

Materials of Construction*

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INTRODUCTION*

Corrosion is not a favorite subject of engineers. Many a proud designer or project engineer has developed a new component or process with outstanding performance only to have it fail prematurely because of corrosion. Furthermore, despite active research by corrosion engineers, a visit to the local scrap yard shows that large percentages of cars and domestic appliances still fail because of corrosion; this loss pales by comparison when industrial corrosion failures are included. As a result, the annual cost of corrosion and corrosion protection in the United States is on the order of \$300 billion, far more than the annual budgets of some small countries.

One of the principal reasons for failure due to reaction with the service environment is the relatively complex nature of the reactions involved. Yet, in spite of all the complex corrosion jargon, whether a metal corrodes depends on the simple electrochemical cell set up by the environment. This might give the erroneous impression that it is possible to calculate such things as the corrosion rate of a car fender in the spring muck of salted city streets. Dr. M. Pourbaix has done some excellent work in the application of thermodynamics to corrosion, but this cannot yet be applied directly to the average complex situation.

Yet, corrosion engineering and science is no longer an empirical art; dissecting a large corrosion problem into its basic mechanisms allows the use of quite sophisticated electrochemical techniques to accomplish satisfactory results. On that positive side, there is real satisfaction and economic gain in designing a component that can resist punishing service conditions under which other parts fail. In some cases, we cannot completely prevent corrosion, but we can try to avoid obsolescence of the component due to corrosion.

FLUID CORROSION

In the selection of materials of construction for a particular fluid system, it is important first to take into consideration the **characteristics**

of the system, giving special attention to all factors that may influence corrosion. Since these factors would be peculiar to a particular system, it is impractical to attempt to offer a set of hard and fast rules that would cover all situations.

The **materials** from which the system is to be fabricated are the second important consideration; therefore, knowledge of the characteristics and general behavior of materials when exposed to certain environments is essential.

In the absence of factual corrosion information for a particular set of fluid conditions, a reasonably good selection would be possible from data based on the resistance of materials to a very similar environment. These data, however, should be used with some reservations. Good practice calls for applying such data for preliminary screening. Materials selected thereby would require further study in the fluid system under consideration.

FLUID CORROSION: GENERAL

Metallic Materials Pure metals and their alloys tend to enter into **chemical** union with the elements of a corrosive medium to form stable compounds similar to those found in nature. When metal loss occurs in this way, the compound formed is referred to as the **corrosion product** and the metal surface is spoken of as being **corroded**.

Corrosion is a complex phenomenon that may take any one or more of several forms. It is usually confined to the metal surface, and this is called **general corrosion**. But it sometimes occurs along grain boundaries or other lines of weakness because of a difference in resistance to attack or local electrolytic action.

In most aqueous systems, the corrosion reaction is divided into an anodic portion and a cathodic portion, occurring simultaneously at discrete points on metallic surfaces. Flow of electricity from the anodic to the cathodic areas may be generated by local cells set up either on a single metallic surface (because of local point-to-point differences on the surface) or between dissimilar metals.

Nonmetallics As stated, corrosion of metals applies specifically to chemical or electrochemical attack. The deterioration of plastics and other nonmetallic materials, which are susceptible to swelling, crazing, cracking, softening, and so on, is essentially **physiochemical** rather than electrochemical in nature. Nonmetallic materials can either be rapidly deteriorated when exposed to a particular environment or, at the other extreme, be practically unaffected. Under some conditions, a nonmetallic may show evidence of gradual deterioration. However, it is seldom possible to evaluate its chemical resistance by measurements of weight loss alone, as is most generally done for metals.

FLUID CORROSION: LOCALIZED

Pitting Corrosion Pitting is a form of corrosion that develops in highly localized areas on the metal surface. This results in the development of cavities or pits. They may range from deep cavities of small diameter to relatively shallow depressions. Pitting examples: aluminum and stainless alloys in aqueous solutions containing chloride. **Inhibitors** are sometimes helpful in preventing pitting.

Crevice Corrosion Crevice corrosion occurs within or adjacent to a crevice formed by contact with another piece of the same or another metal or with a nonmetallic material. When this occurs, the intensity of attack is usually more severe than on surrounding areas of the same surface.

This form of corrosion can result because of a deficiency of oxygen in the crevice, acidity changes in the crevice, buildup of ions in the crevice, or depletion of an inhibitor.

* Abstracted from texts by Flinn and Trojan, with permission of John Wiley & Sons.

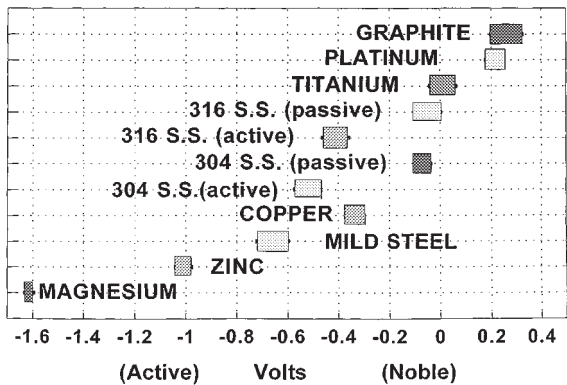
Oxygen-Concentration Cell The oxygen-concentration cell is an electrolytic cell in which the driving force to cause corrosion results from a difference in the amount of oxygen in solution at one point as compared with another. Corrosion is accelerated where the oxygen concentration is least, for example, in a stuffing box or under gaskets. This form of corrosion will also occur under solid substances that may be deposited on a metal surface and thus shield it from ready access to oxygen. Redesign or change in mechanical conditions must be used to overcome this situation.

Galvanic Corrosion Galvanic corrosion is the corrosion rate above normal that is associated with the flow of current to a less active metal (cathode) in contact with a more active metal (anode) in the same environment. Tables 28-1a and 28-1b show the galvanic series of various metals. It should be used with caution, since exceptions to

TABLE 28-1a Galvanic Series of Metals and Alloys

Corroded end (anodic, or least noble)
Magnesium
Magnesium alloys
Zinc
Aluminum alloys
Aluminum
Alclad
Cadmium
Mild steel
Cast iron
Ni-Resist
13% chromium stainless (active)
50-50 lead-tin solder
18-8 stainless type 304 (active)
18-8-3 stainless type 316 (active)
Lead
Tin
Muntz Metal
Naval brass
Nickel (active)
Inconel 600 (active)
Yellow brass
Admiralty brass
Aluminum bronze
Red brass
Copper
Silicon bronze
70-30 cupronickel
Nickel (passive)
Inconel 600 (passive)
Monel 400
18-8 stainless type 304 (passive)
18-8-3 stainless type 316 (passive)
Silver
Graphite
Gold
Platinum
Protected end (cathodic, or most noble)

TABLE 28-1b Galvanic Series in Sea Water (Approx.), Volts vs. Sat. Calomel Ref. Electrode



this series in actual use are possible. However, as a general rule, when dissimilar metals are used in contact with each other and are exposed to an electrically conducting solution, combinations of metals that are as close as possible in the galvanic series should be chosen. Coupling two metals widely separated in this series generally will produce accelerated attack on the more active metal. Often, however, protective oxide films and other effects will tend to reduce galvanic corrosion. Galvanic corrosion can, of course, be prevented by **insulating** the metals from each other. For example, when plates are bolted together, specially designed plastic washers can be used.

Potential differences leading to galvanic-type cells can also be set up on a single metal by differences in temperature, velocity, or concentration (see subsection "Crevice Corrosion").

Area effects in galvanic corrosion are very important. An unfavorable area ratio is a large cathode and a small anode. Corrosion of the anode may be 100 to 1,000 times greater than if the two areas were the same. This is the reason why stainless steels are susceptible to rapid pitting in some environments. Steel rivets in a copper plate will corrode much more severely than a steel plate with copper rivets.

Intergranular Corrosion Selective corrosion in the grain boundaries of a metal or alloy without appreciable attack on the grains or crystals themselves is called intergranular corrosion. When severe, this attack causes a loss of strength and ductility out of proportion to the amount of metal actually destroyed by corrosion.

The **austenitic stainless steels** that are not stabilized or that are not of the extra-low-carbon types, when heated in the temperature range of 450 to 843°C (850 to 1,550°F), have chromium-rich compounds (chromium carbides) precipitated in the grain boundaries. This causes grain-boundary impoverishment of chromium and makes the affected metal susceptible to intergranular corrosion in many environments. Hot nitric acid is one environment which causes severe intergranular corrosion of austenitic stainless steels with grain-boundary precipitation. Austenitic stainless steels stabilized with niobium (columbium) or titanium to decrease carbide formation or containing less than 0.03 percent carbon are normally not susceptible to grain-boundary deterioration when heated in the given temperature range. Unstabilized austenitic stainless steels or types with normal carbon content, to be immune to intergranular corrosion, should be given a solution anneal. This consists of heating to 1,090°C (2,000°F), holding at this temperature for a minimum of 1 h/in of thickness, followed by rapidly quenching in water (or, if impractical because of large size, rapidly cooling with an air-water spray).

Stress-Corrosion Cracking Corrosion can be accelerated by stress, either residual internal stress in the metal or externally applied stress. Residual stresses are produced by deformation during fabrication, by unequal cooling from high temperature, and by internal structural rearrangements involving volume change. Stresses induced by rivets and bolts and by press and shrink fits can also be classified as residual stresses. Tensile stresses at the surface, usually of a magnitude equal to the yield stress, are necessary to produce stress-corrosion cracking. However, failures of this kind have been known to occur at lower stresses.

Virtually every alloy system has its specific environment conditions which will produce stress-corrosion cracking, and the time of exposure required to produce failure will vary from minutes to years. Typical examples include cracking of cold-formed brass in ammonia environments, cracking of austenitic stainless steels in the presence of chlorides, cracking of Monel in hydrofluosilic acid, and caustic embrittlement cracking of steel in caustic solutions.

This form of corrosion can be prevented in some instances by eliminating high stresses. Stresses developed during fabrication, particularly during welding, are frequently the main source of trouble. Of course, temperature and concentration are also important factors in this type of attack.

The presence of **chlorides** does not generally cause cracking of austenitic stainless steels when temperatures are below about 50°C (120°F). However, when temperatures are high enough to concentrate chlorides on the stainless surface, cracking may occur when the chloride concentration in the surrounding media is a few parts per million. Typical examples are cracking of heat-exchanger tubes at the crevices in rolled joints and under scale formed in the vapor space below the top tube sheet in vertical heat exchangers. The cracking of

stainless steel under insulation is caused when chloride-containing water is concentrated on the hot surfaces. The chlorides may be leached from the insulation or may be present in the water when it enters the insulation. Improved design and maintenance of insulation weatherproofing, coating of the metal prior to the installation of insulation, and use of chloride-free insulation are all steps which will help to reduce (but not eliminate) this problem.

Serious stress-corrosion-cracking failures have occurred when chloride-containing hydrotest water was not promptly removed from stainless-steel systems. Use of potable-quality water and complete draining after test comprise the most reliable solution to this problem. Use of chloride-free water is also helpful, especially when prompt drainage is not feasible.

In handling caustic, as-welded steel can be used without developing caustic-embrittlement cracking if the temperature is below 50°C (120°F). If the temperature is higher and particularly if the concentration is above about 30 percent, cracking at and adjacent to non-stress-relieved welds frequently occurs.

Liquid-Metal Corrosion Liquid metals can also cause corrosion failures. The most damaging are liquid metals which penetrate the metal along grain boundaries to cause catastrophic failure. Examples include mercury attack on aluminum alloys and attack of stainless steels by molten zinc or aluminum. A fairly common problem occurs when galvanized-structural-steel attachments are welded to stainless piping or equipment. In such cases it is mandatory to remove the galvanizing completely from the area which will be heated above 260°C (500°F).

Erosion Erosion is the destruction of a metal by abrasion or attrition caused by the flow of liquid or gas (with or without suspended solids). The use of harder materials and changes in velocity or environment are methods employed to prevent erosion attack.

Impingement Corrosion This phenomenon is sometimes referred to as erosion-corrosion or velocity-accelerated corrosion. It occurs when damage is accelerated by the mechanical removal of corrosion products (such as oxides) which would otherwise tend to stifle the corrosion reaction.

Corrosion Fatigue Corrosion fatigue is a reduction by corrosion of the ability of a metal to withstand **cyclic or repeated stresses**.

The surface of the metal plays an important role in this form of damage, as it will be the most highly stressed and at the same time subject to attack by the corrosive media. Corrosion of the metal surface will lower fatigue resistance, and stressing of the surface will tend to accelerate corrosion.

Under cyclic or repeated stress conditions, rupture of protective oxide films that prevent corrosion takes place at a greater rate than that at which new protective films can be formed. Such a situation frequently results in formation of anodic areas at the points of rupture; these produce pits that serve as stress-concentration points for the origin of cracks that cause ultimate failure.

Cavitation Formation of transient voids or vacuum bubbles in a liquid stream passing over a surface is called cavitation. This is often encountered around propellers, rudders, and struts and in pumps. When these bubbles collapse on a metal surface, there is a severe impact or explosive effect that can cause considerable mechanical damage, and corrosion can be greatly accelerated because of the destruction of protective films. Redesign or a more resistant metal is generally required to avoid this problem.

Fretting Corrosion This attack occurs when metals slide over each other and cause mechanical damage to one or both. In such a case, frictional heat oxidizes the metal and this oxide then wears away; or the mechanical removal of protective oxides results in exposure of fresh surface for corrosive attack. Fretting corrosion is minimized by using harder materials, minimizing friction (via lubrication), or designing equipment so that no relative movement of parts takes place.

Hydrogen Attack At elevated temperatures and significant hydrogen partial pressures, hydrogen will penetrate carbon steel, reacting with the carbon in the steel to form methane. The pressure generated causes a loss of ductility (hydrogen embrittlement) and failure by cracking or blistering of the steel. The removal of the carbon from the steel (decarburization) results in decreased strength. Resistance to this type of attack is improved by alloying with molybdenum or chromium. Accepted limits for the use of carbon and low-alloy steels are shown in Fig. 28-1, which is adapted from American Petroleum Institute (API) Publication 941, *Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants*, the so-called Nelson curves.

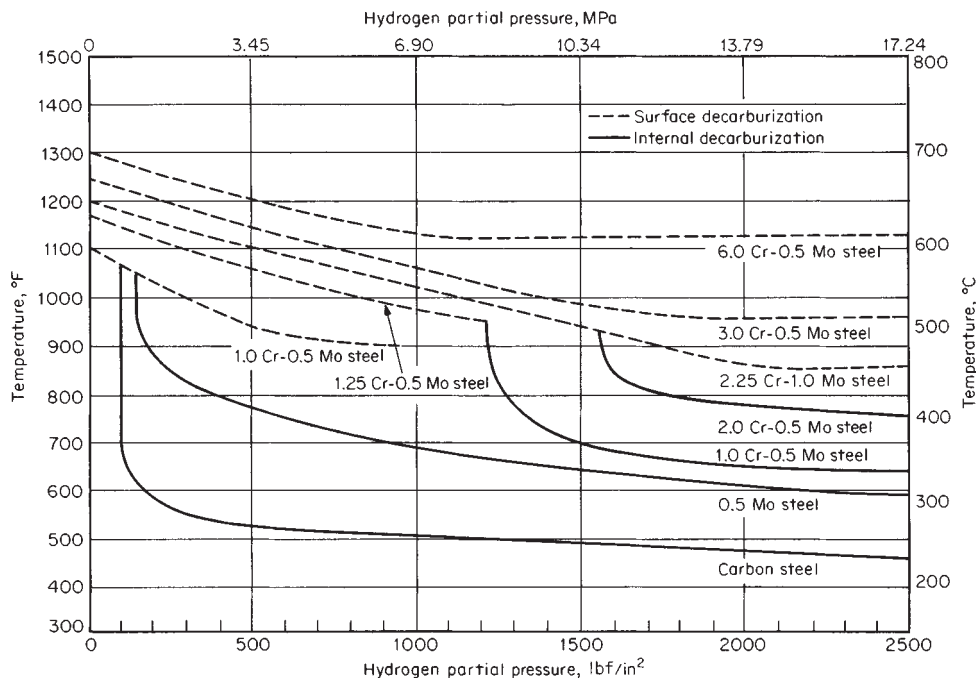


FIG. 28-1 Operating limits for steels in hydrogen service. Each steel is suitable for use under hydrogen-partial-pressure-temperature conditions below and to the left of its respective curve. (Courtesy of National Association of Corrosion Engineers.)

Hydrogen damage can also result from hydrogen generated in electrochemical corrosion reactions. This phenomenon is most commonly observed in solutions of specific weak acids. H_2S and HCN are the most common, although other acids can cause the problem. The atomic hydrogen formed on the metal surface by the corrosion reaction diffuses into the metal and forms molecular hydrogen at microvoids in the metal. The result is failure by embrittlement, cracking, and blistering.

FLUID CORROSION: STRUCTURAL

Graphitic Corrosion Graphitic corrosion usually involves **gray cast iron** in which metallic iron is converted into corrosion products, leaving a residue of intact graphite mixed with iron-corrosion products and other insoluble constituents of cast iron.

When the layer of graphite and corrosion products is impervious to the solution, corrosion will cease or slow down. If the layer is porous, corrosion will progress by galvanic behavior between graphite and iron. The rate of this attack will be approximately that for the maximum penetration of steel by pitting. The layer of graphite formed may also be effective in reducing the galvanic action between cast iron and more noble alloys such as bronze used for valve trim and impellers in pumps.

Low-alloy cast irons frequently demonstrate a superior resistance to graphitic corrosion, apparently because of their denser structure and the development of more compact and more protective graphitic coatings. Highly alloyed **austenitic cast irons** show considerable superiority over gray cast irons to graphitic corrosion because of the more noble potential of the austenitic matrix plus more protective graphitic coatings.

Carbon steels heated for prolonged periods at temperatures above $455^\circ C$ ($850^\circ F$) may be subject to the segregation of carbon, which is transformed into graphite. When this occurs, the structural strength of the steel will be affected. Killed steels or low-alloy steels of chromium and molybdenum or chromium and nickel should be considered for elevated-temperature services.

Parting, or Dealloying, Corrosion This type of corrosion occurs when only one component of an alloy is removed by corrosion. The most common type is dezincification of brass.

Dezincification Dezincification is corrosion of a brass alloy containing zinc in which the principal product of corrosion is metallic copper. This may occur as plugs filling pits (plug type) or as continuous layers surrounding an unattacked core of brass (general type). The mechanism may involve overall corrosion of the alloy followed by redeposition of the copper from the corrosion products or selective corrosion of zinc or a high-zinc phase to leave copper residue. This form of corrosion is commonly encountered in brasses that contain more than 15 percent zinc and can be either eliminated or reduced by the addition of small amounts of **arsenic**, **antimony**, or **phosphorus** to the alloy.

Biological Corrosion The metabolic activity of microorganisms can either directly or indirectly cause deterioration of a metal by corrosion processes. Such activity can (1) produce a corrosive environment, (2) create electrolytic-concentration cells on the metal surface, (3) alter the resistance of surface films, (4) have an influence on the rate of anodic or cathodic reaction, and (5) alter the environment composition.

Microorganisms associated with corrosion are of two types, aerobic and anaerobic. **Aerobic** microorganisms readily grow in an environment containing oxygen, while the **anaerobic** species thrive in an environment virtually devoid of atmospheric oxygen.

The manner in which many of these bacteria carry on their chemical processes is quite complicated and in some cases not fully understood. The role of **sulfate-reducing bacteria** (anaerobic) in promoting corrosion has been extensively investigated. The sulfates in slightly acid to alkaline (pH 6 to 9) soils are reduced by these bacteria to form calcium sulfide and hydrogen sulfide. When these compounds come in contact with underground iron pipes, conversion of the iron to iron sulfide occurs. As these bacteria thrive under these conditions, they will continue to promote this reaction until failure of the pipe occurs.

Several instances of serious biological corrosion occurred when

hydrotest water was not promptly removed from stainless-steel systems. These cases involved both potable and nonpotable waters. Biological activity caused perforation of the stainless steel in a few months. Use of potable-quality water and prompt and complete draining after a test constitute the most reliable solution to this problem.

Microbiologically Influenced Corrosion (MIC)^o While microbiologically influenced corrosion has existed since the beginning of time, it has only been identified to be a real and persistent problem to industry during the past several decades. A considerable amount of multidisciplinary effort has been expended to determine the extent of the problem and to understand the phenomenon. Prevention and control would seem to be a product of this understanding. Unfortunately, the more we learn, the more we find out how little we really understand about the subject. MIC is now recognized as a problem in many industries, including the gas pipeline, nuclear and fossil power, chemical process, and pulp and paper industries. This brief review is presented from an industrial point of view. Subjects include the buried structures, materials selection, hydrotest procedures, and other considerations that corrosion engineers in the field need to take into account in order to prevent or minimize potential MIC problems in the future.

It is widely recognized that microorganisms attach to, form films on, and influence the corrosion of metals and alloys immersed in natural aqueous environments. The microorganisms influence corrosion by changing the electrochemical conditions at the metal surface. Theoretically, these changes may have many effects, ranging from the induction of localized corrosion, to a change in the rate of general corrosion, to corrosion inhibition. In every case, however, the process of corrosion is electrochemical.

Recently, there has developed a greater recognition of the complexity of the MIC process. MIC is rarely linked to a unique mechanism or to a single species of microorganisms. At the present state of knowledge, it is widely accepted that the growth of different microbial species within adherent biofilms facilitates the development of structured consortia that may enhance the microbial effects on corrosion.

Most practicing engineers are not, and do not need to become, experts in the details of MIC. What is needed is to recognize that this corrosion system is active, that process equipment and structures are at risk, and that there are numerous tools available to monitor and detect MIC (see the later sections on laboratory and field corrosion testing, both of which address the subject of MIC). Advances in the detection of MIC have been made principally through education in the methods for proper observation of field samples, sample collection, cultivation of bacteria involved, microscopic analysis of samples, and metallurgical analysis of samples. These have greatly improved our ability to *prove* the involvement of microbes in the corrosion processes. Recent techniques developed in the laboratory make use of specific antibodies directed against organisms known to be MIC-causing organisms, give rapid and quantitative answers to questions regarding the numbers and types of microbes present in field samples, and can be used in the field.

Bacteria, as a group, can grow over a pH range of about 0 to 11. They can be obligate aerobes (require oxygen to survive and grow), microaerophiles (require low oxygen concentrations), facultative anaerobes (prefer aerobic conditions but will live under anaerobic conditions), or obligate anaerobes (will grow only under conditions where oxygen is absent). It should be emphasized that most anaerobes will survive aerobic conditions for quite a while and the same is true for aerobes in anaerobic conditions. Also note that, for a microorganism, anaerobic conditions may be quite easily found in what are thought to be generally aerobic environments. Often these anaerobic microenvironments are in, or under, films, in particulates of debris, inside crevices, and so on.

As a group, the MIC-causing bacteria may use almost any available organic carbon molecules, from simple alcohols or sugars to phenols to wood or various other complex polymers as food (heterotrophs), or they may fix CO_2 (autotrophs) as do plants. Some use inorganic elements or ions (e.g., NH or NO , CH , H , S , Fe , Mn , etc.), as sources of

^o Excerpted from papers by John G. Stoecker II and Oliver W. Siebert, courtesy of NACE International.

energy. The nutritional requirements of these organisms, therefore, range from very simple to very complex. Most fall in between these extremes and require a limited number of organic molecules, moderate temperatures, moist environments, and near-neutral pH.

