluation of pitting # - Grid method
ISO 3651-1	Corrosion • Austenitic stainless steels - Determination of resistance to intergranular # - Part 1: Corrosion test in nitric acid*
ISO 3651-2	Corrosion • Austenitic stainless steels - Determination of resistance to intergranular # - Part 2: Corrosion test in a sulphuric*
ISO 5952	Corrosion • Continuously hot-rolled steel sheet of structural quality with improved atmospheric # resistance
ISO 6957	Corrosion • Copper alloys - Ammonia test for stress # resistance
ISO 4539	Corrosion • Electrodeposited chromium coatings - Electrolytic # testing (EC test)
ISO 7441	Corrosion • Corrosion of metals and alloys - Determination of bimetallic # in outdoor exposure corrosion tests
ISO 8407	Corrosion • Corrosion of metals and alloys - Removal of # products from corrosion test specimens
ISO 7539-1	Corrosion • Corrosion of metals and alloys - Stress # testing - Part 1: General guidance on testing procedures
ISO 7539-2	Corrosion • Corrosion of metals and alloys - Stress # testing - Part 2: Preparation and use of bent-beam specimens
ISO 7539-3	Corrosion • Corrosion of metals and alloys - Stress # testing - Part 3: Preparation and use of U-bend specimens

ISO 7539-4	Corrosion • Corrosion of metals and alloys - Stress # testing - Part 4: Preparation and use of Uniaxially loaded tension specimens
ISO 7539-5	Corrosion • Corrosion of metals and alloys - Stress # testing - Part 5: Preparation and use of C-ring specimens
ISO 7539-6	Corrosion • Corrosion of metals and alloys - Stress # testing - Part 6: Preparation and use of pre-cracked specimens
ISO 7539-7	Corrosion • Corrosion of metals and alloys - Stress # testing - Part 7: Slow strain rate testing
ISO 10446	Corrosion • All-weld metal test assembly for the classification of # resisting chromium and chromium-nickel steel covered arc welding*
ISO 3651-1	Corrosion • Determination of resistance to intergranular corrosion - Part 1: # test in nitric acid medium by measurement of loss in*
ISO 3651-2	Corrosion • Determination of resistance to intergranular corrosion - Part 2: # test in a sulphuric acid/copper sulphate medium in the*
ISO 6743-8	Corrosion • Industrial oils and related products (class L) - Classification - Part 8: Family R (Temporary protection against #)
ISO 4536	Corrosion • Metallic and non-organic coatings on metallic substrates - Saline droplets # test (SD test)
ISO 4541	Corrosion • Metallic and other non-organic coatings - Corrodokote # test (CORR test)
ISO 4543	Corrosion • Metallic and other non-organic coatings - General rules for # tests applicable for storage conditions
ISO 8403	Corrosion • Metallic coatings - Coatings anodic to the substrate - Rating of test specimens subjected to # tests
ISO 4540	Corrosion • Metallic coatings - Coatings cathodic to the substrate - Rating of electroplated test specimens subjected to # tests
ISO 1462	Corrosion • Metallic coatings - Coatings other than those anodic to the basis metal - Accelerated # tests - Method for the evaluation*
ISO 1459	Corrosion • Metallic coatings - Protection against # by hot dip galvanizing - Guiding principles
ISO 4538	Corrosion • Metallic coatings - Thioacetamide # test (TAA test)
ISO 8565	Corrosion • Metals and alloys - Atmospheric # testing - General requirements for field tests
ISO 9400	Corrosion • Nickel-based alloys - Determination of resistance to intergranular #
ISO 9591	Corrosion of aluminum alloys - Determination of resistance to stress corrosion cracking
ISO 9223	Corrosion of metals and alloys - Corrosivity of atmospheres - Classification
ISO 9224	Corrosion of metals and alloys - Corrosivity of atmospheres - Guiding values for the corrosivity categories
ISO 9225	Corrosion of metals and alloys - Corrosivity of atmospheres - Measurement of pollution

ISO 7441	Corrosion of metals and alloys - Determination of bimetallic corrosion in outdoor exposure corrosion tests
ISO 6509	Corrosion of metals and alloys - Determination of dezincification resistance of brass
ISO 8407	Corrosion of metals and alloys - Removal of corrosion products from corrosion test specimens
ISO 8044	Corrosion of metals and alloys - Vocabulary
ISO 4623	Corrosion • Paints and varnishes - Filiform # test on steel
ISO/TR 10129	Corrosion • Plain bearings - Testing of bearing metals - Resistance to # by lubricants under static conditions
ISO 3506	Corrosion - resistant stainless steel fasteners - Specifications
ISO 6315	Corrosion • Road vehicles - Brake linings - Seizure to ferrous mating surface due to # - Test procedure
ISO 6505	Corrosion • Rubber, vulcanized - Determination of adhesion to, and # of, metals
ISO 9455-12	Corrosion • Soft soldering fluxes - Test methods - Part 12: Steel tube # test
ISO/TR 10217	Corrosion • Solar energy - Water heating systems - Guide to material selection with regard to internal#
ISO 4952	Corrosion • Structural steels with improved atmospheric # resistance
ISO 10062	Corrosion tests in artificial atmosphere at very low concentrations of polluting gas(es)
ISO 7384	Corrosion tests in artificial atmosphere - General requirements
ISO 9227	Corrosion tests in artificial atmospheres - salt spray tests
ISO 3160-2	Corrosion • Watch cases and accessories - Gold alloy coverings - Part 2: Determination of fineness, thickness, # resistance and *
ISO 5662	Corrosive • Petroleum products - Electrical insulating oils - Detection of # sulphur
ISO 2746	Corrosive • Vitreous and porcelain enamels - Enameled articles for service under highly # conditions - High voltage test
ISO 6251	Corrosiveness • Liquefied petroleum gases - # to copper-copper Strip Test
ISO 2160	Corrosiveness • Petroleum products - # to copper - Copper strip test

NACE (NATIONAL ASSOCIATION OF CORROSION ENGINEERS)

Corrosion Test Methods

TM-01-69	"Laboratory Corrosion Testing of Metals for the Process Industries"
TM-02-70	"Methods of Conducting Controlled Velocity Laboratory Corrosion Tests"
TM-01-71	"Autoclave Corrosion Testing of Metals in High Temperature Water"
TM-01-77	"Testing of Metals for Resistance to Sulfide Stress Cracking at Ambient Temperatures"

MR-01-75 (1991 Rev)	"Sulfide Stress Cracking Resistance Metallic Materials for Oil Field Equipment"
TM-01-70	"Visual Standard for Surface of New Steel Airblast Cleaned with Sand Abrasive"
TM-01-72	"Antirust Properties of Petroleum Products Pipeline Cargoes"
TM-01-73	"Methods for Determining Water Quality for Subsurface Injection Using Membrane Filters"
TM-01-74	"Laboratory Methods for the Evaluation of Protective Coatings Used as Lining Materials in Immersion Service"
TM-02-74	"Dynamic Corrosion testing of Metals in High Temperature Water"
TM-03-74	"Laboratory Screening Tests to Determine the Ability of Scale Inhibitors to Prevent the Precipitation of Calcium sulfate and Calcium Carbonate from Solution"
TM-01-75	"Visual Standard for Surfaces of New Steel Centrifugally Blast Cleaned with steel Grit and Shot"
TM-02-75	"Performance Testing of Sucker Rods by the Mixed String, Alternate Rod Method"
TM-02-75	"Performance Testing of Sucker Rods by the Mixed String, Alternate Rod Method"
TM-03-75	"Abrasion Resistance Testing of Thin Film Baked Coatings and Linings Using the Falling Sand Method"

3. DEFINITIONS AND TERMINOLOGY

Acceleration Corrosion Test

Method designed to approximate, in a short-time, the deteriorating effect under normal long-term service condition.

Aerated

Solution containing more than 10 PPb (Parts Per billion) oxygen.

Age hardening

Hardening by aging, usually after rapid cooling or cold working.

Aging

A change in the properties of certain metals and alloys that occurs at ambient or moderately elevated temperatures after hot working or a heat treatment (quench aging in ferrous alloys, natural or artificial aging in ferrous and non-ferrous alloys) or after a cold working operation (strain aging). The change in properties is often but not always, due to a phase change (precipitation), but never involves a change in chemical composition of the metal or alloy.

Alloy steel

Is one that contains either silicon or manganese in amounts in excess of those quoted in plain carbon steel or that contains any other element, or elements, as the result of deliberately made alloying additions.

Annealing

A generic term denoting a treatment, consisting of heating to and holding at a suitable temperature, followed by cooling at a suitable rate, used primarily to soften metallic materials, but also to simultaneously produce microstructure. The purpose of such changes may be, but is not confined to improvement of machinability, facilitation of cold work, improvement of mechanical or electrical properties and/or increase in stability of dimensions. When the term is used by itself, full annealing is implied. When applied only for the relief of stress, the process is properly called stress relieving or stress-relief annealing.

Austenite

A solid solution of one or more elements in face-centered cubic iron. Unless otherwise designated (such as nickel austenite) the solute is generally assumed to be carbon.

Bainite

A metastable aggregate of ferrite and cementite resulting from the transformation of austenite at temperatures below the pearlite but above the martensite start temperature.

Brittle fracture

Separation of a solid accompanied by little or no macroscopic plastic deformation. Typically, brittle fracture occurs by rapid crack propagation with less expenditure of energy than for ductile fracture.

Case hardening

A generic term covering several processes applicable to steel that change the chemical composition of the surface layer by absorption of carbon, nitrogen or a mixture of the two and, by diffusion, create a concentration gradient. The outer portion, or case, is made substantially harder than the inner portion, or core.

Caustic embrittlement

An obsolete historical term denoting a form of stress corrosion cracking most frequently encountered in carbon steels or iron-chromium-nickel alloys that are exposed to concentrated hydroxide solutions at temperatures of 200 to 250°C.

Cold working

Deforming metal plastically under conditions of temperature and strain rate that induce strain hardening usually, but not necessarily, conducted at room temperature. Contrast with hot working.

Hot working

Deforming metal plastically at such a temperature and strain rate that recrystallization takes place simultaneously with the deformation, thus avoiding any strain hardening. Contrast with cold working.

Hydrogen sulfide

Without H ₂ S:	Environment containing less than 1 PPM H ₂ S.
With H ₂ S	Environment containing more than 1 PPM H ₂ S.
Low H ₂ S	Greater than 3 PPM but less than 6 PPM H ₂ S.
High H ₂ S	More than 6 PPM.

Killed steel

Thoroughly deoxidized steel, for example, by addition of aluminum or silicon, in which the reduction between carbon and oxygen during solidification is suppressed.

Normalizing

Heating a ferrous alloy to a suitable temperature above the transformation range and then cooling in air to a temperature substantially below the transformation range.

Pearlite

A metastable lamellar aggregate of ferrite and cementite resulting from the transformation of austenite at temperatures above the bainite range.

Powder metallurgy

The art of producing metal powders and utilizing metal powders for production of massive materials and shaped objects.

Precipitation hardening

Hardening caused by the precipitation of a constituents from a supersaturated solution. See also age hardening and aging.

Quench aging

Aging induced by rapid cooling after solution heat treatment.

Quench-age embrittlement

Embrittlement of low carbon steels resulting from precipitation of solute carbon of existing dislocations and from precipitation hardening of the steel caused by differences in the solid solubility of carbon in ferrite at different temperatures. Quench age embrittlement usually is caused by rapid cooling of the steel from temperature slightly below AC_1 (The temperature at which austenite begins to form), and can be minimized by quenching from lower temperature.

Quench cracking

Fracture of a metal during quenching from elevated temperature. Most frequently observed in hardened carbon steel, alloy steel, or tool steel parts of high hardness and low toughness. Cracks often emanate from filets, holes, corners, or other stress raisers and result from high stresses due to the volume changes accompanying transformation to martensite.

Quench hardening

(1) In ferrous alloys, hardening by austenitizing and then cooling at a rate such that a substantial amount of austenite transforms to martensite. (2) In copper and titanium alloys hardening by solution treating and quenching to develop a martensite like structure.

Quenching

Rapid cooling of metals (often steels) from a suitable elevated temperature. This generally is accomplished by immersion in water, oil, polymer solution, or salt, although forced air is sometimes used.

Sensitization heat treatment

A heat treatment, whether accidental, intentional, or incidental (as during welding) that causes precipitation of constituents at grain boundaries, often causing the alloy to become susceptible to intergranular corrosion, cracking or S.C.C (Stress Corrosion Cracking).

Sensitization

In Austenitic stainless steels the precipitation of chromium carbide usually at grain boundaries, on exposure to temperatures of about 550 to 850°C.

Steel:

Ferrite

Ferrite is the name given to the body centered cubic allotropes of iron, α and δ iron, and to body centered cubic solid solutions

Austenite

Austenite is the name given to the face centered cubic, or γ , variety of iron, and to the face centered cubic solid solutions.

Cementite

Is the name given to the carbide of iron, Fe_3C . This is an extremely hard and brittle constituents.

Pearlite

Pearlite is the eutectoid mixture of ferrite and cementite, and is formed when Austenite decomposes during cooling. It consists of alternate thin layers, or lamellae, of ferrite and cementite.

Martensite

This is the name given to the very hard and brittle constituent that is formed when a steel is very rapidly cooled from the Austenitic state. It is a ferrite, highly super saturated with dissolved carbon.

Sorbite and troostite

These are names given to the structures produced when martensite or bainite is tempered, that is, heated to same temperature not exceeding 700°C for the purpose of reducing brittleness and hardness.

Bainite

This is the term that is given to the decomposition product that is formed when austenite decomposes by either isotherm transformation, or at a cooling rate intermediate between the very rapid cooling necessary for martensite and the slower rate of cooling at which pearlite is formed.

Plain carbon steel

Is a steel containing up to 1.5 percent of carbon together with not more than 0.5 percent of silicon and not more than 1.5 percent of manganese, and only traces of other elements.

Alloy steel

Is one that contains either silicon or manganese in amounts in excess of those quoted above, or that contains any other element, or elements, as the result of deliberately made alloying additions.

Tempering

To reheat hardened steel or hardened cast Iron to some temperature below the eutectoid temperature for the purpose of decreasing hardness and increasing toughness.

Transition temperature

Temperature within a range in which the ductility changes rapidly with temperature.

Tensile strength

The ratio of maximum load to original cross section area.

4. UNITS

This Standard is based on International System of Units (SI), except where otherwise specified.

5. GENERAL

Today, there is a great deal of refinement in the availability of materials of construction, varying from metallic to non-metallic. Also there are a large number of factors to be taken into consideration when selecting a material for a given application; these factors can be put into following major groups:

5.1 Environment

Corrosion consideration arise when environment exploits the chemical or physical properties of a material. Therefore an understanding of the various type of environments is necessary to select a stable and resistance material.

5.2 Cost

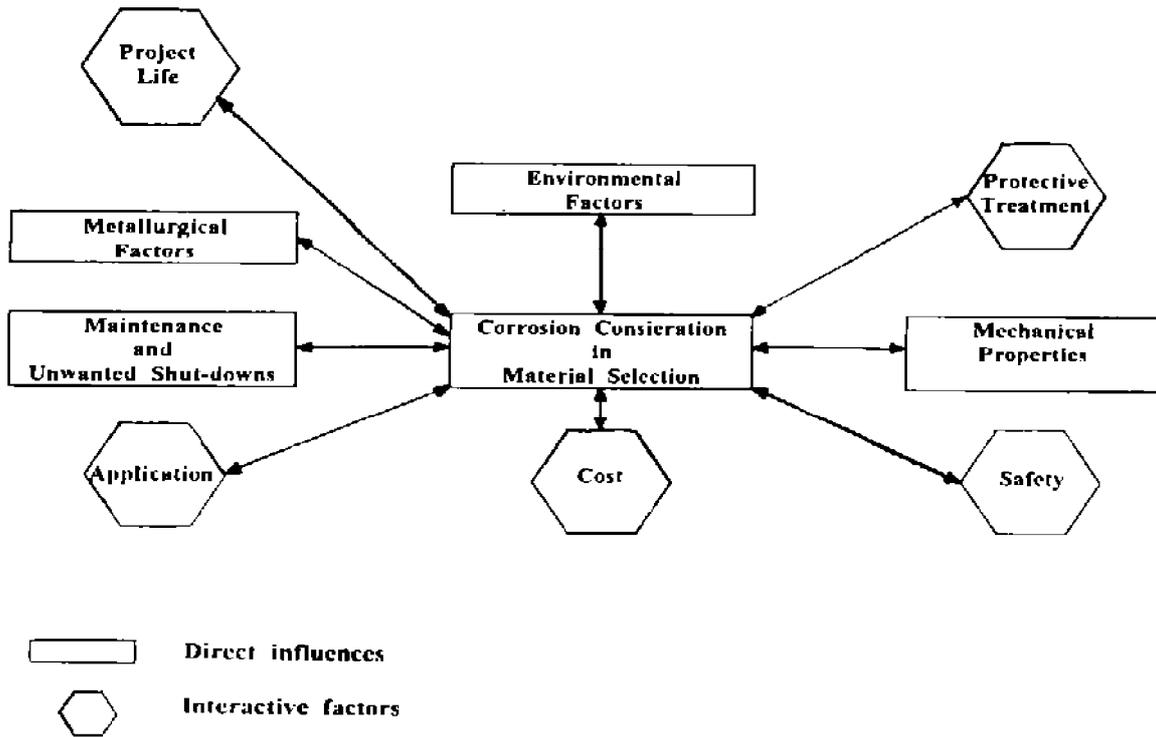
Selection of a material for use in a corrosive situation must be based on sound economics. Both the cost of the material and the on going cost of preventive measures must be included. A sound judgment on materials must recognize that the relative corrosion resistance of materials and the cost of supplementary protective measures can change significantly from one corrosive media to another.

5.3 Safety

Most environments in oil, gas and petrochemical industries involve flammable hydrocarbon streams, highly toxic and explosive gases, strong acids or caustics that are often at elevated temperatures and pressures. Therefore in this engineering standards corrosion considerations in material selection cover safety for such areas.

5.4 Others

Fig. 1 shows the factors affecting the corrosion consideration in material selection.



FACTORS AFFECTING THE CORROSION CONSIDERATION IN MATERIAL SELECTION

Fig. 1

Factors which influence corrosion consideration in material selection are distinguished from those which interact in a more complex fashion. For example "application" influence selection because the type of process, variables during operation, etc., will define whether a material can be used for the intended purpose or not. On the other hand mechanical and metallurgical properties are not uniquely defined for all environments. If the material is to be used at low temperature then embrittlement can be a serious problem.

Therefore these considerations involve the kind of information on those factors which have direct influence on corrosion consideration in material selection. However when there is discrepancy among sections of this Standard or between this and other disciplines for selection of materials following priorities shall be regarded:

- Client discretion & in house experience,
- specific industry standards,
- general material selection procedure (Section 9).

6. CORROSIVE ENVIRONMENTS

6.1 General

The first step in the material selection is a through review of the corrosive environments & equipment operating conditions.

This Section briefly classifies the corrosive environments.

6.2 Atmospheric Environments

Atmospheric environments is defined under categories of dry, damp, humid, rural, industrial, coastal, municipal etc.

Generally increase in humidity, temperature and the percentage of acidic gases such as CO_2 , H_2S , SO_2 , CO , Cl_2 will increase its corrosivity. (For more information see IPS-E-TP-100).

6.3 Soil

Most of the industrial equipment in contact with soil or embedded underground will suffer corrosion. Increase in water content and decrease in pH and resistivity will enhance corrosivity of soil. For detail see IPS-E-TP-820.

6.4 Sea Water

Greatest attack on offshore structures occurs in the splash zone due to alternate wetting and drying and also aeration. In quite stagnant condition the effect of bacteria and pitting type corrosion are predominant. The rapid growth of marine fouling in the tropics may provide a protective shield which counteracts the effect of the greater activity of the hotter water.

6.5 Natural Waters

The corrosivity of natural waters depends on their constituents such as dissolved solids, gases and sometimes colloidal or suspended matters. The effect may be either one of stimulation or one of suppression the corrosion reactions.

Constituents or impurities of water are dissolved gases such as oxygen, CO_2 , SO_2 , NH_3 , H_2S which part of them are the results of bacteria activity.

Dissolved mineral salts are mostly calcium, magnesium, sodium, bicarbonate, sulfate, chloride and nitrate. The effect of each of these ions on corrosion rate is different but briefly the chlorides have received the most study in this regard.

Organic contaminants of water directly and indirectly can affect the corrosion rate of metals and alloys. Bacteria, under favorable conditions can be doubled in 10-60 minutes. This characteristic is typical of wide spread biodeterioration caused by microbes in all industries of which corrosion is a special case. With a few exceptions such as synthetic polymers, all materials can be attacked by bacteria.

6.6 Chemicals

A chemical may be defined as a substance containing over 95% of the principal chemical.

To classify all the chemical environment and suitable material, is impossible because of the enormity of collating such a large amount of data. For example if some 400 chemicals are identified as being handled and processed on a large scale and there are 10 suitable materials, then 4000 systems would have to be considered. Since temperature, concentration and solution velocity are important in determining corrosion rate, and if only five levels of each of the three variables are considered, then the number of environments to be considered would be $4000 \times 5^3 = 600000$. Therefore in appendices of this Standard only those chemical environments which are corrosive and have a detrimental effect on material selection in Oil, Gas and Petrochemical Industries are briefly discussed.

The particular forms of corrosion in oil and gas production, transportation and storage are discussed in Appendix A. Also for specific corrosion problems or forms in refining and petrochemical operation refer to Appendix B.

7. THE MATERIALS OF ENGINEERING

7.1 General

7.1.1 Today's engineers have a vast range, comprising of several thousand materials available to them. Also parallel to the invention of new and improved materials there have been equally important, developments in materials processing including vacuum melting and casting, new molding techniques for polymers, ceramics and composites, and new joining technology.

7.1.2 In addition to the need for an increased knowledge of materials and technology, other challenges are having to be met by material engineers. In earlier times, with a much smaller number of materials available, engineers often select for their designs by a process of trial and error, in many cases using more material than was really necessary. Today there is a requirement to have the knowledge about materials more effectively and efficiently in order to minimize cost.

7.2 The Range of Materials

The complete range of materials can be classified into the 4 categories:

- Metals
- Polymers
- Ceramics and inorganic glasses
- Composites

The classification composites, contains materials with constituents from any two of the first three categories.

TABLE 7.1 - COMPARISON OF PROPERTIES OF METALS, CERAMICS AND POLYMERS

PROPERTY	METALS	CERAMICS	POLYMERS
Density ($\text{kg/m}^3 \times 10^{-3}$)	2-16 (average 8)	2-17 (average 5)	1-2
Melting points	Low to high Sn 232°C, W 3400°C	High, up to 4000°C	Low
Hardness	Medium	High	Low
Machineability	Good	Poor	Good
Tensile strength (MPa)	Up to 2500	Up to 400	Up to 120
Compressive strength (MPa)	Up to 2500	Up to 5000	Up to 350
Young's Modulus (GPa)	40-400	150-450	0.001 - 3.5
High temperature creep resistance	Poor	Excellent	—
Thermal expansion	Medium to high	Low to medium	Very high
Thermal conductivity	Medium	Medium but often decreases rapidly with temperature	Very low
Thermal shock resistance	Good	Generally poor	—
Electrical properties	Conductors	Insulators	Insulators
Chemical resistance	Low to medium	Excellent	Generally good
Oxidation resistance at high temperatures	Poor, except for rare metals	Oxides excellent SiC and Si ₃ N ₄ good	—

TABLE 7.2 - MATERIAL PROPERTIES AND QUALITIES

Physical properties	Density, melting point, hardness. Elastic moduli. Damping capacity.
Mechanical properties	Yield, tensile, compressive and torsional strengths. Ductility. Fatigue strength. Creep strength. Fracture toughness.
Manufacturing properties	Ability to be shaped by: moulding and casting, plastic deformation, powder processing, machining . Ability to be joined by adhesives, welding, etc.
Chemical properties	Resistance to oxidation, corrosion, solvents and environmental factors.
Other non-mechanical properties	Electrical, magnetic, optical and thermal properties.
Economic properties	Raw material and processing costs. Availability.
Aesthetic properties	Appearance, texture and ability to accept special finishes.

TABLE 7.3 - PROPERTIES (AT 25°C) OF SOME GROUPS OF MATERIALS

MATERIAL	E (GPa)	YIELD STRENGTH (MPa)	TENSILE STRENGTH (MPa)	FRACTURE TOUGHNESS (Mpa M ^{1/2})	DENSITY (kg m ⁻³ × 10 ⁻³)
Steels	200-220	200-1800	350-2300	80-170	7.8-7.9
Cast irons	150-180	100-500	300-1000	6-20	7.2-7.6
Aluminum alloys	70	25-500	70-600	5-70	2.7-2.8
Copper alloys	90-130	70-1000	220-1400	30-120	8.4-8.9
Magnesium alloys	40-50	30-250	60-300		1.7-1.8
Nickel alloys	180-220	60-1200	200-1400	>100	7.9-8.9
Titanium alloys	100-120	180-1400	350-1500	50-100	4.4-4.5
Zinc alloys	70-90	50-300	150-350		6.7-7.1
Polyethylene (LDPE)	0.12-0.25		1-16	1-2	0.91-0.94
Polyethylene (HDPE)	0.45-1.4		20-38	2-5	0.95-0.97
Polypropylene (PP)	0.5-1.9		20-40	3.5	0.90-0.91
PTFE	0.35-0.6		17-28		2.1-2.25
Polystyrene (PS)	2.8-3.5		35-85	2	1.0-1.1
Rigid PVC	2.4-4.0		24-60	2.4	1.4-1.5
Acrylic (PMMA)	2.7-3.5		50-80	1.6	1.2
Nylons (PA)	2.0-3.5		60-100	3-5	1.05-1.15
PF resins	5-8		35-55		1.25
Polyester resins	1.3-4.5		45-85	0.5	1.1-1.4
Epoxy resins	2.1-5.5		40-85	0.3-0.5	1.2-1.4
GFRP	10-45		100-300	20-60	1.55-2.0
CFRP	70-200		70-650	30-45	1.40-1.75
Soda glass	74		50*	0.7	2.5
Alumina	380		300-400*	3-5	3.9
Silicon carbide	410		200-500*		3.2
Silicon nitride	310		300-850*	4	3.2
Concrete	30-50		7*	0.2	2.4-2.5

* Modulus of rupture value.

7.3 Properties of Engineering Materials

A broad comparison of the properties of metals, ceramics and polymers is given in Table 7.1.

Very many properties, or qualities, of materials have to be considered when choosing a material to meet a design requirement (see Table 7.2). These include a wide range of physical, chemical and mechanical properties together with forming, or manufacturing characteristic, cost and availability data, and in addition, more subjective aesthetic qualities such as appearance and texture. Some of these values for different materials are given in Table 7.3.

Although it is not the purpose of this consideration, the detailed coverage of the properties of all materials, but just as a quick reference Appendix C (informative) briefly classifies those materials used in moderately large quantities in oil industries.

8. CORROSION PREVENTION MEASURES

8.1 General

To select required materials for a given process, necessarily and economically, feasible protective measures shall also be considered.

Basically, protection comprises those protective measures providing separation of metal surfaces from corrosive environments or those which cater for adjustment or altering the environments.

Since there are specific IPS Standards on these fields there is no necessity to further enlarge this section. For this reason only an outline of corrosion preventive measures recorded in this section.

8.2 Cathodic Protection

Cathodic protection is possible only when the structure to be protected and the auxiliary anode are in both electronic and electrolytic contact.

A reduction in metal to electrolyte potential of -0.850 Volt (reference to saturated copper sulfate electrode) is specified as the necessary potential which must be obtained for either optimum or absolute protection of ferrous structures in soil or water.

Cathodic protection is applied by one of two methods, power impressed current or sacrificial anodes. For more detail refer to IPS-E-TP-820.