Buried Structures Corrosion of buried pipelines caused by sulfate-reducing bacteria has been studied for almost a century. Quite by accident, industry has been protecting buried iron-based structures from bacterial damage through the use of cathodic protection. Cathodic protection produces an elevated alkaline or basic environment on the surface of the buried structure ($\text{pH} \geq 10$) which is not conducive to microbiological growth. Booth was one of the early investigators to present this finding, but caution should be exercised when using his recommendations. The user of cathodic protection must also consider the material being protected with regard to caustic cracking; a cathodic potential driven to the negative extreme of -0.95 V for microbiological protection purposes can cause caustic cracking of a steel structure. The benefits and risks of cathodic protection must be weighed for each material and each application.

There has been no dramatic improvement in the microbiological protection of buried structures over the years. Cathodic protection in conjunction with a protective coating system has continued to be the best defense against this form of MIC as well as against other underground corrosive damage. Cathodic protection provides caustic-environment protection at the holes or holidays in the coating that are sure to develop with time due to one cause or another. Experience has been that coating systems, by themselves, do not provide adequate protection for a buried structure over the years; for best results, a properly designed and maintained cathodic protection system *must* be used in conjunction with a protective coating (regardless of the quality of the coating, as applied).

Backfilling with limestone or other alkaline material is an added step to protect buried structures from microbiological damage. Providing adequate drainage to produce a dry environment both above and below ground in the area of the buried structure will also reduce the risk of this type of damage.

Waters While MIC-causing bacteria may arrive at the surface of their corrosion worksite by almost any transportation system, there is always water present to allow them to become active and cause MIC to occur. There are plenty of examples of even superpure waters having sufficient microorganisms present to feed, divide, and multiply when even the smallest trace of a viable food-stuff is present (e.g., the so-called *water for injection* in the pharmaceutical industry has been the observed subject of extensive corrosion of polished stainless steel tanks, piping, and so on).

The initial MIC examples studied in the 1970s were weld failures of stainless steel piping that saw only potable drinking water. The numbers of water-exposed systems that have been verified as being affected by MIC are legion.

Hydrostatic Testing Waters Microbiological species in the water used for hydrostatic (safety) testing of process equipment and for process batch water have caused considerable MIC damage and expense in the past. Guidelines for hydrotesting have been adopted by several industrial and governmental organizations in an effort to prevent this damage. Generally, good results have been reported for those who have followed this practice. Unfortunately, this can be a *very* expensive undertaking where the need cannot be totally quantified (and, thus, justified to management). Cost-cutting practices which either ignore these guides or follow an adulteration of proven precautions can lead to major MIC damage to equipment and process facilities.

Obviously, natural freshwater from wells, lakes, or rivers is the least desirable and its use should be avoided. Even potable waters are not free of organic species that cause MIC damage to conventional materials of construction; for example, steel, stainless steels, and so on. If the size of the facility argues strongly against the use of demineralized water or steam condensate, potable water must be evaluated for test use. Perhaps it would be possible to use a biocide such as hydrogen peroxide or ozone in the potable water; most organic biocides cause disposal problems. Obviously, chlorine must be used only with great care because of the extensive damage it will cause to the 300-series, austenitic stainless steels. In all cases, as soon as the test is over, the

water *must* be completely drained and the system thoroughly dried so that no vestiges of water are allowed to be trapped in occluded areas.

The literature abounds with instructions as to the proper manner in which to accomplish the necessary and MIC-safe testing procedures. The engineering personnel planning these test operations should avail themselves of that knowledge.

Materials of Construction MIC is a process in which manufactured materials deteriorate through microbiological action. This process can be either direct or indirect.

Microbial biodeterioration of a great many materials (including concretes, glasses, metals and their alloys, and plastics) occurs by diverse mechanisms.

The corrosion engineers' solution to corrosion problems sometimes includes an upgrading of the materials of construction. This is a natural approach, and since microbiological corrosion has usually been considered a form of crevice or under-deposit attack, this option is logical. Unfortunately, with MIC, the use of more corrosion-resistant materials can many times be a shortcut to disaster; MIC is dependent upon the species of organism involved. As an example, an upgrade from type 304 to 316 stainless steel does not always help. Kobrin reported biological corrosion of delta ferrite stringers in weld metal. Obviously, this upgrade was futile; type 316 stainless steel can contain as much or more delta ferrite as does type 304. Kobrin also reported MIC of nickel, nickel-copper Alloy 400, and nickel-molybdenum Alloy B heat exchanger tubes. Although the Alloy 400 and Alloy B were not pitted as severely as the nickel tubes, the higher alloys did not solve the corrosion problem.

In the past, copper was believed to be toxic to *most* microbiological species. This has not turned out to be the case, as pointed out in the preceding example, reported in many other studies by the authors and their colleagues. As an example, reports from engineers in the power generating industry about MIC of copper and cupro-nickel alloys also indicate that copper is not an automatic deterrent to this corrosion mechanism. It is concluded that copper is toxic to the higher life-forms, for example, barnacles and so on, but it is not a biocide to the simple, single-cell organisms.

At this stage of knowledge about MIC, only titanium, zirconium, and tantalum appear to be immune to microbiological damage.

FACTORS INFLUENCING CORROSION

Solution pH The corrosion rate of most metals is affected by pH. The relationship tends to follow one of three general patterns:

1. Acid-soluble metals such as iron have a relationship as shown in Fig. 28-2a. In the middle pH range (≈ 4 to 10), the corrosion rate is controlled by the rate of transport of oxidizer (usually dissolved O_2) to the metal surface. Iron is weakly amphoteric. At very high temperatures such as those encountered in boilers, the corrosion rate increases with increasing basicity, as shown by the dashed line.

2. Amphoteric metals such as aluminum and zinc have a relationship as shown in Fig. 28-2b. These metals dissolve rapidly in either acidic or basic solutions.

3. Noble metals such as gold and platinum are not appreciably affected by pH, as shown in Fig. 28-2c.

Oxidizing Agents In some corrosion processes, such as the solution of zinc in hydrochloric acid, hydrogen may evolve as a gas. In others, such as the relatively slow solution of copper in sodium chloride, the removal of hydrogen, which must occur so that corrosion may proceed, is effected by a reaction between hydrogen and some oxidizing chemical such as oxygen to form water. Because of the high rates of corrosion which usually accompany hydrogen evolution, metals are rarely used in solutions from which they evolve hydrogen at an appreciable rate. As a result, most of the corrosion observed in practice occurs under conditions in which the oxidation of hydrogen to form water is a necessary part of the corrosion process. For this reason, oxidizing agents are often powerful accelerators of corrosion, and in many cases the **oxidizing power of a solution** is its most important single property insofar as corrosion is concerned.

Oxidizing agents that accelerate the corrosion of some materials may also retard corrosion of others through the formation on their surface of oxides or layers of adsorbed oxygen which make them more

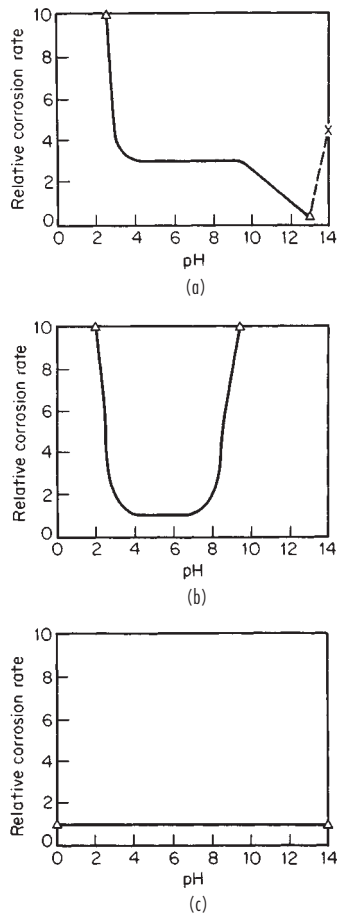


FIG. 28-2 Effect of pH on the corrosion rate. (a) Iron. (b) Amphoteric metals (aluminum, zinc). (c) Noble metals.

resistant to chemical attack. This property of chromium is responsible for the principal corrosion-resisting characteristics of the stainless steels.

It follows, then, that oxidizing substances, such as dissolved air, may accelerate the corrosion of one class of materials and retard the corrosion of another class. In the latter case, the behavior of the material usually represents a balance between the power of oxidizing compounds to preserve a protective film and their tendency to accelerate corrosion when the agencies responsible for protective-film breakdown are able to destroy the films.

Temperature The rate of corrosion tends to increase with rising temperature. Temperature also has a secondary effect through its influence on the solubility of air (oxygen), which is the most common oxidizing substance influencing corrosion. In addition, temperature has specific effects when a temperature change causes phase changes which introduce a corrosive second phase. Examples include condensation systems and systems involving organics saturated with water.

Velocity An increase in the velocity of relative movement between a corrosive solution and a metallic surface frequently tends to accelerate corrosion. This effect is due to the higher rate at which the corrosive chemicals, including oxidizing substances (air), are brought to the corroding surface and to the higher rate at which corrosion products, which might otherwise accumulate and stifle corrosion, are carried away. The higher the velocity, the thinner will be the films which corroding substances must penetrate and through which soluble corrosion products must diffuse.

Whenever corrosion resistance results from the accumulation of layers of insoluble corrosion products on the metallic surface, the effect of high velocity may be either to prevent their normal formation or to remove them after they have been formed. Either effect allows corrosion to proceed unhindered. This occurs frequently in small-diameter tubes or pipes through which corrosive liquids may be circulated at high velocities (e.g., condenser and evaporator tubes), in the vicinity of bends in pipe lines, and on propellers, agitators, and centrifugal pumps. Similar effects are associated with cavitation and impingement corrosion.

Films Once corrosion has started, its further progress very often is controlled by the nature of films, such as passive films, that may form or accumulate on the metallic surface. The classical example is the thin **oxide film** that forms on stainless steels.

Insoluble corrosion products may be completely impervious to the corroding liquid and, therefore, completely protective; or they may be quite permeable and allow local or general corrosion to proceed unhindered. Films that are nonuniform or discontinuous may tend to localize corrosion in particular areas or to induce accelerated corrosion at certain points by initiating electrolytic effects of the concentration-cell type. Films may tend to retain or absorb moisture and thus, by delaying the time of drying, increase the extent of corrosion resulting from exposure to the atmosphere or to corrosive vapors.

It is agreed generally that the characteristics of the **rust films** that form on steels determine their resistance to atmospheric corrosion. The rust films that form on low-alloy steels are more protective than those that form on unalloyed steel.

In addition to films that originate at least in part in the corroding metal, there are others that originate in the corrosive solution. These include various salts, such as carbonates and sulfates, which may be precipitated from heated solutions, and insoluble compounds, such as "beer stone," which form on metal surfaces in contact with certain specific products. In addition, there are films of oil and grease that may protect a material from direct contact with corrosive substances. Such oil films may be applied intentionally or may occur naturally, as in the case of metals submerged in sewage or equipment used for the processing of oily substances.

Other Effects Stream **concentration** can have important effects on corrosion rates. Unfortunately, corrosion rates are seldom linear with concentration over wide ranges. In equipment such as distillation columns, reactors, and evaporators, concentration can change continuously, making prediction of corrosion rates rather difficult. Concentration is important during plant shutdown; presence of moisture that collects during cooling can turn innocuous chemicals into dangerous corrosives.

As to the effect of time, there is no universal law that governs the reaction for all metals. Some corrosion rates remain constant with time over wide ranges, others slow down with time, and some alloys have increased corrosion rates with respect to time. Situations in which the corrosion rate follows a combination of these paths can develop. Therefore, extrapolation of corrosion data and corrosion rates should be done with utmost caution.

Impurities in a corrodent can be good or bad from a corrosion standpoint. An impurity in a stream may act as an inhibitor and actually retard corrosion. However, if this impurity is removed by some process change or improvement, a marked rise in corrosion rates can result. Other impurities, of course, can have very deleterious effects on materials. The chloride ion is a good example; small amounts of chlorides in a process stream can break down the passive oxide film on stainless steels. The effects of impurities are varied and complex. One must be aware of what they are, how much is present, and where they come from before attempting to recommend a particular material of construction.

HIGH-TEMPERATURE ATTACK

Physical Properties The suitability of an alloy for high-temperature service [425 to 1,100°C (800 to 2,000°F)] is dependent upon properties inherent in the alloy composition and upon the conditions of application. Crystal structure, density, thermal conductivity, electrical resistivity, thermal expansivity, structural stability, melting

range, and vapor pressure are all physical properties basic to and inherent in individual alloy compositions.

Of usually high relative importance in this group of properties is **expansivity**. A surprisingly large number of metal failures at elevated temperatures are the result of excessive thermal stresses originating from constraint of the metal during heating or cooling. Such constraint in the case of hindered contraction can cause rupturing.

Another important property is alloy **structural stability**. This means freedom from formation of new phases or drastic rearrangement of those originally present within the metal structure as a result of thermal experience. Such changes may have a detrimental effect upon strength or corrosion resistance or both.

Mechanical Properties Mechanical properties of wide interest include creep, rupture, short-time strengths, and various forms of ductility, as well as resistance to impact and fatigue stresses. Creep strength and stress rupture are usually of greatest interest to designers of stationary equipment such as vessels and furnaces.

Corrosion Resistance Possibly of greater importance than physical and mechanical properties is the ability of an alloy's chemical composition to resist the corrosive action of various hot environments. The forms of high-temperature corrosion which have received the greatest attention are **oxidation** and **scaling**.

Chromium is an essential constituent in alloys to be used above 550°C (1,000°F). It provides a tightly adherent oxide film that materially retards the oxidation process. Silicon is a useful element in imparting oxidation resistance to steel. It will enhance the beneficial effects of chromium. Also, for a given level of chromium, experience has shown oxidation resistance to improve as the nickel content increases.

Aluminum is not commonly used as an alloying element in steel to improve oxidation resistance, as the amount required interferes with both workability and high-temperature-strength properties. However, the development of high-aluminum surface layers by various methods, including spraying, cementation, and dipping, is a feasible means of improving heat resistance of low-alloy steels.

Contaminants in fuels, especially alkali-metal ions, vanadium, and sulfur compounds, tend to react in the combustion zone to form molten fluxes which dissolve the protective oxide film on stainless steels, allowing oxidation to proceed at a rapid rate. This problem is becoming more common as the high cost and short supply of natural gas and distillate fuel oils force increased usage of residual fuel oils and coal.

COMBATING CORROSION

Material Selection The objective is to select the material which will most economically fulfill the process requirements. The best source of data is well-documented experience in an identical process unit. In the absence of such data, other data sources such as experience in pilot units, corrosion-coupon tests in pilot or bench-scale units, laboratory corrosion-coupon tests in actual process fluids, or corrosion-coupon tests in synthetic solutions must be used. The data from such alternative sources (which are listed in decreasing order of reliability) must be properly evaluated, taking into account the degree to which a given test may fail to reproduce actual conditions in an operating unit. Particular emphasis must be placed on possible composition differences between a static laboratory test and a dynamic plant as well as on trace impurities (chlorides in stainless-steel systems, for example) which may greatly change the corrosiveness of the system. The possibility of severe localized attack (pitting, crevice corrosion, or stress-corrosion cracking) must also be considered.

Permissible **corrosion rates** are an important factor and differ with equipment. Appreciable corrosion can be permitted for tanks and lines if anticipated and allowed for in design thickness, but essentially no corrosion can be permitted in fine-mesh wire screens, orifices, and other items in which small changes in dimensions are critical.

In many instances use of **nonmetallic materials** will prove to be attractive from an economic and performance standpoint. These should be considered when their strength, temperature, and design limitations are satisfactory.

Proper Design Design considerations with respect to minimizing corrosion difficulties should include the desirability for free and

complete drainage, minimizing crevices, and ease of cleaning and inspection. The installation of baffles, stiffeners, and drain nozzles and the location of valves and pumps should be made so that free drainage will occur and washing can be accomplished without holdup. Means of access for inspection and maintenance should be provided whenever practical. Butt joints should be used whenever possible. If lap joints employing fillet welds are used, the welds should be continuous.

The use of dissimilar metals in contact with each other should generally be minimized, particularly if they are widely separated in their nominal positions in the galvanic series (see Table 28-1a). If they are to be used together, consideration should be given to insulating them from each other or making the anodic material area as large as possible.

Equipment should be supported in such a way that it will not rest in pools of liquid or on damp insulating material. Porous insulation should be weatherproofed or otherwise protected from moisture and spills to avoid contact of the wet material with the equipment. Specifications should be sufficiently comprehensive to ensure that the desired composition or type of material will be used and the right condition of heat treatment and surface finish will be provided. Inspection during fabrication and prior to acceptance is desirable.

Altering the Environment Simple changes in environment may make an appreciable difference in the corrosion of metals and should be considered as a means of combating corrosion. **Oxygen** is an important factor, and its removal or addition may cause marked changes in corrosion. The treatment of boiler feedwater to remove oxygen, for instance, greatly reduces the corrosiveness of the water on steel. Inert-gas purging and blanketing of many solutions, particularly acidic media, generally minimize corrosion of copper and nickel-base alloys by minimizing air or oxygen content. Corrosiveness of acid media to stainless alloys, on the other hand, may be reduced by aeration because of the formation of passive oxide films. Reduction in temperature will almost always be beneficial with respect to reducing corrosion if no corrosive phase changes (condensation, for example) result. Velocity effects vary with the material and the corrosive system. When pH values can be modified, it will generally be beneficial to hold the acid level to a minimum. When acid additions are made in batch processes, it may be beneficial to add them last so as to obtain maximum dilution and minimum acid concentration and exposure time. Alkaline pH values are less critical than acid values with respect to controlling corrosion. Elimination of moisture can and frequently does minimize, if not prevent, corrosion of metals, and this possibility of environmental alteration should always be considered.

Inhibitors The use of various substances or inhibitors as additives to corrosive environments to decrease corrosion of metals in the environment is an important means of combating corrosion. This is generally most attractive in closed or recirculating systems in which the annual cost of inhibitor is low. However, it has also proved to be economically attractive for many once-through systems, such as those encountered in petroleum-processing operations. Inhibitors are effective as the result of their controlling influence on the cathode- or anode-area reactions.

Typical examples of inhibitors used for minimizing corrosion of iron and steel in aqueous solutions are the chromates, phosphates, and silicates. Organic sulfide and amine materials are frequently effective in minimizing corrosion of iron and steel in acid solution.

The use of inhibitors is not limited to controlling corrosion of iron and steel. They frequently are effective with stainless steel and other alloy materials. The addition of copper sulfate to dilute sulfuric acid will sometimes control corrosion of stainless steels in hot dilute solutions of this acid, whereas the uninhibited acid causes rapid corrosion.

The effectiveness of a given inhibitor generally increases with an increase in **concentration**, but inhibitors considered practical and economically attractive are used in quantities of less than 0.1 percent by weight.

In some instances the amount of inhibitor present is critical in that a deficiency may result in localized or pitting attack, with the overall results being more destructive than when none of the inhibitor is present. Considerations for the use of inhibitors should therefore include review of experience in similar systems or investigation of requirements and limitations in new systems.

Cathodic Protection This electrochemical method of corrosion control has found wide application in the protection of carbon steel underground structures such as pipe lines and tanks from external soil corrosion. It is also widely used in water systems to protect ship hulls, offshore structures, and water-storage tanks.

Two methods of providing cathodic protection for minimizing corrosion of metals are in use today. These are the sacrificial-anode method and the impressed-emf method. Both depend upon making the metal to be protected the cathode in the electrolyte involved.

Examples of the sacrificial-anode method include the use of zinc, magnesium, or aluminum as anodes in electrical contact with the metal to be protected. These may be anodes buried in the ground for protection of underground pipe lines or attachments to the surfaces of equipment such as condenser water boxes or on ship hulls. The current required is generated in this method by corrosion of the sacrificial-anode material. In the case of the impressed emf, the direct current is provided by external sources and is passed through the system by use of essentially nonsacrificial anodes such as carbon, noncorrodible alloys, or platinum buried in the ground or suspended in the electrolyte in the case of aqueous systems.

The requirements with respect to current distribution and anode placement vary with the resistivity of soils or the electrolyte involved.

Anodic Protection This electrochemical method relies on an external potential control system (potentiostat) to maintain the metal or alloy in a noncorroding (passive) condition. Practical applications include acid coolers in sulfuric acid plants and storage tanks for sulfuric acid.

Coatings and Linings The use of nonmetallic coatings and lining materials in combination with steel or other materials has and will continue to be an important type of construction for combating corrosion.

Organic coatings of many kinds are used as linings in equipment such as tanks, piping, pumping lines, and shipping containers, and they are often an economical means of controlling corrosion, particularly when freedom from metal contamination is the principal objective. One principle that is now generally accepted is that thin nonreinforced paintlike coatings of less than 0.75-mm (0.03-in) thickness should not be used in services for which full protection is required in order to prevent rapid attack of the substrate metal. This is true because most thin coatings contain defects or holidays and can be easily damaged in service, thus leading to early failures due to corrosion of the substrate metal even though the coating material is resistant. Electrical testing for continuity of coating-type linings is always desirable for immersion-service applications in order to detect holiday-type defects in the coating.

The most dependable barrier linings for corrosive services are those which are bonded directly to the substrate and are built up in multiple-layer or laminated effects to thicknesses greater than 2.5 mm (0.10 in). These include flake-glass-reinforced resin systems and elastomeric and plasticized plastic systems. Good surface preparation and thorough inspections of the completed lining, including electrical testing, should be considered as minimum requirements for any lining applications.

Linings of this type are slightly permeable to many liquids. Such permeation, while not damaging to the lining, may cause failure by causing disbonding of the lining owing to pressure buildup between the lining and the steel.

Ceramic or carbon-brick linings are frequently used as facing linings over plastic or membrane linings when surface temperatures exceed those which can be handled by the unprotected materials or when the membrane must be protected from mechanical damage. This type of construction permits processing of materials that are too corrosive to be handled in low-cost metal constructions.

Glass-Lined Steel By proprietary methods, special glasses can be bonded to steel, providing an impervious liner 1.5 to 2.5 mm (0.060 to 0.100 in) thick. Equipment and piping lined in this manner are routinely used in severely corrosive acid services. The glass lining can be mechanically damaged, and careful attention to details of design, inspection, installation, and maintenance is required to achieve good results with this system.

The cladding of steel with an alloy is another approach to this problem. There are a number of cladding methods in general use. In one,

a sandwich is made of the corrosion-resistant metal and carbon steel by hot rolling to produce a **pressure weld** between the plates.

Another process involves **explosive bonding**. The corrosion-resistant metal is bonded to a steel backing metal by the force generated by properly positioned explosive charges. Relatively thick sections of metal can be bonded by this technique into plates.

In a third process, a **loose liner** is fastened to a carbon steel shell by welds spaced so as to prevent collapse of the liner. A fourth method is **weld overlay**, which involves depositing multiple layers of alloy weld metal to cover the steel surface.

All these methods require careful design and control of fabrication methods to assure success.

Metallic Linings for Mild Environments **Zinc coatings** applied by various means have good corrosion resistance to many atmospheres. Such coatings have been extensively used on steel. Zinc has the advantage of being anodic to steel and therefore will protect exposed areas of steel by electrochemical action.

Steel coated with tin (**tinplate**) is used to make food containers. Tin is more noble than steel; therefore, well-aerated solutions will galvanically accelerate attack of the steel at exposed areas. The comparative absence of air within food containers aids in preserving the tin as well as the food. Also the reversible potential which the tin-iron couple undergoes in organic acids serves to protect exposed steel in food containers.

Cadmium, being anodic to steel, behaves quite similarly to zinc in providing corrosion protection when applied as a coating on steel. Tests of zinc and cadmium coatings should be conducted when it becomes necessary to determine the most economical selection for a particular environment.

Lead has a good general resistance to various atmospheres. As a coating, it has had its greatest application in the production of ternary plate, which is used as a roofing, comicing, and spouting material.

Aluminum coatings on steel will perform in a manner similar to zinc coatings. Aluminum has good resistance to many atmospheres; in addition, being anodic to steel, it will galvanically protect exposed areas. Aluminum-coated steel products are quite serviceable under high-temperature conditions, for which good oxidation resistance is required.

CORROSION-TESTING METHODS*

The primary purpose of materials selection is to provide the optimum equipment for a process application in terms of materials of construction, design, and corrosion-control measures. *Optimum* here means that which comprises the best combination of cost, life, safety, and reliability.

The selection of materials to be used in design dictates a basic understanding of the behavior of materials and the principles that govern such behavior. If proper design of suitable materials of construction is incorporated, the equipment should deteriorate at a uniform and anticipated gradual rate, which will allow scheduled maintenance or replacement at regular intervals. If localized forms of corrosion are characteristic of the combination of materials and environment, the materials engineer should still be able to predict the probable life of equipment, or devise an appropriate inspection schedule to preclude unexpected failures. The concepts of predictive, or at least preventive, maintenance are minimum requirements to proper materials selection. This approach to maintenance is certainly intended to minimize the possibility of unscheduled production shutdowns because of corrosion failures, with their attendant possible financial losses, hazard to personnel and equipment, and resultant environmental pollution.

Chemical processes may involve a complex variety of both inorganic and organic chemicals. Hard and fast rules for selecting the appropriate materials of construction can be given when the composition is known, constant, and free of unsuspected contaminants; when the relevant parameters of temperature, pressure, velocity, and concentra-

* Includes information excerpted from papers by Oliver W. Siebert, John G. Stoecker II, and Ann Chidester Van Orden, courtesy of NACE International; and Oliver W. Siebert, courtesy ASTM.

tion are defined; and when the mechanical and environmental degradation of the material is uniform, that is, free of localized attack. For example, it is relatively simple to select the materials of construction for a regimen of equipment for the storage and handling of cold, concentrated sulfuric acid. On the other hand, the choice of suitable materials for producing phosphoric acid by the digestion of phosphate rock with sulfuric acid is much more difficult because of the diversity in kind and concentration of contaminants, the temperatures of the reactions, and the strength of sulfuric and phosphoric acid used or formed. Probably the best way to approach the study of materials selection is to categorize the types of major chemicals that might be encountered, describe their inherent characteristics, and generalize about the corrosion characteristics of the prominent materials of construction in such environments.

The background information that materials selection is based on is derived from a number of sources. In many cases, information as to the corrosion resistance of a material in a specific environment is not available and must be derived experimentally. It is to this need that the primary remarks of this subsection are addressed.

Unfortunately, there is no standard or preferred way to evaluate an alloy in an environment. While the chemistry of the operating plant environment can sometimes be duplicated in the laboratory, factors of velocity, hot and cold wall effects, crevice, chemical reaction of the fluid during the test, stress levels of the equipment, contamination with products of corrosion, trace impurities, dissolved gases, and so forth also have a controlling effect on the quality of the answer. Then, too, the progress of the corrosion reaction itself varies with time. Notwithstanding, immersion testing remains the most widely used method for selecting materials of construction.

There is no standard or preferred way to carry out a corrosion test; the method must be chosen to suit the purpose of the test. The principal types of tests are, in decreasing order of reliability:

1. Actual operating experience with full-scale plant equipment exposed to the corroding medium.
2. Small-scale plant-equipment experience, under either commercial or pilot-plant conditions.
3. Sample tests in the field. These include coupons, stressed samples, electrical-resistance probes exposed to the plant corroding medium, or samples exposed to the atmosphere, to soils, or to fresh, brackish, or saline waters.
4. Laboratory tests on samples exposed to "actual" plant liquids or simulated environments.

Plant or field corrosion tests are useful for:

1. Selection of the most suitable material to withstand a particular environment and to estimate its probable durability in that environment
2. Study of the effectiveness of means of preventing corrosion

CORROSION TESTING: LABORATORY TESTS

Metals and alloys do not respond alike to all the influences of the many factors that are involved in corrosion. Consequently, it is impractical to establish any universal standard laboratory procedures for corrosion testing except for inspection tests. However, some details of laboratory testing need careful attention in order to achieve useful results.

In the selection of materials for the construction of a chemical plant, resistance to the corroding medium is often the determining factor; otherwise, the choice will fall automatically on the cheapest material mechanically suitable. Laboratory corrosion tests are frequently the quickest and most satisfactory means of arriving at a preliminary selection of the most suitable materials to use. Unfortunately, however, it is not yet within the state of the art of laboratory tests to predict with accuracy the behavior of the selected material under plant-operating conditions. The outstanding difficulty lies not so much in carrying out the test as in interpreting the results and translating them into terms of plant performance. A laboratory test of the conventional type gives mainly one factor—the chemical resistance of the proposed material to the corrosive agent. There are numerous other factors entering into the behavior of the material in the plant, such as dissolved gases, velocity, turbulence, abrasion, crevice condi-

tions, hot-wall effects, cold-wall effects, stress levels of metals, trace impurities in corrodent that act as corrosion inhibitors or accelerators, and variations in composition of corrodent.

Immersion Test One method of determining the chemical-resistance factor, the so-called **total-immersion test**, represents an unaccelerated method that has been found to give reasonably concordant results in approximate agreement with results obtained on the large scale when the other variables are taken into account. Various other tests have been proposed and are in use, such as salt-spray, accelerated electrolytic, alternate-immersion, and aerated-total-immersion; but in view of the numerous complications entering into the translation of laboratory results into plant results the simplest test is considered the most desirable for routine preliminary work, reserving special test methods for special cases. The total-immersion test serves quite well to eliminate materials that obviously cannot be used; further selection among those materials which apparently can be used can be made on the basis of a knowledge of the properties of the materials concerned and the working conditions or by constructing larger-scale equipment of the proposed materials in which the operating conditions can be simulated.

The National Association of Corrosion Engineers (NACE) TMO169-95 "Standard Laboratory Corrosion Testing of Metals for the Process Industries," and ASTM G31 "Recommended Practice for Laboratory Immersion Corrosion Testing of Metals" are the general guides for immersion testing. Small pieces of the candidate metal are exposed to the medium, and the loss of mass of the metal is measured for a given period of time. Immersion testing remains the best method to eliminate from further consideration those materials that obviously cannot be used. This technique is frequently the quickest and most satisfactory method of making a preliminary selection of the best candidate materials.

Probably the most serious disadvantage of this method of corrosion study is the assumed average-time weight loss. The corrosion rate could be high initially and then decrease with time (it could fall to zero). In other cases the rate of corrosion might increase very gradually with time or it could cycle or be some combination of these things.

The description that follows is based on these standards.

Test Piece The size and the shape of specimens will vary with the purpose of the test, nature of the material, and apparatus used. A large surface-to-mass ratio and a small ratio of edge area to total area are desirable. These ratios can be achieved through the use of rectangular or circular specimens of minimum thickness. Circular specimens should be cut preferably from sheet and not bar stock to minimize the exposed end grain.

A circular specimen of about 38-mm (1.5-in) diameter is a convenient shape for laboratory corrosion tests. With a thickness of approximately 3 mm ($\frac{1}{8}$ in) and an 8- or 11-mm- ($\frac{5}{16}$ - or $\frac{7}{16}$ -in-) diameter hole for mounting, these specimens will readily pass through a 45/50 ground-glass joint of a distillation kettle. The total surface area of a circular specimen is given by the equation:

$$A = \frac{\pi}{2} (D^2 - d^2) + t\pi D$$

where t = thickness, D = diameter of the specimen, and d = diameter of the mounting hole. If the hole is completely covered by the mounting support, the final term ($t\pi D$) in the equation is omitted.

Strip coupons [50 by 25 by 1.6 or 3.2 mm (2 by 1 by $\frac{1}{16}$ or $\frac{1}{8}$ in)] may be preferred as corrosion specimens, particularly if interface or liquid-line effects are to be studied by the laboratory test.

All specimens should be measured carefully to permit accurate calculation of the exposed areas. An area calculation accurate to plus or minus 1 percent is usually adequate.

More uniform results may be expected if a substantial layer of metal is removed from the specimens to eliminate variations in condition of the original metallic surface. This can be done by chemical treatment (pickling), electrolytic removal, or grinding with a coarse abrasive paper or cloth, such as No. 50, using care not to work-harden the surface. At least 2.5×10^{-3} mm (0.0001 in) or 1.5 to 2.3 mg/cm² (10 to 15 mg/in²) should be removed. If clad alloy specimens are to be used, special attention must be given to ensure that excessive metal is not removed. After final preparation of the specimen surface, the speci-

mens should be stored in a desiccator until exposure if they are not used immediately.

Specimens should be finally degreased by scrubbing with bleach-free scouring powder, followed by thorough rinsing in water and in a suitable solvent (such as acetone, methanol, or a mixture of 50 percent methanol and 50 percent ether), and air-dried. For relatively soft metals such as aluminum, magnesium, and copper, scrubbing with abrasive powder is not always needed and can mar the surface of the specimen. The use of towels for drying may introduce an error through contamination of the specimens with grease or lint. The dried specimen should be weighed on an analytic balance.

Apparatus A versatile and convenient apparatus should be used, consisting of a kettle or flask of suitable size (usually 500 to 5,000 mL), a reflux condenser with atmospheric seal, a sparger for controlling atmosphere or aeration, a thermowell and temperature-regulating device, a heating device (mantle, hot plate, or bath), and a specimen-support system. If agitation is required the apparatus can be modified to accept a suitable stirring mechanism such as a magnetic stirrer. A typical resin-flask setup for this type of test is shown in Fig. 28-3. Open-beaker tests should not be used because of evaporation and contamination.

In more complex tests, provisions might be needed for continuous flow or replenishment of the corrosive liquid while simultaneously maintaining a controlled atmosphere.

Apparatus for testing materials for heat-transfer applications is shown in Fig. 28-4. Here the sample is at a higher temperature than the bulk solution.

If the test is to be a guide for the selection of a material for a particular purpose, the limits of controlling factors in service must be determined. These factors include oxygen concentration, temperature, rate of flow, pH value, and other important characteristics.

The **composition of the test solution** should be controlled to the fullest extent possible and be described as thoroughly and as accurately as possible when the results are reported. Minor constituents should not be overlooked because they often affect corrosion rates. Chemical content should be reported as percentage by weight of the solution. Molarity and normality are also helpful in defining the concentration of chemicals in the test solution. The composition of the test solution should be checked by analysis at the end of the test to

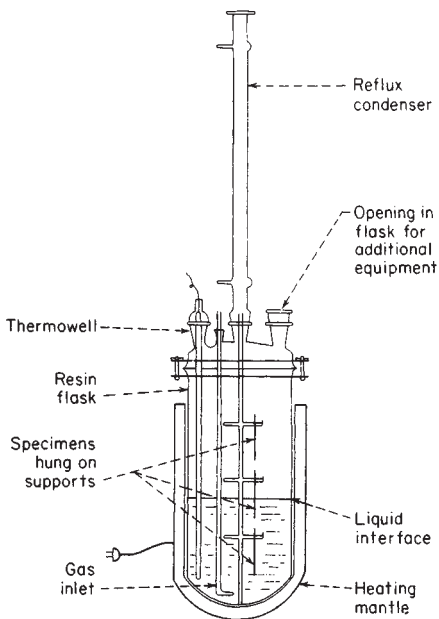


FIG. 28-3 Laboratory-equipment arrangement for corrosion testing. (Based on NACE Standard TMO169-95.)

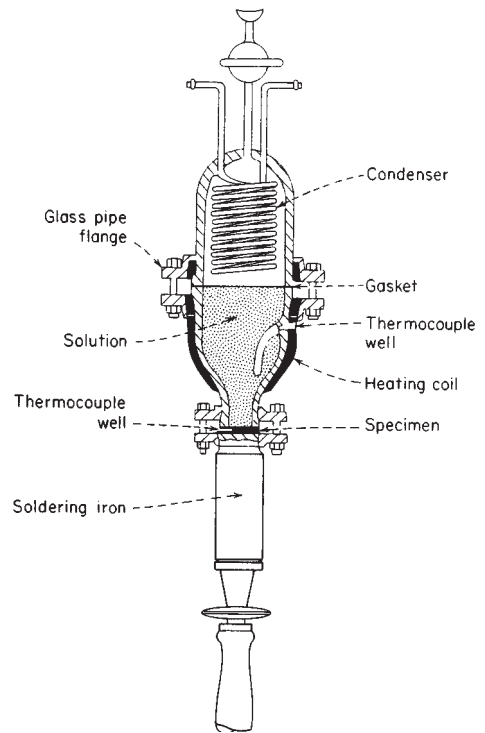


FIG. 28-4 Laboratory setup for the corrosion testing of heat-transfer materials.

determine the extent of change in composition, such as might result from evaporation.

Temperature of Solution Temperature of the corroding solution should be controlled within $\pm 1^\circ\text{C}$ ($\pm 1.8^\circ\text{F}$) and must be stated in the report of test results.

For tests at ambient temperatures, the tests should be conducted at the highest temperature anticipated for stagnant storage in summer months. This temperature may be as high as 40 to 45°C (104 to 113°F) in some localities. The variation in temperature should be reported also (e.g., $40^\circ\text{C} \pm 2^\circ\text{C}$).

Aeration of Solution Unless specified, the solution should not be aerated. Most tests related to process equipment should be run with the natural atmosphere inherent in the process, such as the vapors of the boiling liquid. If aeration is used, the specimens should not be located in the direct air stream from the sparger. Extraneous effects can be encountered if the air stream impinges on the specimens.

Solution Velocity The effect of velocity is not usually determined in laboratory tests, although specific tests have been designed for this purpose. However, for the sake of reproducibility some velocity control is desirable.

Tests at the boiling point should be conducted with minimum possible heat input, and boiling chips should be used to avoid excessive turbulence and bubble impingement. In tests conducted below the boiling point, thermal convection generally is the only source of liquid velocity. In test solutions of high viscosities, supplemental controlled stirring with a magnetic stirrer is recommended.

Volume of Solution Volume of the test solution should be large enough to avoid any appreciable change in its corrosiveness through either exhaustion of corrosive constituents or accumulation of corrosion products that might affect further corrosion.

A suitable volume-to-area ratio is 20 mL (125 mL) of solution/cm² (in²) of specimen surface. This corresponds to the recommendation of ASTM Standard A262 for the Huey test. The preferred volume-to-

area ratio is 40 mL/cm² (250 mL/in²) of specimen surface, as stipulated in ASTM Standard G31, Laboratory Immersion Testing of Materials.

Method of Supporting Specimens The supporting device and container should not be affected by or cause contamination of the test solution. The method of supporting specimens will vary with the apparatus used for conducting the test but should be designed to insulate the specimens from each other physically and electrically and to insulate the specimens from any metallic container or supporting device used with the apparatus.

Shape and form of the specimen support should assure free contact of the specimen with the corroding solution, the liquid line, or the vapor phase, as shown in Fig. 28-3. If clad alloys are exposed, special procedures are required to ensure that only the cladding is exposed (unless the purpose is to test the ability of the cladding to protect cut edges in the test solution). Some common supports are glass or ceramic rods, glass saddles, glass hooks, fluorocarbon plastic strings, and various insulated or coated metallic supports.

Duration of Test Although the duration of any test will be determined by the nature and purpose of the test, an excellent procedure for evaluating the effect of time on corrosion of the metal and also on the corrosiveness of the environment in laboratory tests has been presented by Wachter and Treseder [*Chem. Eng. Prog.*, 315–326 (June 1947)]. This technique is called the **planned-interval test**. Other procedures that require the removal of solid corrosion products between exposure periods will not measure accurately the normal changes of corrosion with time.

Materials that experience severe corrosion generally do not need lengthy tests to obtain accurate corrosion rates. Although this assumption is valid in many cases, there are exceptions. For example, lead exposed to sulfuric acid corrodes at an extremely high rate at first while building a protective film; then the rate decreases considerably, so that further corrosion is negligible. The phenomenon of forming a protective film is observed with many corrosion-resistant materials, and therefore short tests on such materials would indicate high corrosion rates and would be completely misleading.

Short-time tests also can give misleading results on alloys that form passive films, such as stainless steels. With borderline conditions, a prolonged test may be needed to permit breakdown of the passive film and subsequently more rapid attack. Consequently, tests run for long periods are considerably more realistic than those conducted for short durations. This statement must be qualified by stating that corrosion should not proceed to the point at which the original specimen size or the exposed area is drastically reduced or the metal is perforated.

If anticipated corrosion rates are moderate or low, the following equation gives a suggested test duration:

$$\text{Duration of test, } h = \frac{78,740}{\text{corrosion rate, mm/y}}$$

$$= \frac{2000}{\text{corrosion rate, mils/y}}$$

Cleaning Specimens after Test Before specimens are cleaned, their appearance should be observed and recorded. Locations of deposits, variations in types of deposits, and variations in corrosion products are extremely important in evaluating localized corrosion such as pitting and concentration-cell attack.

Cleaning specimens after the test is a vital step in the corrosion-test procedure and, if not done properly, can give rise to misleading test results. Generally, the cleaning procedure should remove all corrosion products from specimens with a minimum removal of sound metal. Set rules cannot be applied to cleaning because procedures will vary with the type of metal being cleaned and the degree of adherence of corrosion products.

Mechanical cleaning includes scrubbing, scraping, brushing, mechanical shocking, and ultrasonic procedures. Scrubbing with a bristle brush and a mild abrasive is the most widely used of these methods; the others are used principally as supplements to remove heavily encrusted corrosion products before scrubbing. Care should be used to avoid the removal of sound metal.

Chemical cleaning implies the removal of material from the surface of the specimen by dissolution in an appropriate chemical agent. Solvents such as acetone, carbon tetrachloride, and alcohol are used to remove oil, grease, or resin and are usually applied prior to other methods of cleaning. Various chemicals are chosen for application to specific materials; some of these treatments in general use are outlined in the NACE standard.

Electrolytic cleaning should be preceded by scrubbing to remove loosely adhering corrosion products. One method of electrolytic cleaning that has been found to be useful for many metals and alloys is as follows:

Solution: 5 percent (by weight) H₂SO₄
 Anode: carbon or lead
 Cathode: test specimen
 Cathode current density: 20 A/dm² (129 A/in²)
 Inhibitor: 2 cm³ organic inhibitor per liter
 Temperature: 74°C (165°F)
 Exposure period: 3 min

Precautions must be taken to ensure good electrical contact with the specimen, to avoid contamination of the solution with easily reducible metal ions, and to ensure that inhibitor decomposition has not occurred. Instead of using 2 mL of any proprietary inhibitor, 0.5 g/L of inhibitors such as diorthotolyl thiourea or quinoline ethiodide can be used.

Whatever treatment is used to clean specimens after a corrosion test, its effect in removing metal should be determined, and the weight loss should be corrected accordingly. A “blank” specimen should be weighed before and after exposure to the cleaning procedure to establish this weight loss.

Evaluation of Results After the specimens have been reweighed, they should be examined carefully. Localized attack such as pits, crevice corrosion, stress-accelerated corrosion, cracking, or intergranular corrosion should be measured for depth and area affected.

Depth of localized corrosion should be reported for the actual test period and not interpolated or extrapolated to an annual rate. The rate of initiation or propagation of pits is seldom uniform. The size, shape, and distribution of pits should be noted. A distinction should be made between those occurring underneath the supporting devices (concentration cells) and those on the surfaces that were freely exposed to the test solution. An excellent discussion of pitting corrosion has been published [*Corrosion*, 25t (January 1950)].

The specimen may be subjected to simple bending tests to determine whether any **embrittlement** has occurred.

If it is assumed that localized or internal corrosion is not present or is recorded separately in the report, the **corrosion rate** or penetration can be calculated alternatively as

$$\frac{\text{Weight loss} \times 534}{(\text{Area})(\text{time})(\text{metal density})} = \text{mils/y (mpy)}$$

$$\frac{\text{Weight loss} \times 13.56}{(\text{Area})(\text{time})(\text{metal density})} = \text{mm/y (mmpy)}$$

where weight loss is in mg, area is in in² of metal surface exposed, time is in hours exposed, and density is in g/cm³. Densities for alloys can be obtained from the producers or from various metal handbooks.

The following **checklist** is a recommended guide for reporting all **important information and data**:

- Corrosive media and concentration (changes during test)
- Volume of test solution
- Temperature (maximum, minimum, and average)
- Aeration (describe conditions or technique)
- Agitation (describe conditions or technique)
- Type of apparatus used for test
- Duration of each test (start, finish)
- Chemical composition or trade name of metals tested
- Form and metallurgical conditions of specimens
- Exact size, shape, and area of specimens
- Treatment used to prepare specimens for test
- Number of specimens of each material tested and whether specimens were tested separately or which specimens were tested in the same container

Method used to clean specimens after exposure and the extent of any error expected by this treatment

Actual weight losses for each specimen

Evaluation of attack if other than general, such as crevice corrosion under support rod, pit depth and distribution, and results of microscopic examination or bend tests

Corrosion rates for each specimen expressed as millimeters (mils) per year

Effect of Variables on Corrosion Tests It is advisable to apply a factor of safety to the results obtained, the factor varying with the degree of confidence in the applicability of the results. Ordinarily, a factor of from 3 to 10 might be considered normal.

Among the more important points that should be considered in attempting to base plant design on laboratory corrosion-rate data are the following.

Galvanic corrosion is a frequent source of trouble on a large scale. Not only is the use of different metals in the same piece of equipment dangerous, but the effect of cold working may be sufficient to establish potential differences of objectionable magnitude between different parts of the same piece of metal. The mass of metal in chemical apparatus is ordinarily so great and the electrical resistance consequently so low that a very small voltage can cause a very high current. Welding also may leave a weld of a different physical or chemical composition from that of the body of the sheet and cause localized corrosion.

Local variations in temperature and crevices that permit the accumulation of corrosion products are capable of allowing the formation of **concentration cells**, with the result of accelerated local corrosion.

In the laboratory, the **temperature** of the test specimen is that of the liquid in which it is immersed, and the measured temperature is actually that at which the reaction is taking place. In the plant (heat being supplied through the metal to the liquid in many cases), the temperature of the film of (corrosive) liquid on the inside of the vessel may be a number of degrees higher than that registered by the thermometer. As the relation between temperature and corrosion is a logarithmic one, the rate of increase is very rapid. Like other chemical reactions, the speed ordinarily increases twofold to threefold for each 10°C temperature rise, the actual relation being that of the equation $\log K = A + (B/T)$, where K represents the rate of corrosion and T the absolute temperature. This relationship, although expressed mathematically, must be understood to be a qualitative rather than strictly a quantitative one.

Cold walls, as in coolers or condensers, usually have somewhat decreased corrosion rates for the reason just described. However, in some cases, the decrease in temperature may allow the formation of a more corrosive second phase, thereby increasing corrosion.