8.3 Coating, Painting and Lining Materials

More metal surfaces are protected by coating, painting and lining than by all other methods combined. Coating, painting and linings that act as a protective film to isolate the substrate from the environment exist in a number of different forms. Therefore the selection of a proper corrosion-resistance system depends on a number of factors. For more detail see following IPS standards.

IPS-C-TP-101	"Surface Preparation"
IPS-E-TP-350	"Lining"
IPS-C-TP-350	"Construction Standards for Lining"
IPS-E-TP-100	"Paints"

8.4 Inhibitors

Altering the environments provide a versatile means for reducing corrosion. Typical changes in medium which are often employed in petroleum industries are:

- Lowering temperature,
- decreasing velocity,
- removing oxygen or oxidizer,
- filtration,
- changing concentration of corrosives,
- use of corrosion inhibitors.

An inhibitor is a substance which, when added in small concentrations to an environment decrease the corrosion rate considerably. To be fully effective all inhibitors require to be present above a certain minimum concentration.

Corrosion inhibitors are chemicals which may be divided in different categories. Among these, the most used class in oil industries is the film forming ones. The effect of film forming inhibitor is thus to establish a molecular layer just on the steel surface and a second layer of aliphatic tail in hydrocarbon. Therefore water cannot reach the steel surface and promote corrosion. The efficiency of an inhibitors in reducing corrosion depends on concentration, rate of dispersion, film persistency, velocity, temperature, pH, flow regime, presence of disturbances able to perturbate the flow, and fluid composition.

For detail see IPS-I-TP-802 "Corrosion Survey and Inhibitor Evaluation" and IPS-E-TP-780 "Chemical Control of Corrosive Environments".

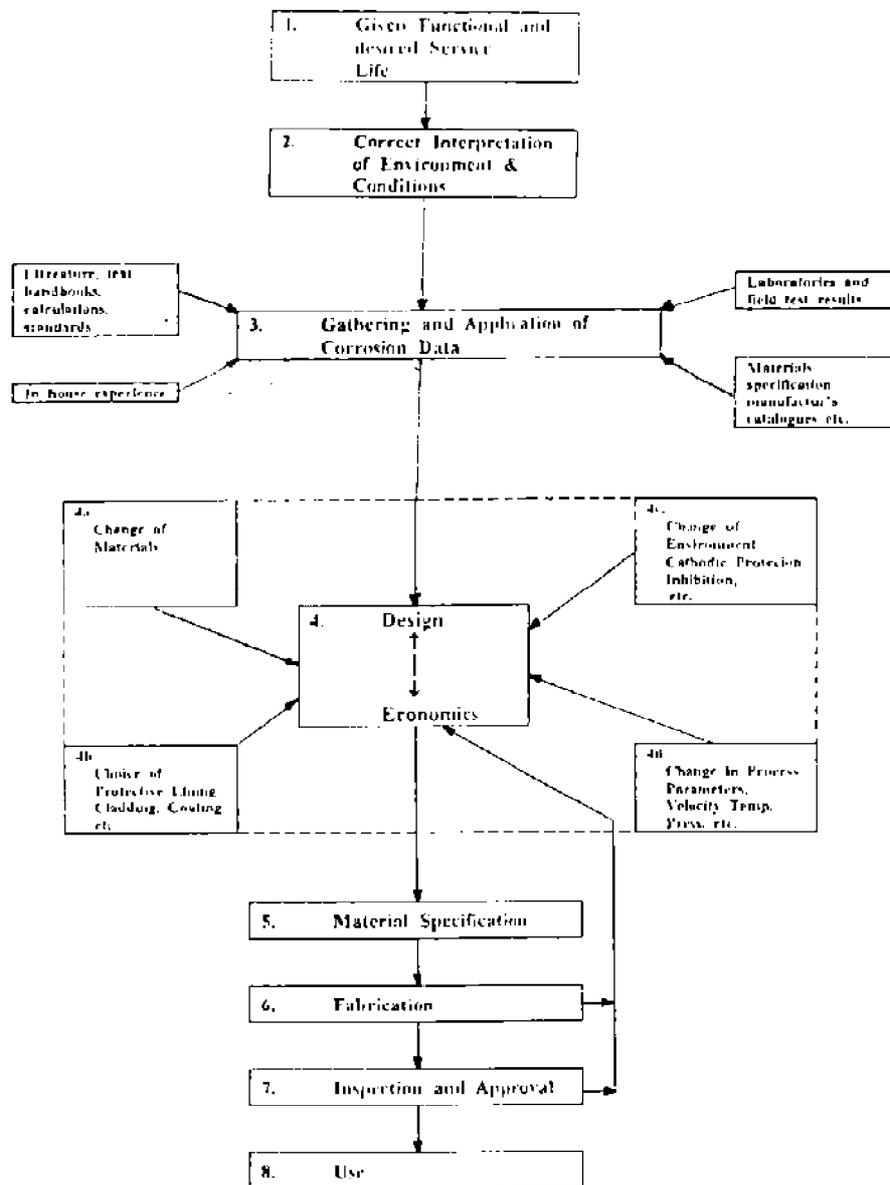
9. MATERIAL SELECTION PROCEDURE

9.1 General

This section of analysis deals with the procedure and the order of appreciation, evaluation and selection of materials both for their functional suitability and for their ability to sustain this positive function for the required length of time at a reasonable cost.

Considering the profusion of materials and material oriented literature, this procedure is, of necessity, schematic (Fig. 1).

It attempts only to indicate the system of parallel evaluation of corrosivity of different petroleum environments, the effect of process parameters, estimation of corrosion rates, determination of corrosion allowances for a given life and a few guidelines in selection of materials in conjunction with corrosion control measures and economic principals.



SCHEMATIC CORROSION CONTROL USED FOR MATERIAL SELECTION

Fig. 2

However the knowledge of materials is so vast and far reaching that close co-operation of the designer with metallurgists, material engineers, corrosion engineers and other materials specialists is stressed.

9.2 Guidelines on Material Selection

9.2.1 Materials shall be selected with due consideration to their functional suitability and ability to maintain their function safely for an economical period of time at a reasonable cost. The particular material selected shall be accurately specified.

9.2.2 The whole material complex shall be considered as an integrated entity, rather than each material separately. The more highly resistant materials shall be chosen for the critical components and where relatively high fabrication costs are involved. It may be necessary to compromise and sacrifice some mechanically advantageous properties to satisfy corrosion requirements and vice versa.

9.2.3 Where corrosion rate is either very low or very high, the choice of materials is simple; where it is moderately low, a thorough analysis of all aspects is required.

9.2.4 In dry environments and carefully controlled fluids, many materials can be used-and these often may be left unprotected. Under atmospheric conditions, even polluted atmospheres, such metals as stainless steels and aluminum alloys may be left unprotected. Also copper and lead have a long life. In a more severe wet environment, for example in marine conditions, it is generally more economic to use relatively cheap structural materials (mild steel) and apply additional protection, rather than use the more expensive ones. For severest corrosive conditions it is preferable in most cases to use materials resistant to the corrosive, than to use cheaper material with an expensive protection.

9.2.5 Materials more expensive than absolutely necessary shall not be chosen unless it is economical in the long run and necessary for safety of personnel or product or for other important reasons. Using fully corrosion-resistant materials is not always the correct choice, a balance between first cost and cost of subsequent maintenance shall be found over the full estimated life of the designed utility.

9.2.6 Certain combinations of metal and corrosive are a natural choice:

- a) Aluminum-non-staining atmospheric exposure;
- b) chromium-containing alloys-oxidizing solutions;
- c) copper and alloys-reducing and non-oxidising environments;
- d) hastelloys (chlorimets)-hot hydrochloric acid;
- e) lead-dilute sulphuric acid;
- f) monel-hydrofluoric acid;
- g) nickel and alloys-caustic, reducing and non-oxidizing environments;
- h) stainless steels-nitric acid;
- i) steel-concentrated sulphuric acid;
- j) tin-distilled water;
- k) titanium-hot strong oxidizing solutions;
- l) tantalum-ultimate resistance.

9.2.7 Composition of alloy alone does not ensure quality of the product. Evaluation of resistance to corrosion in a given environment, adverse effect of corrosion products on utility or contents, susceptibility to a specific type of corrosion and fouling, and tendency to corrosion failure due to fabrication and assembly processes such as welding, forming, machining, heat treatment, etc., are of prime importance for selection of material.

9.2.8 Due consideration shall be given to special treatments required to improve resistance to corrosion, e.g. special welding techniques, stress relieving, blast peening, metallizing, sealing of welds, etc. Also to any fabrication or assembly methods which would aggravate any tendency of the material to corrosion failure.

9.2.9 Alloys in as highly alloyed a condition as necessary shall be used when the cost of fabrication is higher than the cost of basic material. Proportional cost of material in some multishaped or complicated components is much less than in the simple ones.

9.2.10 An alloy or temper shall be selected which is free of susceptibility to the localized corrosion under the respective general and local environmental conditions in the utility and that meets the strength and fabrication properties required for the job. It is sometimes better to use a somewhat weaker but less sensitive alloy, than to use the one which does not lend itself to reliable heat treatment and, due to this, whose resistance to a particular form of corrosion is poor.

9.2.11 If heat treatment after fabrication is not feasible, materials and method of fabrication chosen shall give optimum corrosion resistance in the as-fabricated condition. Materials prone to stress corrosion cracking shall be avoided in environments conducive to failure, observing that stress relieving alone is not always a reliable cure.

9.2.12 When corrosion or erosion is expected an increase in wall thickness of the structure or piping shall be provided over that required by other functional design requirements. This allowance in the judgment of the designer should be consistent with the expected life of the structure or piping. The allowance should secure that various types of corrosion or erosion (including pitting) do not reduce the thickness of structure or piping below the thickness that is required for mechanical stability of the product. Where no thickening can be allowed or where lightening of product is contemplated a proportionally more corrosion resistant alloy or better protection measure shall be used.

9.2.13 Short-life materials shall not be mixed with long-life materials in non-reparable subassemblies. Materials forming thick scale shall not be used where heat transfer is important.

9.2.14 Where materials could be exposed to atomic radiation it is necessary to consider whether the effect will be derogatory or beneficial, observing that some controlled radiation may enhance the property of a metal.

9.2.15 Not only the structural materials themselves but also their basic treatment shall be evaluated for suitability (e.g. chromate passivation, cadmium plating, etc.) at the same time.

9.2.16 Non-metallic materials complying with the following requirements are preferred: low moisture absorption, resistance to fungi and microbes, stability through temperature range, compatibility with other materials, resistance to flame and arc, freedom from out-gassing and ability to withstand weathering.

9.2.17 Flammable materials shall not be used in critical places. Their heat could affect corrosion stability of structural materials. Toxic materials producing dangerous volumes of toxic or corrosive gases when under fire or high temperature conditions should not be used.

9.2.18 Fragile or brittle materials which are not, by design, protected against fracture should not be used in corrosion-prone spaces.

9.2.19 Materials which produce corrosion products that can have an adverse effect on the quality of contents should not be used, especially when the cost of wasted contents exceeds the cost of container.

9.2.20 All effort shall be made to obtain from the suppliers of equipment an accurate detailed description of materials used within their products.

9.2.21 The following shall be noted with regard to electrical equipment. The use of hygroscopic materials and of desiccants should be avoided. The latter, when their use is necessary, should not be in contact with an unprotected metallic part.

- Fasteners shall be of a well-selected corrosion-resistant material, or materials better protected than the parts which they join together.

- Materials selected shall be suitable for the purpose and be either inherently resistant to deterioration or adequately protected against deterioration by compatible coatings, especially in problem areas where corrosion can cause low conductivity, noise, short circuits or broken leads, thus leading to degradation of performance.

- Insulation materials used shall not be susceptible to moisture. Stainless steels or precipitation hardening stainless steel shall be passivated.

9.2.22 Appendices A and B briefly discuss the corrosion behavior and materials in oil & gas industries and refinery & petrochemical plants.

9.3 Procedure

9.3.1 The first step in material selection is a through review of the corrosive environment, process parameters, and equipment operating conditions including temperature, pressure, flow rates, liquid versus gaseous phase, aqueous versus anhydrous phase, continuous versus intermittent operation, media used for cooling or heating, etc. The contribution of some of these factors to corrosion rate is considered in Appendix A.

9.3.2 The second step, the corrosion rate (C.R) shall be predicted and the corrosion allowances (C.A) shall be determined for the service life of the equipment and its various components in carbon steel material. (See 9.5).

9.3.3 The third step, when the determined total wall thickness (Mechanical + C.A) is not acceptable by other discipline, great effort shall be exercised to select and evaluate a suitable corrosion preventive measure to lower the required corrosion allowance. Some of these measures can not withstand process conditions, that is, temperature too high for polymer lining, no facilities for chemical injection, no continuous electrolyte for cathodic protection, so on.

9.3.4 The fourth step, if the preventive measures can not reduce the corrosion rates of carbon steel to an acceptable level, then a more corrosion resistance material shall be considered. Many materials shall be immediately excluded because of service conditions.

9.3.5 The fifth step, if required, conduction of standard test methods for evaluation of nominated materials in simulated environment. These tests give the assurance to the right selection (9.5.4).

9.3.6 The sixth step, the evaluation of the cost of material for service life of plant. Also comparison between selection of an expensive material and a cheaper one plus a protective measure. (see 9.6)

9.3.7 When materials of construction are selected, the preparation of a clear and concise specification to ensure that the material is fabricated and obtained as ordered and meets the requirement of the specific material standards is mandatory.

9.3.8 Any problem associated in fabrication of equipment with selected material or rejection during inspection shall be reported for re-analysis and ratification in selection and specification.

Note:

It should be realized that specified material may fail owing to undesirable or unknown properties induced during fabrication or installation, such as metallurgical changes, inclusion and chemical composition changes, etc. Measures which may be required to prevent or limit such factors (e.g. special heat treatment) are outside the scope of this Standard.

9.4 Process Parameters

The major factors controlling corrosion in oil & gas industries are:

- The CO₂ partial pressure,
- The H₂S partial pressure,
- The fluid temperature,
- The water cut,
- The water salinity,
- The flow dynamics,
- The pH of solution,

It must be emphasized that corrosion is likely to occur only in the water phase. Vaporised water in streams at temperatures above the dew point are considered non-corrosive. For more data on the main corrosion processes in oil, gas and petrochemical industries refer to Appendices A and B.

9.5 Corrosion Rate and Corrosion Allowances

9.5.1 General

Corrosion rate means a uniform decrease in thickness of a material per year.

Corrosion allowance, expressed in terms of thickness, is a measure of extra thickness with which a material can survive its design life.

Therefore to determine a suitable material with enough corrosion allowance for design life of a plant, primarily the corrosion rate shall be predicted. This is possible by followings:

- Calculation,
- corrosion abstracts and data survey handbooks,
- experiences and in house data,
- materials vendors data,
- equipment fabricators,
- testing of materials.

9.5.2 Calculation

May different formula, nomograph, curves and software based on laboratory or field experiences exist to evaluate the general corrosion rate*. Results obtained following these approaches shall be considered "worst case corrosion rate" or R_{max} .

***Note:**

Due to the complexity of the corrosion phenomenon and the diversity of the operating conditions in oil, gas and petrochemical plants, the selected calculation model shall be presented to company for review and approval.

This rate may be adjusted by considering the influence of the rest of the environment. The final corrosion rate may be thus expressed as following:

$$R_{(corr)} = R_{max.} \times F_{(s)} \times F_{(i)} \times F_{(c)} \times F_{(o)} \times F_{(w)} \times F_{(pH)}$$

Where:

$F_{(s)}$	=	Scale factor
$F_{(i)}$	=	Inhibition factor
$F_{(c)}$	=	Condensation factor
$F_{(w)}$	=	The percentage of water
$F_{(o)}$	=	The percentage of oil
$F_{(pH)}$	=	(pH) factor

(For more information see Appendix A)

9.5.3 Corrosion study by literature survey

In corrosion studies undertaken for the purpose of finding a suitable material to withstand a particular service, it is best, first to take advantage of the vast amount of published literatures in the field of corrosion.

Such a study will in general give a very good clue as the general types of metals or alloys that shall prove most satisfactory for the particular job.

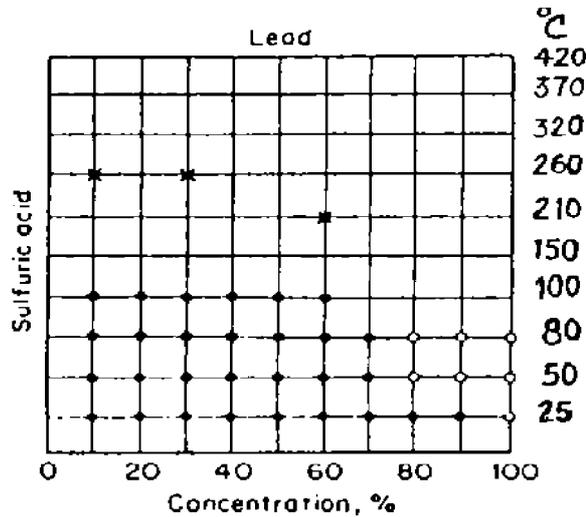
9.5.3.1 NACE; corrosion data survey handbook, have two sections:

- Metals,
- non-metals.

There are more than 50000 points of data (Nelson method*) on the performance of metallic and non-metallic materials of construction in corrosive environments. Also NACE corrosion survey & KO DAB software is highly recommended.

Note:

The method Nelson has used for many years to present corrosion information. This example, shows the corrosion of lead by sulfuric acid as a function of temperature and concentration.



The symbols used represent corrosion rates as follows:

- = Corrosion rate less than 3 mpy (0.05 mm/y)
- o = Corrosion rate less than 20 mpy (0.5 mm/y)
- b = Corrosion rate from 20 to 50 mpy (0.5 - 1.25 mm/y)
- x = Corrosion rate greater than 50 mpy (> 1.25 mm/y)

NELSON’S METHOD FOR SUMMARIZING CORROSION DATA

Fig. 3

9.5.3.2 IPS standards

IPS-E-PI-221 and E-PI-220 are standards for piping material selection and give the general types of metals or alloys.

9.5.4 Corrosion tests

9.5.4.1 General

Corrosion tests are the best appropriate technique for aquisition of data for material selection.

In most corrosion data survey handbooks, corrosion rates are evaluated just for a few factors (e.g. temperature and concentration). However there are many other factors besides concentration and temperature which influence corrosion rates. While they are often extremely important, it is impossible to list them all in a survey of this type.

9.5.4.2 Test methods

Corrosion tests are primarily aimed at the acquisition of data in relatively short times compared to service lifetimes, to predict service behavior. Corrosion test methods may be divided into 3 categories:

- Laboratory tests,
- pilot plant tests,
- full size equipment tests.

The complexities of service situations by many factors; such as velocity, temperature, pressure, aeration, heat flux, the presence of oxidizing agents, partial pressure of corrosive gases, inhibitor concentration etc., which can either increase or decrease the corrosion rate; may cause pilot plant exposure tests to be preferred to laboratory tests.

9.5.4.3 The need for testing

The necessity for corrosion testing depends on:

- degree of uncertainty after available information has been considered,
- the consequences of making a less-than-optimum selection,
- the time available for evaluation

Therefore company material/corrosion engineer shall determine when and which type of tests are required.

9.5.4.4 Pilot plant tests

These tests give more information for a primary selection of materials than most laboratory tests. Test conditions are more like the final application, therefore the results are more reliable.

9.5.4.5 Full size tests

Reliability is further enhanced when it is possible to test full size components fabricated from candidate material.

9.5.4.6 Laboratory tests

In some cases laboratory testing is the only mean for final material selection. The primary laboratory tests on the selected materials shall be as simple as possible.

Depend on the nature of the environment in which the material is to be used, at least the more important corrosion controlling factors shall be simulated in tests.

Briefly, test for metallic material shall at least covers the following:

- Actual fluids shall be used or mixtures simulating the actual.
- Test coupons shall be provided from the selected material.
- Generally, experimental time is approximately one week.
- Microscopic examination is essential to look for local attack.

and for non-metals, test shall cover,

- Weight, volume, hardness, strength and appearance changes before and after exposure.
- Generally, test period is 1-3 month.

In any laboratory test great care shall be taken in the interpretation of the data. At best the results can only be qualitative and a great deal of common sense and experience has to be applied to such results before they become useful to the engineer.

Although it is not the intention here to catalogue the various standard test methods in details, but those listed below may be helpful where and when required.

9.5.4.6.1 Standard corrosion test methods

For standard corrosion test method refer to Section 2 of this Standard (References).

Such test methods can be used to compare the many variables in material composition, manufacturing and field performance.

The tests also can be used to compare different type of materials, or the same material grade from various manufacturers using different manufacturing process; and to evaluate different corrosion control measure. However the objective set of variables for the test dictates the selection of test methods. Therefore a careful study of both process and material, (physical, chemical and mechanical) properties and the type of protective measure (e.g. inhibition) is usually required to make the proper selection of test method.

9.5.4.6.2 Reporting test results: Test results shall be tabulated to indicate at least the followings:

- Chemical composition of material,
- heat treatment,
- pre-test metallurgy,
- post-test metallurgy,
- estimated corrosion rate,
- type of localized attack (if any),
- pH of test solution,
- other information pertinent to the evaluation of material such as pressure, temperature, additives to the test solution, etc.,
- method of corrosion rate calculation.

9.5.5 Corrosion allowance

The minimum corrosion allowance to be considered for an equipment, depends on the required service life of the equipment multiplied by the expected corrosion rate under process conditions.

$$C.A_{(in\ mm)} \geq Life_{(year)} \times C.R_{(mm/y)}$$

Where:

- C.A = Corrosion allowance
- C.R = Corrosion rate

9.5.5.1 According to the above equation the following classes shall be considered for an equipment with a design life of 20 years.

TABLE 9.1 - CORROSION ALLOWANCES VERSES CORROSION RATE FOR 20 YEARS SERVICE LIFE

CLASS	AVERAGE CORROSION RATE mm/year	CORROSION ALLOWANCE (mm) FOR A DESIGN LIFE OF 20 YEARS
A-mild corrosion	< 0.05	1.0
B-medium	0.05 - 0.15	3
C-sever	0.15 - 0.30	6.0

9.5.5.2 Where the corrosion rate is more than 0.3 mm/y or the total corrosion over the design life exceed 6 mm then other alternatives shall be evaluated. These alternatives may include the following:

- a) Replacement at intervals (e.g. every 10 years where corrosion rate is 0.6 mm/year),
- b) corrosion resistance linings,
- c) alternative solid corrosion resistance materials.

9.5.6 Selection of corrosion-resistance alloys

Alloy selection, from a corrosion standpoint, can be considered to be a three-step process. First, resistance to general corrosion must be ensured. This is primarily a function of the chromium content of the alloy. Second, resistance to localized attack also must be ensured. This is primarily a function of molybdenum content. Finally, resistance to environmental stress cracking is sought at the highest feasible strength level. Nickel content plays a principal role in this instance, particularly in providing resistance to anodic cracking.

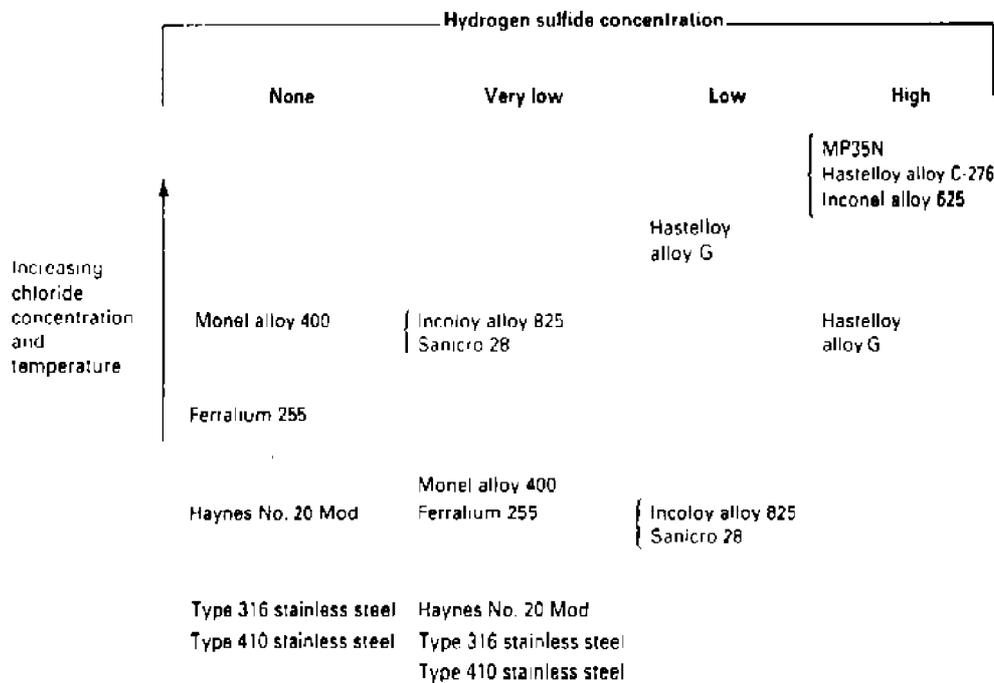
The close correlation between pitting resistance and resistance to anodic cracking should be noted. This apparently results from the ease of crack initiation under the low-pH high-chloride conditions found in pits. Therefore, higher molybdenum can also increase resistance to anodic cracking.

With the procedures given below, regions of alloy applicability can be shown schematically as a qualitative function of environmental severity. This has been attempted in Fig. 4 in which an aqueous, CO₂-containing environment (hence low pH) has been assumed and the effects of temperature, chloride, and H₂S concentration are illustrated. The effect of yield strength is not shown, but if environmental cracking is the limiting factor, reducing the yield strength should extend applicability to more severe environments.

The reader should be cautioned that a diagram such as Fig. 4 is really more of a guide to alloy qualification than to direct selection for a particular application. Therefore, it may aid in developing a more efficient approach to alloy testing. (see 9.5.4.6). For more information see Appendix C.

Note:

Where the corrosion problem is not general (uniform), and is localized such as; stress corrosion cracking, pitting, crevice, sulfide stress cracking, etc.; the material selection shall be on the basis of specific corrosion problem. In these cases the selection procedure is to follow all parts of foresaid section except for corrosion rate calculation (9.5.2) and corrosion allowance (9.5.5).



SCHEMATIC SHOWING CORROSION-RESISTANT ALLOY SELECTION FOR PRODUCTION ENVIRONMENTS CONTAINING AQUEOUS CO₂ AND H₂S

Fig. 4

9.6 Economics in Material Selection

9.6.1 General

Corrosion is basically an economic problem. Thus, the corrosion behavior of materials is an important consideration in the economic evaluation of any project.

The two extremes for selecting materials on an economic basis without consideration of other factors are:

9.6.1.1 Minimum cost: Selection of the least expensive material, followed by scheduled periodic replacement or correction of problems as they arise.

9.6.1.2 Minimum corrosion: Selection of the most corrosion-resistance material regardless of installed cost or life of equipment.

9.6.2 Cost effective selection

Generally falls somewhere between these extremes and includes consideration of many other factors (see IPS-E-TP-760).