The effect of **impurities** in either structural material or corrosive material is so marked (while at the same time it may be either accelerating or decelerating) that for reliable results the actual materials which it is proposed to use should be tested and not types of these materials. In other words, it is much more desirable to test the actual plant solution and the actual metal or nonmetal than to rely upon a duplication of either. Since as little as 0.01 percent of certain organic compounds will reduce the rate of solution of steel in sulfuric acid 99.5 percent and 0.05 percent bismuth in lead will increase the rate of corrosion over 1000 percent under certain conditions, it can be seen how difficult it would be to attempt to duplicate here all the significant constituents.

Electrical Resistance The measurement of corrosion by electrical resistance is possible by considering the change in resistance of a thin metallic wire or strip sensing element (probe) as its cross section decreases from a loss of metal. Since small changes in resistance are encountered as corrosion progresses, changes in temperature can cause enough change in the wire resistance to complicate the results. Commercial equipment, such as the Corrosometer[®], have a protected reference section of the specimen in the modified electrical Wheatstone bridge (Kelvin) circuit to compensate for these temperature changes. Since changes in the resistance ratio of the probe are not linear with loss of section thickness, compensation for this variable must be included in the circuit. In operation, the specimen probe is exposed to the environment and instrument readings are periodically

recorded. The corrosion rate is the loss of metal averaged between any two readings.

The corrosion rate can be studied by this method over very short periods of time, but not instantaneously. The environment does not have to be an electrolyte. Studies can be made in corrosive gas exposures. The main disadvantage of the technique is that local corrosion (pitting, crevice corrosion, galvanic, stress corrosion cracking, fatigue, and so forth) will probably not be progressively identified. If the corrosion product has an electrical conductivity approaching that of the lost metal, little or no corrosion will be indicated. The same problem will result from the formation of conducting deposits on the specimen.

The electrical-resistance measurement has nothing to do with the electrochemistry of the corrosion reaction. It merely measures a bulk property that is dependent upon the specimen's cross-section area. Commercial instruments are available (Fig. 28-5).

Advantages of the electrical-resistance technique are:

1. A corrosion measurement can be made without having to see or remove the test sample.
2. Corrosion measurements can be made quickly—in a few hours or days, or continuously. This enables sudden increases in corrosion rate to be detected. In some cases, it will be possible then to modify the process to decrease the corrosion.
3. The method can be used to monitor a process to indicate whether the corrosion rate is dependent on some critical process variable.
4. Corrodent need not be an electrolyte (in fact, need not be a liquid).
5. The method can detect low corrosion rates that would take a long time to detect with weight-loss methods.

Limitations of the technique are:

1. It is usually limited to the measurement of uniform corrosion only and is not generally satisfactory for localized corrosion.
2. The probe design includes provisions to compensate for temperature variations. This feature is not totally successful. The most reliable results are obtained in constant-temperature systems.

EMF versus pH (Pourbaix) Diagrams Potential (EMF) versus pH equilibrium (Pourbaix) diagrams derived from physical property data about the metal and its environment provide a basis for the expression of a great amount of thermodynamic data about the corrosion reaction. These relatively simple diagrams graphically represent the thermodynamics of corrosion in terms of electromotive force, that is, an indication of oxidizing power and pH, or acidity. As an aid in corrosion prediction, their usefulness lies in providing direction for establishing a corrosion study program.

Figure 28-6 is a typical Pourbaix diagram. Generally, the diagrams show regions of immunity (the metal), passivity (the surface film), and corrosion (metallic ions). While of considerable qualitative usefulness, these diagrams have important limitations. Since they are calculated from thermodynamic properties, they represent equilibrium conditions and do not provide kinetic information. Thus, while they show conditions where corrosion will not occur, they do not necessarily indicate under what conditions corrosion will occur. To determine the quantitative value of corrosion, kinetic rate measurement would still be required. Pourbaix diagrams were developed for the study of pure metals. Since few engineering structures are made of pure metals, it is

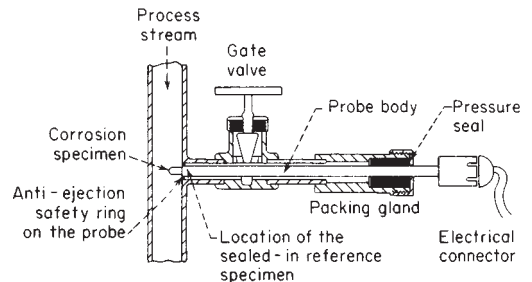


FIG. 28-5 Typical retractable corrosion probe.

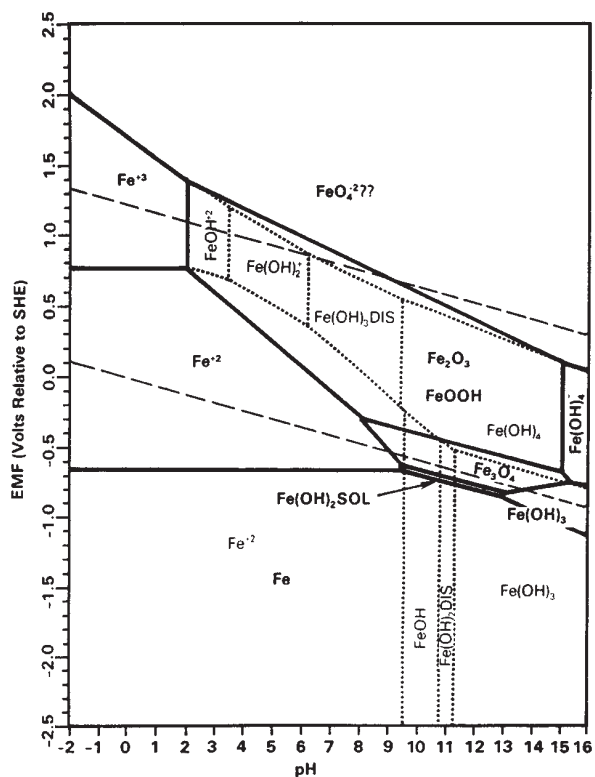


FIG. 28-6 EMF-pH diagram for an iron-water system at 25°C. All ions are at an activity of 10^{-6} .

important to extend this technique to include information on the passive behavior of alloys of engineering interest. Values of the open circuit corrosion potential (OCP) or a controlled potential occur, if a steady site potential can be used in conjunction with the solution pH and these diagrams to show what component is stable in the system defined by a given pH and potential. Theoretical diagrams so developed estimate the corrosion product in various regions. The use of computers to construct diagrams for alloy systems provides an opportunity to mathematically overcome many of the limitations inherent in the pure metal system.

A potentiokinetic electrochemical hysteresis method of diagram construction has led to consideration of three-dimensional Pourbaix diagrams for alloy systems useful in alloy development, evaluation of the influence of crevices, prediction of the tendency for dealloying, and the inclusion of kinetic data on the diagram is useful in predicting corrosion rather than just the absence of damage. These diagrams are kinetic, not thermodynamic, expressions. The two should not be confused as being the same reaction, as they are not.

Tafel Extrapolation Corrosion is an electrochemical reaction of a metal and its environment. When corrosion occurs, the current that flows between individual small anodes and cathodes on the metal surface causes the electrode potential for the system to change. While this current cannot be measured, it can be evaluated indirectly on a metal specimen with an inert electrode and an external electrical circuit. Polarization is described as the extent of the change in potential of an electrode from its equilibrium potential caused by a net current flow to or from the electrode, galvanic or impressed (Fig. 28-7).

Electrochemical techniques have been used for years to study fundamental phenomenological corrosion reactions of metals in corrosive environments. Unfortunately, the learning curve in the reduction of these electrochemical theories to practice has been painfully slow. However, a recent survey has shown that many organizations in the

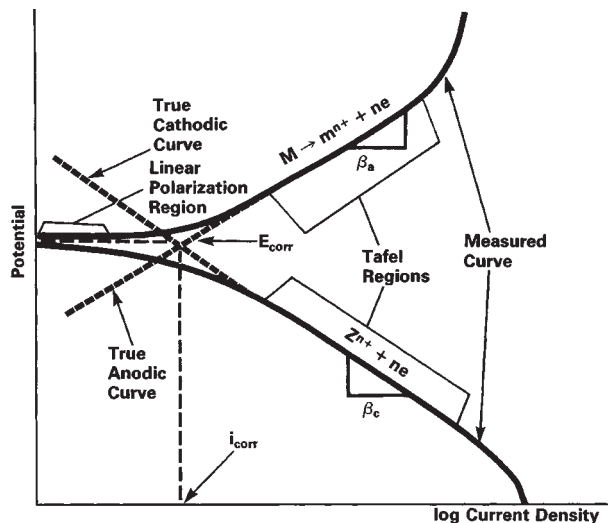


FIG. 28-7 Tafel extrapolation and linear polarization curves.

chemical process industries are now adding electrochemical methods to their materials selection techniques. Laboratory electrochemical tests of metal/environment systems are being used to show the degree of compatibility and describe the limitations of those relationships. The general methods being used include electrical resistance, Tafel extrapolation, linear polarization, and both slow and rapid-scan potentiodynamic polarization. Depending upon the study technique used, it has also been possible to indicate the tendency of a given system to suffer local pitting or crevice attack or both. These same tools have been the basis of design protection of less-noble structural metals.

To study the anode reaction of a specimen in an environment, sufficient current is applied to change the freely corroding potential of the metal in a more electropositive direction with respect to the inert electrode (acting as a cathode). The opposite of this so-called anodic polarization is cathodic polarization. Polarization can be studied equally well by varying the potential and measuring the resultant changes in the current. Both of the theoretical (true) polarization curves are straight lines when plotted on a semilog axis. The corrosion current can be measured from the intersection of the corrosion potential and either the anodic or cathodic curve. The corrosion rate of the system is a function of that corrosion current. Experimentally derived curves are not fully linear because of the interference from the reactions between the anodes and cathodes in the region close to the corrosion potential. IR losses often obscure the Tafel behavior. Away from the corrosion potential, the measured curves match the theoretical (true) curves. The matching region of the measured curves is called the **Tafel region**, and their (Tafel) slopes are constant. Corrosion rates can be calculated from the intersection of the corrosion potential and the extrapolation of the Tafel region. The main advantage of the technique is that it is quick; curves can be generated in about an hour.

The technique is of limited value where more than one cathodic reduction reaction occurs. In most cases it is difficult to identify a sufficient linear segment of the Tafel region to extrapolate accurately. Since currents in the Tafel region are one to two orders of magnitude larger on the log scale than the corrosion current, relatively large currents are required to change the potentials from what they are at the corrosion potential. The environment must be a conductive solution. The Tafel technique does not indicate local attack, only an average, uniform corrosion rate.

The primary use of this laboratory technique today is as a quick check to determine the order of magnitude of a corrosion reaction. Sometimes the calculated rate from an immersion test does not "look" correct when compared to the visual appearance of the metal coupon.

While the specific corrosion rate number determined by Tafel extrapolation is seldom accurate, the method remains a good confirmation tool.

Linear Polarization Some of the limitations of the Tafel extrapolation method can be overcome by using the linear-polarization technique to determine the corrosion rate. A relationship exists between the slope of the polarization curves E/I (with units of resistance, linear polarization is sometimes termed *polarization resistance*) and instantaneous corrosion rates of a freely corroding alloy. The polarization resistance is determined by measuring the amount of applied current needed to change the corrosion potential of the freely corroding specimen by about 10-mV deviations. The slope of the curves thus generated is directly related to the corrosion rate by Faraday's law. Several instruments are available that are used in linear polarization work. The main advantage is that each reading on the instrument can be translated directly into a corrosion rate.

As with all electrochemical studies, the environment must be electrically conductive. The corrosion rate is directly dependent on the Tafel slope. The Tafel slope varies quite widely with the particular corroding system and generally with the metal under test. As with the Tafel extrapolation technique, the Tafel slope generally used is an assumed, more or less average value. Again, as with the Tafel technique, the method is not sensitive to local corrosion.

The amount of externally applied current needed to change the corrosion potential of a freely corroding specimen by a few millivolts (usually 10 mV) is measured. This current is related to the corrosion current, and therefore the corrosion rate, of the sample. If the metal is corroding rapidly, a large external current is needed to change its potential, and vice versa.

The measuring system consists of four basic elements:

1. **Electrodes.** Test and reference electrodes and, in some cases, an auxiliary electrode.
2. **Probe.** It connects the electrodes in the corrodent on the inside of a vessel to the electrical leads.
3. **Electrical leads.** They run from the probe to the current source and instrument panel.
4. **Control system.** Current source (batteries), ammeter, voltmeter, instrument panel, and so on.

Commercial instruments have either two or three electrodes. Also, there are different types of three-electrode systems. The application and limitations of the instruments are largely dependent upon these electrode systems.

Potentiodynamic Polarization Not all metals and alloys react in a consistent manner in contact with corrosive fluids. One of the common intermediate reactions of a metal (surface) is with oxygen, and those reactions are variable and complex. Oxygen can sometimes function as an electron acceptor; that is, oxygen can act as an oxidizing agent, and remove the "protective" film of hydrogen from the cathodic area, **cathodic depolarization**. The activation energy of the oxygen/hydrogen reaction is very large. This reaction does not normally occur at room temperature at any measureable rate. In other cases, oxygen can form protective oxide films. The long-term stability of these oxides also varies; some are soluble in the environment, others form more stable and inert or passive films.

Because corrosion is an electrochemical process, it is possible to evaluate the overall reaction by the use of an external electrical circuit called a **potentiostat**. When corrosion occurs, a potential difference exists between the metal and its ions in solution. It is possible to electrically control this potential; changes in potential cause changes in current (corrosion). Oxidation is a reaction with a loss of electrons (anodic—the reacting electrode is the anode); reduction is a reaction with a gain of electrons (cathodic—the reacting electrode is the cathode). Rather than allowing the electrons being evolved from the corrosion reaction to combine with hydrogen, these electrons can be removed by internal circuitry, and sent through a potentiostat, causing a cathodic (or anodic) reaction to occur at a platinum counter electrode. This is always true for the external polarization method; it is not unique for a potentiostat.

It is now well established that the activity of pitting, crevice corrosion, and stress-corrosion cracking is strongly dependent upon the corrosion potential (i.e., the potential difference between the corroding

metal and a suitable reference electrode). By using readily available electronic equipment, the quantity and direction of direct current required to control the corrosion potential in a given solution at a given selected value can be measured. A plot of such values over a range of potentials is called a polarization diagram. By using proper experimental techniques, it is possible to define approximate ranges of corrosion potential in which pitting, crevice corrosion, and stress-corrosion cracking will or will not occur. With properly designed probes, these techniques can be used in the field as well as in the laboratory.

The potentiostat has a three-electrode system: a reference electrode, generally a saturated calomel electrode (SCE); a platinum counter, or auxiliary, electrode through which current flows to complete the circuit; and a working electrode that is a sample of interest (Fig. 28-8). The potentiostat is an instrument that allows control of the potential, either holding constant at a given potential, stepping from potential to potential, or changing the potential anodically or cathodically at some linear rate.

In the study of the anode/cathode polarization behavior of a metal/environment system, the potentiostat provides a plot of the relationship of current changes resulting from changes in potential most often presented as a plot of log current density versus potential, or Evans diagram. A typical active/passive metal anodic polarization curve is seen in Fig. 28-9, generally showing the regions of active corrosion and passivity and a transpassive region.

Scan Rates Sweeping a range of potentials in the anodic (more electropositive) direction of a potentiodynamic polarization curve at a high scan rate of about 60 V/h (high from the perspective of the corrosion engineer, slow from the perspective of a physical chemist) is to indicate regions where intense anodic activity is likely. Second, for otherwise identical conditions, sweeping at a relatively slow rate of potential change of about 1 V/h will indicate regions wherein relative inactivity is likely. The rapid sweep of the potential range has the object of minimizing film formation, so that the currents observed relate to relatively film-free or thin-film conditions. The object of the slow sweep rate experiment is to allow time for filming to occur. A zero scan rate provides the opportunity for maximum stability of the metal surface, but at high electropositive potentials the environment could be affected or changed. A rapid scan rate compromises the steady-state nature of the metal surface but better maintains the stability of the environment. Whenever possible, corrosion tests should be conducted using as many of the techniques available, potentiodynamic polarization at various scan rates, crevice, stress, velocity, and so

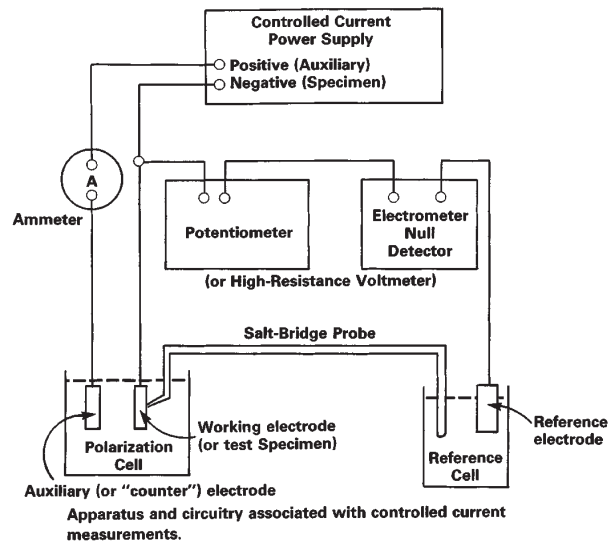


FIG. 28-8 The potentiostat apparatus and circuitry associated with controlled potential measurements of polarization curves.

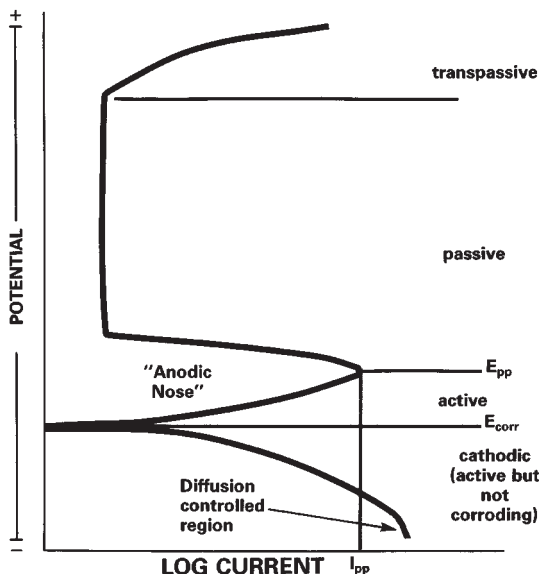


FIG. 28-9 Typical electrochemical polarization curve for an active/passive alloy (with cathodic trace) showing active, passive, and transpassive regions and other important features. (NOTE: E_{pp} = primary passive potential, E_{corr} = free corrosion potential).

forth. An evaluation of these several results, on a holistic basis, can greatly reduce or temper their individual limitations.

Slow-Scan Technique In ASTM G5 "Polarization Practice for Standard Reference Method for Making Potentiostatic and Potentiodynamic Anodic Polarization Measurements," all oxygen in the test solution is purged with hydrogen for a minimum of 0.5 h before introducing the specimen. The test material is then allowed to reach a steady state of equilibrium (open circuit corrosion potential, E_{corr}) with the test medium before the potential scan is conducted. Starting the evaluation of a basically passive alloy that is already in its "stable" condition precludes any detailed study of how the metal reaches that protected state (the normal intersection of the theoretical anodic and cathodic curves is recorded as a zero applied current on the ASTM potentiostatic potential versus applied current diagram). These intersections between the anodic and cathodic polarization curves are the condition where the total oxidation rate equals the total reduction rate (ASTM G3 "Recommended Practice for Conventions Applicable to Electrochemical Measurements in Corrosion Testing").

Three general reaction types compare the activation-control reduction processes. In Fig. 28-10, in Case 1, the single reversible corrosion potential (anode/cathode intersection) is in the active region. A wide range of corrosion rates is possible. In Case 2, the cathodic curve intersects the anodic curve at three potentials, one active and two passive. If the middle active/passive intersection is not stable, the lower and upper intersections indicate the possibility of very high corrosion rates. In Case 3, corrosion is in the stable, passive region, and the alloys generally passivate spontaneously and exhibit low corrosion rates. Most investigators report that the ASTM method is effective for studying Case 1 systems. An alloy-medium system exhibiting Case 2 and 3 conditions generally cannot be evaluated by this conventional ASTM method.

The potentiodynamic polarization electrochemical technique can be used to study and interpret corrosion phenomena. It may also furnish useful information on film breakdown or repair.

Rapid-Scan Corrosion Behavior Diagram (CBD) Basically, all the same equipment used in the conductance of an ASTM G5 slow-scan polarization study is used for rapid-scan CBDs (that is, a standard test cell, potentiostat, voltmeters, log converters, X-Y recorders, and electronic potential scanning devices). The differences

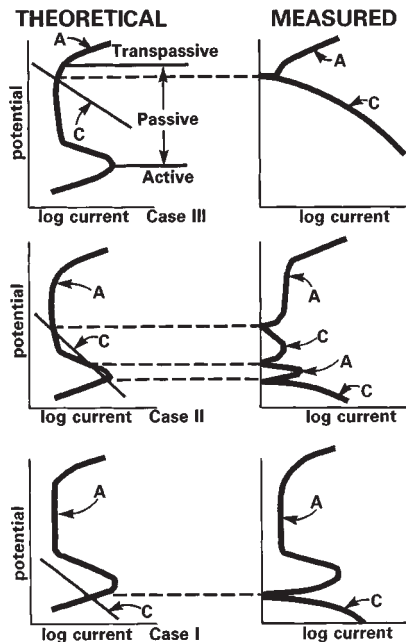


FIG. 28-10 Six possible types of behavior for an active/passive alloy in a corrosive environment.

are in technique: the slow scan is run at a potential sweep rate of about 0.6 V/h; the rapid-scan CBDs at about 50 V/h.

In the conductance of rapid-scan CBDs, the test specimen is mechanically and chemically cleaned immediately before immersion in the test cell. Without any further delay, a cathodic polarization scan is made at a sweep rate of about 50 V/h (compared to the 0.6 V/h for the ASTM method). This rapid cathodic charging (hydrogen evolution) further cleans the specimen of oxygen so that the subsequent anodic polarization enables a full study of how the corrosion reaction progresses as the potential is changed potentiodynamically in the more noble (positive) direction without the interference of any pre-existing passive or corrosion product film or scale. The test is run open to the atmosphere without any purge gas, and the rapid scan rate permits completion of the anodic curve before oxygen is replenished. This cathodic cleaning further activates the specimen and allows it to follow the pattern of its corrosion reaction(s) before it has an opportunity to spontaneously passivate or return to equilibrium with its environment.

Different from the slow-scan technique, which is generally limited to Case 1 alloy/medium systems, the rapid-scan technique allows full anodic polarization study of alloys showing all Case 1, 2, and 3 behavior. In Case 1, the single reversible corrosion potential (the anode/cathode intersection) is in the active region. A wide range of corrosion rates is possible. In Case 2, the cathodic curve intersects the anodic curve at three potentials, one in the active region and two in the passive. Since the middle active/passive intersection is not stable, the intersections indicate the possibility of very high corrosion rates depending on the environment or even slight changes to the exposure/environment system. In Case 3, the curves intersect in the most stable, passive region; the alloys generally passivate spontaneously and exhibit low corrosion rates. Case 2 exhibits the most corrosion, is difficult to study, and presents the most risk for materials of construction selection. Anything that can change the oxygen solubility of the oxidizing agent can alter the corrosion reaction. Seemingly identical environmental conditions from one day to another, from one laboratory or plant to another, and so forth, can give rise to widely differing results. Those desiring a more detailed review of the subject are directed to the works of Pourbaix, Edeleanu, and other studies referred to in their publications.