In most instances, there will be different alternative materials which may be considered for a specific application. Calculation of true long-term costs requires estimation of the followings:

9.6.2.1 Total cost of fabricated equipment and piping (see Note).

9.6.2.2 Total installation cost.

9.6.2.3 Service life.

9.6.2.4 Maintenance cost.

9.6.2.5 Time and cost requirement to replace or repair at the end of service life.

9.6.2.6 Cost of downtime to replace or repair.

9.6.2.7 Cost of inhibitors, extra facilities or train which require to assure achievement of predicted service life.

9.6.2.8 Time value of money.

9.6.2.9 Factors which impact taxation, such as depreciation and tax rates.

9.6.2.10 Inflation rate.

Note:

It should be realized that the costs of processed products, such as sheet, plate, sections and forgings will be much higher than ingot. Every process and every heat treatment will give added value and increase the final material cost. Also the process of alloying will mean that, generally, the cost of alloys will be higher than those for unalloyed metals. (see Table 9.2, 9.3)

**TABLE 9.2 - ESTIMATED COSTS OF SOME MATERIALS* (1),
BY MASS AND BY VOLUME(2)**

MATERIAL	COST (\$/kg)	MATERIAL	COST (\$/100 cm ³)
Germanium	365.75	Germanium	213.50
Silver	163.98	Silver	172.20
Cobalt	31.54	Cobalt	27.42
PTFE	12.25	Nickel	7.95
Nickel	8.93	Chromium	5.90
Chromium	8.31	Tin	4.43
Tin	6.06	Brass (sheet)	4.17
Titanium	5.41	Beryllium-copper	3.45
Brass (sheet)	5.02	Cadmium	2.94
Al/Cu alloy sheet	4.38	Phosphor bronze (ingot)	2.85
Beryllium-copper	3.90	18/8 stainless (sheet)	2.71
Nylon 66 (PA 66)	3.85	PTFE	2.63
18/8 stainless (sheet)	3.50	Copper (tubing)	2.45
Cadmium	3.40	Titanium	2.43
Phosphor bronze (ingot)	3.24	Copper (grade A ingot)	2.12
Magnesium (ingot)	2.89	Manganese	1.87
Acrylic (PMMA)	2.80	Brass (ingot)	1.84
Copper (tubing)	2.75	Al/Cu alloy sheet	1.30
ABS	2.63	Zinc (ingot)	0.81
Manganese	2.52	Lead (ingot))	0.67
Copper (grade A ingot)	2.38	Magnesium (ingot)	0.51
Brass (ingot)	2.18	Mild steel (sheet)	0.47
Amino resin thermoset	1.49	Nylon 66 (PA 66)	0.44
Aluminum (ingot)	1.37	Aluminum (ingot)	0.37
P-F thermoset	1.31	Acrylic (PMMA)	0.33
Silicon	1.24	Silicon	0.30
Polystyrene	1.12	ABS	0.28
Zinc (ingot)	1.12	Mild steel (ingot)	0.25
Polyethylene(HDPE)	1.09	Amino resin thermoset	0.23
Polypropylene (PP)	1.00	Cast iron	0.19
Natural rubber	0.98	P-F thermoset	0.16
Polyethylene (LDPE)	0.74	Polystyrene	0.12
Rigid PVC	0.72	Natural rubber	0.12
Mild steel (sheet)	0.60	Polyethylene (HDPE)	0.11
Lead (ingot)	0.60	Rigid PVC	0.11
Mild steel (ingot)	0.32	Polypropylene (PP)	0.09
Cast iron	0.26	Polyethylene (LDPE)	0.07
Portland cement	0.09	Portland cement	0.03
Common brick	0.07	Common brick	0.01
Concrete (ready mixed)	0.04	Concrete (ready mixed)	0.01

(1) The costs are based for bulk quantities quoted in July 1991.

(2) It is usual to see the cost of materials quoted per unit mass. This may give a misleading picture as often it is the volume of material which is important than its mass.

TABLE 9.3 - COST BUILD-UP (STEEL PRODUCTS)*

MATERIAL	COST (\$ per tonne)
Iron from blast furnace	210
Mild steel (ingot)	315
Mild steel (black bar)	490
Mild steel (cold drawn bright bar)	665
Mild steel (hot rolled sections)	498.75
Mild steel (hot rolled strip coil)	476
Mild steel (cold rolled strip coil)	593.25
Mild steel (galvanized sheet)	689.50
Austenitic stainless steel (cold rolled sheet)	3500

*These cost figures applied in July 1991.

9.6.3 Economic evaluation techniques

Several different techniques exist for economic appraisal of different materials and alternative corrosion control measures. Among these are the concept of:

- Internal rate of return (IROR),
- discounted pay back (DPB),
- present worth (PW), also referred to as net present value (NPV),
- present worth of future revenue requirements (PWRR),
- benefit-cost ratios (BCR).

Some of these techniques lack adequate sophistication; others are unduly complex and do not lend themselves readily to comprehension and use especially as calculation.

Generally, the applied method shall embodied accepted economic terminology at the accounting and managerial levels; so that a material/corrosion engineer's judgment can be properly expressed to and understood by project management.

Therefore, for economic evaluation reference is made to the NACE Standard method "RP-02-72, "Direct Calculation of Economic Appraisal of Corrosion Control Measures".

Also reference shall be made to IPS-E-TP-760 Section 13 in which the excellent presentation of the subject matter makes it superfluous to enlarge on the details of factors to be considered in economic evaluation.

9.7 Materials Appreciation and Optimization

9.7.1 General

To indicate, approximately, the general trend of parallel appreciation of materials, selective check-off lists are given in this Section. These can, of course, vary for different materials or designs and a selective adjustment will be required.

It is obvious from the contents of these selection lists that a thorough expert knowledge is required, both in engineering and in corrosion control, to complete and evaluate the required data. Only very seldom, and then mostly in simple or repetitive projects, can this task be left to an individual, normally, close co-operation of designer and corrosion or material engineer is needed, and each will have to bring into play his overall and specialized expertise.

The data obtained in such a selection list, after appropriate evaluation and comparative appreciation, should serve as a base for decision as to whether the appreciated conglomerate of material and its fabrication methods are suitable for the considered purpose. Although in some cases a clear-cut confirmation of suitability may be secured, in many more cases several materials and methods may be evaluated before the optimal one is found. Even then such materials will not always satisfy all required properties and under such circumstances the most satisfactory compromise should be accepted.

9.7.2 Material appreciation

9.7.2.1 Metals; selective check-of list

9.7.2.1.1 Physical character of material

a) General

- Ballistic properties
- Chemical composition (%)
- Contamination of contents by corrosion products

Corrosion characteristics in:

- atmosphere
- waters
- soil
- chemicals
- gases
- molten metals
- other environments

Creep characteristics verses temperature

Crystal structure

Damping coefficient

Density (g/cm^3)

Effect of cold working

Effect of high temperature on corrosion resistance

Effect on strength after exposure to hydrogen

Effect on strength after exposure to higher temperature

Electrical conductivity (mho/cm)

Electrical resistivity (ohm/cm)

Fire resistance

Hardenability

Hydraulic permeability

Magnetic properties (Curie point)

Maximum temperature not affecting strength ($^{\circ}\text{C}$)

Melting point ($^{\circ}\text{C}$)

Position in electromotive series

Rapidity of corrosion-corrosion factor

Susceptibility to various types of corrosion:

- general
- hydrogen damage
- pitting
- galvanic
- stress corrosion cracking
- corrosion fatigue
- fretting
- concentration cell/crevice
- corrosion/erosion
- cavitation damage
- intergranular
- selective attack
- high temperature
- others

Thermal coefficient of expansion ($^{\circ}\text{C}^{-1}$)

Thermal conductivity ($\text{W}/(\text{m}\cdot^{\circ}\text{C})$)

Toxicity

Wearing quality:

- inherent
- given by heat treatment
- given by plating

b) Strength or mechanical

Above strength properties:

- at elevated temperatures and for long holding times at temperature
- at room temperature after exposure to elevated temperatures

Bearing ultimate* (N/mm² or kN/m² or kg/mm²)

Complete stress-strain curve for tension and compression

Compression modulus of elasticity (kg/mm²)

Compression yield * (N/mm² or Kg/mm²)

Fatigue properties:

- S-N curve
- endurance limit

Hardness (Vickers)

Impact properties (Charpy kg/cm² at 20°C):

- notch sensitivity
- effect of low temperature
- maximum transition temperature (°C)

Poisson's ratio

Response to stress-relieving methods

Shear modulus of elasticity (kg/mm²)

Shear ultimate* (Pa)

Tangent modulus curves in compression - with and across grain

Tension modulus of elasticity (Pa)

Tension - notch sensitivity

Tension yield*

* Typical and design values, variability - with and across grain.

9.7.2.1.2 Design limitations**Restrictions**

- Size and thickness
- Velocity
- Temperature
- Contents
- Bimetallic attachment
- Geometric form
- Static and cyclic loading
- Surface configuration and texture
- Protection methods and techniques
- Maintainability

9.7.2.1.3 Fabrication character of materials

a) Brazing and soldering

Compatibility
Corrosion effect
Flux and rod

b) Formability at elevated and room temperatures

Ageing characteristics
Annealing procedure
Corrosion effect of forming
Heat treating characteristics
Quenching procedure
Sensitivity to variation
Tempering procedure
Effect of heat on prefabrication treatment

c) Formability in annealed and tempered states

Apparent stress \times local strain curve

Characteristics in:

- bending
- dimpling
- drawing
- jogging
- shrinking
- stretching

Corrosion effect of forming
Elongation \times gage length
Standard hydropress specimen test
True stress-strain curve
Uniformity of characteristics

d) Machinability

Best cutting speed

Corrosion effect of:

- drilling
- milling
- routing
- sawing
- shearing
- turning

Fire hazard
Lubricant or coolant
Material and shape of cutting tool

Qualitative suitability for:

- drilling
- milling
- routing
- sawing
- shearing
- turning

e) Protective coating

- Anodising
- Cladding
- Ecology
- Galvanising
- Hard surfacing
- Metallizing

Necessity of application for:

- storage
- processing
- service

- Paint adhesion and compatibility
- Plating
- Prefabrication treatment
- Sensitivity to contamination
- Suitability
- Type of surface preparation optimal

f) Quality of finish

- Appearance
- Cleanliness
- Grade
- Honing
- Polishing
- Surface effect

g) Weldability

- Arc welding
- Atomic hydrogen welding
- Corrosion effect of welding
- Cracking tendency
- Effect of prefabrication treatment
- Electric flash welding
- Flux
- Friction welding
- Heat zone effect
- Heli-arc welding
- Pressure welding
- Spot welding

Torch welding
Welding rod

h) Torch cutting

Cutting speed

9.7.2.1.4 Economic factors

a) Availability

In required quantities:

- single
- multiple
- limited
- unlimited

In different forms:

- bar
- casting (sand, centrifugal, die, permanent mould)
- extrusion
- forging
- impact extrusion
- pressing
- sintered
- powder pressing

In metallized and pretreated forms:

- galvanized
- plastic coated
- plated
- prefabrication treated

In clad forms

Uniformity of material

Freedom from defects

Time of delivery:

- present
- future

b) Cost in different forms

Bar, shape or plate

Casting (sand, centrifugal, die, permanent mould)

Extrusion

Forging

Impact extrusion

Pressing

Sintered

Powder Pressing

c) Size limitation in different forms

Gage
Length
Weight
Width

d) Size tolerances for different forms**9.7.2.2 Plastics: Selective check-off list, to be adjusted for generic groups****9.7.2.2.1 Physical character of material****a) General**

Anisotropy characteristics-main and cross-direction
Area factor ($\text{mm}^2 \text{kg}^{-1} \text{micron}^1$)
Burning rate (cm/min in sec)
Bursting strength (1 mm thick, Mullen points)
Change in linear dimensions at 100°C for 30 min (%)
Clarity
Color
Contamination of contents (decomposition and extract)
Creep characteristics verses temperature-creep-apparent-modulus ($10^\circ \text{kg}/\text{mm}^2$)
Crystal structure
Crystalline melting point
Damping coefficient
Decay characteristics in:
 atmosphere
 alcohol
 chemicals
 gases
 high relative humidity
 hydraulic oils
 hydrocarbons
 lubricants and fats
 solvents
 sunlight
 water
 other environments
Deflection temperature (°C)
Density (g/cm^3)
Dielectric constant (60 c/s, 10^3 c/s, 10^4 c/s)
Dielectric strength - V to laminations (v/mm):
 short time
 step by step
Dissipation factor (1 MΩ)
Effect of high temperature on decay

Effect of low temperature on decay
Effect on strength after exposure to temperature
Electrical conductivity (mho/cm)
Electrical properties at room temperature per thickness
Electrical loss factor (1 MΩ)
Electrical power factor (60 c/s, 10³ c/s, 10⁴ c/s)

Electrical resistivity:
 arc/sec
 insulation (96 h at 90% RH and 35°C) MΩ
 volume (Ω/cm - 50% RH and 25°C)

Evolution of combustion products
Evolution of corrosives
Fillers
Fire resistance
Flammability (ignited by flame)
Folding endurance
Fuming on application

Gas permeability (cm³/M²/mm thick/24 h/atm at 25°C):
 CO₂, H₂, N₂, O₂

Generic group and composition
Gloss
Haze (%)
Heat distortion temperature
Heat expansion
 (coefficient of linear thermal expansion)
Heat degradation
Heat insulation (thermal conductivity (Kcal/m² · h⁻¹ · °C · cm⁻¹))
Heat sealing temperature range
Hydraulic permeability
Intensity of color
Light transmission, total white (%)
Maximum service temperature (°C)
Maximum temperature not affecting strength (°C)
Melt index (dg/min)
Migration of plasticisers
Minimum temperature not affecting strength (°C)
Opacity
Rate of water vapor transmission (g/100 cm²/24 h - mg/m²/24 h/mm) at 37.8°C
Reflectance
Refractive index (n_d)
Reinforcement
Softening temperature (°C)
Specific gravity (25°C)
Specific heat (Kcal/°C g⁻¹)
Stability of color
Stiffness-Young's modulus

Susceptibility to various types of deterioration:
 general
 cavitation/erosion
 erosion

fatigue
fouling
galvanic (metal-filled plastics)
impingement
stress cracking and crazing
others

Taste
Thermal conductivity (W/(m.°C))
Toxicity
Transmittance (%)
Unit weight (m³/kg)
Water absorption (24 h/l cm thick/%)
Wearing quality:
 inherent
 given by treatment

b) Strength or mechanical

Abrasion resistance
Average yield (cm² kg⁻¹ mm⁻¹)
Bearing ultimate * (N/mm²)
Bonding strength (kg/thickness)
Brittleness
Bursting pressure (kg/mm²)
Complete stress-strain curve for tension and compression

Compressive strength:
 flatwise (N/mm²)
 axial (N/mm²)
 at 10% deflection (N/mm²)

Deformation under load
Elongation (%)
Elongation at break (%) (24°C)

Fatigue properties

 S-N curve
 endurance limit

Flexibility and flex life
Flexural strength* (N/mm²)
Hardness (Rockwell)
Impact strength, Izod
Inherent rigidity

Modulus of elasticity (kg/mm²)

 in compression (kg/mm²)
 in flexure (kg/mm²)
 in tension (kg/mm²)
 in shear (kg/mm²)

Resistance to fatigue
Safe operating temperature (°C)
Shear, ultimate* (Pa)

Tear strength:
propagating (g/mm)
initial (kg/cm)

Tensile strength (kg/mm²)
Vacuum collapse temperature

*Typical and design values, variability—with and across grain.

9.7.2.2.2 Design limitations

Size and thickness
Velocity
Temperature

Compatibility with adjacent materials:
at ambient temperature
at elevated temperature

Geometric form
Static and cyclic loading
Surface configuration and texture
Protection methods and techniques
Maintenance

9.7.2.2.3 Fabrication character of materials

a) Moulding and injection

Compression ratio
Compression moulding pressure (kg/cm²)
Compression moulding temp. (°C)
Injection moulding pressure (kg/cm²)
Injection moulding temp. (°C)
Moulding qualities
Mould (linear) shrinkage (cm/cm)
Specific volume, etc. (cm³/g)

b) Lamination

Laminating pressure (kg/cm²)
Laminating temperature (°C), etc.

c) Formation at elevated temperatures

d) Machinability

Adverse effect of:
drilling
milling

sawing
shearing
turning

Best cutting speed
Fire hazard
Machining qualities
Material and shape of cutting tool, etc.

e) Protective coating

Cladding
Painting
Plating
Sensitivity to contamination
Suitability
Type of surface preparation optimal

f) Quality of finish

Appearance
Cleanliness
Grade
Polishing
Surface and effect

g) Joining

Adhesive joining
Bonding
Cracking tendency
Heat zone effect
Welding, etc.

9.7.2.2.4 Economic factors

a) Availability

Cladded forms
Forms available
Maximum width (cm)
Thickness range
Treated forms
Uniformity of material
Freedom from defects

b) Cost of different forms

c) Size limitations

d) Size tolerances

9.7.2.3 Natural and synthetic elastomers: selective check-off list

9.7.2.3.1 Physical character of material

a) Uncured properties

Color
Consistency
Shelf life
Viscosity

b) Cured properties

Chemical composition
Compression set
Contamination of contents by contact
Creep
Drift (room temperature)
Elasticity
Elastic memory
Flexing
Hardness range
Linear shrinkage (%)
Permeability to gases
Permanent set
Resilience
Self-damping
Specific gravity
Swelling resistance (in various environments)

c) Thermal properties

Coefficient of thermal expansion $\times 10^{-3}$ per °C
Drift at elevated temperature
Elongation % at elevated temperature
Flame resistance
Heat ageing
Low temperature-brittle point (°C)
Low temperature-stiffening (°C)
Maximum service temperature range (°C)
Tensile strength-elevated temperature (Pa)
Thermal conductivity ($\text{kcal h}^{-1} \text{m}^{-3} \text{°C m}^{-1}$)

d) Electrical properties

Dielectric constant
Dielectric strength
Dissipation factor
Electrical resistivity (Ω/cm)
Volume resistivity

9.7.2.3.2 Mechanical properties

- Crack resistance
- Cut growth
- Elongation % plain
- Elongation % reinforced
- Resistance to abrasion
- Resistance to impact and shock
- Resistance to wear
- Tear resistance
- Tensile strength-reinforced (mPa)
- Tensile strength-unreinforced (mPa)

9.7.2.3.3 Environmental properties

Chemical resistance in:

- water
- acid
- alkali
- aliphatic hydrocarbons
- aromatic hydrocarbons
- halogenated hydrocarbons
- alcohol
- oil and greases
- synthetic lubricants (e.g. diester)
- hydraulic fluids-silicates, phosphates

Light

Oxidation

Radiation

Weather

9.7.2.3.4 Subjective properties

- Odor
- Staining
- Taste

9.7.2.3.5 Fabrication-character of materials

- Bonding to rigid materials
- Limits of geometric form
- Moulding limits
- Processing characteristics
- Sagging

9.7.2.3.6 Corrosion effect on substrate

- Fumes in combustion
- Physical contact
- Vapor on setting and set

9.7.2.3.7 Fabrication character of materials

9.7.2.3.8 Economic factors

9.7.2.4 Adhesives: selective check-off list

9.7.2.4.1 Physical character of material

a) General

Chemical composition

Color

Contamination of contents by adhesive

Characteristics in:

atmosphere

waters and humidity

soil

chemicals

lubricating oil

hydraulic fluid

degreasing solvent

gases

other environments

Creep characteristics and temperature

Density

Effect of forming on substrate

Effect of organic vapors on substrate

Effect of high temperatures

Effect of low temperatures

Effect on strength after exposure to higher temperature

Electrical conductivity

Electrical resistivity

Fire resistance

Flammability

b) Strength or mechanical

Load on glue line:

cleavage (kg/cm of width)

peel (kg/cm of width)

shear (kg/cm²)

tension (kg/cm²)

9.7.2.4.2 Design limitations

Utility:

development

field repair

production

prototype

Application:

- bonding
- reinforced joint
- restriction on joined area
- restriction on pressure
- scaling
- type of drying

Surface types:

- base metal
- finish

Type of joint:

- edge
- filled
- lap

Hydraulic permeability

Maximum temperature not affecting strength

Melting point

Odor

Smoke development on fire

Surface effect (corrosion):

- metals
- non-metals
- coatings

Susceptibility to environments:

- outdoor sheltered
- outdoor direct exposure
- outdoor sunlight only
- indoor room condition
- indoor controlled
- stored sealed
- stored sealed (opened for test)
- stored outdoor sheltered

APPENDICES

APPENDIX A CORROSION IN OIL & GAS PRODUCTS

Corrosion occurrence has been widely experienced in the oil and gas industry. In the following, the main corrosion processes in oil and gas phases are discussed.

First of all it must be emphasized that corrosion is likely to occur only in the water phase, as the oil phase is considered non corrosive. Consequently, the presence of free water is necessary for corrosion to occur, i.e. vaporized water in streams at temperatures above the dew point are considered non-corrosive.

In addition, it is necessary, especially for mixed phases streams (oil+gas+water) to verify the water wetting of materials, in fact, if water is confined in the middle of the stream, or trapped by oil, no corrosion attack may develop.

The principle factors controlling corrosion are:

- the CO₂ partial pressure;
- the H₂S partial pressure;
- the fluid temperature;
- the water salinity;
- the water cut;
- the fluidynamics.
- the pH

Additional factors influencing corrosion rates in petroleum refineries and petrochemical plants including offsite facilities and pollution control facilities are:

- Organic acids (naphthenic acids)
- Hydrogen (atomic)
- Amine solution
- Sulfur
- Sodium hydroxide
- Ammonia
- Hydrofluoric acid
- Glycol
- Cyanide
- Sulfuric acid
- Galvanic couple
- Stress (Plus Chlorides, Caustic, Ammonia, Amines, Polythionic Acid)
- Bacteria
- Concentration of corrosives
- Aeration
- Heat flux
- Welding defects
- High temperature oxidation and corrosion

Some of these specific factors discussed in Appendix B.

A.1 Effect of CO₂

Dry CO₂ is non-corrosive until about 400°C, while it is corrosive when dissolved in water phase.

CO₂ corrosion in presence of free water is known to cause sweet corrosion. CO₂ dissolves in the water phase forming carbonic acid, which decreases the water acidity; the final pH of the solution will depend on temperature and CO₂ partial pressure.

The corrosivity of CO₂ saturated solutions is much higher than other acid solutions at the same pH, because of a direct action of CO₂ in the corrosion phenomena.

A.1.1 Effect of temperature

Same studies in laboratories (Fig. 1) shows that the corrosion rate increases up to 70°C, probably due to the increase of mass transfer and charge transfer rates. Above these temperatures, the corrosion rate starts to decrease. This fact is attributed to the formation of a more protective scale, due to a decrease in iron carbonate solubility, and consequently a diffusion process becomes the rate determining step.

A.1.2 Effect of pressure

The partial pressure of CO₂ has a detrimental effect on corrosion rate. Since the partial pressure of CO₂ is proportional to the total pressure by $P_{CO_2} = P \times \text{Mole per cent } CO_2$, therefore the corrosion rate will increase by increasing pressure.

A.1.3 Prediction of CO₂ corrosion rate

The evaluation of corrosion rate of carbon steels in CO₂ saturated waters may be done *according to DE Waard and Milliams formula /1/, where the corrosion rate is an exponential function of CO₂ partial pressure and temperature. Results obtained following this approach should be considered worst case corrosion.

The formula is easily usable in the form of a curve (Fig. 1) and nomogram (Fig. 2):

***Note:**

Several corrosion rate prediction models have been developed by oil companies and research institute, due to complexity of the phenomenon and the diversity of the operation conditions in oil and gas production and treatment network. Therefore the model itself, and all modifications, in order to use it for calculation of CO₂ corrosion in a specific regime should be presented to company for review and approval.

$$\text{Log}(R_{\text{max}}) = 5.8 - \frac{1710}{T} + 0.67 \text{Log}(P_{CO_2})$$

Where:

- R_{max} is the corrosion rate (mm/y)
- T is the temperature (°K)
- P_{CO2} = P m (CO₂)

being P the total pressure (bar) and m (CO₂) the CO₂ molar fraction in the gas phase.

For high pressures, it is recommended to substitute the partial pressure with the fugacity, defined as:

$$f_{CO_2} = a \cdot P_{CO_2}$$

being a the activity coefficient, given by:

$$\text{Log}(a) = (0.0031 - \frac{1.4}{T}) P$$

The validity limits under which the above mentioned formula was originated are:

- P (CO₂) <2 bar
- temperature <70°C

- distilled water
- flowrate = 1 m/s

The fitness of this formula has been confirmed also for CO₂ partial pressures much higher than the original experimental work and for high flowrate (Fig. 3) /2/.

This rate, called R_{max}, may be adjusted by considering the influence of the rest of the environment, other than P(CO₂) and T. The final corrosion rate may be thus expressed as:

$$R_{\text{corr}} = R_{\text{max.}} \times F(\text{g}) \times F(\text{s}) \times F(\text{w}) \times F(\text{i}) \times F(\text{c}) \times F(\text{pH})$$

where these reduction factors are applicable.

A.1.4 Effect of Glycol - F(g)

In wet CO₂ containing pipelines and flowlines, glycol is often injected to prevent hydrate formation. Glycols have a significant inhibitive effect on corrosion. The reduction of the expected corrosion rate due to the presence of Triethylene Glycol (TEG) can be conservatively expressed by F(g):

$$\text{Log}(F_g) = 1.6 \text{ Log } W(\text{g}) - 3.2$$

For mono and die-ethylene glycol the available data are more limited, but the results are also covered by the above F(g) factor.

A.1.5 Effect of scaling - F(s)

At temperatures higher than about 70°C, the steel may be protected by its corrosion products (iron carbonate, FeCO₃), and consequently the corrosion rate may be depressed, by a coefficient F scale representing the scaling factor:

$$\text{Log}(F_s) = \frac{2400}{T} - 0.6 \text{ Log}(f\text{CO}_2) - 6.7 \leq 1$$

In the range of temperature between 70 and 150°C, carbon steels are more prone to localized attack in case of high turbulence, as a consequence of the failure of the FeCO₃ film. In this case, corrosion rate may be much higher, as predicted by /3/.

At temperatures higher than 150°C and CO₂ partial pressure below 50 bar, the steel is protected by a strong film of FeCO₃ which is not removed even by high turbulent streams, and the corrosion rate becomes negligible.

A summary of temperature range and corrosion morphology is drawn in Fig. 4/3/.

Corrosion morphology may be either uniform or localised (mesa or pitting), according to the process parameters (temperature, CO₂ partial pressure, water phase composition, flowrate).

A.1.6 Effect of water cut - F(w)

Oil presence is generally considered beneficial, as far as oil exerts a kind of inhibition effect. Oil, in fact, may form on a steel surface a film enough thick and adherent to inhibit water wetting. On the contrary, gas and condensates do not generally exert any beneficial effect, as they have no inhibition property.

Hydrocarbon condensates are assumed not to influence corrosion significantly. Field experience has shown that, as opposite to oil, the hydrophobic behavior of condensates is negligible.

As far as vertical tubing is concerned, an oil film on the steel surfaces is stable up to about 20-40% water cuts. For higher water quantities the corrosion rate can be correctly predicted by De Waard and Milliams, as the steel may be considered water wet.

As far as horizontal pipes is concerned, the amount of water is not an important factor. In fact, as water is generally heavier than oil, gas and condensed products, in case of stratified flow, it may separate on the lowest surfaces, generally at 6 o'clock position. In this case, the expected corrosion will occur only on the water wetted surfaces.

In case of stratified flow, corrosion is also likely to occur in the top of the line, due to the condensation of water droplets from the wet gas. The effect of inhibition is poor in this case, and experience shows that corrosion rate in the top of the line can be assumed as 10% of the predicted rate in fully immersed conditions, with a maximum of about 0.3 mm/y, irrespective of the CO₂ content ^{4/}. To increase the inhibition efficiency in case of stratified flow, periodical pig launch should be made to allow the inhibitor film to be formed in the top of the line.

Along flowlines and pipelines, minimum areas are expected, as shown in Fig. 5, where free water may become stagnant, particularly if the flow is not able to remove it (low velocity). In these cases, corrosion attack will be localized at 6 o'clock position, as schematically shown in Fig. 6b, and the rate may be anyway correctly predicted with the approach discussed in this paragraph.

Pigging of the line is generally useful to remove the water remaining stagnant on the pipe bottom at 6 o'clock position. This will allow also a better inhibition of the pipe surfaces; in fact, being inhibitors oil soluble products, they are transported by the oil phase, and stagnant water may result more difficult to be inhibited. When corrosion inhibitors protection is utmost important, it is common practice to pig the lines regularly (daily or weekly).

In case of higher gas flowrate, the flow pattern may become annular, as shown for horizontal pipes in Fig. 7b. In this case, a continuous liquid film (which varies in thickness around the circumference of the pipe) exist over the full pipe circumference, whilst gas is flowing in the middle of the pipe. Since the steel surface is completely wetted, corrosion is equally likely to occur at any point around the circumference. As far as the use of the flow pattern diagrams, superficial velocity may be defined as the velocity the (liquid/gas) phase would exhibit if it flowed through the total cross section of the pipe alone ^{5/}.

Protection in this case may be achieved through continuous injection of film forming corrosion inhibitors, as they can be transported by the water phase and film on the full pipe surface. Attention should be paid in this case to the flow velocity, as highly turbulent flow may produce high shear stresses on the pipe wall and remove the inhibitor film. Another important factor in this case is the avoidance (or reduction) of disturbances, like small radius bends, over penetrated root welds, as shown schematically in Fig. 6a^{6/}, sudden change of diameter or direction, as they could create turbulence and impingement after the discontinuities, remove the inhibitor film and promote high rate corrosion.

To conclude, for light hydrocarbon condensate water wetting may occur at any velocity, thus F(w) is always set equal to 1.

A.1.7 Effect of corrosion inhibitors - F(i)

It has been common practice for many years to inject corrosion inhibitors into CO₂ containing production tubing and process streams carried by carbon steels. In some cases inhibitors have been injected into nominally dry gas lines as a second defence to back-up the drying process in the event of misoperation. In some other cases, inhibitors are applied as the first line of defence against corrosion in carbon steel lines carrying wet gas from satellite to central gathering facilities where bulk drying can be carried out. Temperature drops can be considerable over such intrafield lines, so that condensation of water and hence corrosion will take place around the full internal pipe surface.

Corrosion inhibitors are chemicals which may be divided in a few categories. Among these, the most used class in horizontal flowlines/pipelines is the film forming amine type.

In this case, inhibitor is composed by a flat aromatic molecule (amine), which is polar and is attracted by the steel surface, being able to establish some absorption link; the molecule has also an aliphatic long tail, which is oil soluble. The effect of film forming inhibitor is thus to establish a first layer of flat molecules just on the steel surface, a second layer of aliphatic tails and a third layer of oil/condensates. Water cannot thus reach the steel surface and promote corrosion.

The stability of this film is dependent on the chemistry and fluidynamics of the transported fluids, as they can remove the inhibitors, because of chemical affinity between oil products and the aliphatic tail, from the steel surface, or to promote breaking of this film by impingement of water droplets.

The effect of velocity on corrosion inhibitor performance is to reduce film life and increase the concentration of inhibitor required to maintain protection.

It is generally accepted to define the capacity of inhibitors to protect against corrosion using a parameter, called efficiency, defined as:

$$\text{Inh. Eff.} = \frac{R_{\text{corr}} (\text{with - inhibitors})}{R_{\text{corr}} (\text{without - inhibitors})}$$

Often used as a percentage. To give an example, if a system would exhibit 2 mm/y corrosion rate without inhibitors and 0.2 mm/y with inhibitors injection, the calculated efficiency is 90%.

Under ideal conditions for inhibitors application, an inhibitor efficiency of above 85% can be achieved when comparing the corrosion rate seen and that predicted by De Waard-Milliams nomogram. However, an efficiency of 85% is dependent upon even distribution of inhibitor over the whole circumference of the pipe wall, something unlikely to be achieved in flowlines transporting a mixture of fluid and gas. In addition, areas of extreme turbulence can appear in connection with disturbances, which reduce the level of protection that an inhibitor can provide. Such disturbances have been seen at flanges and at over penetrations at welds and may also occur in areas of growing corrosion damage^{7/}.

Some recent data have been published by Tulsa University^{5/}, where for all inhibitors tested under two flow conditions, corrosion rates increased as superficial gas velocity increased; inhibition efficiency, above 95% in single phase flow decreased significantly as shown in Fig. 8 in the range 40-95%, highlighting the necessity of qualifying the chemicals before injection through properly designed corrosion testing.

The inhibitors film persistency on steel surfaces depends on the inhibitor type (Fig. 9) and dosage (Fig. 10). Moreover, it was found^{8/} that the capacity of an inhibitor to produce resistant films is dependent also on the environment pH. Moreover, it was shown that increasing inhibitor concentration is usually required when high flowrate (i.e. high shear stresses) is expected, as shown in Fig. 11.

Most inhibitors exhibit a maximum temperature, above which they do not function properly. Generally, it is believed that inhibitors in pipelines can work up to about 90°C.

According with some other reference^{9/}, for a given oil soluble inhibitor, the parameters of primary importance that control corrosion rates in inhibited systems include inhibitor concentration, dispersion of inhibitor in water, film persistency and velocity. The parameters of secondary importance in predicting corrosion in inhibited wet gas pipeline include partial pressure of CO₂, temperature (if below a critical level) and composition of aqueous environment (including pH). In other words, if the local concentration of an appropriate inhibitor is sufficiently high, corrosion may be controlled regardless of CO₂ partial pressure, fluid composition, or temperature in the range normally found in pipelines.

From this last approach, instead of calculating the expected corrosion rate or inhibitors efficiency, the reliability of corrosion inhibitors is the most important task to define. (see IPS-E-TP-780).

To conclude, the inhibitors efficiency is a very difficult task to establish, being dependent on:

- Proper inhibitors selection and dosage;
- fluid velocity and flow regime;
- presence of disturbances able to perturbate the flow;
- operating temperature, in order to ensure persistency of inhibitors film.

It is general practice, in the design stage, to assume 0.9* inhibitors efficiency, thus F(i) = 0.1. However, lower figures should be considered where high flow velocities are expected to produce erosion corrosion attacks in presence of disturbances. In fact it is possible to have erosive liquid flow at local flow disturbances such as weld beads, pin ends in connections, bends, size reduction, flanges, even where the bulk liquid flow rate is not high.

For all these cases, the capacity of field repairing and repair costs should become the effective design criteria.

Note:*

More precisely this figure shall be 0.85 for condensate, 0.9 for gas and 0.95 for oil stream.

A.1.8 Effect of condensing phase - F(c)

In case of water condensation from saturated vapor as a consequence of the stream cooling along the route of piping, corrosion is likely to occur under the condensed droplets. These conditions are very likely to produce a protective film, as scale deposition and adherence are favored because of the quiescent conditions. In fact, experiments and experience demonstrated that, in spite the nomogram predicts the same value in immersed and condensing conditions, the corrosion rate drops at max. 0.3 mm/y, irrespective of the partial pressure of CO₂.

Similar reduction in the corrosion rate may be applied to reduce the expected corrosion rate for the top surface of vessels and separators etc. It is also applicable to top of pipelines where the flow regime is stratified, or nominally dry gas lines where cooling below the dew point occurs. No reduction is applicable to immersed conditions.

Such a reduction factor may be evaluated as:

$$F_{\text{cond}} = 0.4 (\text{cond. rate, g/(m}^2\cdot\text{s)}) \leq 1$$

In most cases, the adoption of F(c) = 0.1 is suggested, where applicable.

A.1.9 Effect of water salinity - F(pH)

Corrosion in production fluids is mainly controlled by the presence of free water, which may come from the reservoir itself (formation water) and/or condense along the route (condensation water).

These two kind of waters differ very much as regard composition and the effects on the corrosion phenomena.

In fact, whereas condensate being free of salts can achieve very low pH, the salts dissolved in formation waters may have a high buffering effect, which leads to higher pH at the same CO₂ partial pressures. The solution pH will depend, finally, on the amount and kind of dissolved solids, and the dissolved gases.

In addition, the presence of ions (like Ca⁺⁺, Mg⁺⁺) can increase the resistance of the corrosion product film, where the corrosion resistance may be influenced by this phenomena.

To evaluate F(pH), the saturation pH must be first calculated as the lowest of the two following:

$$\text{pH}_{\text{sat}} = 1.36 + \frac{1307}{T} - 0.17 \text{ Log}(f\text{CO}_2)$$

which refers to the formation of Fe₃O₄ and

$$\text{pH}_{\text{sat}} = 5.4 - 0.66 \text{ Log}(f\text{CO}_2)$$

which refers to the formation of FeCO₃.

Once known the real environment pH, called pH_{act}, the corrective factor F(pH) may be calculated as:

$$\text{if: } \text{pH}_{\text{sat}} \geq \text{pH}_{\text{act}}$$

$$\text{Log}(F_{\text{pH}}) = 0.32 (\text{pH}_{\text{sat}} - \text{pH}_{\text{act}})$$

$$\text{if: } \text{pH}_{\text{sat}} \leq \text{pH}_{\text{act}}$$

$$\text{Log}(F_{\text{pH}}) = - 0.13 (\text{pH}_{\text{act}} - \text{pH}_{\text{sat}})^{1.6}$$

The adoption of such a reduction factor is not allowed if also F_{scale} is used, thus F_{pH} is set to 1 if F_{scale} is lower than 1.

If the real environment pH is unknown, F(pH) is set at 1.

A.2 Effect of H₂S

H₂S in presence of water is known to cause sour corrosion. This name includes different mechanisms, known as uniform corrosion, sulphide stress cracking (SSC) and hydrogen induced cracking (HIC).

The definition of sour service is generally made in accordance with ¹⁰/.

A.2.1 Uniform corrosion

H₂S is a weak acid, so it causes a small decrease in the pH of the water solution. Nevertheless, it may corrode also in neutral solutions, with a uniform corrosion rate generally quite low, as shown in Fig. 12/¹¹/.

Furthermore, H₂S may play an important role in the mechanical resistance of corrosion products film, increasing or decreasing their strength, depending on the relative amount, as shown in Fig. 13-14/¹²/.

A.2.2 Hydrogen induced cracking

This form of attack, also known as Stepwise Cracking, is typical of carbon steels, showing ferritic structures, when in presence of MnS (Type II) elongated inclusions as a consequence of rolling manufacturing process.

This kind of attack may develop if the operating conditions fall above the limits proposed in ¹⁰/, as shown in Fig. 15 for sour gas systems and Fig. 16 for sour multiphase systems.

At operating temperatures higher than 65°C the risk of HIC is anyway very low, and precautions against HIC damage are generally unnecessary.

This kind of attack must be avoided through proper selection of carbon steel chemical analysis and corrosion resistance verified through testing during manufacturing.

A.2.3 Sulphide stress cracking

This kind of attack occurs under the combined action of tension stresses, aggressive environment (H₂S) when in presence of a susceptible material.

Standards define the conditions for sour service (Figs. 15 and 16) and specify acceptable limits for the materials to be used in these conditions. The requirements imposed by the standard ¹⁰/ are a restriction to the list of approved materials and a limitation in materials hardness. (see also Appendix B.5)

A.3 Effect of Fluidynamics

Fluidynamics exerts an important influence on the corrosion rate.

When increasing the flowrate, the primary effect is a higher mass transfer from the bulk of the solution to the near metal surface, which enhances both the corroding species and the corrosion products mobility. This effect is shown in Fig. 17/¹³/, where the rate calculated using De Waard and Milliams approach is 4.6 mm/y (approach valid at 1 m/s flowrate): higher flowrate produce higher corrosion rates.

The dependence of the corrosion rate on liquid flow velocity decreases with increased pH, as demonstrated in Fig. 18/¹⁴/.

This is important for practical situations, where dissolved FeCO₃ can increase the pH significantly.

The effect of velocity on corrosion rate of steels is also depended on steel composition and microstructures. Steels with more homogeneously distributed carbides like in tempered martensite and in bainitic structures are not expected to form lamellar cementite, which can act as a cathodic depolarizer and stimulator of the CO₂ corrosion. Also the effect of Cr appears to be a partial blockage of the surface, probably by Cr-oxide which interferes with the corrosion reaction. Fig. 19 gives an example to demonstrate the differences obtained for the two groups of steels. The differences in the baselines with Cr% = 0 or C% = 0 indicates that martensitic steels could corrode somewhat faster than normalized ones.

When flowrate produces friction stresses on the corrosion products (or inhibitors) film, it may break them, with the result of much higher corrosion rate.

On the contrary, like on horizontal pipes, low flowrate are generally not able to remove the free water which is stagnant at the 6 o'clock position.

When the flowrate is high, it is possible that corrosion products protective or inhibitors films are removed, giving chance of high corrosion rate to occur. This kind of attack is also called Erosion-Corrosion. API RP-14E^{15/} contains a simple formula for estimating the velocity beyond which accelerated corrosion due to erosion corrosion may occur.

The formula is empirical and derived from field experiences, and is meant to describe the velocity for the possible onset of erosion corrosion in uninhibited corrosive oil and gas well surface production equipment fabricated from carbon steel in the absence of sand^{15/}:

$$V = \frac{122}{\sqrt{\rho}}$$

Where:

- V** = that velocity beyond which accelerated corrosion due to high velocity may occur (m/sec)
 ρ = fluid density (Kg/m³)

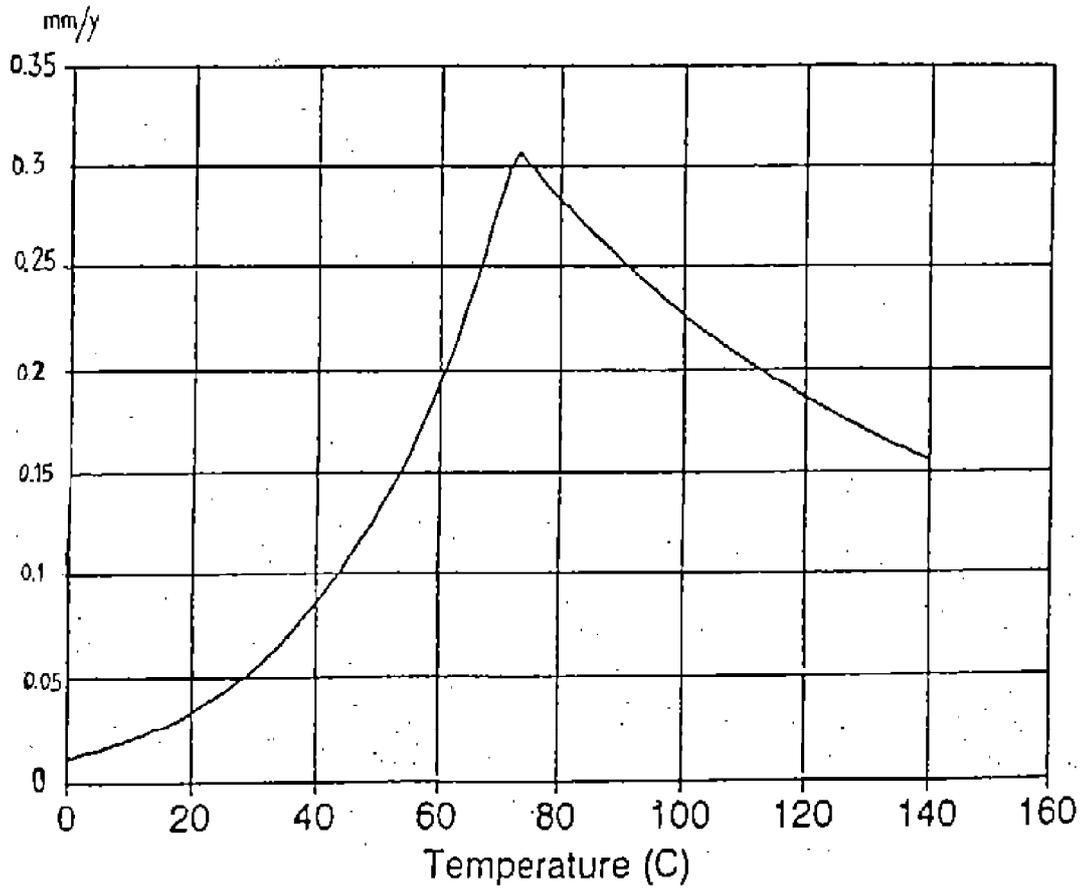
Several authors have observed that erosion corrosion happens in annular mist regime. It is also indicated that the increase of the corrosion rate with velocity at Khuff Gas sour production system (Fig. 20)^{17/} was associated with the onset of annular mist regime in multi-phase flow, as indicated also in Fig. 21. Here, without inhibitors injection, corrosion rate dramatically increases at about 5 m/s flowrate, with inhibitor injection, on straight sections, this change happens at about 7-8 m/s. Of course these figures are strictly valid for the Khuff Gas experience only, and cannot be extrapolated to other conditions.

From this experience, the following general rules can be derived:

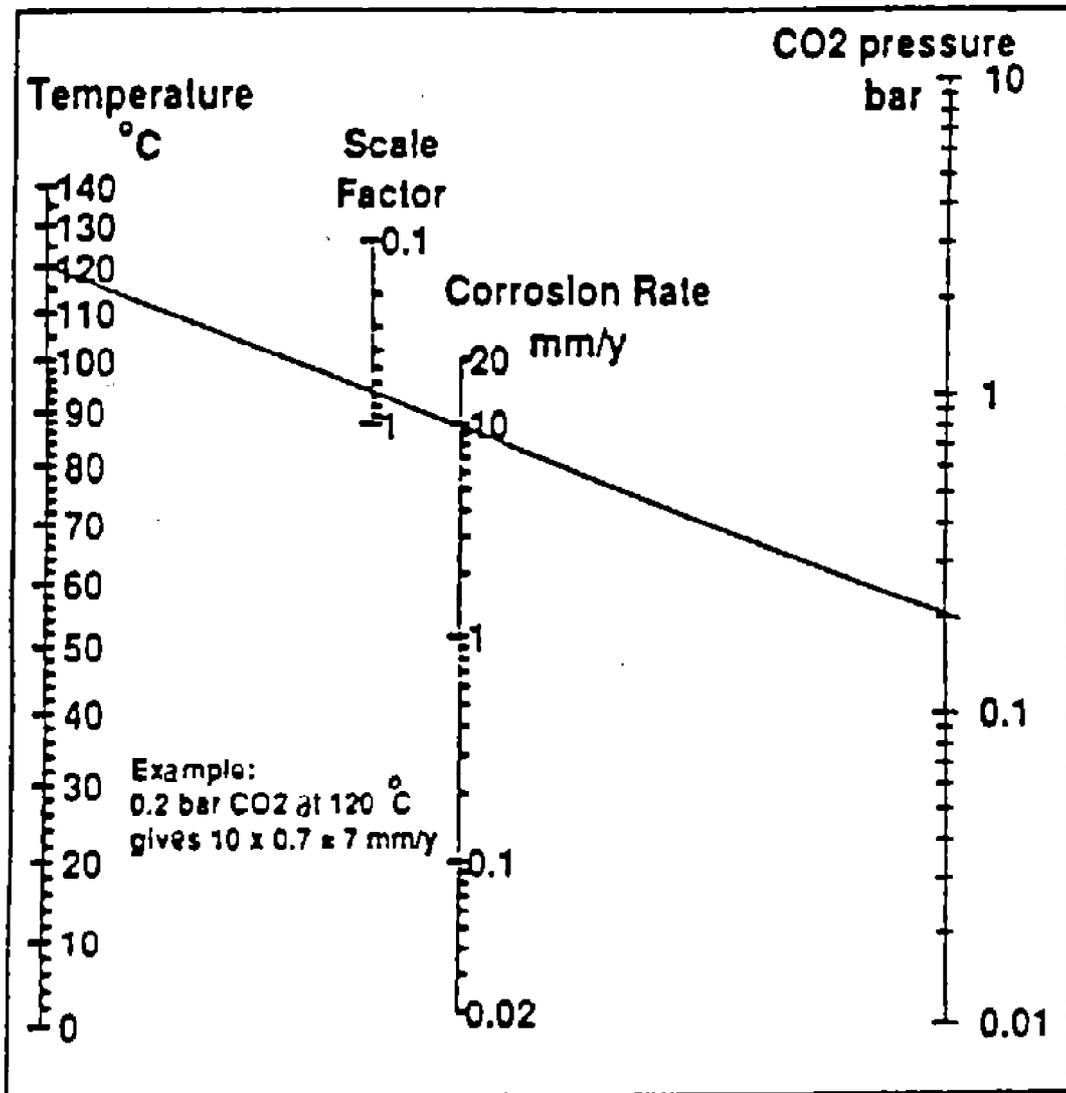
- the calculated API erosional velocity is associated with the onset of annular mist flow;
- the onset of erosion corrosion in uninhibited systems is associated with the onset of annular mist flow regime in multiphase flow in the surface piping;
- the onset of erosion corrosion in inhibited systems (straight portions) occurs at a velocity of about 1.5 times the calculated API erosional velocity.

CO₂ CORROSION

ACCORDING WITH DE WAARD-MILLIAMS

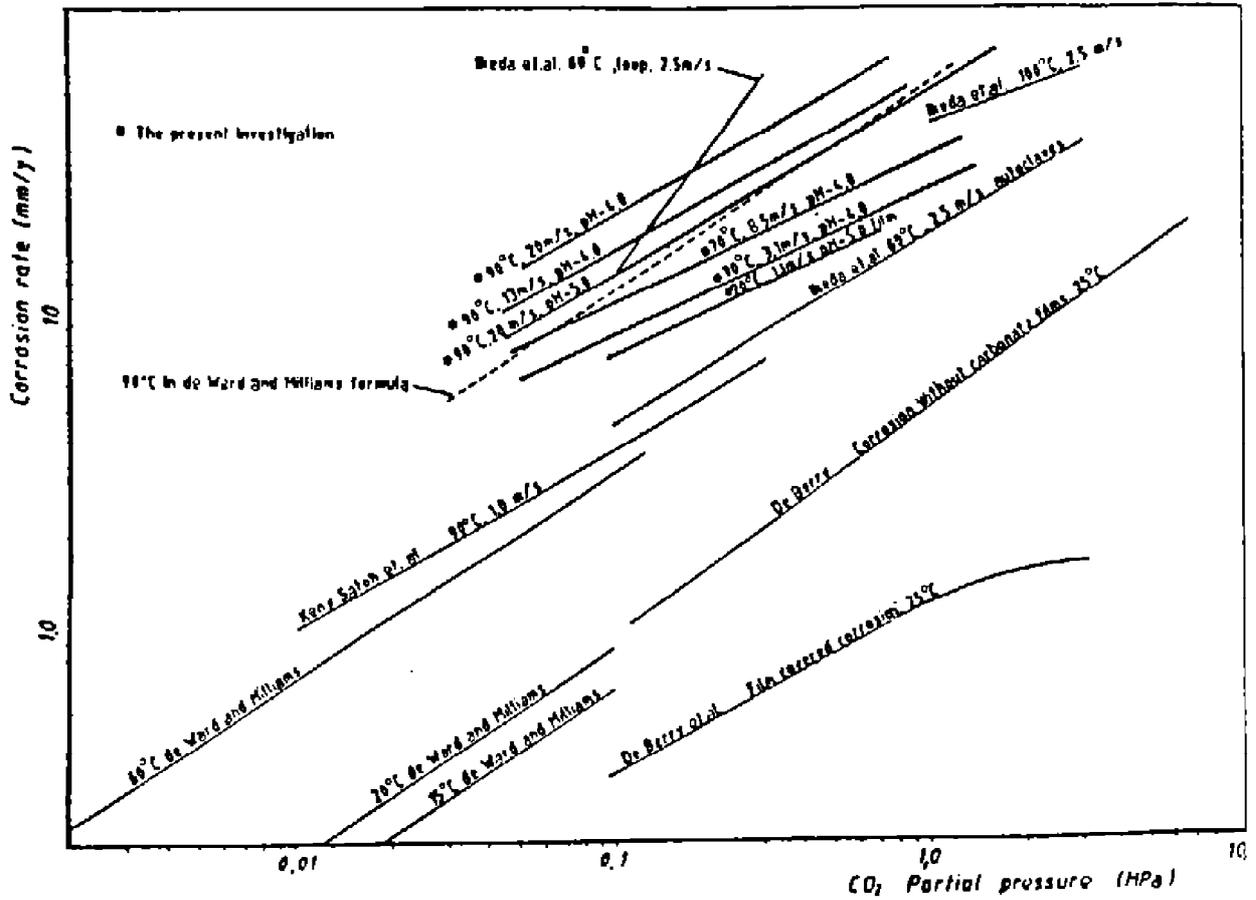


CORROSION RATE EVALUATION ACCORDING TO DE WAARD AND MILLIAMS^{1/}.
Fig. 1



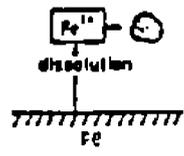
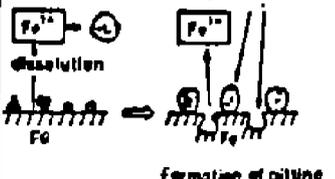
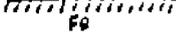
NOMOGRAM FOR CALCULATION OF CORROSION RATES AS A FUNCTION OF CO₂ PARTIAL PRESSURE AND TEMPERATURE. EXAMPLE SHOWN: AT 0.2 bar CO₂ AND 120°C, CORROSION RATE IS 10 mm/y. SCALE FACTOR = 0.7, THUS EXPECTED CORROSION RATE IS 7 mm/y¹.

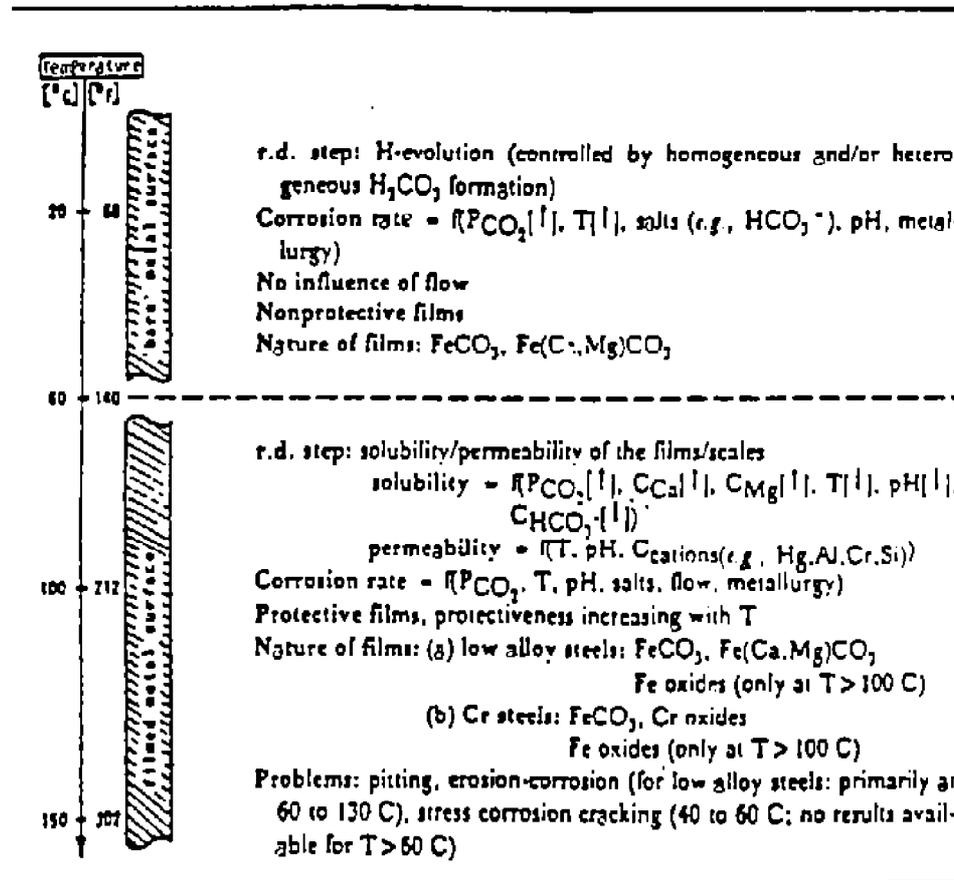
Fig. 2



CORROSION RATES AS A FUNCTION OF CO₂ PARTIAL PRESSURE.
DATA FROM VARIOUS SOURCES^{2/1}.