The test to generate a CBD is generally as follows. At a rapid scan rate of about 50 V/h, the clean specimen is cathodically charged (polarized) starting at an electronegative position (with respect to SCE) that will produce a current density of $10^4 \mu\text{A}/\text{cm}^2$ (nickel, chromium, and iron alloys in aggressive environments) and proceed in a noble (positive) direction. After completing the cathodic curve, proceed anodically until the current density reaches $10^3 \mu\text{A}/\text{cm}^2$. The scan direction is reversed and potentials/currents recorded back to the starting point. The potentiostat is then shut off. The freely corroding potential (FCP), also referred to as the open circuit potential (OCP), is recorded after 10 min or when it is stable; that is, when the potential value remains constant. A third cathodic polarization curve is then generated by scanning from the corrosion potential in the negative direction to iron, again at a scan rate of 50 V/h. As noted earlier, this diagram can be produced in about 15 min; see Fig. 28-11.

The CBD diagram can provide various kinds of information about the performance of an alloy/medium system. The technique can be used for a direct calculation of the corrosion rate as well as for indicating the conditions of passivity and tendency of the metal to suffer local pitting and crevice attack.

Corrosion Rate by CBD Somewhat similarly to the Tafel extrapolation method, the corrosion rate is found by intersecting the extrapolation of the linear portion of the second cathodic curve with the equilibrium stable corrosion potential. The intersection corrosion current is converted to a corrosion rate (mils penetration per year [mpy], 0.001 in/y) by use of a conversion factor (based upon Faraday's law, the electrochemical equivalent of the metal, its valence and gram atomic weight). For 13 alloys, this conversion factor ranges from 0.42 for nickel to 0.67 for Hastelloy B or C. For a quick determination, 0.5 is used for most Fe, Cr, Ni, Mo, and Co alloy studies. Generally, the accuracy of the corrosion rate calculation is dependent upon the degree of linearity of the second cathodic curve; when it is less than 0.5 decade long, it becomes more difficult to extrapolate accurately. Obviously, the longer the better.

Expected Order of Magnitude of Corrosion by CBD The third cathodic curve will generally fall between the first two, or the first and third will coincide and fall positive to the second curve. These two curve configurations are only valid relationships for the projection

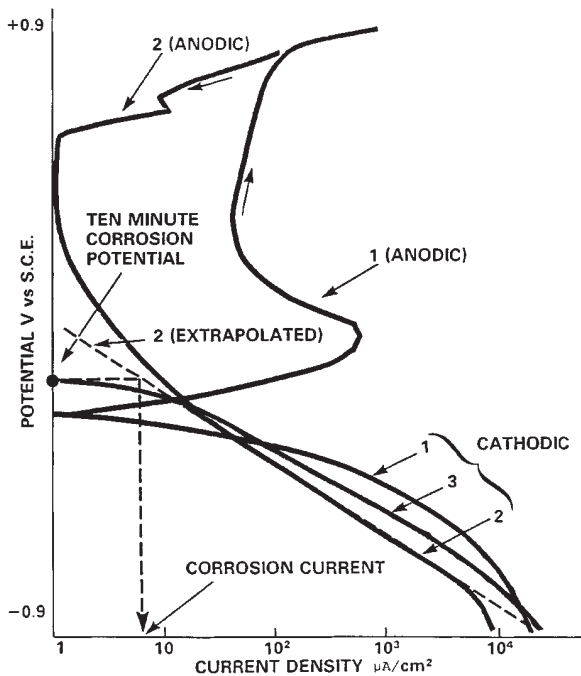


FIG. 28-11 Corrosion behavior diagram (CBD).

of accurate corrosion rates. When, however, the second or third curve falls positive to the other two curves, a very high corrosion rate may be indicated. Another possibility is that the second or third curve in this positive position is not controlling corrosion because of surface films and so forth.

Spontaneous Passivation The anodic nose of the first curve describes the primary passive potential E_{pp} and critical anodic current density (the transition from active to passive corrosion). If the initial active/passive transition is $10^3 \mu\text{A}/\text{cm}^2$ or less, the alloy will spontaneously passivate in the presence of oxygen or any strong oxidizing agent.

Anodic Protection On the reverse anodic scan there will be a low current region (LCR) in the passive range. The passive potential range of the LCR is generally much narrower than the passive region seen on a forward slow scan. In anodic protection (AP) work the midpoint of the LCR potential is the preferred design range. This factor was verified for sulfuric acid in our laboratory and field studies.

Pitting and Crevice Corrosion The general literature for predicting pitting tendency with the slow scan reviews the use of the reverse scan: If a hysteresis loop develops that comes back to the repassivation potential E_{repass} below the FCP (E_{corr}) the alloy will pit at crevices, when the value of the repassivation potential, identified by the return of the hysteresis loop, is above the FCP (E_{corr}), the pits will tend to grow. These rules of thumb have been expanded for rapid-scan.

1. If E_{corr} is equal to or greater than the pitting potential E_{pit} , both pitting and crevice-type attack are likely to occur on the specimen in an immersion test.
2. If E_{corr} is less than E_{pit} , pitting-type attack of the specimen is unlikely in an immersion test.
3. If the repassivation potential E_{repass} is greater than E_{corr} , crevice-type attack is possible in an immersion test.
4. If E_{corr} is equal to or larger than E_{repass} , crevice-type attack is probably in an immersion test.
5. If no E_{pit} can be determined, but cathodic Curves 1 and 2 cross at E_x forming a hysteresis loop, crevice-type attack during the rapid scan is indicated.
6. If E_x is equal to or greater than E_{pit} , pitting-type attack will be predominant during the rapid-scan test.
7. If E_{pit} is equal to or greater than E_x plus 100 mV, crevice-type attack is indicated during the rapid-scan test.
8. If the plot of Curve 1 continues from E_{pit} with a large increase in current density versus a small increase in voltage, the test specimen will suffer vigorous local attack during the rapid-scan test.
9. If the Curve 1, positive with respect to the value of E_{pit} , plots with a small increase in current density per large increase in voltage, the test specimen in the rapid-scan test will suffer only mild local attack (ASTM G31).

Scan Rates: Advantages versus Disadvantages As to the question of disadvantages of using the rapid-scan CBD, we believe it is more a case of looking to the limitations of the various benefits. In many of the places where these limitations to the use of the CBD show themselves, where the limitation provides information, for example, the corrosion rate will be too high, and so forth. Only in the case of interpretation of unstable active/passive conditions do we see the results of the rapid scan as a possible weakness of the technique (but it is not handled any better by other techniques). When the FCP is noble (positive) to the primary passive potential E_{pp} , the alloy is passive; when the FCP is active (negative) to the E_{pp} , the alloy will corrode in the active state; and when the FCP is only slightly more noble (positive) than the E_{pp} , the alloy could show active/passive tendencies. When the FCP oscillates and will not stabilize, the potential should be plotted against time. The alloy will probably not be resistant without AP but in these latter two cases, the CBD does not tell for sure.

Logic Sequence Diagram In order to expedite the interpretation of the 50.0-V/h anodic polarization data, three logic sequence diagrams (LSDs) were constructed (Figs. 28-12 through 28-14). These diagrams can be linked to each other to provide a more complete analysis of behavior if necessary. These LSDs contain benchmark values that have been derived from conducting more than 10,000 potentiodynamic experiments at scan rates of either 50.0 or 60.0 V/h.

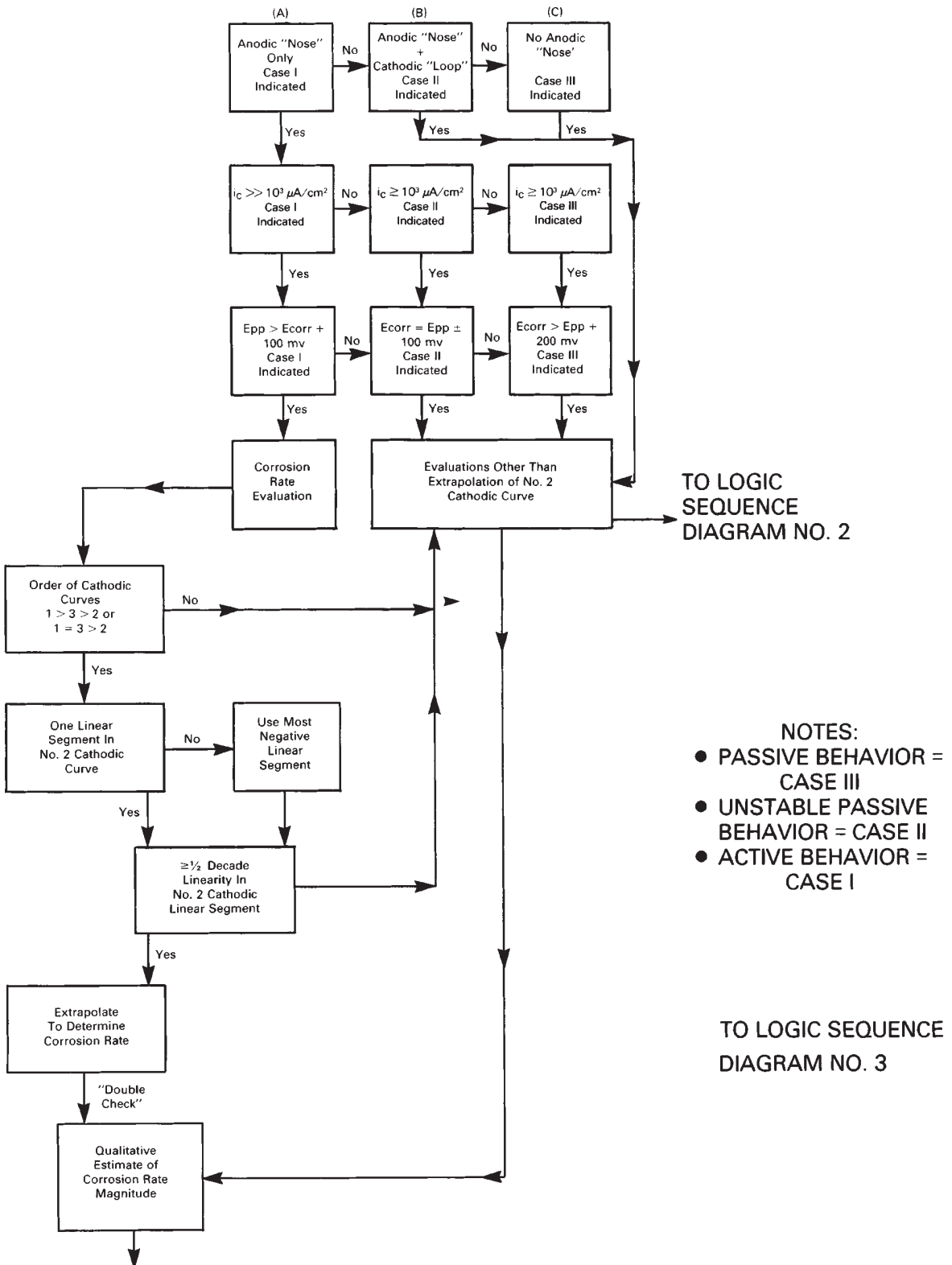


FIG. 28-12 Logic sequence Diagram 1 used to determine behavior type (Case 1, 2, and 3) and corrosion rate from a CBD.

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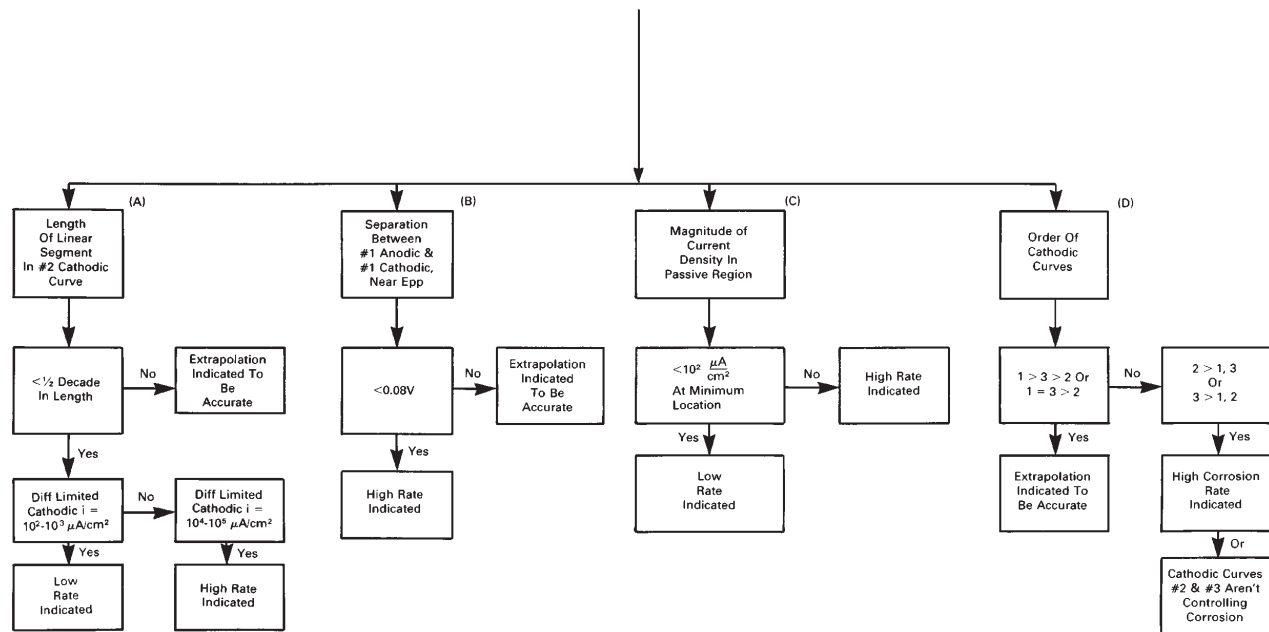


FIG. 28-13 Logic sequence Diagram 2 used to evaluate localized corrosion resistance from a CBD.

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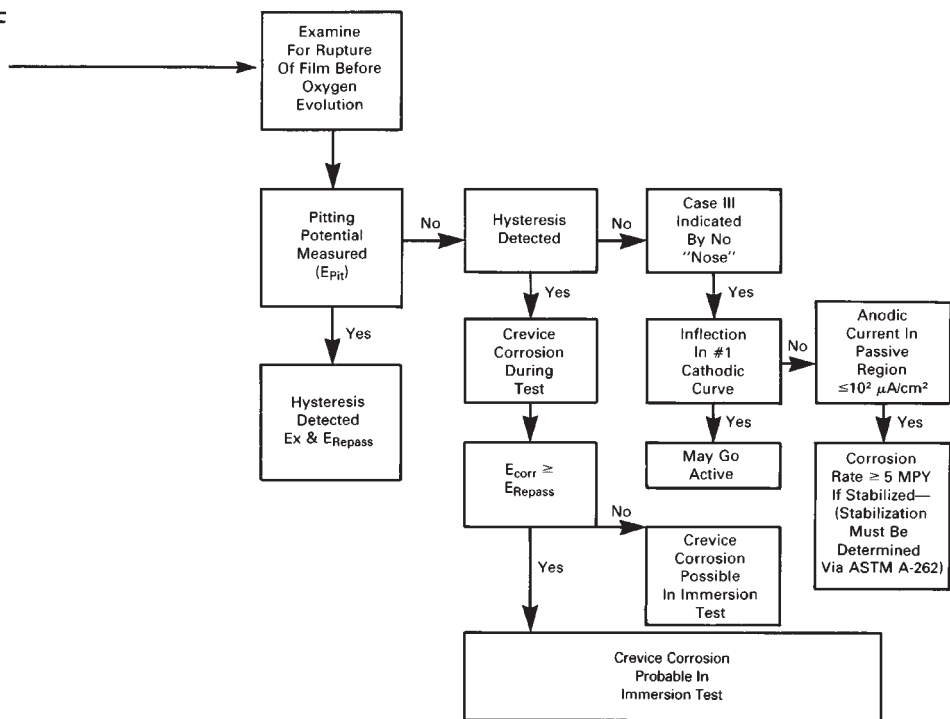


FIG. 28-14 Logic sequence Diagram 3 used to qualitatively evaluate the degree of corrosion for systems that cannot be evaluated by extrapolation of the cathodic polarization Curve 2 from a CBD.

Crevice Corrosion Prediction The most common type of localized corrosion is the occluded mode crevice corrosion. Pitting can, in effect, be considered a self-formed crevice. A crevice must be wide enough to permit liquid entry, but sufficiently narrow to maintain a stagnant zone. It is nearly impossible to build equipment without mechanical crevices; on a microlevel, scratches can be sufficient crevices to initiate or propagate corrosion in some metal/environment systems. The conditions in a crevice can, with time, become a different and much more aggressive environment than those on a nearby, clean, open surface. Crevices may also be created by factors foreign to the original system design, such as deposits, corrosion products, and so forth. In many studies, it is important to know or to be able to evaluate the crevice corrosion sensitivity of a metal to a specific environment and to be able to monitor a system for predictive maintenance.

Historically, the immersion test technique involved the use of a crevice created by two metal test specimens clamped together or a metal specimen in contact with an inert plastic or ceramic. The Materials Technology Institute of the Chemical Process Industries, Inc. (MTI) funded a study that resulted in an electrochemical cell to monitor crevice corrosion. It consists of a prepared crevice containing an anode that is connected through a zero-resistance ammeter to a freely exposed cathode. A string bridge provides a solution path that is attached externally to the cell. The electrochemical cell is shown in Fig. 28-15. A continuous, semiquantitative, real-time indication of crevice corrosion is provided by the magnitude of the current flowing between an anode and a cathode, and a qualitative signal is provided by shifts in electrode potential. Both the cell current and electrode potential produced by the test correlate well with the initiation and propagation of crevice corrosion. During development of the MTI test technique, results were compared with crevice corrosion produced by a grooved TFE Teflon® plastic disk sandwich-type crevice cell. In nearly every instance, corrosion damage on the anode was similar in severity to that produced by the sandwich-type cell.

Velocity For corrosion to occur, an environment must be brought into contact with the metal surface and the metal atoms or ions must be allowed to be transported away. Therefore, the rate of transport of the environment with respect to a metal surface is a major factor in the corrosion system. Changes in velocity may increase or decrease attack depending on its effect involved. A varying quantity of dissolved gas may be brought in contact with the metal, or velocity changes may

alter diffusion or transfer of ions by changing the thickness of the boundary layer at the surface. The boundary layer, which is not stagnant, moves except where it touches the surface. Many metals depend upon the development of a protective surface for their corrosion resistance. This may consist of an oxide film, a corrosion product, an adsorbed film of gas, or other surface phenomena. The removal of these surfaces by effect of the fluid velocity exposes fresh metal, and as a result, the corrosion reaction may proceed at an increasing rate. In these systems, corrosion might be minimal until a so-called **critical velocity** is attained where the protective surface is damaged or removed and the velocity is too high for a stable film to reform. Above this critical velocity, the corrosion may increase rapidly.

The NACE Landrum Wheel velocity test, originally TM0270-72, is typical of several mechanical-action immersion test methods to evaluate the effects of corrosion. Unfortunately, these laboratory simulation techniques did not consider the fluid mechanics of the environment or metal interface, and service experience very seldom supports the test predictions. A rotating cylinder within a cylinder electrode test system has been developed that operates under a defined hydrodynamics relationship (Figs. 28-16 and 28-17). The assumption is that if the rotating electrode operates at a shear stress comparable to that in plant geometry, the mechanism in the plant geometry may be modeled in the laboratory. Once the mechanism is defined, the appropriate relationship between fluid flow rate and corrosion rate in the plant equipment as defined by the mechanism can be used to predict the expected corrosion rate. If fluid velocity does affect the corrosion rate, the degree of mass transfer control, if that is the controlling mechanism (as opposed to activation control), can be estimated. Conventional potentiodynamic polarization scans are conducted as described previously. In other cases, the corrosion potential can be monitored at a constant velocity until steady state is attained. While the value of the final corrosion potential is virtually independent of velocity, the time to reach steady state may be dependent on velocity. The mass-transfer control of the corrosion potential can be proportional to the velocity raised to its appropriate exponent. The rate of breakdown of a passive film is velocity-sensitive.

Environmental Cracking The problem of environmental cracking of metals and their alloys is very important. Of all the failure mechanism tests, the test for stress corrosion cracking (SCC) is the most illusive. Stress corrosion is the acceleration of the rate of corrosion damage by static stress. SCC, the limiting case, is the spontaneous cracking that may result from combined effects of stress and corrosion. It is important to differentiate clearly between **stress corrosion cracking** and **stress accelerated corrosion**. Stress corrosion cracking is considered to be limited to cases in which no significant corrosion damage occurs in the absence of a corrosive environment. The material exhibits normal mechanical behavior under the influence of stress; before the development of a stress corrosion

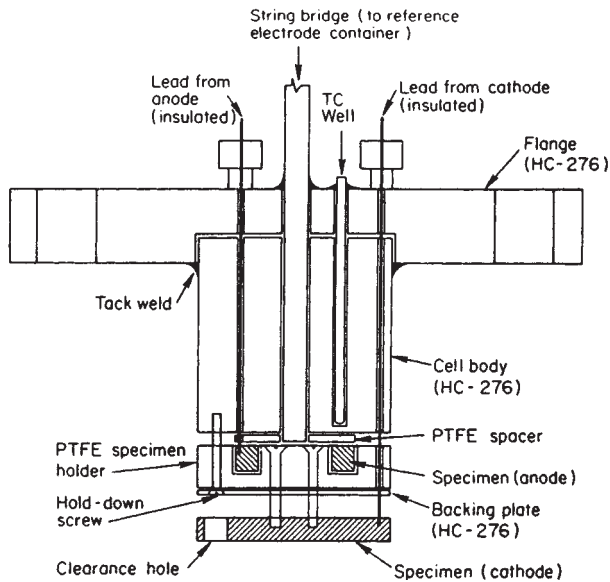


FIG. 28-15 Schematic diagram of the electrochemical cell used for crevice corrosion testing. Not shown are three hold-down screws, gas inlet tube, and external thermocouple tube.

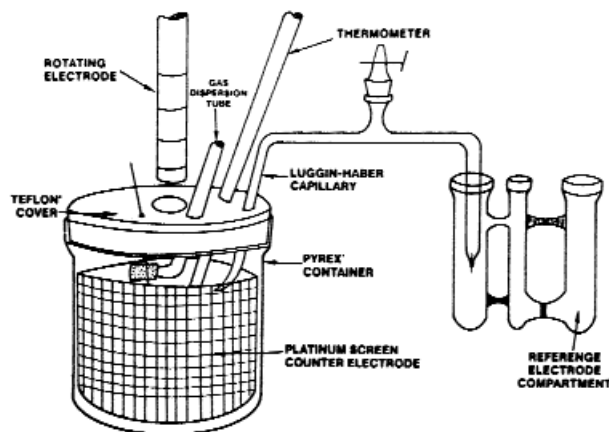


FIG. 28-16 Rotating cylinder electrode apparatus.