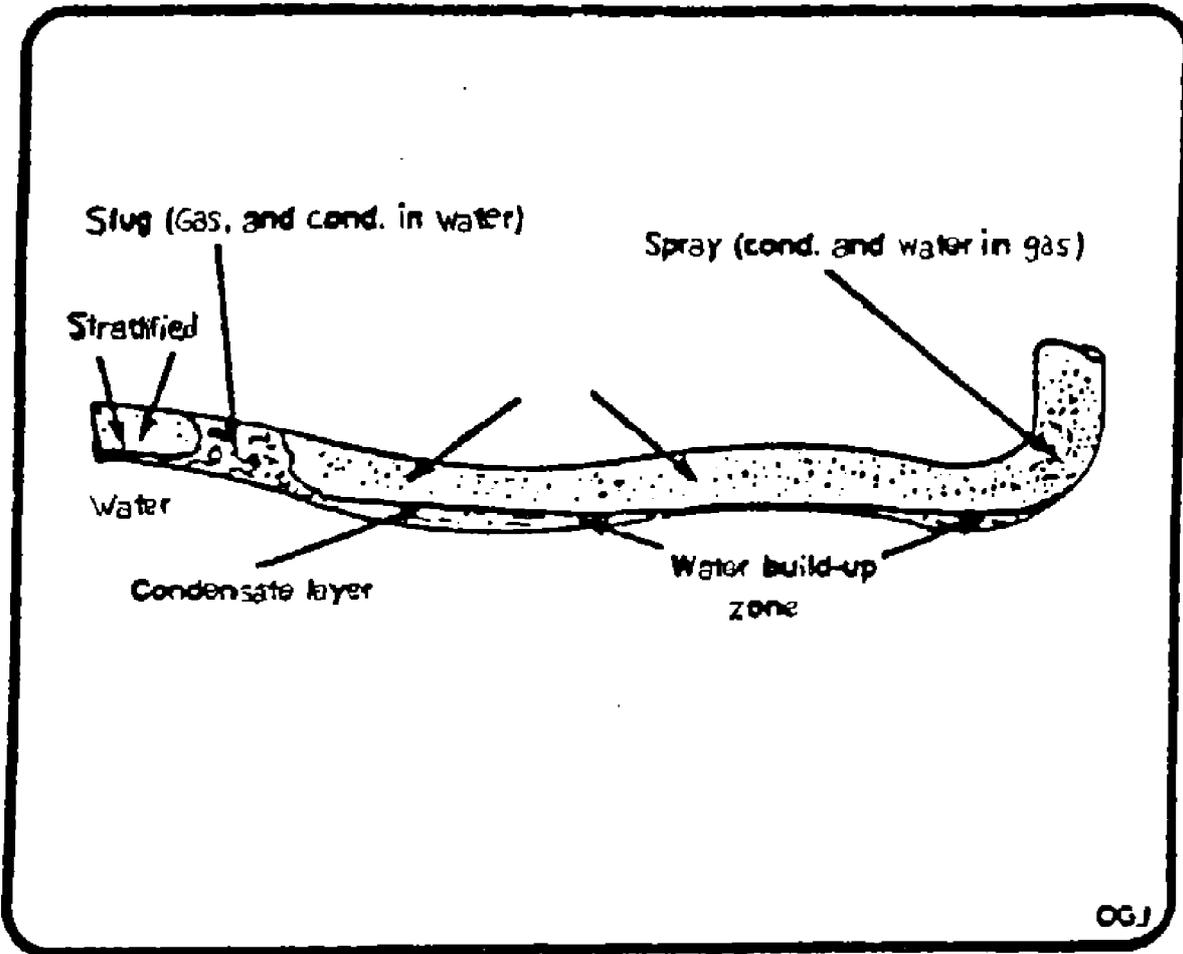
Fig. 3

Type 1	Type 2	Type 3
low temp [-40°C (100°F)]	intermediate temp [-100°C (212°F)]	high temp [-150°C (302°F)]
general corrosion	deep pitting	enh-corrosion
<p>bulk deposition of FeCO₃</p>  <p>Fe²⁺ dissolution</p> <p>Fe</p>	<p>bulk deposition of FeCO₃</p>  <p>Fe²⁺ dissolution</p> <p>Fe</p> <p>Fe²⁺</p> <p>growing and/or stripping of FeCO₃ film</p> <p>formation of pitting</p>	<p>formation of light and thin FeCO₃ film due to the increased initial Fe²⁺ dissolution rate</p>  <p>Fe</p>

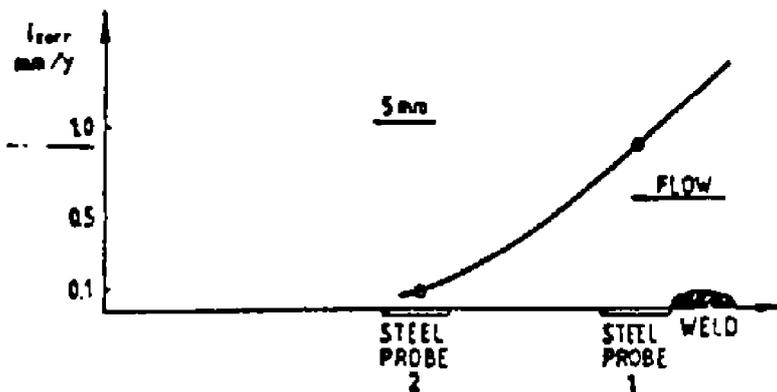


SCHEMATIC SUMMARY OF NATURE AND MORPHOLOGY OF CORROSION IN THE DIFFERENT TEMPERATURE RANGES^{3/}

Fig. 4

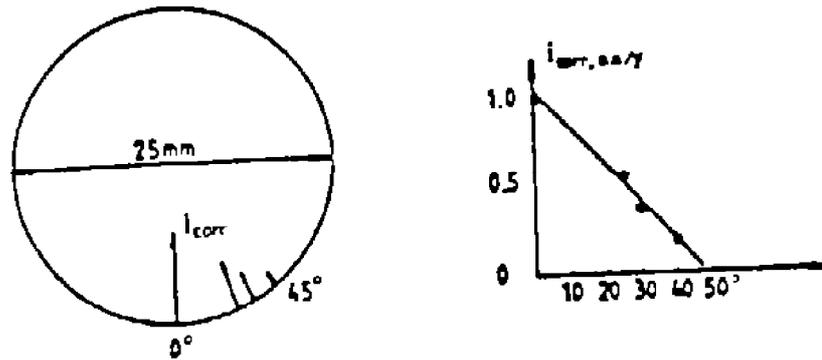


SCHMATIC SUMMARY OF FLOW REGIME IN GAS FLOWLINES
Fig. 5



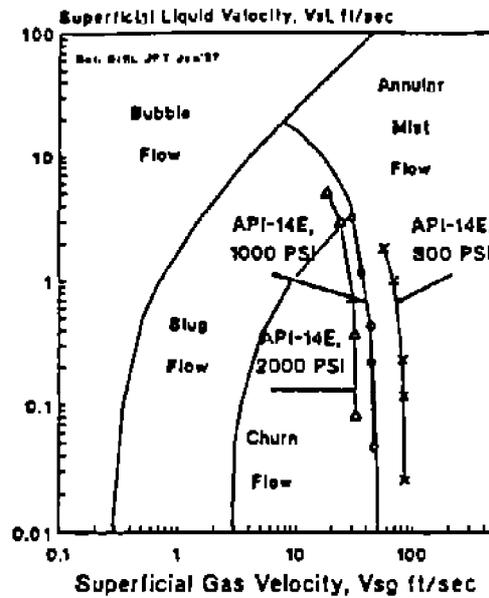
CORROSION RATE AT TWO DISTANCES FROM THE SIMULATED WELD IN FLOWING OIL/WATER MIXTURE. LIQUID FLOW RATE ABOUT 1 m/s /⁶.

Fig. 6a



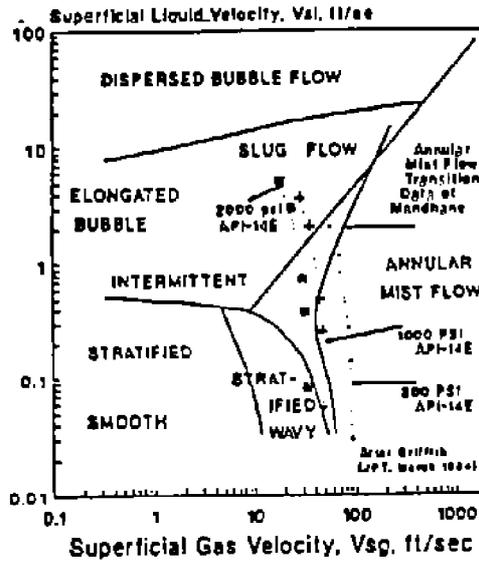
CORROSION RATE IN THE PIPE BOTTOM AND AT VARIOUS ANGLES FROM THE PIPE BOTTOM IN A FLOWING OIL/WATER MIXTURE AT 20°C. 5% WATER (4% NaCl) IN OIL. LIQUID FLOW RATE ABOUT 1 m/s ¹⁶.

Fig. 6b

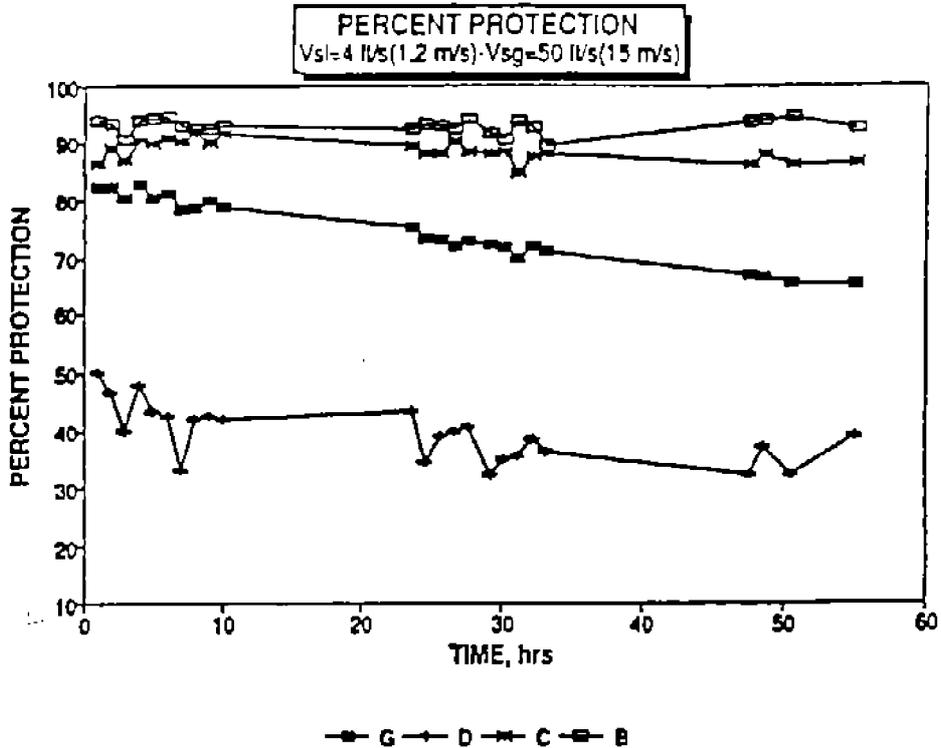


FLOW PATTERN IN VERTICAL MULTIPHASE FLOW ¹⁵.

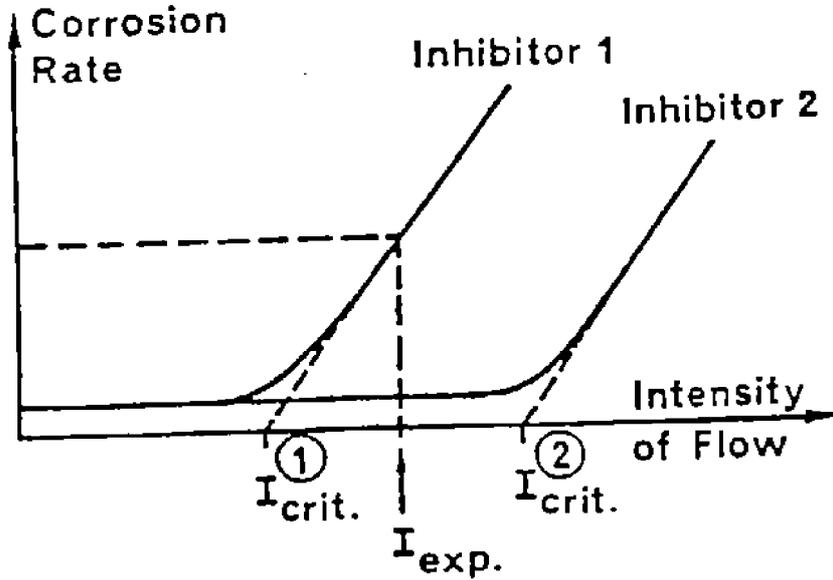
Fig. 7a



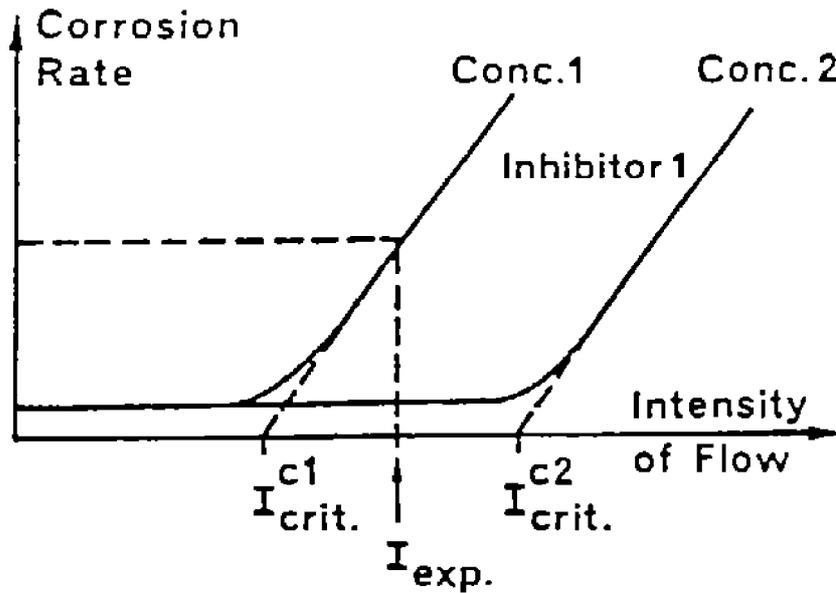
FLOW PATTERN IN HORIZONTAL MULTIPHASE FLOW /^{15/},
Fig. 7b



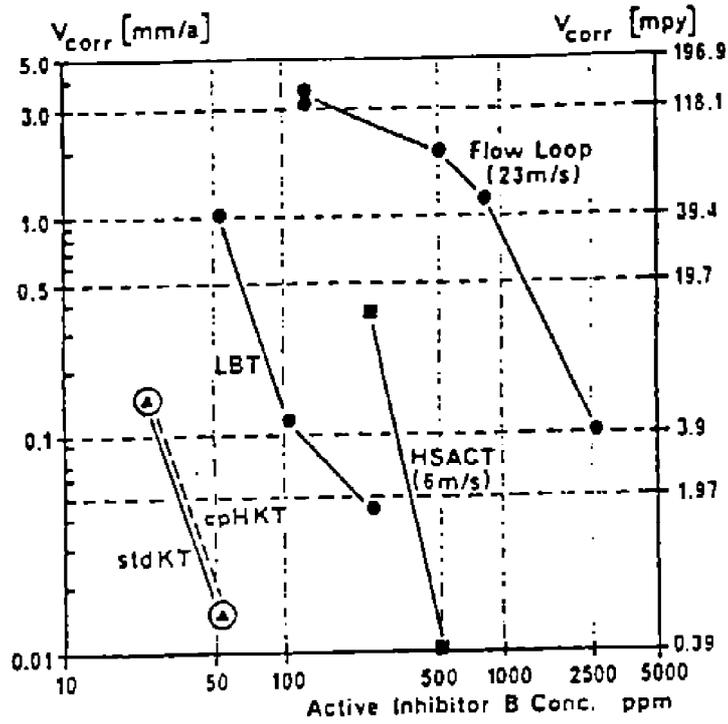
PERCENT PROTECTION FOR 4 COMMERCIAL INHIBITORS UNDER
TWO-PHASE FLOW CONDITIONS /^{5/}
Fig. 8



EFFECT OF THE NATURE OF INHIBITORS ON CRITICAL FLOW VELOCITY^{8/}.
Fig. 9



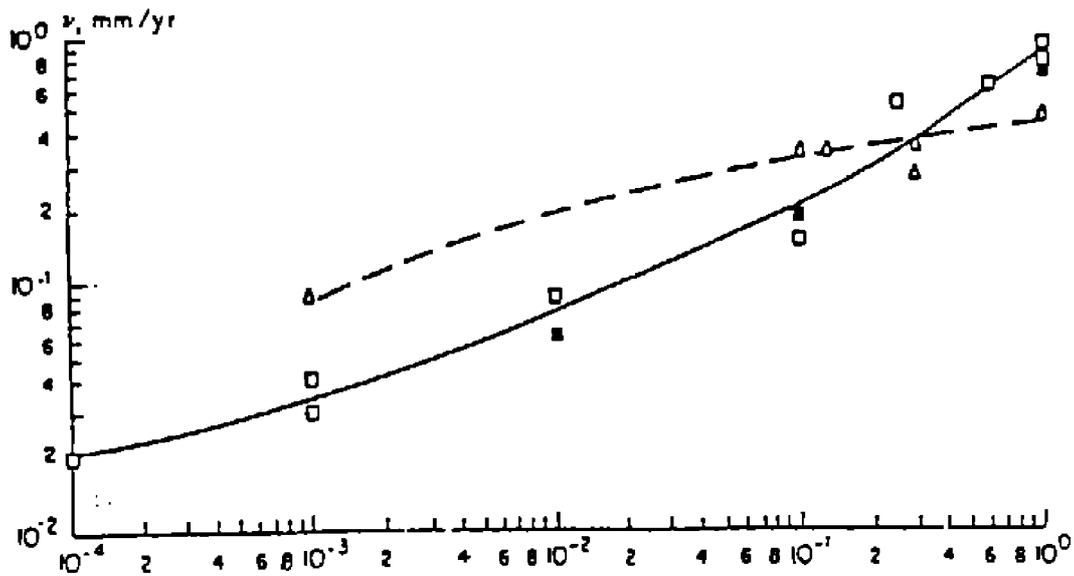
EFFECT OF INHIBITOR CONCENTRATION ON CRITICAL FLOW INTENSITY^{8/}.
Fig. 10



PERFORMANCE/CONCENTRATION CURVES FOR ONE INHIBITOR TYPE FOR CONDITIONS OF INCREASING SEVERITY^{8/}.

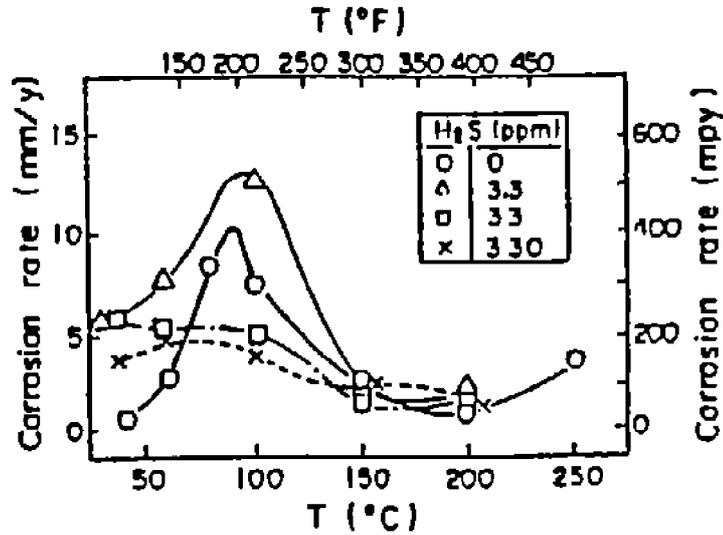
Fig. 11

- △ 0.1% NaCl
- 10% NaCl
- 10% NaCl (1m/s)



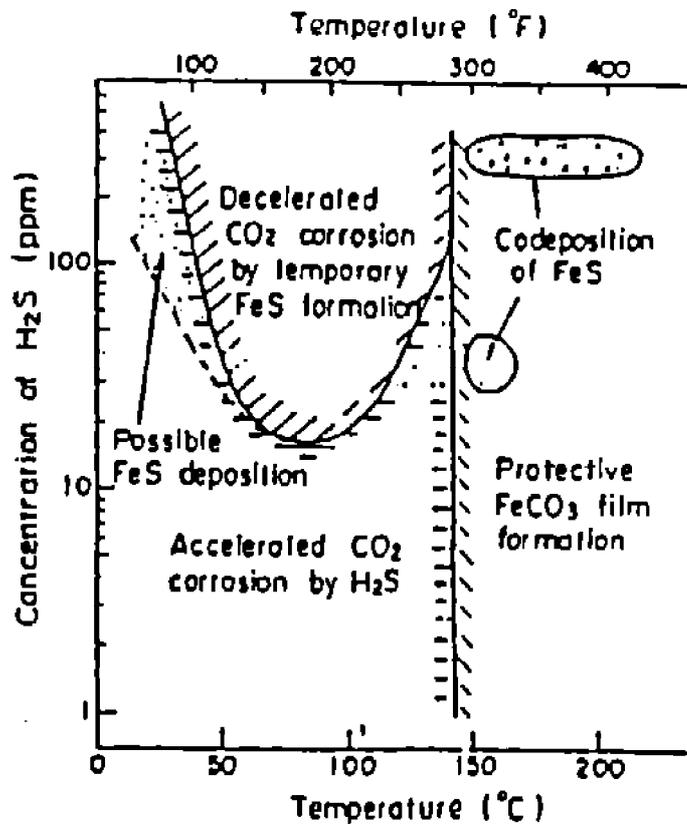
INFLUENCE OF $p(H_2S)$ ON CORROSION RATE OF STEEL^{11/}

Fig. 12



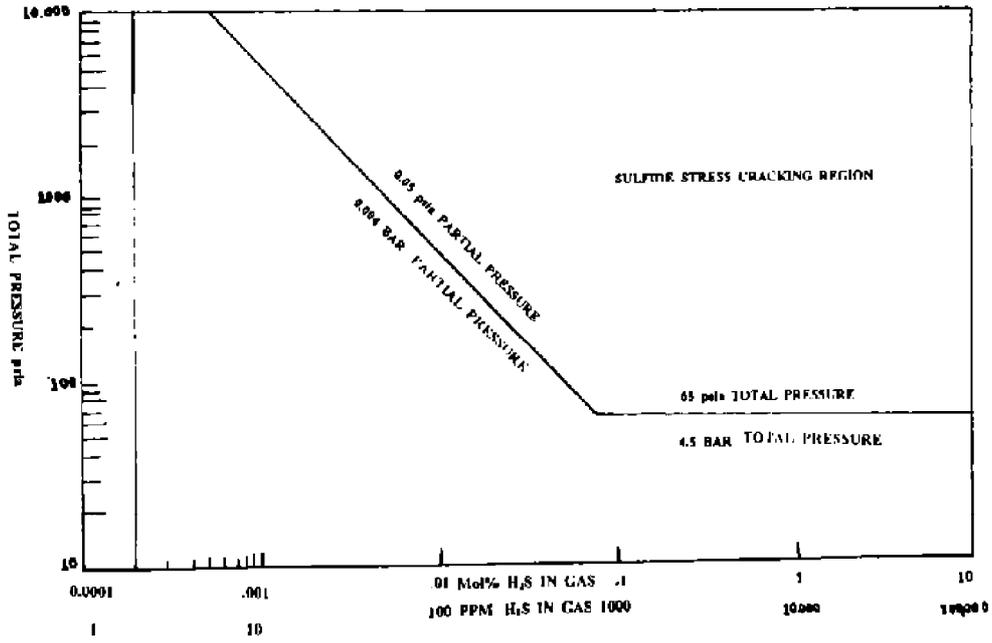
EFFECT OF THE ADDITION OF A SMALL QUANTITY OF H₂S AND OF THE TEMPERATURE ON THE CORROSION RATE OF PURE IRON (5% NaCl, 3.0 Mpa CO₂ + H₂S @ 25°C; TEST DURATION 96 HOURS; FLOWRATE 2.5 m/s; SPECIFIC VOLUME 25 cc/cm²)^{12/}.