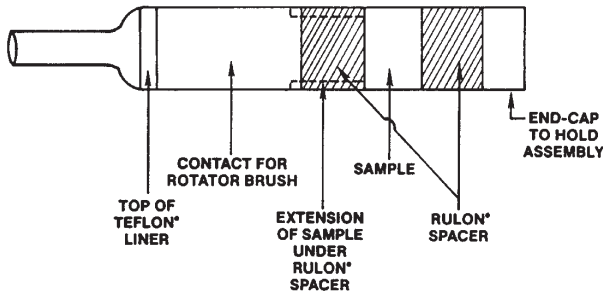


FIG. 28-17 Inner rotating cylinder used in laboratory apparatus of Fig. 28-16.

crack, there is little deterioration of strength and ductility. Stress corrosion is the case of an interaction between chemical reaction and mechanical forces that results in structural failure that otherwise would not occur. SCC is a type of brittle fracture of a normally ductile material by the interaction between specific environments and mechanical forces, for example, tensile stress. Stress corrosion cracking is an incompletely understood corrosion phenomenon. Much research activity (aimed mostly at mechanisms) plus practical experience has allowed crude empirical guidelines, but these contain a large element of uncertainty. No single chemical, structural, or electrochemical test method has been found to respond with enough consistent reproducibility to known crack-causing environmental/stressed metal systems to justify a high confidence level.

As was cited in the case of immersion testing, most SCC test work is accomplished using mechanical, nonelectrochemical methods. It has been estimated that 90 percent of all SCC testing is handled by one of the following methods: (1) constant strain, (2) constant load, or (3) precracked specimens. Prestressed samples, such as are shown in Fig. 28-18, have been used for laboratory and field SCC testing. The variable observed is "time to failure or visible cracking." Unfortunately, such tests do not provide acceleration of failure.

Since SCC frequently shows a fairly long induction period (months to years), such tests must be conducted for very long periods before reliable conclusions can be drawn.

In the constant-strain method, the specimen is stretched or bent to a fixed position at the start of the test. The most common shape of the specimens used for constant-strain testing is the U-bend, hairpin, or horseshoe type. A bolt is placed through holes in the legs of the specimen, and it is loaded by tightening a nut on the bolt. In some cases, the stress may be reduced during the test as a result of creep. In the constant-load test the specimen is supported horizontally at each end

and is loaded vertically downward at one or two points and has maximum stress over a substantial length or area of the specimen. The load applied is a predetermined, fixed dead weight. Specimens used in either of these tests may be precracked to assign a stress level or a desired location for fracture to occur or both as is used in fracture mechanics studies. These tensile-stressed specimens are then exposed in situ to the environment of study.

Slow Strain-Rate Test In its present state of development, the results from slow strain-rate tests (SSRT) with electrochemical monitoring are not always completely definitive; but, for a short-term test, they do provide considerable useful SCC information. Work in our laboratory shows that the SSRT with electrochemical monitoring and the U-bend tests are essentially equivalent in sensitivity in finding SCC. The SSRT is more versatile and faster, providing both mechanical and electrochemical feedback during testing.

The SSRT is a test technique where a tension specimen is slowly loaded in a test frame to failure under prescribed test conditions. The normal test extension rates are from 2.54×10^{-7} to 2.54×10^{-10} m/s (10^{-5} to 10^{-8} in/s). Failure times are usually 1 to 10 days. The failure mode will be either SCC or tensile overload, sometimes accelerated by corrosion. An advantage behind the SSRT, compared to constant-strain tests, is that the protective surface film is thought to be ruptured mechanically during the test, thus giving SCC an opportunity to progress. To aid in the selection of the value of the potential at which the metal is most sensitive to SCC that can be applied to accelerate SSRT, potentiodynamic polarization scans are conducted as described previously. It is common for the potential to be monitored during the conduct of the SSRT. The strain rates that generate SCC in various metals are reported in the literature. There are several disadvantages to the SSRT. First, indications of failure are not generally observed until the tension specimen is plastically stressed, sometimes significantly, above the yield strength of the metal. Such high-stressed conditions can be an order of magnitude higher than the intended operating stress conditions. Second, crack initiation must occur fairly rapidly to have sufficient crack growth that can be detected using the SSRT. The occurrence of SCC in metals requiring long initiation times may go undetected.

Modulus Measurements Another SCC test technique is the use of changes of modulus as a measure of the damping capacity of a metal. It is known that a sample of a given test material containing cracks will have a lower effective modulus than does a sample of identical material free of cracks. The technique provides a rapid and reliable evaluation of the susceptibility of a sample material to SCC in a specific environment. The so-called internal friction test concept can also be used to detect and probe nucleation and progress of cracking and the mechanisms controlling it.

The Young's modulus of the specimen is determined by accurately measuring its resonant frequency while driving it in a standing longi-

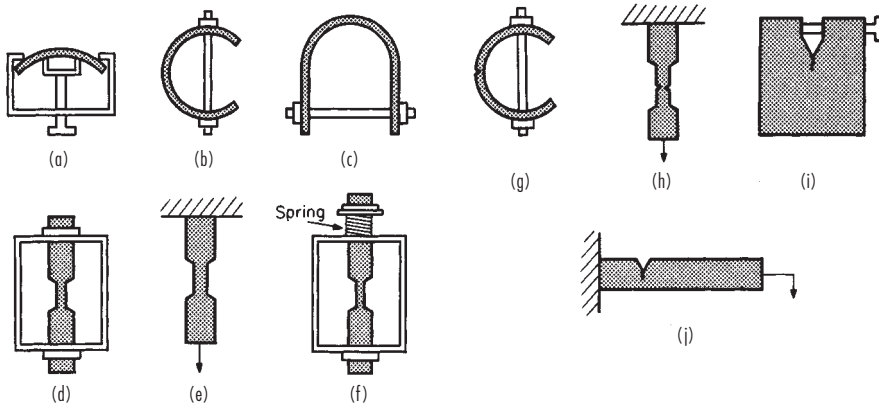


FIG. 28-18 Specimens for stress-corrosion tests. (a) Bent beam. (b) C ring. (c) U bend. (d) Tensile. (e) Tensile. (f) Tensile. (g) Notched C ring. (h) Notched tensile. (i) Precracked, wedge open-loading type. (j) Precracked, cantilever beam. [Chem. Eng., 78, 159 (Sept. 20 1971).]

itudinal wave configuration. A Marx composite piezoelectric oscillator is used to drive the specimen at a resonant frequency. The specimen is designed to permit measurements while undergoing applied stress and while exposed to an environmental test solution. The specimens are three half-wavelengths long; the gripping nodes and solution cup are silver-soldered on at displacement nodes, so they do not interfere with the standing wave (Fig. 28-19). As discussed for SSRT, potentiodynamic polarization scans are conducted to determine the potential that can be applied to accelerate the test procedure. Again, the potential can be monitored during a retest, as is the acoustic emission (AE) as an indicator of nucleation and progress of cracking.

Conjunctive Use of Slow- and Rapid-Scan Polarization The use of the methods discussed in the preceding requires a knowledge of the likely potential range for SCC to occur. Potentiodynamic polarization curves can be used to predict those SCC-sensitive potential ranges. The technique involves conducting both slow- and rapid-scan sweeps in the anodic direction of a range of potentials. Comparison of the two curves will indicate any ranges of potential within which high anodic activity in the film-free condition reduces to insignificant activity when the time requirements for film formation are met. This should indicate the range of potentials within which SCC is likely. Most of the SCC theories presently in vogue predict these domains of behavior to be between the primary passive potential and the onset of passivity. This technique shortens the search for that SCC potential.

Separated Anode/Cathode Realizing, as noted in the preceding, that localized corrosion is usually active to the surrounding metal surface, a stress specimen with a limited area exposed to the test solution (the anode) is electrically connected to an unstressed specimen (the cathode). A potentiostat, used as a zero-resistance ammeter, is placed between the specimens for monitoring the galvanic current. It is possible to approximately correlate the galvanic current I_g and potential to crack initiation and propagation, and, eventually, catastrophic fail-

ure. By this arrangement, the galvanic current I_g is independent of the cathode area. In other words, the potential of the anode follows the corrosion potential of the cathode during the test. The SSRT apparatus discussed previously may be used for tensile loading.

Fracture Mechanics Methods These have proved very useful for defining the minimum stress intensity K_{ISCC} at which stress corrosion cracking of high-strength, low-ductility alloys occurs. They have so far been less successful when applied to high-ductility alloys, which are extensively used in the chemical-process industries.

Work on these and other new techniques continues, and it is hoped that a truly reliable, accelerated test or tests will be defined.

Electrochemical Impedance Spectroscopy (EIS) and AC Impedance* Many direct-current test techniques assess the overall corrosion process occurring at a metal surface, but treat the metal/solution interface as if it were a pure resistor. Problems of accuracy and reproducibility frequently encountered in the application of direct-current methods have led to increasing use of electrochemical impedance spectroscopy (EIS).

Electrode surfaces in electrolytes generally possess a surface charge that is balanced by an ion accumulation in the adjacent solution, thus making the system electrically neutral. The first component is a double layer created by a charge difference between the electrode surface and the adjacent molecular layer in the fluid. Electrode surfaces may behave at any given frequency as a network of resistive and capacitive elements from which an electrical impedance may be measured and analyzed.

The application of an impressed alternating current on a metal specimen can generate information on the state of the surface of the specimen. The corrosion behavior of the surface of an electrode is related to the way in which that surface responds to this electrochemical circuit. The AC impedance technique involves the application of a small sinusoidal voltage across this circuit. The frequency of that alternating signal is varied. The voltage and current response of the system are measured.

The so-called white-noise analysis by the Fast Fourier transform technique (FFT) is another viable method. The entire spectrum can be derived from one signal. The impedance components thus generated are plotted on either a Nyquist (real versus imaginary) or Bode (log real versus log frequency plus log phase angle versus log frequency) plot. These data are analyzed by computer; they can be used to determine the polarization resistance and, thus, the corrosion rate if Tafel slopes are known. It is also thought that the technique can be used to monitor corrosion by examining the real resistance at high and low frequency and by assuming the difference is the polarization resistance. This can be done in low- and high-conductivity environments. Systems prone to suffer localized corrosion have been proposed to be analyzed by AC impedance and should aid in determining the optimum scan rate for potentiodynamic scans.

The use of impedance electrochemical techniques to study corrosion mechanisms and to determine corrosion rates is an emerging technology. Electrode impedance measurements have not been widely used, largely because of the sophisticated electrical equipment required to make these measurements. Recent advantages in microelectronics and computers has moved this technique almost overnight from being an academic experimental investigation of the concept itself to one of shelf-item commercial hardware and computer software, available to industrial corrosion laboratories.

Use and Limitations of Electrochemical Techniques A major caution must be noted as to the general, indiscriminate use of all electrochemical tests, especially the use of AC and EIS test techniques, for the study of corrosion systems. AC and EIS techniques are applicable for the evaluation of very thin films or deposits that are uniform, constant, and stable—for example, thin-film protective coatings. Sometimes, researchers do not recognize the dynamic nature of some passive films, corrosion products, or deposits from other sources; nor do they even consider the possibility of a change in the surface conditions during the course of their experiment. As an example, it is note-

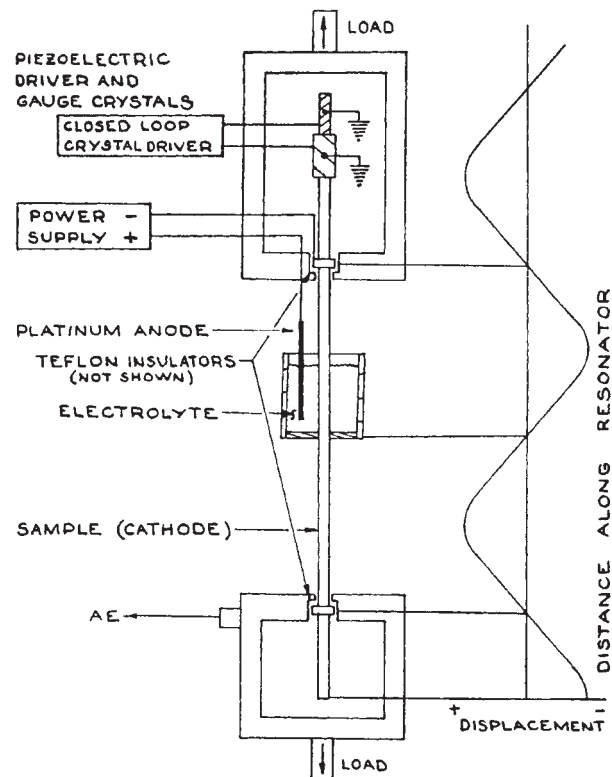


FIG. 28-19 Equipment for measuring internal friction (modulus) changes during in situ tensile exposure of a metal in a corrosive environment.

* Excerpted from papers by Oliver W. Siebert, courtesy of NACE International and ASTM.

worthy that this is a *major* potential problem in the electrochemical evaluation of microbiological corrosion (MIC).

MIC depends on the complex structure of corrosion products and passive films on metal surfaces as well as on the structure of the biofilm. Unfortunately, electrochemical methods have sometimes been used in complex electrolytes, such as microbiological culture media, where the characteristics and properties of passive films and MIC deposits are *quite active* and not fully understood. It must be kept in mind that microbial colonization of passive metals can drastically change their resistance to film breakdown by causing *localized* changes in the type, concentration, and thickness of anions, pH, oxygen gradients, and inhibitor levels at the metal surface during the course of a normal test; viable single-cell microorganisms divide at an exponential rate. These changes can be expected to result in important modifications in the electrochemical behavior of the metal and, accordingly, in the electrochemical parameter measured in laboratory experiments.

Warnings are noted in the literature to be careful in the *interpretation* of data from electrochemical techniques applied to systems in which complex and often poorly understood effects are derived from surfaces which contain *active* or *viable* organisms, and so forth. Rather, it is even more important to not use such test protocol unless the investigator fully understands both the corrosion mechanism and the test technique being considered—and their interrelationship.

CORROSION TESTING: PLANT TESTS

It is not always practical or convenient to investigate corrosion problems in the laboratory. In many instances, it is difficult to discover just what the conditions of service are and to reproduce them exactly. This is especially true with processes involving changes in the composition and other characteristics of the solutions as the process is carried out, as, for example, in evaporation, distillation, polymerization, sulfonation, or synthesis.

With many natural substances also, the exact nature of the corrosive is uncertain and is subject to changes not readily controlled in the laboratory. In other cases, the corrosiveness of the solution may be influenced greatly by or even may be due principally to a constituent present in such minute proportions that the mass available in the limited volume of corrosive solution that could be used in a laboratory setup would be exhausted by the corrosion reaction early in the test, and consequently the results over a longer period of time would be misleading.

Another difficulty sometimes encountered in laboratory tests is that contamination of the testing solution by corrosion products may change its corrosive nature to an appreciable extent.

In such cases, it is usually preferable to carry out the corrosion-testing program by exposing specimens in operating equipment under **actual conditions of service**. This procedure has the additional advantages that it is possible to test a large number of specimens at the same time and that little technical supervision is required.

In certain cases, it is necessary to choose materials for equipment to be used in a process developed in the laboratory and not yet in operation on a plant scale. Under such circumstances, it is obviously impossible to make plant tests. A good procedure in such cases is to construct a pilot plant, using either the cheapest materials available or some other materials selected on the basis of past experience or of laboratory tests. While the pilot plant is being operated to check on the process itself, specimens can be exposed in the operating equipment as a guide to the choice of materials for the large-scale plant or as a means of confirming the suitability of the materials chosen for the pilot plant.

Test Specimens In carrying out plant tests it is necessary to install the test specimens so that they will not come into contact with other metals and alloys; this avoids having their normal behavior disturbed by galvanic effects. It is also desirable to protect the specimens from possible mechanical damage.

There is no single standard size or shape for corrosion-test coupons. They usually weigh from 10 to 50 g and preferably have a large surface-to-mass ratio. Disks 40 mm (1½ in) in diameter by 3.2 mm (¼ in) thick and similarly dimensioned square and rectangular coupons are

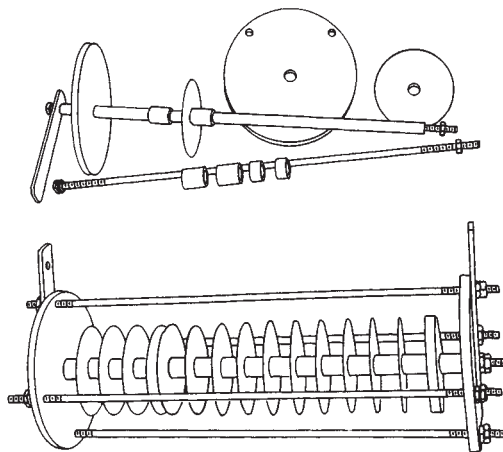


FIG. 28-20 Assembly of a corrosion-test spool and specimens. (Mantell, ed., Engineering Materials Handbook, McGraw-Hill, New York, 1958.)

the most common. Surface preparation varies with the aim of the test, but machine grinding of surfaces or polishing with a No. 120 grit is common. Samples should not have sheared edges, should be clean (no heat-treatment scale remaining unless this is specifically part of the test), and should be identified by stamping. See Fig. 28-20 for a typical plant test assembly.

The choice of materials from which to make the holder is important. Materials must be durable enough to ensure satisfactory completion of the test. It is good practice to select very resistant materials for the test assembly. Insulating materials used are plastics, porcelain, Teflon, and glass. A phenolic plastic answers most purposes; its principal limitations are unsuitability for use at temperatures over 150°C (300°F) and lack of adequate resistance to concentrated alkalis.

The method of supporting the specimen holder during the test period is important. The preferred position is with the long axis of the holder horizontal, thus avoiding dripping of corrosion products from one specimen to another. The holder must be located so as to cover the conditions of exposure to be studied. It may have to be submerged, or exposed only to the vapors, or located at liquid level, or holders may be called for at all three locations. Various means have been utilized for supporting the holders in liquids or in vapors. The simplest is to suspend the holder by means of a heavy wire or light metal chain. Holders have been strung between heating coils, clamped to agitator shafts, welded to evaporator tube sheets, and so on. The best method is to use test racks.

In a few special cases, the standard "spool-type" specimen holder is not applicable and a suitable special test method must be devised to apply to the corrosion conditions being studied.

For conducting tests in **pipe lines** of 75-mm (3-in) diameter or larger, a spool holder as shown in Fig. 28-21, which employs the same disk-type specimens used on the standard spool holder, has been used. This frame is so designed that it may be placed in a pipe line in any position without permitting the disk specimens to touch the wall of the pipe. As with the strip-type holder, this assembly does not materially interfere with the fluid through the pipe and permits the study of corrosion effects prevailing in the pipe line.

Another way to study corrosion in pipe lines is to install in the line short sections of pipe of the materials to be tested. These test sections should be insulated from each other and from the rest of the piping system by means of nonmetallic couplings. It is also good practice to provide insulating gaskets between the ends of the pipe specimens where they meet inside the couplings. Such joints may be sealed with various types of dope or cement. It is desirable in such cases to paint the outside of the specimens so as to confine corrosion to the inner surface.

It is occasionally desirable to expose corrosion-test specimens in operating equipment without the use of specimen holders of the type

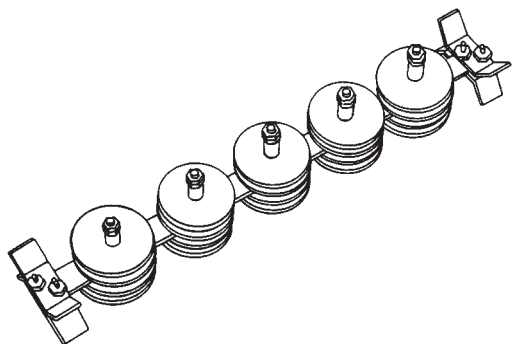


FIG. 28-21 Spool-type specimen holder for use in 3-in-diameter or larger pipe. (Mantell, ed., Engineering Materials Handbook, McGraw-Hill, New York, 1958.)

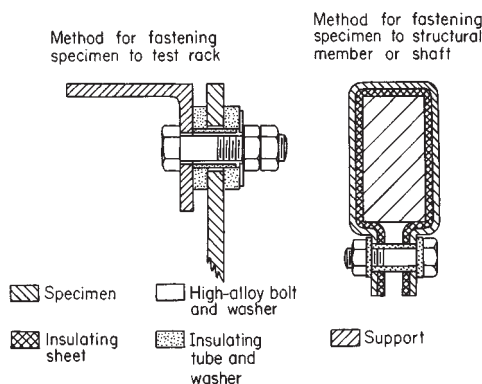


FIG. 28-22 Methods for attaching specimens to test racks and to parts of moving equipment. (Mantell, ed., Engineering Materials Handbook, McGraw-Hill, New York, 1958.)

described. This can be accomplished by attaching specimens directly to some part of the operating equipment and by providing the necessary insulation against galvanic effects as shown in Fig. 28-22. The suggested method of attaching specimens to racks has been found to be very suitable in connection with the exposure of specimens to corrosion in seawater.

Test Results The methods of cleaning specimens and evaluating results after plant corrosion tests are identical to those described earlier for laboratory tests.

Electrochemical On-Line Corrosion Monitoring* On-line corrosion monitoring is used to evaluate the status of equipment and piping in chemical process industries (CPI) plants. These monitoring methods are based on electrochemical techniques. To use on-line monitoring effectively, the engineer needs to understand the underlying electrochemical test methods to be employed. This section covers many of these test methods and their applications as well as a review of potential problems encountered with such test instruments and how to overcome or avoid these difficulties.

Most Common Types of Probes There are three most common types of corrosion monitoring probes used. Other types of probes are used, but in smaller numbers.

1. **Weight loss probes.** Coupons for measuring weight loss are still the primary type of probe in use. These may be as simple as samples of the process plant materials which have been fitted with electrical connections and readouts to determine intervals for retrieval and weighing, to commercially available coupons of specified material,

geometry, stress condition, and other factors, ready to be mounted on specially designed supports at critical points in the process. Coupons can be permanently installed prior to plant start-up or during a shut-down. This type of permanent installation requires a plant shutdown for probe retrieval as well. Shutdown can be avoided by installing the probe in a bypass.

2. **Electrical resistance probes.** These probes are the next most common type of corrosion probes after coupons. This type of probe measures changes in the electrical resistance as a thin strip of metal gets thinner with ongoing corrosion. As the metal gets thinner, its resistance increases. This technique was developed in the 1950s by Dravinieks and Cataldi and has undergone many improvements since then.

3. **Linear polarization resistance probes.** LPR probes are more recent in origin, and are steadily gaining in use. These probes work on a principle outlined in an ASTM guide on making polarization resistance measurements, providing instantaneous corrosion rate measurements (G59, "Standard Practice for Conducting Potentiodynamic Polarization Resistance Measurements").

LPR probes measure the electrochemical corrosion mechanism involved in the interaction of the metal with the electrolyte. To measure linear polarization resistance R_p , Ω/cm^2 , the following assumptions must be made:

- The corrosion rate is uniform.
- There is only cathodic and one anodic reaction.
- The corrosion potential is not near the oxidation/reduction potential for either reaction.

When these conditions are met, the current density associated with a small polarization of the metal (less than +10 mV) is directly proportional to the corrosion rate of the metal.

Multiinformational Probes Corrosion probes can provide more information than just corrosion rate. The next three types of probes yield information about the type of corrosion, the kinetics of the corrosion reaction, as well as the local corrosion rate.

Electrochemical impedance spectroscopy, AC probes. EIS, although around since the 1960s, has primarily been a laboratory technique. Commercially available probes and monitoring systems that measure EIS are becoming more widely used, especially in plants that have on-staff corrosion experts to interpret the data or to train plant personnel to do so.