Fig. 13

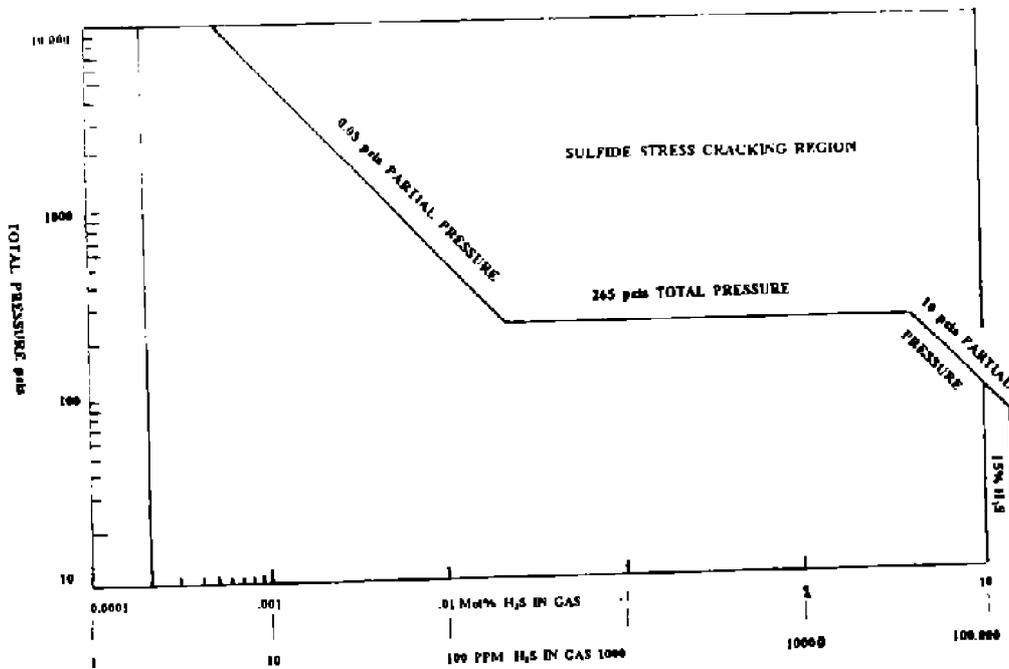


EFFECT OF THE H₂S CONTAMINATION ON THE CO₂ CORROSION RATE^{12/}

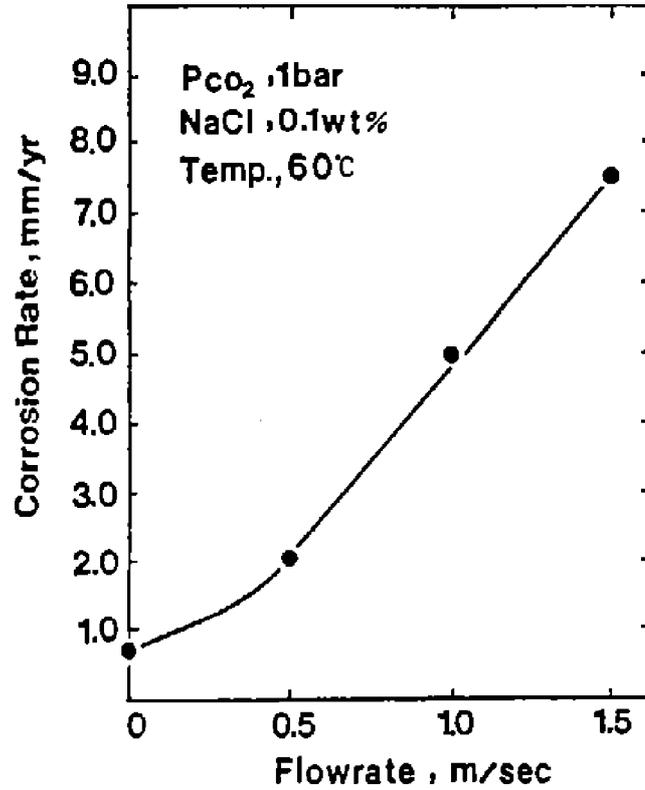
Fig. 14



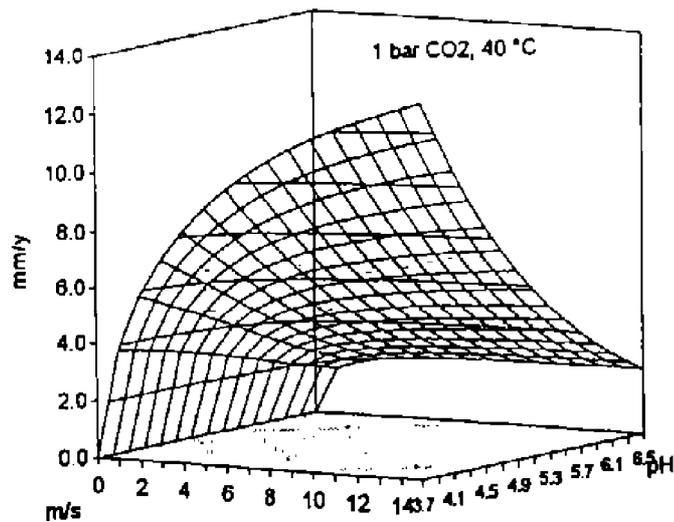
SOUR GAS SYSTEMS /¹⁰/
Fig. 15



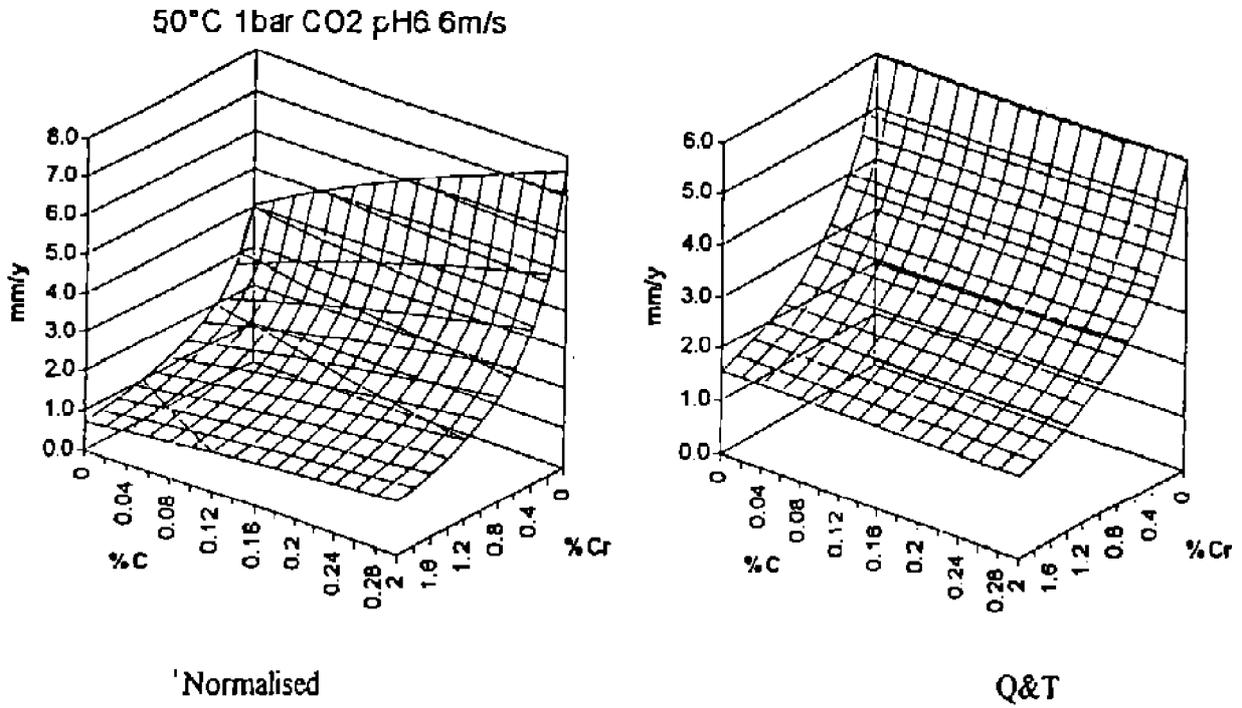
SOUR MULTIPHASE SYSTEMS /¹⁰/
Fig. 16



THE EFFECT OF FLOW RATE ON THE CORROSION RATE OF CARBON STEEL IN CO₂ SATURATED WATER^{13/}. CALCULATED CORROSION RATE ACCORDING TO ^{1/} IS 4.6 mm/y.
Fig. 17

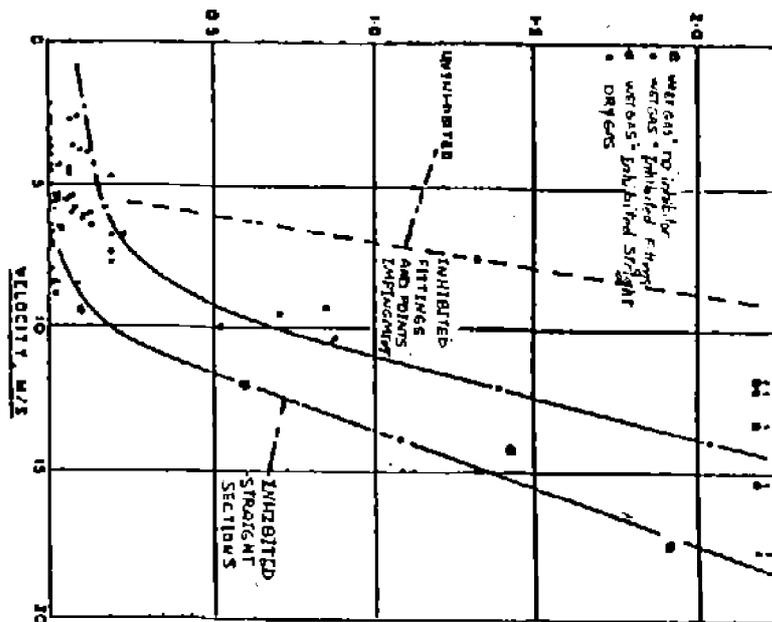


EFFECT OF FLOWRATE AND pH AT 40°C, 1 bar CO₂
Fig. 18



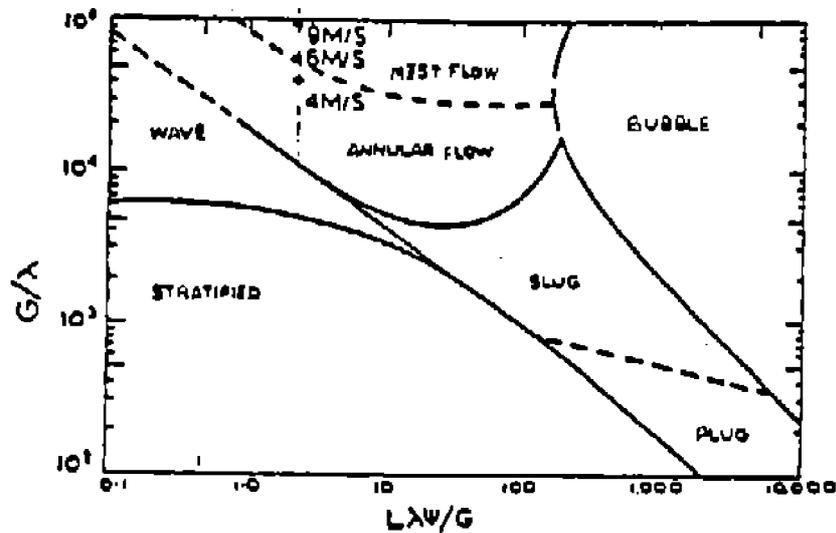
EXAMPLE OF CALCULATED EFFECT OF COMPOSITION OF LOW ALLOY STEELS ON CO₂ CORROSION RATES

Fig. 19



EFFECT OF VELOCITY ON CORROSION IN KHUFF GAS^{17/}

Fig. 20



FLOW PATTERN REGIONS ACCORDING TO BAKER, SHOWING THE TRANSITION FROM ANNULAR TO MIST FLOW IN WET KHUFF GAS STREAMS^{17/}.

Fig. 21

A.4 References

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APPENDIX B

SPECIAL CONSIDERATION IN REFINERIES AND PETROCHEMICAL PLANTS⁽¹⁾

B.1 Corrosives and Corrosion Problems

The following are the main corrosives and corrosion problems in addition to those explained in Appendix A which require special material consideration in petroleum refineries⁽²⁾ and petrochemical plants.

B.1.1 Sulfur content

Organic sulfur-bearing fluids (≥ 0.1 wt%) corrode steel at high temperature. Based on accumulated experience in actual plant design, chromium-molybdenum steel is normally employed instead of carbon-steel for the parts, where the operating temperature requires it.

B.1.2 Erosion

A serious erosion problem may arise around H.D.S piping and effluent air coolers downstream of the water injection point. Materials and fluid velocity shall be determined by R.L. Piehls Method⁽³⁾.

B.1.3 Naphtenic acid

Crude oil with an acidic value exceeding 0.5 mg KOH/g may pose serious corrosion problems for heater tubes, piping and rotary machines. Austenitic stainless steel of 316 grade shall be selected for parts handling high-temperature (over 260°C) crude oil having high acidity.

B.1.4 Hydrogen

High temperature and pressure sections are subject to hydrogen attack. Materials for such services shall be selected using the curves in the latest edition of API⁽⁴⁾. This shall also be considered for equipment located downstream of the waste heat boiler.

B.1.5 Polythionic stress cracking

Normal 304 stainless steel becomes subject to polythionic stress corrosion cracking because it sensitizes after welding and/or long term exposure under high-temperature service. To avoid sensitization, stabilized austenitic stainless steel such as Type 321 or 347 may be selected.

B.1.6 Caustic embrittlement by amine solution

Piping and equipment in direct contact by amine solution shall be stress relieved to avoid caustic embrittlement, provided that the operating temperature exceeds 90°C.

B.1.7 Salts

If the salt concentration of the crude oil is over (1 lb/1000 bbls) of crude, consideration need to be given, to the problem of chloride fouling and corrosion caused by hydrochloric acid resulting from the hydrolysis of $MgCl_2$ and $CaCl_2$ in distillation tower, crude preheating exchangers, as following:

- a) In cases where the salt concentration is between 1-10 ptb, the corrosion prevention measures shall be provided.
- b) If the salt concentration is over 10 ptb a desalter must be necessarily provided to reduce it to under 1 ptb, or to reduce it to around 1 ptb and then corrosion preventive measures shall be provided.

B.1.8 Condensate

To prevent condensation of water and corrosion, the operating temperature at top section of the atmospheric distillation tower is raised. Therefore, namely, more economical materials can be used here.

B.1.9 High temperature

Regarding material selection for high temperature piping and reformer tubes used in reforming furnace, selection shall be made with consideration given to economic because of very expensive materials used.

B.1.10 CO₂ corrosion

Carbon steel has no corrosion resistance in wet reforming gas services at the temperatures above 40°C (see Appendix A).

B.1.11 Amine solution

The use of copper and copper alloys shall be avoided. The corrosiveness of rich amine solution is the highest in the case of hydrogen units and town gas units where only CO₂ is handled, and moderate in the case of F.C.C units where CO₂ + H₂S (H₂S/(CO₂ + H₂S) = 0.01) is handled and lowest in the case of hydrodesulfurization, where only H₂S is handled. Equipment which undergo maximum corrosion are Lean/Rich heat exchangers, regenerator, reboiler, reclainer and overhead condenser.

B.1.12 H₂S

Parts and components to come in contact with wet hydrogen sulfide shall be provided with sulfide stress corrosion cracking prevention measures in accordance with NACE MR 01-75 latest edition. (see B.5)

B.1.1.3 H₂SO₄

Sulfuric acid in concentrations above 85% by weight are usually not corrosive to carbon steel if temperatures are below 40°C. Cold-worked metal (usually bends) shall be stress relieved. Flow velocities above 1.2 m/s can destroy protective iron sulfate film. Also localized attack immediately downstream of piping welds has been attributed to a spheroidized structure; a normalizing postweld heat treatment at 870°C is required to minimize corrosion. All valves and pumps require corrosion resistance internals or trim. In addition to sulfuric acid, reactor effluent contains traces of alkyl and dialkyl sulfates from secondary alkylation reaction. These esters decompose in reboilers to form sulfur dioxide and polymeric compounds and finally sulfurous acids which can cause severe corrosion in overhead condensers (particularly deisobutanizer tower).

Neutralizers or filming amine corrosion inhibitors can be injected into the overhead vapor lines of various towers to prevent corrosion.

B.1.14 Hydrogen fluoride

In general, hydrofluoric acid is less corrosive than hydrochloric acid because it passivate most metals. However if these films are destroyed by dilution or else, sever corrosion in the form of hydrogen blistering of carbon steel and stress cracking of hardened bolts will occur.

Specific areas where corrosion is likely to occur include the bottom of the acid rerun tower, depropanizer towers, the overhead condensers of these towers, the reboiler of the propane stripper and piping around the acid rerun tower.

By proper design practices to keep the feed stocks dry, and prescribed maintenance procedures to keep the equipment dry during shutdowns, there will be few corrosion problems by this catalyst.

B.1.15 Acetic acid

Corrosion by acetic acid can be a problem in petrochemical process units. As a rule even tenth of a percent of water in acetic acid can have a significant influence on corrosion rate of this acid. Temperature increases the corrosion rate, bromide and chloride contamination causes pitting and S.C.C, while addition of oxidizing agents, including air, can reduce corrosion rate.

Type 304 stainless steel can be use for temperatures below 90°C and Type 316 and 317 for hot acetic acid applications.

B.1.16 Ammonia

Ammonia cause two types of S.C.C in petrochemical plants. The first is cracking of carbon steel in anhydrous ammonia service, and the second type is cracking of copper alloys. Use of low strength steels, postweld heat treatment of welds and regular inspection are some actions to be taken to minimize cracking. Cracking of copper alloys tube bundles during shut downs should be prevented by neutralizing the residual ammonia by acid.

B.1.17 Fuel ash

Corrosion by fuel ash deposits can be one of the most serious operating problems with boiler and preheat furnaces.

All fuels except natural gas contain certain inorganic contaminants that leave the furnace with products of combustion. In particular, vanadium pentoxide vapor (V_2O_5) reacts with sodium sulfate (Na_2SO_4) to form sodiumvanadate ($Na_2O \cdot 6V_2O_5$). This compound will react with steel, forming a molten slag that runs off and exposes fresh metal to attack.

In general, alloys with high chromium and nickel contents provide the best resistance to this type of attack. Also addition of magnesium type compound raise the melting points of fuel ash deposits and prevent the formation of highly corrosive films. These additives also offer additional benefits with regard to cold-end corrosion in boilers by condensation (150-170°C) of sulfuric acid produced by sulfur content of fuel, by forming magnesium sulfate.

B.1.18 Micro organism

The corrosion action of the sulfate reducing bacteria (S.R.B) is well known in oil industries, especially in cooling water systems, fire water loops, after hydrotesting of tanks & vessels and in mothballed or water flooded systems.

B.2 Special Material Requirements for Refinery's Equipment

B.2.1 Austenitic stainless steel

The use of austenitic stainless steel shall be kept to a minimum. When the use of such a material cannot be avoided and where there is danger of transgranular stress corrosion cracking, the use of higher alloy materials such as stabilized Incolloys or ferritic stainless steel such as Type 444 (18 Cr-2 Mo) shall be considered.

B.2.2 Parts to be welded

For parts to be welded, including tank plates and structural steel, no bottom or side, air or enriched air-blown converter steels shall be used. Oxygen-blown converter steel may be used only below the creep temperature range.

B.2.3 Copper base alloy

The use of copper base alloys in direct contact streams in which ammonia acetylene or its homologues may be present is prohibited.

B.2.4 Carbon content

Carbon content and a carbon equivalent, based on $C+Mn/6$ for any plain carbon or carbon manganese steel that is to be joined by welding, shall not exceed 0.25% and 0.41%, respectively.

In cases where the above requirements are not met, welding procedure qualification tests in accordance with applicable codes shall be performed, and welding procedures for the portions to be subjected to the tests shall be submitted for agreement separately.

B.2.5 Ferritic stainless steel

The use of ferritic stainless steel shall be considered on the basis of the following characteristics:

- 1) Weldability
- 2) 474°C (885°F) embrittlement
- 3) Pitting corrosion
- 4) Caustic Embrittlement

B.3 Special Equipment Requirements

B.3.1 Pressure vessels (including exchanger shells, channels, etc.)

B.3.1.1 Low temperature vessels

When pressure vessels are subjected to low temperatures, i.e. below 0°C, materials and fabrication practices, e.g. post-weld heat treatment, shall be selected to minimize the risk of brittle fracture. Requirements for material selection depending upon the minimum design temperature. However, where this minimum design temperature is not a normal continuous operating condition, for example, if it arises as a result of autorefrigeration due to rapid depressurization, the full range of temperatures and coincident pressures shall be evaluated in order to determine the appropriate conditions for material selection.

The use of post-weld heat treatment can extend the use of carbon steel to temperatures lower than would be acceptable for as-welded vessels. However, unless post-weld heat treatment is required for process reasons, it should be specified only when the requirement cannot be met by using carbon steel in the as-welded condition.

B.3.1.2 Corrosion resistance

Carbon steel should normally be selected for pressure vessels, and an appropriate corrosion allowance applied where total corrosion is not expected to exceed 6 mm over the design life of the vessel.

Where the corrosion rate is predicted to exceed 6 mm over the design life, the various alternatives shall be evaluated. These alternatives may include, but should not be limited to, the following:

- a) Replacement at intervals, e.g. every 12 years,
- b) increased corrosion allowance,
- c) corrosion resistant internal linings,
- d) alternative solid corrosion resistant material.

Where pressure vessels are relatively thin in the absence of any corrosion allowance, the use of solid corrosion resistant alloys such as stainless steel and nickel based alloys may be more suitable than corrosion allowances or the use of internal cladding. However, for thicker vessels it is likely that internal corrosion resistant alloy cladding will provide the most economic solution. In certain circumstances, the use of coal tar epoxy, glass flake reinforced resins or other non-metallic coatings may be appropriate. Followings should be considered where there is a choice between clad or lining and solid corrosion resistance material;

B.3.1.2.1 The alloy material of vessel shells and heads required for corrosion resistance may be provided as alloy clad plate or as alloy cladding provided that the backing material of the clad plate is suitably resistant to the other conditions of the designated service.

B.3.1.2.2 The choice between alloy plate or alloy clad plate shall be made and be based on economic considerations. However, when austenitic stainless steel is the material required for corrosion resistance, alloy cladding should be used.

B.3.1.2.3 The use of alloy sheet lining, instead of cladding or deposit lining for vessel shells and heads shall be subjected to separate approval and shall be considered only for localized areas where the use of lining may be desirable from an economic standpoint.

B.3.1.2.4 For heavy shells and heads, alloy deposit lining may be used in lieu of cladding. The automatic strip-arc deposit welding process is acceptable. In all overlay weld metal the ferrite content shall be between 4 to 5%.

B.3.1.2.5 Where the anticipated erosion-corrosion rates on carbon steel wear plates exceed 1.5 mm per year, alloy steel wear plates shall be employed to prevent this corrosion rate being exceeded.

B.3.1.2.6 Cast iron pressure-retaining parts shall not be used in process fluid services, but may be used in fresh cooling water services for heat exchanger channels and cover sections.

B.3.1.2.7 Strip clad plate shall not be used if post-weld heat treatment is required.

B.3.2 Storage tanks

B.3.2.1 The decision on steel used for storage tanks shall be made from an economic viewpoint, between either normal or high tensile steel, however the yield strength of the plate, weld metal and heat-affected zone shall be 60 kg/mm² maximum.

B.3.2.2 Steels containing deliberately added chromium, nickel or molybdenum shall not normally be used for tankage.

B.3.2.3 Austenitic stainless steels shall not be used for swing arm cables.

B.3.3 Heat exchanger tube bundles

B.3.3.1 Materials for heat exchanger tubes and tubesheets shall be selected for resistance against both shell and tube side fluids.

Allowances for corrosion shall be made on both sides of single tubesheets.

B.3.3.2 For water-cooled heat exchangers, the following considerations should be made.

B.3.3.2.1 Sea-water-cooled heat exchanger

B.3.3.2.1.1 For heat exchangers on seawater duty where long life is required, titanium may be used. Alternatively, Cu/Ni alloys may be selected provided that the fluid velocities are kept within the range specified in specifications.

B.3.3.2.1.2 Normally, seawater is permitted only on the tube-side of a heat exchanger. On some high pressure gas coolers, however, this is not possible because of the risk of tubes collapsing under external pressure. In such cases titanium tubes and shell are necessary to allow seawater to be used on the shell-side.

B.3.3.2.1.3 Where the materials of interconnecting seawater piping and the mating surfaces of the heat exchanger are dissimilar, rubber lined couplings will be required if galvanic corrosion would otherwise occur. This is particularly important in the case of titanium and Cu/Ni dissimilar metal joints. An alternative solution which may be considered is the use of sacrificial spool pieces of austenitic spheroidal graphitic cast iron between the titanium and Cu/Ni components.

B.3.3.2.1.4 Titanium plate exchangers should be used in closed circuit systems where treated fresh water is exchanged with seawater.

B.3.3.2.1.5 Whether tubes shall be either inhibited aluminum brass or aluminum bronze, tubesheets shall be of the same material as tubes.

B.3.3.2.1.6 Where corrosion of copper base alloys by sulphides in the hydrocarbon stream are excessive, consideration shall be given to either providing a greater corrosion allowance than normal or to the use of materials such as nickel based alloys (such as Monel, incoloy 801), aluminum alloys (such as Alclad), and titanium alloys.

B.3.3.2.2 Fresh-water-cooled heat exchanger

Carbon steel tubes may be used only where the water has a low dissolved solid content and where a water recirculation system is employed.

B.3.3.2.3 Copper-based alloys subject to stress corrosion cracking in hydrocarbon streams containing free ammonia (with pH exceeding 7.2 even for short periods) shall not be employed in heat exchangers. Cu-Ni (70-30) alloy may be considered satisfactory for such applications.

B.3.3.2.4 For hydrocarbon/hydrocarbon heat exchangers, where one or both hydrocarbon streams have a high H₂S content, consideration should be given to the use of double dip-aluminized material for the material in contact with liquids in order to prevent corrosion due to sulphide scale fouling.

B.3.3.2.5 Unstabilized austenitic stainless steel shall not be used for U-tubes. Low carbon unstabilized stainless steels such as Type 304L or Type 316L are acceptable for U-tubes.

B.3.3.2.6 Normally air-cooled heat exchanger tubes shall be carbon steel. For corrosive or heavy fouling services, the application of internal coatings will be considered, if required.

B.3.4 Furnaces

B.3.4.1 Material for furnace tubes shall be selected from an economic viewpoint. However, high temperature strength, corrosion resistance and scaling resistance factors must be satisfied.

B.3.4.2 Regarding furnace tube wall thickness, material selection and calculation shall be based on 100,000 hours operation in accordance with API RP 530⁽⁵⁾.

B.3.4.3 Corrosion rates in excess of 0.5 mm per year are not normally acceptable. The design corrosion rate of furnace tubes shall be determined on the basis of available information from corrosion experience in similar applications.

In the absence of any suitable information, a minimum corrosion allowance of 3.2 mm shall be provided for furnace tubing in hydrocarbon services, and 1.6 mm in steam services.

B.3.4.4 Material selected for furnace tubes and other parts of furnace coils exposed to firebox conditions shall be such that free scaling temperatures will not be exceeded under normal operation.

B.3.4.5 The composition, and physical and mechanical properties of materials for headers and return bends, irrespective of whether they are cast or wrought, rolled or welded in, shall be compatible with those tubes to which they will be connected and shall be of a weldable quality. The use of cast alloy steel parts shall require approval.

B.3.4.6 Carbon steel tubes for steam generating units shall be seamless.

B.3.5 Piping

B.3.5.1 Materials for piping shall be selected from an economic viewpoint, however the strength based on the pressure-temperature rating against corrosion resistance shall be satisfied.

B.3.5.2 Where high alloy or non-ferrous material is employed, special consideration shall be given to decide the economical limits of the pipe size for which a clad or solid design is to be adopted.

B.3.5.3 Low-temperature piping

Where piping systems are subjected to low temperatures, i.e. below 0°C, materials and fabrication practices, e.g. post-weld heat treatment, shall be selected to minimize the risk of brittle fracture. However, where this minimum design temperature is not a normal continuous operating condition, e.g. if it arises as a result of autorefrigeration due to rapid depressurization, the full range of temperatures and coincident pressures shall be evaluated in order to determine the appropriate conditions for material selection.

The use of post-weld heat treatment can extend the use of carbon steel to temperatures lower than would be acceptable for as-welded pipework. However, unless post-weld heat treatment is required for process reasons, it should be specified only where the requirement cannot be met by using carbon steel in the as-welded condition.

B.3.5.4 Corrosion resistance piping

Where carbon steel is the selected material for piping, and the total corrosion is not expected to exceed 6 mm over the design life of the piping, an appropriate corrosion allowance shall be applied.

Where the corrosion rate is predicated to exceed 6 mm over the design life, the various alternatives shall be evaluated. These alternatives may include, but should not be limited to, the following:

- a) Replacement at intervals, e.g. every 10 years,
- b) increased corrosion allowance,
- c) application of internal corrosion resistant cladding,
- d) alternative solid corrosion resistant material,
- e) injection of corrosion inhibitor, or other treatment of the process stream.

Where the choice is between options (c) or (d) selection will generally be governed by costs. However, austenitic stainless steel in solid form shall be used in a marine environment only where the external skin temperature does not exceed 50°C, and should normally be AISI Type 316, because of the risk of chloride stress corrosion cracking.

B.3.5.5 Where the external skin temperature exceeds 50°C, carbon steel lines internally clad with austenitic stainless steel may be used. Alternatively, solid pipe of one of the duplex stainless steels may be used, as they exhibit much greater resistance to chloride stress corrosion cracking. They also possess much higher yield strengths, and their use therefore results in weight saving.

B.3.5.6 Where carbon steel vessels or pipework are connected to pipework which is either internally clad or of solid corrosion resistant alloy, and where galvanic corrosion of the carbon steel is likely, such corrosion shall be prevented by installing electrically isolating joints, insulating flanges or pipe spools coated internally with a non-metallic lining, whichever is appropriate for the conditions. It should be noted that, in many locations, insulating flanges and joints will be rendered ineffective by electrical short circuiting through connections to the supporting steelwork.

B.3.5.7 Piping for seawater duty should normally be of 90/10 Cu/Ni conforming to piping specification. High-molybdenum austenitic and 25% Cr duplex stainless steels may offer cost and weight advantages over Cu/Ni, and shall be evaluated for specific projects. These stainless steels have, in addition to much higher strength, excellent resistance to pitting corrosion, chloride stress corrosion cracking and flow induced erosion and, therefore, may permit the use of higher flow velocities which in turn may permit the use of smaller bore piping, and thinner pipe walls, thus saving weight and cost.