In EIS, a potential is applied across a corroding metal in solution, causing current to flow. The amount of current depends upon the corrosion reaction on the metal surface and the flow of ions in solution. If the potential is applied as a sine wave, it will cause harmonics of the current output. The relationship between the applied potential and current output is the impedance, which is analogous to resistance in a DC circuit.

Since the potential and current are sinusoidal, the impedance has a magnitude and a phase, which can be represented as a vector. A sinusoidal potential or current can be pictured as a rotating vector. For standard AC current, the rotation is at a constant angular velocity of 60 Hz.

The voltage can also be pictured as a rotating vector with its own amplitude and frequency. Both current and potential can be represented as having real (observed) and imaginary (not observed) components.

In making electrochemical impedance measurements, one vector is examined, using the others as the frame of reference. The voltage vector is divided by the current vector, as in Ohm's law. Electrochemical impedance measures the impedance of an electrochemical system and then mathematically models the response using simple circuit elements such as resistors, capacitors, and inductors. In some cases, the circuit elements are used to yield information about the kinetics of the corrosion process.

Polarization probes. Polarization methods other than LPR are also of use in process control and corrosion analysis, but only a few systems are offered commercially. These systems use such polarization techniques as galvanodynamic or potentiodynamic, potentiostatic or galvanostatic, potentiostaircase or galvanostaircase, or cyclic polarization methods. Some systems involving these techniques are, in fact, used regularly in processing plants. These methods are used in situ or

* Excerpted from papers by Ann Chidester Van Orden and Oliver W. Siebert, courtesy of NACE International and Oliver W. Siebert, courtesy of ASTM.

in the laboratory to measure corrosion. Polarization probes have been successful in reducing corrosion-related failures in chemical plants.

Polarization probes rely on the relationship of the applied potential to the output current per unit area (current density). The slope of applied potential versus current density, extrapolated through the origin, yields the polarization resistance R_p , which can be related to the corrosion rate.

There are several methods for relating the corrosion current, the applied potential, and the polarization resistance. These methods involve various ways of stepping or ramping either the potential or current. Also, a constant value of potential or current can be applied.

Electrochemical noise monitoring probes. Electrochemical noise monitoring is probably the newest of these methods. The method characterizes the naturally occurring fluctuations in current and potential due to the electrochemical kinetics and the mechanism of the corroding metal interface. Measurements are taken without perturbing the interface by applying a potential or current to it. In this way, electrochemical processes are not interrupted and the system is measured without being disturbed. Methods including signal processing and mathematical transformation are used to provide information on the reaction kinetics at the surface and the corrosion rate.

This technique, originally discovered in the 1960s, remained a laboratory technique until recently, when some manufacturers began producing commercial devices. There are a few cases where electrochemical noise is being used in process-plant-type environments, and an ASTM committee has been formed to look at standardization of this technique. However, in general it remains a laboratory method with great potential for on-line monitoring.

Indirect Probes Some types of probes do not measure corrosion directly, but yield measurements that also are useful in detecting corrosion. Examples include:

Pressure probes. Pressure monitors or transducers may be of use in corrosion monitoring in environments where buildup of gases such as hydrogen or H_2S may contribute to corrosion.

Gas probes. The hydrogen patch probe allows users to determine the concentration of hydrogen in the system. This is an important measurement since hydrogen can foster corrosion. Detecting production of certain gases may give rise to process changes to eliminate or limit the gaseous effluent and, therefore, lower the possibility of corrosion caused by these gases.

pH probes. Monitoring the pH may also aid in the early detection of corrosion. The acidity or alkalinity of the environment is often one of the controllable parameters in corrosion. Monitoring of the pH can be combined with other corrosion measurements to provide additional data about process conditions and give another level of process control.

Ion probes. Determining the level of ions in solution also helps to control corrosion. An increase in concentration of specific ions can contribute to scale formation, which can lead to a corrosion-related failure. Ion-selective electrode measurements can be included, just as pH measurements can, along with other more typical corrosion measurements. Especially in a complete monitoring system, this can add information about the effect of these ions on the material of interest at the process plant conditions.

Microbially induced corrosion (MIC) probes. Devices are available to measure the amount of microbial activity in some environments. Microbially induced corrosion is known to be an actor in many corrosion-related problems in processing plants. The monitoring devices for MIC are limited in their range and, at present, are available only for a few specific environments. This is an exciting area for development of corrosion probes and monitoring systems.

Use of Corrosion Probes The major use of corrosion monitoring probes is to measure the corrosion rate in the plant or the field. In addition to corrosion-rate measurements, corrosion probes can be used to detect process upsets that may change the corrosion resistance of the equipment of interest. This is usually equally as important a measurement as corrosion rate since a change in the process conditions can lead to dramatic changes in the corrosion rate.

If the upset can be detected and dealt with in short order, the system can be protected. Some of the probes that measure parameters

such as pH, ion content, and others are sensitive to process upsets and may give the fastest most complete information about such changes.

Monitoring can also be used to optimize the chemistry and level of corrosion inhibitors used. If too little inhibitor is used, enhanced corrosion can result and failure may follow. If too much is used, costs will increase without providing any additional protection. Optimization of the addition of inhibitor in terms of time, location in the process, and method of addition can also be evaluated through the use of carefully placed probes.

Another area where probes can be used effectively is in monitoring of deposits such as scale. One method of measurement is detecting specific ions that contribute to scale buildup or fouling; another is measuring the actual layers. Scale and fouling often devastate the corrosion resistance of a system, leading to a costly corrosion-related plant shutdown.

A final type of measurement is the detection of localized corrosion, such as pitting or crevice attack. Several corrosion-measuring probes can be used to detect localized corrosion. Some can detect localized corrosion instantaneously and others only its result. These types of corrosion may contribute little to the actual mass loss, but can be devastating to equipment and piping. Detection and measurement of localized corrosion is one of the areas with the greatest potential for the use of some of the newest electrochemically based corrosion monitoring probes.

Corrosion Rate Measurements Determining a corrosion rate from measured parameters (such as mass loss, current, or electrical potential) depends on converting the measurements into a corrosion rate by use of relationships such as Faraday's law.

Information on the process reaction conditions may be important to prolonging the lifetime of process equipment. Techniques such as EIS and potentiodynamic polarization can provide just such information without being tied to a specific corrosion-rate measurement.

This is also the case with methods that yield information on localized corrosion. The overall corrosion rate may be small when localized attack occurs, but failure due to perforation or loss of function may be the consequence of localized attack.

Measuring Corrosion Rate with Coupons Corrosion rate determined with typical coupon tests is an average value, averaged over the entire life of the test. Changes in the conditions under which the coupons are tested are averaged over the time the coupon is exposed. *Uniform attack is assumed to occur.* Converting measured values of loss of mass into an average corrosion rate has been covered extensively by many authors, and standard practices exist for determining corrosion rate.

Corrosion rates may vary during testing. Since the rate obtained from coupon testing is averaged over time, the frequency of sampling is important. Generally, measurements made over longer times are more valid. This is especially true for low corrosion rates, under 1 mil/y, mpy (0.001 in/y). When corrosion rates are this low, longer times should be used.

Factors may throw off these rates—these are outlined in ASTM G31, "Standard Practice for Laboratory Immersion Corrosion Testing of Metals." Coupon-type tests cannot be correlated with changing plant conditions that may dramatically affect process equipment lifetimes. Other methods must be used if more frequent measurements are desired or correlation with plant conditions are necessary.

A plot of mass loss versus time can provide information about changes in the conditions under which the test has been run. One example of such a plot comes from the ASTM Standard G96, "Standard Guide."

Heat Flux Tests Removable tube test heat exchangers find an ideal use in the field for monitoring heat flux (corrosion) conditions, NACE TMO286-94 (similar to laboratory test, Fig. 28-4, page 28-12).

The assumption of uniform corrosion is also at the heart of the measurements made by the electrical resistance (ER) probes. Again, ASTM Standard G96 outlines the method for using ER probes in plant equipment. These probes operate on the principle that the electrical resistance of a wire, strip, or tube of metal increases as its cross-sectional area decreases:

$$R = \frac{\rho L}{A}$$

where R = resistance, Ω
 ρ = resistivity, Ω/cm
 L = length, cm
 A = cross-sectional area, cm^2

Usually, in practice, the resistance is measured as a ratio between the actual measuring element and a similar element protected from the corrosive environment (the reference), and is given by R_M/R_R where subscript M is for measured and R is for reference.

Measurements are recorded intermittently or continuously. Changes in the slope of the curve obtained thus yields the corrosion rate.

The initial measurement of electrical resistance must be made after considerable time. Phenomenological information has been determined based on the corrosion rate expected at what period of time to initiate readings of the electrical resistance. Since these values are based on experiential factors rather than on fundamental (so-called *first*) principles, correlation tables and lists of suggested thicknesses, compositions, and response times for usage of ER-type probes have developed over time, and these have been incorporated into the values read out of monitoring systems using the ER method.

Electrochemical Measurement of Corrosion Rate There is a link between electrochemical parameters and actual corrosion rates. Probes have been specifically designed to yield signals that will provide this information. LPR, ER, and EIS probes can give corrosion rates directly from electrochemical measurements. ASTM G102, "Standard Practice for Calculation of Corrosion Rates and Related Information from Electrochemical Measurements," tells how to obtain corrosion rates directly. Background on the approximations made in making use of the electrochemical measurements has been outlined by several authors.

ASTM G59, "Standard Practice for Conducting Potentiodynamic Polarization Resistance Measurements," provides instructions for the graphical plotting of data (from tests conducted using the above-noted ASTM Standard G103) as the linear potential versus current density, from which the polarization resistance can be found.

Measurements of polarization resistance R_p , given by LPR probes, can lead to measurement of the corrosion rate at a specific instant, since values of R_p are instantaneous.

To obtain the corrosion current I_{corr} from R_p , values for the anodic and cathodic slopes must be known or estimated. ASTM G59 provides an experimental procedure for measuring R_p . A discussion of the factors which may lead to errors in the values for R_p , and cases where R_p technique cannot be used, are covered by Mansfeld in "Polarization Resistance Measurements—Today's Status, Electrochemical Techniques for Corrosion Engineers" (NACE International, 1992).

Some data from corrosion-monitoring probes do not measure corrosion rate, but rather give other useful information about the system. For example, suppose conditions change dramatically during a process upset. An experienced corrosion engineer can examine the data and correlate it with the upset conditions. Such analysis can provide insight into the process and help to improve performance and extend equipment lifetime. Changes in simple parameters such as pH, ion content, and temperature may lead to detection of a process upset. Without careful analysis, process upsets can reduce the corrosion lifetime of equipment and even cause a system failure.

Analysis of biological activity does not automatically lead directly to a corrosion-rate measurement. However, with detection and correlation with process conditions, such information may also lead to improvements in the corrosion lifetime of the process equipment.

Evidence of localized corrosion can be obtained from polarization methods such as potentiodynamic polarization, EIS, and electrochemical noise measurements, which are particularly well suited to providing data on localized corrosion. When evidence of localized attack is obtained, the engineer needs to perform a careful analysis of the conditions that may lead to such attack. Correlation with process conditions can provide additional data about the susceptibility of the equipment to localized attack and can potentially help prevent failures due to pitting or crevice corrosion. Since pitting may have a delayed initiation phase, careful consideration of the cause of the localized attack is critical. Laboratory testing and involvement of an

experienced corrosion engineer may be needed to understand the initiation of localized corrosion. Theoretical constructs such as Pourbaix diagrams can be useful in interpreting data obtained by on-line monitors.

Combinations of several types of probes can improve the information concerning corrosion of the system. Using only probes that provide corrosion-rate data cannot lead to as complete an analysis of the process and its effect on the equipment as with monitoring probes, which provide additional information.

Other Useful Information Obtained by Probes Both EIS and electrochemical noise probes can be used to determine information about the reactions that affect corrosion. Equivalent circuit analysis, when properly applied by an experienced engineer, can often give insight into the specifics of the corrosion reactions. Information such as corrosion product layer buildup, or inhibitor effectiveness, or coating breakdown can be obtained directly from analysis of the data from EIS or indirectly from electrochemical noise data. In most cases, this is merely making use of methodology developed in the corrosion laboratory.

Some assumptions must be made to do this, but these assumptions are no different from those made in the laboratory. Recent experience involving in-plant usage of EIS has shown that this technique can be used effectively as a monitoring method and has led to development of several commercial systems.

Major use of the information from monitoring probes, combined with the storage and analysis capabilities of portable computers and microprocessors, seems the best method for understanding corrosion processes. Commercial setups can be assembled from standard probes, cables, readout devices, and storage systems. When these are coupled with analysis by corrosion engineers, the system can lead to better a understanding of in-plant corrosion processes.

Limitations of Probes and Monitoring Systems There are limitations even with the most up-to-date systems. Some of the things which cannot be determined using corrosion probes include:

Specifics on the type of biological attack. This must be done by some other method such as chemical analysis of the solution (plus consideration given to limitations to the use of these several electrochemical techniques for MIC studies, noted previously under "Corrosion Testing: Laboratory Tests" and subsequent subsections).

Actual lifetime of the plant equipment. Corrosion monitoring provides data, which must then be analyzed with additional input and interpretation. However, only estimates can be made of the lifetime of the equipment of concern. Lifetime predictions are, at best, carefully crafted guesses based on the best available data.

Choices of alternative materials. Corrosion probes are carefully chosen to be as close as possible to the alloy composition, heat treatment, and stress condition of the material that is being monitored. Care must be taken to ensure that the environment at the probe matches the service environment. Choices of other alloys or heat treatments and other conditions must be made by comparison. Laboratory testing or coupon testing in the process stream can be used to examine alternatives to the current material, but the probes and the monitors can only provide information about the conditions which are present during the test exposure and cannot extrapolate beyond those conditions.

Failure analysis. Often, for a corrosion-related failure, data from the probes are examined to look for telltale signs that could have led to detection of the failure. In some cases, evidence can be found that process changes were occurring which led to the failure. This does not mean that the probes should have detected the failure itself. Determination of an imminent corrosion-related failure is not possible, even with the most advanced monitoring system.

The aforementioned limitations are not problems with the probes or the monitoring systems but occur when information is desired that cannot be measured directly or which requires extrapolation. Many of the problems that are encountered with corrosion-monitoring systems and probes are related to the use to which probes are put.

Potential Problems with Probe Usage Understanding the electrochemical principles upon which probes are based helps to eliminate some of the potential problems with probes. However, in some situations, the information desired is not readily available.

For example, consider localized corrosion. Although data from corrosion probes indicate corrosion rate, it is not possible to tell that localized corrosion is the problem.

This is an example of measuring the wrong thing. In this case, the probes work adequately, the monitoring system is adequate, as is the monitoring interval, but detection of the type of corrosion cannot be made based on the available data. Different types of probes and testing are required to detect the corrosion problem.

Another problem can occur if the probes and monitors are working properly but the probe is placed improperly. Then the probe does not measure the needed conditions and environment. The data obtained by the probe will not tell the whole story.

An example of this is in a condenser where the corrosion probe is in a region where the temperature is lower than that at the critical condition of interest. Local scale buildup is another example of this type of situation, as is formation of a crevice at a specific location.

The type of probe, its materials, and method of construction must be carefully considered in designing an effective corrosion-monitoring system. Since different types of probes provide different types of information, it may be necessary to use several types.

Incorrect information can result if the probe is made of the wrong material and is not heat treated in the same way as the process equipment (as well as because of other problems). The probe must be as close as possible to the material from which the equipment of interest is made. Existence of a critical condition, such as weldments or galvanic couples or occluded cells in the equipment of concern, makes the fabrication, placement, and maintenance of the probes and monitoring system of critical importance, if accurate and useful data are to be obtained.

Before electrochemical techniques are used in the evaluation of any given, viable MIC environment/metal system, such a test protocol

should receive considerable review by personnel quite experienced in both electrochemical testing and microbiologically influenced corrosion.

The data obtained from probes and monitoring systems are most useful when analyzed by a corrosion specialist. Data not taken, analyses not made, or expertise not sought can quickly lead to problems even with the most up-to-date corrosion probes and monitoring system.

ECONOMICS IN MATERIALS SELECTION

In most instances, there will be more than one alternative material which may be considered for a specific application. Calculation of true long-term costs requires estimation of the following:

1. Total cost of fabricated equipment and piping
2. Total installation cost
3. Service life
4. Maintenance costs: amount and timing
5. Time and cost requirements to replace or repair at the end of service life
6. Cost of downtime to replace or repair
7. Cost of inhibitors, extra control facilities, and so on, required to assure achievement of predicted service life
8. Time value of money
9. Factors which impact taxation, such as depreciation and tax rates
10. Inflation rate

Proper economic analysis will allow comparison of alternatives on a sound basis. Detailed calculations are beyond the scope of this section. The reader should review the material in the NACE Publication 3C194, Item No. 24182, "Economics of Corrosion," Sept., 1994.

PROPERTIES OF MATERIALS

GUIDE TO TABULATED DATA

Note from the Sec. 28 editors to the readers of this handbook: Historically, previous editions of *Perry's Chemical Engineers' Handbook* carried an extensive series of so-called corrosion resistance tables [listing recommended materials of construction (MOC) versus various corrosive environments]. This practice goes back, at least, to the *Materials of Construction Sec. 18, 1941, 2d ed.* Unfortunately, if valid at all, *these data are only usable as indicators of what will not work; for sure, these listings should not be used as recommendations of what materials are corrosion resistant.* The section editors have elected to no longer include these data tabulations.

Beyond the simple resistance of a material of construction to dissolution in a given chemical, many other properties enter into consideration when making an appropriate or optimum MOC selection for a given environmental exposure. These factors include the influence of velocity, impurities or contaminants, pH, stress, crevices, bimetallic couples, levels of nuclear, UV, or IR radiation, microorganisms, temperature heat flux, stray currents, properties associated with original production of the material and its subsequent fabrication as an item of equipment, as well as other physical and mechanical properties of the MOC, the *Proverbial Siebert Changes in the Phase of the Moon*, and so forth.

Therefore, the seventh edition no longer includes these endless tabulations of data; rather, there is an extensive coverage of corrosion mechanisms, the manner in which these various factors effect the corrosion system, as well as more detail as to the testing protocol necessary to assist in a sound MOC selection.

A few collections of more generic information as to the overall acid and alkali resistance of broad classes of materials remain. These are only intended to be used as *indicators* of the tendencies of these MOC to react; they are not included as a substitute for the application of good, sound engineering evaluations.

MATERIALS STANDARDS AND SPECIFICATIONS

There are obvious benefits to be derived from consensus standards which define the chemistry and properties of specific materials. Such standards allow designers and users of materials to work with confidence that the materials supplied will have the expected minimum properties. Designers and users can also be confident that comparable materials can be purchased from several suppliers. Producers are confident that materials produced to an accepted standard will find a ready market and therefore can be produced efficiently in large factories.

While a detailed treatment is beyond the scope of this section, a few of the organizations which generate standards of major importance to the chemical-process industries in the United States are listed here. An excellent overview is presented in the *Encyclopedia of Chemical Technology* (3d ed., Wiley, New York, 1978-1980).

1. **American National Standards Institute (ANSI)**, formerly American Standards Association (ASA). ANSI promulgates the piping codes used in the chemical-process industries.
2. **American Society of Mechanical Engineers (ASME)**. This society generates the Boiler and Pressure Vessel Codes.
3. **American Society for Testing and Materials (ASTM)**. This society generates specifications for most of the materials used in the ANSI Piping Codes and the ASME Boiler and Pressure Vessel Codes.
4. **International Organization for Standardization (ISO)**. This organization is engaged in generating standards for worldwide use. It has 80 member nations.

FERROUS METALS AND ALLOYS

Steel Carbon steel is the most common, cheapest, and most versatile metal used in industry. It has excellent ductility, permitting many cold-forming operations. Steel is also very weldable.

The grades of steel most commonly used in the chemical-process industries have tensile strength in the 345- to 485-MPa (50,000 to 70,000-lbf/in²) range, with good ductility. Higher strength levels are achieved by cold work, alloying, and heat treatment.

Carbon steel is easily the most commonly used material in process plants despite its somewhat limited corrosion resistance. It is routinely used for most organic chemicals and neutral or basic aqueous solutions at moderate temperatures. It is also used routinely for the storage of concentrated sulfuric acid and caustic soda [up to 50 percent and 55°C (130°F)]. Because of its availability, low cost, and ease of fabrication steel is frequently used in services with corrosion rates of 0.13 to 0.5 mm/y (5 to 20 mils/y), with added thickness (**corrosion allowance**) to assure the achievement of desired service life. Product quality requirements must be considered in such cases.

Low-Alloy Steels Alloy steels contain one or more alloying agents to improve mechanical and corrosion-resistant properties over those of carbon steel.

A typical low-alloy grade [American Iron and Steel Institute (AISI) 4340] contains 0.40 percent C, 0.70 percent Mn, 1.85 percent Ni, 0.80 percent Cr, and 0.25 percent Mo. Many other alloying agents are used to produce a large number of standard AISI and proprietary grades.

Nickel increases toughness and improves low-temperature properties and corrosion resistance. Chromium and silicon improve hardness, abrasion resistance, corrosion resistance, and resistance to oxidation. Molybdenum provides strength at elevated temperatures.

The addition of small amounts of alloying materials greatly improves corrosion resistance to atmospheric environments but does not have much effect against liquid corrosives. The alloying elements produce a tight, dense adherent rust film, but in acid or alkaline solutions corrosion is about equivalent to that of carbon steel. However, the greater strength permits thinner walls in process equipment made from low-alloy steel.

Cast Irons Generally, cast iron is not a particularly strong or tough structural material, although it is one of the most economical and is widely used industrially.

Gray cast iron, low in cost and easy to cast into intricate shapes, contains carbon, silicon, manganese, and iron. Carbon (1.7 to 4.5 percent) is present as combined carbon and graphite; combined carbon is dispersed in the matrix as iron carbide (cementite), while free graphite occurs as thin flakes dispersed throughout the body of the metal. Various strengths of gray iron are produced by varying size, amount, and distribution of graphite.

Gray iron has outstanding damping properties—that is, ability to absorb vibration—as well as wear resistance. However, gray iron is brittle, with poor resistance to impact and shock. Machinability is excellent.

With some important exceptions, gray-iron castings generally have corrosion resistance similar to that of carbon steel. They do resist atmospheric corrosion as well as attack by natural or neutral waters and neutral soils. However, dilute acids and acid-salt solutions will attack this material.

Gray iron is resistant to concentrated acids (nitric, sulfuric, phosphoric) as well as to some alkaline and caustic solutions. Caustic fusion pots are usually made from gray cast iron with low silicon content; cast-iron valves, pumps, and piping are common in sulfuric acid plants.

White cast iron is brittle and difficult to machine. It is made by controlling the composition and rate of solidification of the molten iron so that all the carbon is present in the combined form. Very abrasive- and wear-resistant, white cast iron is used as liners and for grinding balls, dies, and pump impellers.

Malleable iron is made from white cast iron. It is cast iron with free carbon as dispersed nodules. This arrangement produces a tough, relatively ductile material. Total carbon is about 2.5 percent. Two types are produced: standard and pearlitic (combined carbon plus nodules). Standard malleable iron is easily machined; pearlitic, less so. Both types will withstand bending and cold working without cracking. Large welded areas are not recommended with fusion welding because welds are brittle. Corrosion resistance is about the same as for gray cast iron.