Recent limited laboratory testing indicates that the stainless steels may be susceptible to chloride crevice corrosion in seawater at temperatures above about 30°C. This shall be taken into consideration for piping downstream of heat exchangers.

B.3.5.8 Non-metallic materials, such as Glass Reinforced Plastics (GRP), may offer advantages for seawater pipework, particularly in respect of corrosion resistance and weight saving. However, specialist expertise in design, fabrication and installation techniques will be required for the evaluation of factors such as cost, susceptibility to mechanical damage, and safety implications, before such materials are selected. Any proposal to use non-metallic materials shall be subject to approval by Company. Also, it may be necessary to obtain waivers from the statutory authorities regarding the use of combustible materials.

B.3.6 Corrosion resistance valves

B.3.6.1 In general, valve bodies and bonnets should be manufactured in a material similar to that used for the piping or vessel to which they are attached. Valve trims shall be manufactured in a more resistant material to prevent erosion/corrosion; the choice of materials being dependent upon the process conditions.

B.3.6.2 Where electrolless nickel plating of valve internals is approved by Company (e.g. for ball valves or parallel slide gate valves), the following requirements shall be met:

B.3.6.2.1 The sub-strate shall be stainless alloy for High Integrity Valves, e.g. those for sub-sea applications, although carbon steel may be permitted for other applications.

B.3.6.2.2 Phosphorous content of the coating shall be within the range 8 to 11% by weight.

B.3.6.2.3 Plating thickness shall be not less than 0.075 mm.

B.3.6.2.4 Components shall not be baked after plating.

B.3.6.2.5 Plated components shall be subjected to a ferroxyl test to ASTM B 733 for evidence of porosity or cracking.

B.3.6.2.6 Plated test pieces shall be sectioned and checked for coating thickness using a micrometer.

B.3.6.2.7 The adhesion of the nickel coating shall be evaluated using coated test pieces subject to testing in accordance with ASTM B 733 and ASTM B 571.

B.3.7 Flare systems

B.3.7.1 For high pressure flares of the Indair type, alloy 800 H should be used for the bowl and stool. For Mardair type flares, Incoloy DS should be used for the trumpet. The gas filled parts and base may be fabricated in alloy 800 H; however, AISI Type 316 may be used if there is a heat shield in incoloy DS with ceramic fibre insulation.

Note:

Indair and Mardair are trade names of kaldair limited. Incoloy is a trade name of inco limited.

B.3.8 Rotating machinery

Generally, pump casings are fabricated in a material which matches that used for the piping system. Pump internals are usually fabricated in corrosion resistant materials with additional resistance to erosion; the choice of materials being dependent upon the process conditions. Pumps handling seawater or brine above 40°C contaminated with oil and H₂S shall be fabricated in one of the super duplex stainless steels or a more corrosion resistant material.

When a wet gas stream is corrosive, the first stage of wet gas compressors shall be fabricated in a corrosion resistant material such as 13% Cr steel.

Exhaust stacks for gas turbines shall be fabricated in corrosion resisting carbon steel. Also stacks shall be protected externally by aluminum metal spray with an aluminum silicone sealer. Care shall be taken to ensure that the design eliminates thermal fatigue.

B.4 Special Material Requirement in Petrochemical Plants

In selecting materials for petrochemical plants, considerable effort should be paid to fluid composition, sizing of lines, valve and pumps details and processing temperature and pressure. Most environments in petrochemical processes involve flammable hydrocarbon systems, highly toxic chemicals, explosive gases and strong acids and caustics. Therefore corrosion could be mysterious and costly enemy to the safety of personnels and community. Following tables indicate materials in use in different processes of a petrochemical plant. However these tables are just informative and material and corrosion allowances shall be selected on the basis of corrosion tests and procedures outlined in section 9 of this Standard.

INDEX OF PIPING SERVICES

INDEX OF PIPING SERVICES					
NO	SERVICE	RATING-PAGE TEMP-PRESS	BASIC MATERIAL	VALVE BODY/ TRIM	CORROSION ALLOWANCE
1	CAUSTIC (STRESS RELIEVED)	CLASS 150, RP	CARBON STEEL	CARBON STEEL NONE	3.18 MM (0.125")
2	GENERAL PROCESS	CLASS 150, RP 399C (750F) MAX	CARBON STEEL	CARBON STEEL 11-13 CR	NONE
3	CORROSIVE PROCESS	CLASS 150, RP 399C (750F) MAX	304 SS	316 SS 316 SS	NONE
4	WILDLY CORROSIVE PROCESS	CLASS 150, RP 399C (750F) MAX	CARBON STEEL	CARBON STEEL 316 SS	3.14 MM (0.125")
5	CORROSIVE PROCESS	CLASS 150, RP 399C (750) MAX	CARBON STEEL	CARBON STEEL 316 SS	3.18 MM (0.125")
6	CORROSIVE PROCESS	CLASS 150, RP 399C (750) MAX	CARBON STEEL	CARBON STEEL 316 SS	6.6 MM (0.251")
7	LOW TEMPERATURE PROCESS	CLASS 150, RP -46C TO -30C (-50F TO -21F)	LTC5	316 SS & LTC5 316 SS	NONE
8	UREA SOLUTION/ MELT PROCESS VAPOUR CONDENSATE	CLASS 150 RP 427C/800F MAX	304L SS	316L SS 316L SS	NONE
9	UREA SOLUTION/ MELT PROCESS VAPOUR CONDENSATE	CLASS 150 RP 427C/800F MAX	316L SS	316L SS 316L SS	NONE
10	STEAM, RFW CONDENSATE	CLASS 150, RP 399C (750F) MAX	CARBON STEEL	CS UNIVERSAL	3.27 MM (0.05")
11	LUBE AND SEAL OIL	CLASS 150, RP 66C (150F) MAX	304 SS	CARBON STEEL	NONE
12	GENERAL PROCESS	CLASS 300, RP 427C (800F) MAX	CARBON STEEL	CARBON STEEL 11-13 CR	NONE
13	HYDROGEN & HYDROCARBON	CLASS 300, RP 592C (1100F) MAX	1 1/4CR-1/2ND	1 1/4CR-1/2ND 11-13 CR	3.27 MM (0.05")
14	CORROSIVE PROCESS	CLASS 300, RP 399 (750F) MAX	304 SS	316 SS 316 SS	NONE
15	WILDLY CORROSIVE PROCESS	CLASS 300, RP 427C (800F) MAX	CARBON STEEL	CARBON STEEL 316 SS	3.14 MM (0.125")
16	CORROSIVE PROCESS	CLASS 300, RP 427C (800F) MAX	CARBON STEEL	CARBON STEEL 316 SS	3.14 MM (0.125")
17	LOW TEMPERATURE PROCESS	CLASS 300, RP -46C TO -30C (-50F TO -21F)	LTC5	316 SS & LTC5 316 SS	NONE
18	STEAM, RFW CONDENSATION	CLASS 300, RP 427C (800F) MAX	CARBON STEEL	CARBON STEEL UNIVERSAL	3.27 MM (0.05")
19	LUBE AND SEAL OIL	CLASS 300, RP 66C (150F) MAX	304 SS	CARBON STEEL 11-13 CR	NONE
20	UREA SOLUTION/ MELT PROCESS	CLASS 300, RP 427C/800F MAX	304 LSS	316 L SS 316 L SS	NONE

(to be continued)

(continued)

NO	SERVICE	ATING-1&CR TEMP-PRESS	BASIC MATERIAL	VALVE BODY/ TRIM	CORROSION ALLOWANCE
21	URRA SOLUTION PROCESS VAPOUR CONDENSATE	CLASS 300 RP 427C/800F MAX	316 L SS	316 L SS 316 L SS	NONE
22	GENERAL PROCESS	CLASS 600, RP 427 C (800F) MAX	CARBON STEEL	CARBON STEEL 11-13 CR	NONE
23	HYDROGEN HYDROCARBONS	CLASS 600, RP 593C (1100F) MAX	1 1/4CR-1/2NO	1 1/4CR-1/2NO 11-13 CR	1.27 MM (0.05")
24	CORROSIVE PROCESS	CLASS 600, RP 593C (1100F) MAX	304 SS	316 SS 316 SS	NONE
25	CORROSIVE PROCESS	CLASS 600, RP 427C (800F) MAX	CARBON STEEL	CARBON STEEL 316 SS	1.18 MM (0.125")
26	STEAM, BFW & CONDENSATE	CLASS 600, RP 427C (800F) MAX	CARBON STEEL	CARBON STEEL UNIVERSAL	1.27 MM (0.05")
27	STEAM & BFW	CLASS 600, RP 593C (1100F) MAX	1 1/4CR-1/2NO	1 1/4CR-1/2NO UNIVERSAL	1.27 MM (0.05")
28	LUBR AND SEAL OIL	CLASS 600, RP 56°C (130F) MAX	304 SS	CARBON STEEL 11-13 CR	NONE
29	GENERAL PROCESS	CLASS 900, RP 427°C (800°F) MAX	CARBON STEEL	CARBON STEEL 11-13 CR	NONE
30	LOW TEMPERATURE PROCESS	CLASS 900, RP -46°C TO 30°C (-50°F TO -21°F)	L7CS	316 SS 316 SS	NONE
31	STEAM AND BFW	CLASS 900, RP 427°C (800°F) MAX	CARBON STEEL	CARBON STEEL FULL H.F.	1.27 MM (0.05")
32	STEAM AND BFW	CLASS 900, RP 593°C (1100°F) MAX	1 1/4CR-1/2NO	1 1/4CR-1/2NO FULL H.F.	1.27 MM (0.05")
33	LUBR AND SEAL OIL	CLASS 900, RP 66°C (150°F) MAX	304 SS	CARBON STEEL 11-13 CR	NONE
34	URRA SOLN, CARBONATE SOLN, CO ₂ PROCESS VAPOUR	CLASS 1500, RP 750°F (399°C) MAX	316 L SS	316 L SS FERROLIUM	NONE
35	GENERAL PROCESS	CLASS 1500, RP 427°C (800°C) MAX	CARBON STEEL	CARBON STEEL 11-13 CR	NONE
36	HYDROGEN HYDROCARBONS	CLASS 1500, RP 593°C (1100°F) MAX	1-1/4CR-1/2NO	1 1/4 CR FULL H.F.	1.27 MM (0.05")
37	STEAM AND BFW	CLASS 1500, RP 427°C (800°F) MAX	CARBON STEEL	CARBON STEEL FULL H.F.	1.27 MM (0.05")
38	STEAM AND BFW	CLASS 1500, RP 600°C (1100°F) MAX	CARBON STEEL	CARBON STEEL/H.F.	1.27 MM (0.05")
39	STEAM AND BFW	CLASS 1500, RP 593°C (1100°F) MAX	1 1/4CR-1/2NO	1 1/4CR/H.F.	1.27 MM (0.05")
40	PROCESS ALLOY VERIFIED	CLASS 2500, RP 816°C (1500°F) MAX	304 H SS	304 H SS/ 304 H SS	NONE

(to be continued)

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NO	SERVICE	RATING-PACK TEMP. PRESS.	BASIC MATERIAL	VALVE BODY/ TRIM	CORROSION ALLOWANCE
41	STEAM AND BW	CLASS 2500, RJ	1 3/4CR-1/2ND	1 1/4CR/W.P.	1.27 MM (0.05")
42	STEAM JACKETED UREA REACT	CLASS 150, RF 800°F (427°C) MAX	304L/CS JET	CARBON STEEL/ 316 SS	NONE
43	PLANT AIR	CLASS 150, FF 66°C (150°F) MAX	CARBON STEEL	CI/NI CE/13% CR	1.27 MM (0.05")
44	VACUUM EXHAUST	CLASS 125, FP 177°C (350°F) MAX	CARBON STEEL	CARBON STEEL/ UNIVERSAL	1.27 MM (0.05")
45	COOLING WATER (ABOVE GROUND)	CLASS 125, FP 66°C (150°F) MAX	CARBON STEEL	CARBON STEEL/ CAST (BON)	1.27 MM (0.05")
46	COOLING WATER (UNDER GROUND)	CLASS 125, FP 66°C (150°F) MAX	CARBON STEEL	CI/NI/ CI	1.27 MM (0.05")
47	DEMINERALIZED WATER	CLASS 150, FP 204°C (400°F) MAX	304 SS	316 SS/ 316 SS	NONE
48	UREA SOLUTION, PROCESS VAPOR/ CONDENSATE	CLASS 600, BPSF 427°C (800°F) MAX	316 L SS	316 L SS/ 316 SS	NONE
49	POTABLE WATER (ABOVE GROUND)	CLASS 125, FF 66°C (150°F) MAX	GALV. CS	CI/NI/ CI	NONE
50	POTABLE WATER (UNDER GROUND)	150 PSIG MAX 66°C (150°F) MAX	P.V.C.	P.V.C/ P.V.C	NONE
51	FIRE WATER (ABOVE GROUND)	CLASS 125, FP 66°C (150°F) MAX	CARBON STEEL	CARBON STEEL/ CI	3" & 4" CA-2.54
52	FIRE WATER (UNDER-GROUND)	CLASS 125, FP 66°C (150°F) MAX	CARBON STEEL	CI/NI/ CI	3" & 4" CA-2.54
53	INSTRUMENT AIR SUPPLY	CLASS 150, FP 66°C (150°F) MAX	CARBON STEEL	CI/NI/ 11-13 CR	NONE
54	STEAM TRACING	5.30 KG/CM ² (75 PSIG) MAX 316°C (600°F) MAX	316 SS		1.27 MM (0.05")
55	INSTRUMENT PROCESS & ANALYZER SERVICE	101.24 KG/CM ² (1440 PSIG) 399°C (750°F) MAX	304 SS	316 SS/ 316 SS	NONE
56	INSTRUMENT PROCESS & ANALYZER SERVICE	252.08 KG/CM ² (3600 PSIG) 399°C (750°F) MAX	316 SS	316 SS/ 316 SS	NONE
57	INSTRUMENT AIR SIGNAL	14.06 KG/CM ² (125 PSIG) AMBIENT TEMP.	CS/316 SS	CS/ 11-13 CR	NONE
58	INSTRUMENT PROCESS PIPING	104 KG/CM ² (1480 PSIG) AMBIENT TEMP.	CS/304 SS	CARBON STEEL/ 11-13 CR	1.27 MM (0.05")
59	INSTRUMENT PROCESS PIPING	202 KG/CM ² (2880 PSIG) AMBIENT TEMP.	CS/304 SS	CARBON STEEL/ 11-13 CR	1.27 MM (0.05")
60	SEWER (NON-CORROSIVE)	ATMOSPHERIC (AMBIENT TEMP.)	D.I.		NONE

(to be continued)

(continued)

NO	SERVICE	RATING-PACK TEMP-PRESS	BASIC MATERIAL	VALVE BODY/ TRIM	CORROSION ALLOWANCE
61	SEWER (CORROSIVE)	ATMOSPHERIC (AMBIENT TEMP.)	TITANIUM	_____	NONE
62	SEWER (BENFIELD AND URSA SOLUTION)	ATMOSPHERIC 260°C (500°F) MAX	304 L SS	_____	NONE
63	STEAM JACKETED URSA MILK	CLASS 300, RP 127°C (260°F) MAX	CS/304 L SS	304 L SS/ 316 SS	NONE
64	H ₂ SO ₄ (91%-98%)	CLASS 150, LI -20°F TO 166°F (-29°C TO 210°C)	TPR LINED CS	DI/ PPR LINED	NONE
65	RAW WATER (ABOVE GROUND)	CLASS 125, RP 65°C (150°F) MAX	CARBON STEEL	CARBON STEEL/ CAST IRON	2.1 MM (0.1")
66	RAW WATER (BELOW GROUND)	CLASS 125, RP 66°C (150°F)	DUCTILE IRON	CI/MI/ C.I.	NONE
67	HYDROCHLORIC ACID (28%)	CLASS 150, RP (-20°F TO 150°F) -29°C TO 66°C	SARAN LINED	DI/ PPR LINED	NONE
68	MILD CORROSIVE PROCESS	CLASS 300, RP 127°C (260°F) MAX	CARBON STEEL	CARBON STEEL/ 316 SS	2.51 MM (0.1")
69	HIGH TEMPERATURE SEWER (NON-CORROSIVE)	ATMOSPHERIC PRESS	D.I.	_____	NONE
70	CORROSIVE PROCESS ALLOY VERIFIED	CLASS 300, RP 159°C (310°F) MAX	304 SS	316 SS/ 316 SS	NONE
71	HYDROGEN AND HYDROCARBON ALLOY	CLASS 300, RP 159°C (310°F) MAX	1 1/4 CR-1/2 NO	1 1/4 CR/ 1 1/2 CR N.P.	1.27 MM (0.05")

Note:

- SARAN = Polyvinylidene chloride, saran fiber
- M.I = Maleable Iron
- C.I = Cast Iron
- D.I = Ductile Iron
- TFE = Polytetrafluoroethylene
- PFA = Per fluoro alkoxy copolymer

B.5 Supplemental Requirements for Equipment in Sour Service

B.5.1 Equipment in sour service, as set forth in the process data sheet or in the mechanical drawings, shall strictly comply with the requirements of NACE ⁶ standard MR 0175, as supplemented by the following articles.

B.5.2 Carbon steel

B.5.2.1 Process of manufacture

All carbon steel products shall be fully killed and fine grain treated and shall be supplied in the normalized, normalized and tempered or quenched and tempered condition.

Production shall be by a low sulphur and low phosphorus refining process (e.g. electric furnace with double deslagging or in the basic oxygen converter).

The heat shall be vacuum degassed and inclusion shape control treated, preferably by calcium.

B.5.2.2 Chemical analysis

Chemical analysis shall be restricted as follows:

Check analysis		Heat analysis		
Carbon	0.020	% max	0.19	% max
Sulphur	0.003	% max	0.002	% max
Phosphorus	0.020	% max	0.020	% max
Manganese	1.20	% max	1.20	% max
Silicon	0.45	% max	0.45	% max

Residuals

Chromium	0.25	% max
Copper	0.25	% max
Molybdenum	0.10	% max
Nickel	0.30	% max
Vanadium	0.05	% max
Niobium	0.04	% max
Ca+O+N	to be reported	

B.5.2.3 Carbon equivalent (CE)

C.E. shall not exceed 0.42%.

$$C.E. (\%) = C + \frac{Mn}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Ni + Cu)}{15}$$

B.5.2.4 Through-thickness tension testing

Plates 25 mm and greater in thickness, directly exposed to sour environments (see NACE MR 0175 par. 1.3) shall have a minimum reduction of area of tension test specimens (Z value) of 35%.

Testing shall be conducted according to ASTM A-770.

B.5.2.5 Ultrasonic testing

Ultrasonic testing, in accordance with ASTM A-435, shall be carried out on all plates having a thickness greater than 12 mm.

B.5.2.6 Hardness

Hardness across the width and thickness of each product/weld shall not exceed 200 HB.

Specimen for hardness surveys shall be taken in the same area where the coupons are to be removed for mechanical tests.

B.5.2.7 Weldability tests

It shall be demonstrated that the proposed plates are suitable for welding and subsequent post weld heat treatment by carrying out weldability tests on representative plates. The hardness value in heat affected zone shall not exceed 200 HB. Detail of these test should be provided for Company approval.

B.5.3 Stainless steel

Stainless steel products shall be supplied in the fully solution treated condition.

Cold works resulting in a material deformation degree of more than 5%, shall be followed by a solution annealing heat treatment of the parts involved.

B.5.4 Fabrication requirements

B.5.4.1 All carbon steel vessels shall be post weld heat treated after completion of all welding. Minimum temperature shall be 595°C as stated in NACE MR 0175. This condition will lead to specify a PWHT target temperature of 615 ±20°C.

B.5.4.2 Internal and external fittings, and attachments welded to pressure parts, shall be fully penetrated.

B.5.4.3 Nozzles shall be self-reinforced type with integral or welding-neck flanges.

B.5.4.4 Hardness testing shall be conducted on base metal, weld metal and heat affected zone, as follows:

- on macro-examination specimens taken from production test coupons;
- on internal welds of the equipment (one set reading for each longitudinal and/or circumferential shell weld, at least).

Hardness value shall not exceed 200 HB.

B.5.4.5 Because of the significantly greater risk of crevice corrosion in sour/chloride service, the use of screwed couplings and some types of weld details, which could result in a crevice on the process side, is not permitted.

B.5.4.6 C - ½ % Mo welding consumables and those having more than 1% Ni shall not be used for welding Carbon-Manganese steel.

B.5.4.7 Weld repair of plate surface defects will not be permitted without Company approval, and shall be subject to an agreed repair procedure prior to the work being carried out.

B.5.4.8 ERW pipes shall not be used for sour service.

References:

- 1) Corrosion in Petroleum Refining and Petrochemical Operations metals handbook, ninth edition, Volume 13, corrosion.
- 2) API- Guide for inspection of refinery equipment-Chapter II conditions causing deterioration or failure.
- 3) R.L. piehls method for fluid velocity, material performance, Jan 1976, 15.
- 4) A.P.I Publication 941.
- 5) A.P.I Recommended Practice for Calculation of Heater Tube Thickness in Petroleum Refinery.
- 6) NACE Standard MR-01-75 (1991 Rev.) sulfide stress cracking resistance metallic materials for oil field equipment.

**APPENDIX C
ENGINEERING MATERIALS**

C.1 Ferrous Alloys

Some 94 percent of the total world consumption of metallic materials are in the form of steels and cast irons. This is also true in the oil industries with a figure around 98%.

Therefore the primary choice in any material selection is steel or cast iron unless they can not afford the design requirements.

C.1.1 Carbon steels

The strength and hardness of steels vary very considerably with both carbon content and type of heat treatment. Certain names, which relate to the carbon content, are used in connection with steels.

- Mild or low carbon steels: are those containing up to 0.3 percent of carbon.
- Medium carbon steels: steels containing between 0.3 and 0.6 percent of carbon. These may be hardened and tempered.
- High carbon steels or tool steels: steels containing 0.6 percent of carbon and always used in the hardened and tempered condition. Table C.1 gives some typical uses of carbon steels.

TABLE C.1 - COMPOSITIONS AND TYPICAL APPLICATIONS OF STEELS

C (PERCENT)	NAME	APPLICATIONS
0.05	Dead mild steel	Sheet and strip for presswork, car bodies, tin-plate; wire, rod, and tubing
0.08-0.15	Mild steel	Sheet and strip for presswork; wire and rod for nails, screws, concrete reinforcement bar
0.15	Mild steel	Case carburising quality
0.1-0.3	Mild steel	Steel plate and sections, for structural work
0.25-0.4	Medium carbon steel	Bright drawn bar
0.3-0.45	Medium carbon steel	Shafts and high-tensile tubing
0.4-0.5	Medium carbon steel	Shafts, gears, railway tyres
0.55-0.65	High carbon steel	Forging dies, railway rails, springs
0.65-0.75	High carbon steel	Hammers, saws, cylinder linings
0.75-0.85	High carbon steel	Cold chisels, forging die blocks
0.85-0.95	High carbon steel	Punches, shear blades, high-tensile wire
0.95-1.1	High carbon steel	Knives, axes, picks, screwing dies and taps, milling cutters
1.1-1.4	High carbon steel	Ball bearings, drills, wood-cutting and metal-cutting tools, razors

C.1.1.1 Surface hardening

Generally, the toughness of a material decreases as the hardness increases. There are very many service conditions where the requirement is for a tough material of very high surface hardness, such as shafts and gears. Table C.2 shows different methods to accomplish surface hardening.

TABLE C.2 - SURFACE HARDENING METHODS

	CARBURISING	NITRIDING	CYANIDING	CARBONITRIDING
Effect	A high carbon surface is produced on a low carbon steel and is hardened by quenching	A very hard nitride-containing surface is produced on the surface of a strong tough steel	A carbon and nitride-containing surface is produced on a low carbon steel and is hardened by quenching	Carbon and nitrogen are added to the surface of a low carbon steel and permit hardening by an oil quench
Suitability	Suitable for plain carbon or alloy steels containing about 0.15 percent C	Nitralloy steels containing aluminum; a typical nitriding steel contains 0.3 percent C, 1.6 percent Cr, 0.2 percent Mo, 1.1 percent Al. This steel is hardened by oil quenching from 900°C and tempered at 600-700°C before being nitrided	Suitable for plain carbon or alloy steels containing about 0.15 percent C	Suitable for plain carbon steels containing about 0.15 percent C
Method	Low carbon steel is heated at 850-930°C in contact with gaseous, liquid, or solid carbon-containing substances for several hours. The high carbon steel surface produced is then hardened by quenching	The steel is heated at 500-540°C in an atmosphere of ammonia gas for 50-100 hours. No further heat treatment is necessary	Low carbon steel is heated at 870°C in a molten 30 percent sodium cyanide bath for about one hour. Quenching in oil or water from this bath hardens the surface of the steel	Low carbon steel is heated at 700-870°C for several hours in a gaseous ammonia and hydrocarbon atmosphere. Nitrogen in the surface layer increases hardenability and permits hardening by an oil quench
Result	Case depth is about 1.25 mm. Hardness after heat treatment is H _{RC} 65 (H _D 870). Negligible dimension change caused by carburising. Distortion may occur during heat treatment	Case depth is about 0.38 mm. Extreme hardness (H _D 1100). Growth of 0.025-0.05 mm occurs during nitriding. Case is not softened by heating for long times up to 420°C. Case has improved corrosion resistance	Case depth is about 0.25 mm. Hardness is about H _{RC} 65. Negligible dimension change is caused by cyaniding. Distortion may occur during heat treatment	Case depth is about 0.5 mm. Hardness after heat treatment is H _{RC} 65 (H _D 870). Negligible dimension change occurs. Distortion is less than in carburising or cyaniding
Applications	Typical uses are for gears, camshafts and bearings	Typical uses are for valve guides and seatings, and for gears	Typical uses are for small gears, chain links, nuts, bolts and screws	Typical uses are for gears, nuts and bolts

FLAME HARDENING	INDUCTION HARDENING	SILICONISING (IHRIGISING)	HARD CHROMIUM PLATING
The surface of a hardenable steel or iron is heated by a gas torch and quenched	The surface of a hardenable steel or iron is heated by a high-frequency electromagnetic field and quenched	A moderately hard corrosion-resistant surface containing 14 percent silicon is produced on low carbon steels	A hard chromium plate is applied directly to the metal surface
Steel containing 0.4-0.5 percent carbon or cast iron containing 0.4-0.8 percent combined carbon may be hardened by this method	Steel containing 0.4-0.5 percent carbon or cast iron containing 0.4-0.8 percent combined carbon may be hardened by this method	Suitable for plain carbon steels containing 0.1-0.2 percent carbon	Generally used on steels, low or high carbon, soft or hardened
A gas flame quickly heats the surface layer of the steel and a water spray or other type of quench hardens the surface	The section of steel to be hardened is placed inside an induction coil. A heavy induced current heats the steel surface in a few seconds. A water spray or other type of quench hardens the surface	The steel parts are heated at 930-1000°C in contact with silicon carbide and chlorine gas for two hours. No further heat treatment is required	The steel parts are plated in the usual plating bath but without the usual undercoat of nickel. The plating is a thousand times thicker than decorative chromium plating
The hardened layer is about 3 mm thick. Hardness is H _{RC} 50-60 (H _D 500-700). Distortion can often be minimised	The hardened layer is about 3 mm thick. Hardness is H _{RC} 50-60 (H _D 500-700). Distortion can often be minimised. Surface remains clean	Case depth is about 0.63 mm. Hardness is about H _D 200. Case has good corrosion resistance. Growth of 0.025-0.05 mm occurs during siliconising	Plating thickness is about 0.125 mm. Extreme hardness H _D 900. Plating has good corrosion resistance and a low coefficient of friction
Used for gear teeth, sliding ways, bearing surfaces, axles and shafts	Used for gear teeth, sliding ways, bearing surfaces, axles and shafts	Typical uses are for valves, tubing and shafts	Typical uses are for dies, gauges, tools and cylinder bores

C.1.2 Alloy steels

The main effects conferred by specific alloying elements are given in Table C.3. Major categories of steels are as follows:

C.1.2.1 Low alloy steel

Contains up to 3 or 4 percent of one or more alloying elements and is characterized by possessing similar microstructures to, and requiring similar heat treatment to, plain carbon steels; but improved strength and toughness over the plain carbon steels with the same carbon content.

C.1.2.1.1 High strength low-alloy steel

This is a group of low alloy steels with a very fine grain size with tensile yield strengths between 350 and 360 Mpa. This is achieved by addition of small controlled amounts of Nb, Ti or Va.

TABLE C.3 - EFFECTS OF ALLOYING ELEMENTS IN STEELS

ALLOYING ELEMENT	GENERAL EFFECTS	TYPICAL STEELS
Manganese	Increases the strength and hardness and forms a carbide; increases hardenability; lowers the critical temperature range, and when in sufficient quantity, produces austenitic steel; always present in a steel to some extent because it is used as a deoxidizer	Pearlitic steels (up to 2 percent Mn) with high hardenability used for shafts, gears, and connecting rods; 13 percent Mn in Hadfields steel, a tough austenitic steel
Silicon	Strengthens ferrite, raises the critical temperatures; has a strong graphitising tendency; always present to some extent because it is used, with manganese, as a deoxidiser	Silicon steel (0.07 percent C; 4 percent Si) used for transformer cores; used with chromium (3.5 percent Si ; 8 percent Cr) for its high-temperature oxidation resistance in internal combustion engine valves
Chromium	Increases strength and hardness, forms hard and stable carbides; raises the critical temperatures; increases hardenability; amounts in excess of 12 percent render steel stainless	1.0-1.5 percent Cr in medium and high carbon steels for gears, axles, shafts, and springs, ball bearings and metal-working rolls; 12-30 percent Cr in martensitic and ferritic stainless steels; also used in conjunction with nickel (see below)
Nickel	Marked strengthening effect, lowers the critical temperature range; increases hardenability; improves resistance to fatigue; strong graphite-forming tendency; stabilises austenite when in sufficient quantity	0.3-0.4 percent C with up to 5 percent Ni used for crankshafts and axles, and other parts subject to fatigue
Nickel and chromium	Frequently used together in the ratio Ni/Cr = 3/1 in pearlitic steels; good effects of each element are additive, each element counteracts disadvantages of the other; also used together for austenitic stainless steels	0.15 percent C with Ni and Cr used for case carburising; 0.3 percent C with Ni and Cr used for gears, shafts, axles and connecting rods; 18 percent, or more, of chromium and 8 percent, or more, of nickel give austenitic stainless steels
Tungsten	Forms hard and stable carbides; raises the critical temperature range, and tempering temperatures; hardened tungsten steels resist tempering up to 600°C	Major constituent in high-speed tool steels; also used in some permanent magnet steels
Molybdenum	Strong carbide-forming element, and also improves high-temperature creep resistance; reduces temper-brittleness in Ni-Cr steels	Not normally used alone; a constituent of high-speed tool steels, creep-resistant steels and up to 0.5 percent Mo often added to pearlitic Ni-Cr steels to reduce temper-brittleness
Vanadium	Strong carbide-forming element; has a scavenging action and produces clean, inclusion-free steels	Not used on its own, but is added to high-speed steels, and to some pearlitic chromium steels
Titanium	Strong carbide-forming element	Not used on its own, but added as a carbide stabilizer to some austenitic stainless steels
Aluminum	Soluble in ferrite, also forms nitrides	Added to nitriding steels to restrict nitride formation to surface layers
Cobalt	Strengthens, but decreases hardenability	Used in Stellite type alloys, magent steels, and as a binder in cemented carbides
Niobium	Strong carbide former, increases creep resistance	Added for improved creep resistance and as a stabilizer in some austenitic stainless steels
Copper	Increases strength and corrosion resistance. > 0.7% Cu permits precipitation hardening	Added to cast steels to improve fluidity, castability and strength. Used in corrosion resistant architectural steels
Lead	Isoluble in iron	Added to low-carbon steels to give free-machining properties

C.1.2.2 High alloy steels

High alloy steels are those that possess structures and require heat-treatment that differ considerably from those of plain carbon steels. Generally they contain more than 5 percent of alloying element. A few examples of some high alloy steels are given in following paragraphs.

C.1.2.2.1 High-speed tool steels

High carbon steels rich in tungsten and chromium provide wearing metal-cutting tools, which retain their high hardness at temperatures up to 600°C. Example is 18/4/1 steel containing 18 percent tungsten 4 percent of chromium, 1 percent vanadium and 0.8 percent carbon.

C.1.2.2.2 Stainless steels

When chromium is present in amounts in excess of 12 percent, the steel becomes highly resistance to corrosion. There are several types of stainless steel which are summarized below.

C.1.2.2.2.1 Ferritic stainless steels

Ferritic stainless steels contain between 12 and 25 percent of chromium and less than 0.1 percent of carbon. This type of steel can not be heat treated but may be strengthened by work hardening.

C.1.2.2.2.2 Martensitic stainless steels

These class of steels contain between 12 and 18 percent of chromium, together with carbon content ranging from 0.1 to 1.5 percent. These steels can be hardened by quenching from the austenite range temperatures.

C.1.2.2.2.3 Austenitic stainless steels

These are non-magnetic and contain 18 percent chromium, 8 percent nickel and less than 0.15 percent carbon. Carbides may form in these steels if they are allowed to cool slowly from high temperature, or if they are reheated in the range 500-700°C (heat affected zones adjacent to welds). Small stabilizing additions of titanium, or niobium prevent the inter-crystalline corrosion, weld decay. They are widely used in chemical engineering plant.

C.1.2.2.3 Maraging steels

These are very high strength materials. They can be hardened to give tensile strengths of up to 1900 MPa. They contain 18 percent nickel, 7 percent cobalt and small amount of other elements such as titanium. The carbon content is less than 0.05 percent. A major advantages of Maraging steels is that before hardening process they are soft enough to be worked and machined and precipitation hardening treatment is at a fairly low temperature when distortion of machined parts is negligible. Although the basic material cost is very high the final cost of a complex component is less than other high strength because of the much lower machining costs.

C.1.2.2.4 Manganese steels

This is a high alloy steels that contains 12-14 percent of manganese and 1 percent of carbon. They are non-magnetic and are very resistance to abrasion coupled with the fact that the core of material remains comparatively soft and tough. They are used for drill bits, rock crusher jaws, excavator bucket teeth etc.

C.1.3 Cast iron

The carbon content of cast irons is generally between 2 and 4 percent. They are generally cheap, with ease of melting and casting, also high damping capacity and very good machinability. Cast irons classified as either white or grey. These terms arise from the appearance of a freshly fractured surface. The structure of cast irons is affected by the following factors:

- The rate of solidification,
- carbon content,
- the presence of other elements,
- the effect of heat treatment.

Table C.4 indicates the composition and properties of some cast irons.

TABLE C.4 - COMPOSITION AND PROPERTIES OF SOME CAST IRONS

APPROXIMATE COMPOSITION	TENSILE STRENGTH (MN/m ²)	TYPE AND USES
3.2% C, 1.9 % Si	250	Pearlite and graphite. Motor brake drums
3.25 % C, 2.25 % Si	220	Pearlite and graphite. Engine cylinder blocks
3.25 % C, 2.25 % Si, 0.35 % P	185	Ferrite, pearlite and graphite. Light machine castings
3.25 % C, 1.75 % Si, 0.35 % P	200	Ferrite, pearlite and graphite. Medium machine castings
3.25 % C, 1.25 % Si, 0.35 % P	250	Pearlite and graphite. Heavy machine castings
3.6 % C, 2.8 % Si, 0.5 % P	370	Wear resistant. Piston rings
3.6 % C, 1.7 % Si	540	Pearlitic S.G
3.6 % C, 2.2 Si	415	Ferritic S.G
2.8 % C, 0.9 % Si	310	Blackheart malleable
3.3 % C, 0.6 % Si	340	Whiteheart malleable
2.9 % C, 2.1 % Si, 1.75 % Ni, 0.8 % Mo	450	Shock resistant. Crankshafts for petrol and diesel engines
2.9 % C, 2.1 % Si, 15 % Ni,	220	Ni-resist. Corrosion-resistant austenitic iron.
2% Cr, 6% Cu		Used in chemical plant
2.5 % C, 5% Si	170	Sisal. A growth-resistant iron for high-temperature service

S.G = Shaft and gear

C.1.3.1 Malleable irons

These cast irons produced by heat treatment of certain white cast irons. There are two process used giving rise to black heart and white heart irons. The names arise from the appearance of the fracture surface of the treated iron. The white heart structure is composed of ferrite at the surface of casting and ferrite, Pearlite and some graphite nodules at the center.

C.1.3.2 Alloy cast iron

Alloy cast irons, are high strength, hard, and abrasion and corrosion resistance materials and are suitable for high temperature services.

Addition of about 5 percent nickel causes the formation of martensitic structure at the surface of casting which is very hard constituents.

15-25 percent of nickel plus some chromium and copper give the best cast iron for corrosion resistance.

For prolonged service at elevated temperature the carbon content of alloy is kept down to about 2 percent. The alloy contains 5 percent silicon or silicon and nickel. The presence of these, reduces oxide scale formation at high temperature.

C.2 Non-ferrous metals

C.2.1 General

All the other metallic elements (some 70 in number) and their alloys are classified as non-ferrous. Out of all the non-ferrous metals, only a few, aluminum, copper, lead, magnesium, nickel, tin, titanium and zinc are produced in moderately large quantities. Only a brief description of non-ferrous metals and their alloys are mentioned in following paragraphs and a detailed coverage of the metallurgy of these metals is outside the scope of this Standard.

C.2.2 Aluminum

Aluminum possesses a number of properties that make it an extremely useful engineering material. It has good corrosion resistance, low density and good electrical conductivity. The corrosion resistance of aluminum is due to the presence of a thin oxide layer which is only a few atoms in thickness, but it is permeable to oxygen and protects the surface from further attack. The corrosion resistance may be improved by anodising. High purity aluminum is too weak to be used for many purposes. The material commonly termed pure aluminum is an aluminum iron alloy, by adding up to 0.5 percent of iron. This small iron addition gives a considerable increase in strength (see Table 7.8), although there is some reduction in ductility and corrosion resistance. Commercial-purity aluminum is used extensively, and accounts for about nine-tenths of aluminum product sales.

C.2.3 Aluminum alloys

Aluminum may be alloyed with a number of elements to produce a series of useful engineering materials. For properties of some aluminum alloys and their use see Table C.5.

TABLE C.5 - PROPERTIES OF SOME ALUMINUM ALLOYS

ALLOY NUMBER		APPROXIMATE COMPOSITION	CONDITION *	TENSILE STRENGTH	TYPE OF PRODUCT	USES
BRITISH	AMERICAN					
1080	1060	99.99% Al 99.8% Al	O O	45 75	Sheet, strip Sheet, strip	Linings for vessels in food and chemical plant
1200	1200	99.0% Al	O H 14 H 18	90 120 150	Sheet, strip, wire, extruded sections	Lightly stressed and decorative panelling, wire and bus bars, foil for packaging, kitchen and other hollow-ware
3103	3103	Al+1.75 % Mn	O H14 H 18	110 160 210	Sheet, strip, extruded sections	Hollow-ware, roofing, panelling, scaffolding tubing
5251	5052	Al + 2% Mg	O H 24	180 250	Sheet, plate, tubes and extrusions	Stronger deep-drawn articles; ship and small boat construction and other marine applications
5154 A	5454	Al+ 3.5 % Mg	O H 24	240 300		
5056 A	5056 A	Al + 5% Mg	O H 24	280 335		
LM6	S12C	Al + 12% Si	M M	180 ♣ 210 ♣	Sand and die castings	Excellent casting alloy
6082	6082	Al + 0.9% Mg; 1% Si; 0.7% Mn	T4 T6	220 320	Sheet, forgings, extrusions	Structural components for road and rail transport vehicles
2014	2014	Al + 4.5% Cu; 0.5% Mg; 0.8 % Mn	T4 T6	440 480	Sheet, forgings, extrusions,	Highly stressed parts in aircraft construction and general engineering
2024	2024	Al + 4.5% Cu; 1.5% Mg; 0.6% Mn	T3	480	tubing	
2L95 L160		Al + 5.6% Zn; 1.6% Cu; 2.5% Mg	T6	500	Plate Rod and bar	Aircraft construction
7075	7075	Al + 7% Zn; 1.75% Cu; 2% Mg	T6	620	Sheet and extrusions	
2090	2090	Al + 2.2% Li; 2.7 Cu; 0.12% Zr	T6	580	Sheet plate,	Aircraft construction
8090	8090	Al + 2.5% Li; 1.3% Cu; 0.7% Mg	T6	495		

Key:*
The symbols for condition are: O = annealed;
M = as cast;
H 14 = partly work hardened;
H 18 = fully work hardened;
H 24 = hardened and partially annealed;
T3 = solution treated, cold worked and aged;
T4 = solution treated and naturally aged;
T6 = solution treated precipitation hardened.
♣ Sand cast.
♣ Chill or die cast.

C.2.4 Copper

Copper is one of the oldest metals known to man and one of its alloys, bronze, has been worked for over 5000 years. Some applications of the various grades of pure copper are: wire, for electrical windings and wiring; sheet for architectural cladding, tanks and vessels and tubing for heat exchangers in chemical industries. There are very many useful application of copper alloys in industries but due to high price of metal they replaced by cheaper material.

C.2.5 Copper alloys

Copper may be alloyed with a number of elements to provide a range of useful alloys. The important alloy systems are:

- Copper-zinc (brasses)
- Copper-tin (zinc) (bronzes and gun metals)
- Copper-aluminum (aluminum bronzes)
- Copper-nickel (cupronickels)

Small addition of beryllium or chromium to copper give high strength alloys, a small addition of cadmium gives a significant increase in strength with little loss of electrical conductivity, while an addition of tellurium to copper gives an alloy with very good machineability. Properties of copper and some copper alloys are classified in Table C.6.

TABLE C.6 - PROPERTIES OF COPPER AND SOME COPPER ALLOYS

ALLOY	APPROXIMATE COMPOSITION	CONDITION *	TENSILE STRENGTH (MPa)	TYPE OF PRODUCT	USES
Pure copper	99.95% Cu	O	220	Sheet, strip, wire	High conductivity electrical applications
Arsenical copper	99.85% Cu	H	350		
Brasses	99.25% Cu; 0.5% As	O	220	All wrought forms	Chemical plant, deep drawn and spun articles
		H	360		
Gilding metal	90% Cu; 10% Zn	O	220	All wrought forms	Retains strength at elevated temperatures. Heat exchan steam pipes
		H	360		
Cartridge brass	70% Cu; 30% Zn	O	280	Sheet, strip	Imitation jewellery and decorative work
		H	510		
General cold working brass	65% Cu; 35% Zn	O	325	Sheet, strip	High-ductility brass for deep drawing dectorative work
		H	700		
Muntz metal	60% Cu; 40% Zn	O	340	Sheet, strip, extrusions	General purpose cold working alloy
		H	700		
High tensile brass	60% Cu; 40% Zn	M	375	Hot rolled plate and extrusions	Condenser and heat exchanger plates
Bronzes	35% Zn; 2% Mn; 2% Al; 2% Fe; balance Cu	M	600	Cast and hot worked forms	Ships screws, rudders and high-tensile applications
Gunmetal	95.5% Cu; 3% Sn; 1.5% Zn; 5.5% Sn; 0.1% P; Balance Cu	O	325	Strip	British copper coinage
		H	725		
		O	360		
		H	700		
Aluminium bronze	10% Sn; 2% Zn; balance Cu	M	280	Castings	Springs and steam turbine blades General purpose castings and bearings
Cupronicle	75% Cu; 25% Ni	O	300	Castings	Pressure-tight catings, pump and valve bodies
		H	400		
		M	770		
Monel	95% Cu; 5% Al	O	400	Strip, tubing	Imitation jewellery and condenser tubes
		H	770		
Beryllium-copper	10% Al; 2.5% Fe; 2-5% Ni; bal. Cu	M	700	Hot worked and cast products	High strength castings and forgings
Cadmium-copper	75% Cu; 25% Ni	O	360	Strip	British silver coinage
		H	600		
Chromium-copper	70% Cu; 30% Ni	O	375	Sheet, tubing	Condenser tubing, excellent corrosion resistance
		H	650		
Tellurium-copper	29% Cu; 68% Ni; 1.25% Fe; 1.25% Mn	O	550	All forms	Excellent corrosion resistance, used in chemical plant
		H	725		
Beryllium-copper	1 ¾ - 2 ½% Be; ½% Co; balance Cu	WP	1300	Sheet, strip,	Springs, non-spark tools
Cadmium-copper	99% Cu; 1% Cd	O	285	Wire, rod	Overhead electrical wire, spot-welding electrodes
		H	500		
Chromium-copper	0.4-0.8% Cr; bal. Cu	WP	450	Wrought forms and castings	Welding electrodes, commutal segments
Tellurium-copper	0.3-0.7% Te; bal. Cu	O	225	Wrought forms	Free-machining properties
		H	300		

* Key :

O = annealed;

H = work hardened;

M = as manufactured (cast or hot worked);

WP = solution heat treated and precipitation hardend

C.2.6 Lead and its alloys

Lead is soft and malleable, and possesses an excellent resistance to corrosion. It has been used for water pipeworks and waste disposal system but nowadays replaced by other materials. A major application for lead is in manufacture of lead-acid storage batteries which account for almost 30 percent of the annual world consumption of lead. Cable sheathing, soft solders and fusible plugs in sprinklers of fire fighting systems are other application of lead alloys. (see Table C.7).

TABLE C.7 - SOME LEAD ALLOYS

ALLOY	COMPOSITION (percent)					APPLICATIONS
	Pb	Sb	Sn	Bi	Hg	
Antimonial lead	99	1	—	—	—	Cable sheathing
Hard lead	94	6	—	—	—	Lead-acid batteries, lead shot
Plumbers solder	60	2.5	37.5	—	—	Soft solders
Common solder	50	—	50	—	—	
Tinmans solder	38	—	62	—	—	
Type metal	62	24	14	—	—	For casting into printing type
Linotype metal	81	14	5	—	—	
Woods alloy	24	—	14	50	—	(+ 12% Cd) Alloy with M.Pt. of 71°C used for fusible plugs in sprinkler systems
Roses alloy	28	—	22	50	—	Low melting point alloy with M.Pt. of 100°C
Dental alloy	17.5	—	19	53	10.5	Dental cavity filling (M.Pt. 60°C)

C.2.7 Nickel

Pure nickel possesses an excellent resistance to corrosion by alkalis and many acids and, consequently, is used in chemical engineering plant. For cheapness, nickel is frequently used as a cladding of thin sheet on a mild steel base. Nickel may also be electroplated on a number of materials, and an intermediate layer of electrodeposited nickel is essential in the production of chromium plated mild steel.

C.2.8 Nickel alloys

The principal nickel base alloys used industrially are monel, inconel, incoloy and the nimonic series of alloys. Table C.8 indicate composition and use of some nickel alloys.

TABLE C.8 - COMPOSITION AND USES OF SOME NICKEL ALLOYS

NAME	COMPOSITION (percent)										USES
	Ni	Cu	Cr	Fe	Mo	W	Ti	Al	Co	C	
Monel	68	30	—	2	—	—	—	—	—	—	Chemical engineering plant. Steam turbine blades
Inconel	80	—	14	6	—	—	—	—	—	—	Chemical engineering plant. Electric cooker heating elements. Exhaust manifolds
Brightray	80	—	20	—	—	—	—	—	—	—	Heating elements for kettles, toasters, electric furnaces
Hastelloy C	55	—	15	5	17	5	—	—	—	—	Chemical engineering plant.
Hastelloy X	47	—	22	18	9	1	—	—	—	—	Furnace and jet engine components
Nimonic 75	77	—	20	2.5	—	—	0.4	—	—	0.1	Thermocouples sheaths, furnace components, nitriding boxes
Nimonic 90	56.6	—	20	1.5	—	—	2.4	1.4	18	0.06	Gas turbine discs and blades
Nimonic 115	56.5	—	15	0.5	4	—	4	5	15	0.1	Gas turbine discs and blades
Incoloy 825	45	3	22	25	3	—	1.2	0.2	—	0.05	Chemical engineering plant.

C.2.9 Titanium

The useful properties of titanium are its relatively high strength coupled with a low density, and its excellent corrosion resistance. However it does possess some characteristics, that make processing both difficult and costly.

The main use of titanium alloys are where an excellent corrosion resistance is required.

C.3 Polymers

C.3.1 General

The group of materials known as polymers (or plastics) can be sub-divided into thermoplastic, elastomers and thermo-setting materials. The use of plastic materials is continually increasing with a rate of 7 percent per annum. The major increase in the use of plastics are due to low cost, low densities, high resistance to chemical attack, good thermal and electrical insulation properties and ease of fabrication. The main disadvantages are the low strength and elastic modulus values, low softening and thermal degradation temperatures and their comparatively high thermal expansion coefficients. A brief general definitions of sub-divisions of plastics are discussed in this section. Details of the properties and application are given in IPS-E-TP-350 and IPS-C-TP-352.

C.3.2 Thermoplastics

There are several varieties of thermoplastics, but generally they have the property of softening by heating and hardening by cooling within a temperature range (ASTM D 883).

Thermoplastics are categorized as following: (see also Table C.9).

- Polyethylene (PE) consist of : High density polyethylene (HDPE) low density (LDPE), linear low density (LLDPE), ultra high molecular weight (UHMWPE), cross linked (XLPE) and polyethylene foam.
- Ethylene copolymers consist of: Ethylene-vinyl acetate (EVA), Ionomer.
- Polypropylene (PP)

- Polyvinyl chloride (PVC) consist of: unplasticized (UPVC), plasticized (PPVC), copolymers (CPVC and PVDC).
- Polytetrafluoro ethylene (PTFE) consist of: ECTFE
- Polystyrene (PS) consist of: SBR, SAN, ABS
- Acrylic materials consist of: PMMA, PAN
- Polyamides (nylon) (PA) consist of: PA 6, PA 6.6, PA 6.10, PA 6.12, PA 11, PA (R1M)
- Poly carbonate (PC)
- Acetal (POM) polyoxymethylene
- Saturated polyesters: PET, PETP, PCDT, PBT
- Cellulosics : (CN), CA, CAB, CP, EC
- Polyether ether ketone (P.E.E.K)
- Polyphenylenes: ppo, pps
- Polysulphones and polyarylates: PSU, PES, PPSU, PPS
- Polyimides (PI): PEI, PAI

C.3.3 Elastomers

Elastomers are materials that have low elastic module which show great extensibility and flexibility when stressed but which return to their original dimentions, or almost so, when the deforming stress is removed.

There are several classes of elastomers, these being (see also Table C.9).

- Natural rubber (NR),
- synthetic R class elastomers (unsaturated carbon chains),
- m class elastomers (saturated),
- o class elastomers (heterochain with oxygen),
- u class elastomers (heterochain with O,N),
- q class elastomers (heterochain with Si),
- thermoplastic elastomers.

C.3.4 Thermosetting materials

Thermosetting material undergoes chemical changes when first heated and is converted from a plastic mass into a hard and rigid material. There are also a number of materials that will set hard and rigid at ordinary temperatures. The commercially available thermosetting materials are as following:

- Phenolic materials, phenol formaldehyde,
- Amino-formaldehyde materials, urea (UF), melamine (MF),
- Polyester materials,
- Epoxies,
- Polyurethanes,
- Allyl resins, diallyl phtalate (DAP).

C.4 Ceramics and Glasses

Table C.9 gives a summary of some of the main groupings of ceramic and glass materials.

TABLE C.9 - CLASSIFICATION OF SOME NON-METALLIC MATERIALS AND THEIR MAXIMUM WORKING TEMPERATURE

CLASS	No.	CHEMICAL CLASSIFICATION	TRADE NAMES	RECOM. ABBREV. (ASTM/BS/DIN/ISO)	MAXIMUM WORKING TEMP. °C
THERMOSETTING MATERIALS	1.1	Polyethylene, low density	Carlona, L		
	2	Polyethylene, high density	Carlona, H	NR	70
	3	Polypropylene	Carlona P, vulkodurit	NR	120
	4	Polychloride, phthalized	Mipolan	-	90
	5	Polyvinyl chloride, rigid	Carlona, vinyren, Vulkodurit WR	CR	120
	6	Polychlorotrifluoroethylene	Kel-F, Hocl	IR	80
	7	Polytetrafluoroethylene	Teflon TFE/na SL, Hycar OS, GRS	SBR	120
	8	Polyvinyl alcohol	Elvanol, MGRA, Buna N, vulkodurit WT	NBR	120
	9	Polymethyl methacrylate	Perspex, Pflukodurit W50	IR	140
	10	Polyacrylonitrile	Orlon, PAber	-	175
	11	Polyoxymethylene/polyformaldehyde	Deirin, Cell	FKM	230
	12	Polydichloromethyloxetane	Pentam*	-	60
	13	Polystyrene	Carlona, polorsil, silopren	SI	260
	14	Polyamide	Aclaron, N		
	15	Polyisobutylene	Rhepanol, I		750
	16	Chlorosulphonated polyethylene	Hypalon		900
	17	Fluorinated ethylene propylene	Teflon FEP/EB, Vcarb VLA, Diabon N/NS		190
	18	Acrylonitrile butadiene styrene	Cyclocac, kevcarb VCU		190
	19	Polyvinylidene chloride	Saran		1300
	20	Cellulose acetate butyrate	Cellidor B,		200
	21	Polyvinylidene fluoride	Solef, kyma		250
					480
THERMOSETTING MATERIALS	2.1	Polyesters, saturated	Terylene, D		1050
	2	Polyesters, unsaturated, gen. purp.	Platal, Lam		225
	3	Polyesters, unsaturated, spec. purp.	Atloc, cryst		1800
	4	Polyesters, unsaturated, chlorinated	Hetroc, H.J		1700
	5	Phenolics	Kera **, bu		300
	6	Phenolics, modified	Haveg 31, h		300
	7	Phenol formaldehydes	Haveg 41		300
	8	Phenol furfural	Haveg 60, lr 7, SWD		1000
	9	Furanes	Haveg 61, lr 7k, HFR		1000
	10	Ureas	Plastopal, palor 9		180
	11	Amelamines	Formica, ublor 12, Faracin		180
	12	Silicones	Bavsilon		120
	13	Polyurethanes	Durethan Upex, Acador 5		150
	14	Epoxies, cold cured	Epikote (Ep		300
	15	Epoxies, hot cured	Epikote (Ep		
					60
					80
					70
					120
					130
					120
					140

C.5 Composite Materials

There are very many situations in engineering where no single material will be suitable to meet a particular design requirement. However, two materials in combination may possess the desired properties, and provide a feasible solution to the material-selection problem. In this section some of the composites in current use just will be mentioned.

- Timber and plywood, which is built up of thin layers of wood bonded with a water resistance glue or a thermosetting resin, with the grain of successive layers at right angles to each other.
- Fiber reinforced materials, in these composite materials, high strength fibers are encased within a tough matrix. Fibers are such as glass, carbon, polymer, ceramics, wire filaments; and matrixes are such as thermoplastic and thermosetting resins, glasses, ceramics and metals. Many different matrix/fibre combinations have been developed with different properties for different applications.
- Sandwich structures, the structures generally are composed of two skins of high strength with a light weight core. This arrangement provides a material with low density and high specific stiffness, where the maximum tensile and compressive stresses are carried by the skin. These combination also provide useful thermal and sound insulation. Skin material include sheet metal, plywood, plastics (including G.R.P), concrete and plasterboard, with cores that may be metal or paper honeycomb structures, rigid plastic foam, chip board or low density porous masses of glass fibre or rockwool bonded with a plastic resin.