Ductile cast iron includes a group of materials with good strength,

toughness, wear resistance, and machinability. This type of cast iron contains combined carbon and dispersed nodules of carbon. Composition is about the same as gray iron, with more carbon (3.7 percent) than malleable iron. The spheroidal graphite reduces the notch effect produced by graphite flakes, making the material more ductile.

There are a number of grades of ductile iron; some have maximum toughness and machinability; others have maximum resistance to oxidation.

Generally, corrosion resistance is similar to gray iron. But ductile iron can be used at higher temperatures—up to 590°C (1,100°F) and sometimes even higher.

Alloy Cast Irons Cast iron is not usually considered corrosion-resistant, but this condition can be improved by the use of various cast-iron alloys. A number of such materials are commercially available.

High-silicon cast irons have excellent corrosion resistance. Silicon content is 13 to 16 percent. This material is known as Durion. Adding 4 percent Cr yields a product called Durichlor, which has improved resistance in the presence of oxidizing agents. These alloys are not readily machined or welded.

Silicon irons are very resistant to oxidizing and reducing environments, and resistance depends on the formation of a passive film. These irons are widely used in sulfuric acid service, since they are unaffected by sulfuric at all strengths, even up to the boiling point.

Because they are very hard, silicon irons are good for combined corrosion-erosion service.

Another group of cast-iron alloys are called **Ni-Resist**. These materials are related to gray cast iron in that they have high carbon contents (3 percent), with fine graphite flakes distributed throughout the structure. Nickel contents range from 13.5 to 36 percent, and some have 6.5 percent Cu.

Generally, nickel-alloy castings have superior toughness and impact resistance compared with gray irons. The nickel-alloy castings can be welded and machined.

Corrosion resistance of nickel alloys is superior to that of cast irons but less than that of pure nickel. There is little attack from neutral or alkaline solutions. Oxidizing acids such as nitric are highly detrimental. Cold, concentrated sulfuric acid can be handled.

Ni-Resist has excellent heat resistance, with some grades serviceable up to 800°C (1,500°F). Also, a ductile variety is available, as well as a hard variety (Ni-Hard).

Stainless Steel There are more than 70 standard types of stainless steel and many special alloys. These steels are produced in the wrought form (AISI types) and as cast alloys [Alloy Casting Institute (ACI) types]. Generally, all are iron-based, with 12 to 30 percent chromium, 0 to 22 percent nickel, and minor amounts of carbon, niobium (columbium), copper, molybdenum, selenium, tantalum, and titanium. These alloys are very popular in the process industries. They are heat- and corrosion-resistant, noncontaminating, and easily fabricated into complex shapes.

There are three groups of stainless alloys: (1) martensitic, (2) ferritic, and (3) austenitic.

The **martensitic alloys** contain 12 to 20 percent chromium with controlled amounts of carbon and other additives. Type 410 is a typical member of this group. These alloys can be hardened by heat treatment, which can increase tensile strength from 550 to 1,380 MPa (80,000 to 200,000 lbf/in²).

Corrosion resistance is inferior to that of austenitic stainless steels, and martensitic steels are generally used in mildly corrosive environments (atmospheric, fresh water, and organic exposures).

Ferritic stainless contains 15 to 30 percent Cr, with low carbon content (0.1 percent). The higher chromium content improves its corrosion resistance. Type 430 is a typical example. The strength of ferritic stainless can be increased by cold working but not by heat treatment. Fairly ductile ferritic grades can be fabricated by all standard methods. They are fairly easy to machine. Welding is not a problem, although it requires skilled operators.

Corrosion resistance is rated good, although ferritic alloys are not good against reducing acids such as HCl. But mildly corrosive solutions and oxidizing media are handled without harm. Type 430 is widely used in nitric acid plants. In addition, it is very resistant to scaling and high-temperature oxidation up to 800°C (1,500°F).

TABLE 28-2 General Corrosion Properties of Some Metals and Alloys*

Ratings:
 0: Unsuitable. Not available in form required or not suitable for fabrication requirements or not suitable for corrosion conditions.
 1: Poor to fair.
 2: Fair. For mild conditions or when periodic replacement is possible. Restricted use.
 3: Fair to good.
 4: Good. Suitable when superior alternatives are uneconomic.
 5: Good to excellent.
 6: Normally excellent.

Small variations in service conditions may appreciably affect corrosion resistance. Choice of materials is therefore guided wherever possible by a combination of experience and laboratory and site tests.

Materials	Nonoxidizing or reducing media				Liquids								Gases			
	Acid solutions, excluding hydrochloric e.g., phosphoric, sulfuric, most conditions, many organics	Neutral solutions, e.g., many nonoxidizing salt solutions, chlorides, sulfates	Alkaline solutions, e.g.		Oxidizing media			Natural waters				Common industrial media				
			Caustic and mild alkalies, excluding ammonium hydroxide	Ammonium hydroxide and amines	Acid solutions, e.g., nitric	Neutral or alkaline solutions, e.g., per-sulfates, peroxides, chromates	Pitting media,† acid ferric chloride solutions	Freshwater supplies		Seawater		Steam		Furnace gases with incidental sulfur content		Ambient air, city or industrial
								Static or slow-moving	Turbulent	Static or slow-moving	Turbulent	Moist, condensate	Dry at high temperature, promoting slight dissociation	Reducing e.g., heat-treatment furnace gases	Oxidizing, e.g., flue gases	
Cast iron, flake graphite, plain or low-alloy	1	3	4	5	0	4	0	4	3	4	2	4	4	1	1	3
Ductile iron (higher strength and hardness may be attained by composition and heat treatment or both)	1	3	4	5	0	4	0	4	4	4	3	4	4	1	1	3
Ni-Resist corrosion-resistant cast irons	4	5	5	5	0	5	0	5	5	5	5	5	5	3	2	4
14% silicon iron	6	6	2	5	6	6	3	5	5	5	5	6	4	4	3	6
Mild steel, also low-alloy irons and steels	1	3	4	5	0	4	0	4	3	4	2	4	4	1	1	3
Stainless steel, ferritic 17% Cr type	2	4	4	6	5	6	0	4	6	1	4	5	6	3	2	4
Stainless steel, austenitic 18 Cr, 8 Ni type	3	4	5	6	6	6	0	6	6	2	5	6	6	2	3	5

TABLE 28-2 General Corrosion Properties of Some Metals and Alloys* (Concluded)

Ratings:

0: Unsuitable. Not available in form required or not suitable for fabrication requirements or not suitable for corrosion conditions.

1: Poor to fair.

2: Fair. For mild conditions or when periodic replacement is possible. Restricted use.

3: Fair to good.

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5: Good to excellent.

6: Normally excellent.

Small variations in service conditions may appreciably affect corrosion resistance. Choice of materials is therefore guided wherever possible by a combination of experience and laboratory and site tests.

Material	Gases (continued)												Remarks [¶]			
	Halogens and derivatives															
	Halogens		Halide acids, moist, e.g., hydrochloric hydrolysis products of organic halides	Hydrogen halides, dry, [‡] e.g., dry hydrogen chloride, °F	Available forms	Cold formability in wrought and clad form	Weldability	Maximum strength annealed condition × 1000 lb/in ²	Coefficient of thermal expansion, millionths per °F, 70–212°F							
	Moist, e.g., chlorine below dew point	Dry, e.g., fluorine above dew point														
Stainless steel, austenitic 18 Cr; 12 Ni; 2.5 Mo type	4	5	5	6	5	6	1	6	6	3	5	6	6	2	4	6
Stainless steel, austenitic 20 Cr; 29 Ni; 2.5 Mo; 3.5 Cu type	5	6	5	6	5	6	2	6	6	4	6	6	6	2	4	6
Incoloy 825 nickel-iron-chromium alloy (40 Ni; 21 Cr; 3 Mo; 1.5 Cu; balance Fe)	6	6	5	6	5	6	2	6	6	4	6	6	6	2	5	6
Hastelloy alloy C-276 (55 Ni; 17 Mo; 16 Cr; 6 Fe; 4 W)	5	6	5	6	4	6	5	6	6	6	6	6	6	3	4	6
Hastelloy alloy B-2 (61 Ni; 28 Mo; 6 Fe)	6	5	4	4	0	3	0	6	6	4	4	6	5	3	2	5
Inconel 600 (78 Ni; 15 Cr; 7 Fe)	3	6	6	6	3	6	1	6	6	4	6	6	6	2	4	6
Copper-nickel alloys up to 30% nickel	4	5	5	0	0	4	1	6	6	6	6	6	5	2	2	5
Monel 400 nickel-copper alloy (66 Ni; 30 Cu; 2 Fe)	5	6	6	1	0	5	1	6	6	4	6	6	6	2	3	5
Nickel 200—commercial (99.4 Ni)	4	5	6	1	0	5	0	6	6	3	5	6	6	2	2	4
Copper and silicon bronze	4	4	4	0	0	4	0	6	5	4	1	6	5	2	2	5
Aluminum brass (76 Cu; 22 Zn; 2 Al)	3	4	2	0	0	3	0	6	6	4	5	6	5	2	2	5
Nickel-aluminum bronze (80 Cu; 10 Al; 5 Ni; 5 Fe)	4	4	2	0	0	3	0	6	6	4	5	6	5	2	3	5
Bronze, type A (88 Cu; 5 Sn; 5 Ni; 2 Zn)	4	5	4	0	0	4	0	6	6	5	5	6	5	2	2	5
Aluminum and its alloys	1	3	0	6	0–5	0–4	0	4	5	0–5	4	5	2	5	4	5
Lead, chemical or antimonial	5	5	2	2	0	2	0	6	5	5	3	2	0	4	3	5
Silver	4	6	6	0	0	2	0	6	6	5	5	6	5	4	4	4
Titanium	3	6	2	6	6	6	6	6	6	6	6	6	5	3	5	6
Zirconium	3	6	2	6	6	6	2	6	6	6	6	6	6	3	5	6

TABLE 28-2 General Corrosion Properties of Some Metals and Alloys* (Concluded)

Ratings:

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Small variations in service conditions may appreciably affect corrosion resistance. Choice of materials is therefore guided wherever possible by a combination of experience and laboratory and site tests.

Material	Gases (continued)				Available forms	Cold formability in wrought and clad form	Weldability	Maximum strength annealed condition × 1000 lb/in ²	Coefficient of thermal expansion, millionths per °F, 70–212°F	Remarks¶
	Halogens and derivatives									
	Halogens		Halide acids, moist, e.g., hydrochloric products of organic halides	Hydrogen halides, dry, † e.g., dry hydrogen chloride, °F						
	Moist, e.g., chlorine below dew point	Dry, e.g., fluorine above dew point								
Cast iron, flake graphite, plain or low alloy	0	2	0	2 < 400 1 < 750	Cast	No	Fair§	45	6.7	
Ductile iron (higher strength and hardness may be attained by composition and heat treatment or both)	0	2	0	2 < 400 1 < 750	Cast	No	Good§	67	7.5	
Ni-Resist corrosion-resistant cast irons	0	2	3	3 < 400 2 < 750	Cast	No	Good§	22–31	10.3	
Durion—14% silicon iron	0	0	4	1 < 400	Cast	No	No	22	7.4	Very brittle, susceptible to cracking by mechanical and thermal shock
Mild steel, also low-alloy irons and steels	0	3	0	3 < 400 1 < 750	Wrought, cast	Good	Good	67	6.7	High strengths obtainable by alloying, also improved atmospheric corrosion resistance. See ASTM specifications for particular grade
Stainless steel, ferritic 17% Cr type	0	2	0	2 < 400	Wrought, cast, clad	Good	Good§	78	6.0	AISI type 430 ASTM corrosion- and heat-resisting steels
Stainless steel, austenitic 18 Cr, 8 Ni types	0	2	0	3 < 400	Wrought, cast, clad	Good	Good	90	9.6	AISI type 304 ASTM corrosion- and heat-resisting steels; stabilized or LC types used for welding
Stainless steel, austenitic 18 Cr, 12 Ni, 2.5 Mo type	0	3	2	4 < 400 3 < 750	Wrought, cast, clad	Good	Good	90	8.9	AISI type 316 ASTM corrosion- and heat-resisting steel; LC type used for welding

TABLE 28-2 General Corrosion Properties of Some Metals and Alloys* (Concluded)

Ratings:

0: Unsuitable. Not available in form required or not suitable for fabrication requirements or not suitable for corrosion conditions.

1: Poor to fair.

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Small variations in service conditions may appreciably affect corrosion resistance. Choice of materials is therefore guided wherever possible by a combination of experience and laboratory and site tests.

Gases (continued)											
Halogens and derivatives											
Material	Halogens		Halide acids, moist, e.g., hydrochloric hydrolysis products of organic halides	Hydrogen halides, dry, † e.g., dry hydrogen chloride, °F	Available forms	Cold formability in wrought and clad form	Weldability	Maximum strength annealed condition × 1000 lb/in ²	Coefficient of thermal expansion, millionths per °F, 70–212°F	Remarks¶	
	Moist, e.g., chlorine below dew point	Dry, e.g., fluorine above dew point									
Stainless steel, austenitic 20 Cr; 29 Ni; 2.5 Mo; 3.5 Cu type	1	3	3	4 < 400 3 < 750	Wrought, cast	Good	Good	90	9.4	ACI CH-7M; good resistance to sulfuric, phosphoric, and fatty acids at elevated temperatures	
Incoloy 825 nickel-iron-chromium alloy (40 Ni; 21 Cr; 3 Mo; 1.5 Cu; bal. Fe)	2	3	3	4 < 400 3 < 750	Wrought, cast, clad	Good	Good	100	7.3	Special alloy with good resistance to sulfuric, phosphoric, and fatty acids; resistant to chlorides in some environments	
Hastelloy alloy C-276 (55 Ni; 17 Mo; 16 Cr; 6 Fe; 4 W)	5	4	4	4 < 750 3 < 900	Wrought, cast, clad	Fair	Good	145	6.3	Excellent resistance to wet chlorine gas and sodium hypochlorite solutions	
Hastelloy alloy B-2 (61 Ni; 28 Mo; 6 Fe)	1	3	5	4 < 750 3 < 900	Wrought, cast, clad	Fair	Good	135	5.6	Resistant to solutions of hydrochloric and sulfuric acids	
Inconel 600 (78 Ni; 15 Cr; 7 Fe)	2	5	3	5 < 400 4 < 900	Wrought, cast, clad	Good	Good	90	8.9	Wide application in food and pharmaceutical industries	
Copper-nickel alloys up to 30% nickel	1	5	2	4 < 400 3 < 750	Wrought, cast, clad	Good	Good	35–62	9.3–8.5	High-iron types excellent for resisting high-velocity effects in condenser tubes	
Monel 400 nickel-copper alloy (66 Ni; 30 Cu; 2 Fe)	2	6	3	6 < 400 3 < 750 2 < 900	Wrought, cast, clad	Good	Good	77	7.5	Widely used for sulfuric acid pickling equipment; also for propeller shafts in motor boats; precautions needed to avoid sulfur attack during fabrication	
Nickel 200—commercial (99.4 Ni)	2	6	2	6 < 400 5 < 750 4 < 900	Wrought, cast, clad	Good	Good	54	6.6	Widely used for hot concentrated caustic solutions; precautions needed to avoid sulfur attack during fabrication	
Copper and silicon bronze	0	5	2	3 < 400 2 < 750 2 < 400	Wrought, cast, clad	Excellent	Fair	29	9.3–9.5	Unsuitable for hot concentrated mineral acids or for high-velocity HF	
Aluminum brass (76 Cu; 22 Zn; 2 Al)	0	4	2	2 < 400	Wrought, cast	Good	Fair	60	10.3	Possibility of developing localized corrosion in seawater	
Nickel-aluminum bronze (80 Cu; 10 Al; 5 Ni; 5 Fe)	0	4	3	3 < 400 2 < 750	Wrought, cast	Good	Fair	60–80	9.4	Ship propellers an excellent application	
Bronze, type A (88 Cu; 5 Sn; 5 Ni; 2 Zn)	0	4	3	3 < 400 2 < 750	Cast	No	§	45	11.0	High strengths obtained by heat treatment; not susceptible to dezincification	
Aluminum and its alloys	0	6	0	3 < 400 1 < 750	Wrought, cast, clad	Good	Good	9–90	11.5–13.7	Extent of corrosion dependent upon type and concentration of acidic ions; wide range of mechanical properties obtainable by alloying and heat treatment	
Lead, chemical or antimonial	0	1	3	0	Wrought, cast, clad	Excellent	Good	2	16.4–15.1	High purity "chemical lead" preferred for most applications	
Silver	5	5	3	4 < 400 2 < 750	Wrought, cast, clad	Excellent	Good	21	10.6	Used as a lining	
Titanium	6	0	1	0	Wrought, cast	Fair	Good§	6–90	5.0	Possibility of red fuming HNO ₃ initiating explosions; good resistance to solutions containing chlorides	
Zirconium	6	1	6	0	Wrought, cast	Fair	Good§				

*Data courtesy of International Nickel Co.

†On unsuitable materials these media may promote potentially dangerous pitting.

‡Temperatures are approximate.

§Special precautions required.

¶Many of these materials are suitable for resisting dry corrosion at elevated temperatures.

TABLE 28-3 Unified Alloy Numbering System (UNS)

UNS was established in 1974 by ASTM and SAE to reduce the confusion involved in the labeling of commercial alloys. Metals have been placed into 15 groups, each of which is given a code letter. The specific alloy is identified by a five-digit number following this code letter.

Nonferrous metals and alloys	
A00001–A99999	Aluminum and aluminum alloys
C00001–C99999	Copper and copper alloys
E00001–E99999	Rare-earth and rare-earth-like metals and alloys
L00001–L99999	Low-melting metals and alloys
M00001–M99999	Miscellaneous nonferrous metals and alloys
N00001–N99999	Nickel and nickel alloys
P00001–P99999	Precious metals and alloys
R00001–R99999	Reactive and refractory metals and alloys
Ferrous metals and alloys	
D00001–D99999	Specified-mechanical-properties steels
F00001–F99999	Cast irons and cast steels
G00001–G99999	AISI and SAE carbon and alloy steels
H00001–H99999	AISI H steels
K00001–K99999	Miscellaneous steels and ferrous alloys
S00001–S99999	Heat- and corrosion-resistant (stainless) steels
T00001–T99999	Tool steels

When possible, earlier widely used three- or four-digit alloy numbering systems such as those developed by the Aluminum Association (AA), Copper Development Association (CDA), American Iron and Steel Institute (AISI), etc., have been incorporated by the addition of the appropriate alloy-group code letter plus additional digits. For example:

Alloy description	Former designation		UNS designation
	System	No.	
Aluminum + 1.2% Mn	AA	3003	A93003
Copper, electrolytic tough pitch	CDA	110	C11000
Carbon steel, 0.2% C	AISI	1020	G10200
Stainless steel, 18 Cr, 8 Ni	AISI	304	S30400

Proprietary alloys are assigned numbers by the AA, AISI, CDA, ASTM, and SAE, which maintains master listings at their headquarters. Handbooks describing the system are available. (Cf. ASTM publication DS-56AC.)

SOURCE: ASTM DS-56A. (Courtesy of National Association of Corrosion Engineers.)

Austenitic stainless steels are the most corrosion-resistant of the three groups. These steels contain 16 to 26 percent chromium and 6 to 22 percent nickel. Carbon is kept low (0.08 percent maximum) to minimize carbide precipitation. These alloys can be work-hardened, but heat treatment will not cause hardening. Tensile strength in the annealed condition is about 585 MPa (85,000 lbf/in²), but work-hardening can increase this to 2,000 MPa (300,000 lbf/in²). Austenitic stainless steels are tough and ductile.

They can be fabricated by all standard methods. But austenitic grades are not easy to machine; they work-harden and gall. Rigid machines, heavy cuts, and high speeds are essential. Welding, however, is readily performed, although welding heat may cause chromium carbide precipitation, which depletes the alloy of some chromium and lowers its corrosion resistance in some specific environments, notably nitric acid. The carbide precipitation can be eliminated by heat treatment (solution annealing). To avoid precipitation, special stainless steels stabilized with titanium, niobium, or tantalum have been developed (types 321, 347, and 348). Another approach to the problem is the use of low-carbon steels such as types 304L and 316L, with 0.03 percent maximum carbon.

The addition of molybdenum to the austenitic alloy (types 316, 316L, 317, and 317L) provides generally better corrosion resistance and improved resistance to pitting.

In the stainless group, nickel greatly improves corrosion resistance over straight chromium stainless. Even so, the chromium-nickel steels, particularly the 18-8 alloys, perform best under **oxidizing conditions**, since resistance depends on an oxide film on the surface of the alloy. Reducing conditions and chloride ions destroy this film and bring on rapid attack. Chloride ions tend to cause pitting and crevice

TABLE 28-4 Coefficient of Thermal Expansion of Common Alloys*

	UNS	10 ⁻⁶ in/(in·°F)	10 ⁻⁶ mm/(mm·°C)	Temperature range, °C
Aluminum alloy				
AA1100	A91100	13.1	24.	20–100
Aluminum alloy				
AA5052	A95052	13.2	24.	20–100
Aluminum cast alloy				
43	A24430	12.3	22.	20–100
Copper	C11000	9.4	16.9	20–100
Red brass	C23000	10.4	18.7	20–300
Admiralty brass	C44300	11.2	20.	20–300
Muntz Metal	C28000	11.6	21.	20–300
Aluminum bronze D	C61400	9.0	16.2	20–300
Ounce metal	C83600	10.2	18.4	0–100
90-10 copper nickel	C70600	9.5	17.1	20–300
70-30 copper nickel	C71500	9.0	16.2	20–300
Carbon steel, AISI				
1020	G10200	6.7	12.1	0–100
Gray cast iron	F10006	6.7	12.1	0–100
4-6 Cr, ½ Mo steel	S50100	7.3	13.1	20–540
Stainless steel, AISI 410	S41000	6.1	11.0	0–100
Stainless steel, AISI 446	S44600	5.8	10.4	0–100
Stainless steel, AISI 304	S30400	9.6	17.3	0–100
Stainless steel, AISI 310	S31000	8.0	14.4	0–100
Stainless steel, ACI HK	J94224	9.4	16.9	20–540
Nickel alloy 200	N02200	7.4	13.3	20–90
Nickel alloy 400	N04400	7.7	13.9	20–90
Nickel alloy 600	N06600	7.4	13.3	20–90
Nickel-molybdenum alloy B-2	N10665	5.6	10.1	20–90
Nickel-molybdenum alloy C-276	N10276	6.3	11.3	20–90
Titanium, commercially pure	R50250	4.8	8.6	0–100
Titanium alloy T1-6Al-4V	R56400	4.9	8.8	0–100
Magnesium alloy				
AZ31B	M11311	14.5	26.	20–100
Magnesium alloy				
AZ91C	M11914	14.5	26.	20–100
Chemical lead		16.4	30.	0–100
50-50 solder	L05500	13.1	24.	0–100
Zinc	Z13001	18.	32.	0–100
Tin	L13002	12.8	23.	0–100
Zirconium	R60702	2.9	5.2	0–100
Molybdenum	R03600	2.7	4.9	20–100
Tantalum	R05200	3.6	6.5	20–100

*Courtesy of National Association of Corrosion Engineers.

corrosion; when combined with high tensile stresses, they can cause stress-corrosion cracking.

Cast stainless alloys are widely used in pumps, valves, and fittings. These casting alloys are designated under the ACI system. All corrosion-resistant alloys have the letter C plus a second letter (A to N) denoting increasing nickel content. Numerals indicate maximum carbon. While a rough comparison can be made between ACI and AISI types, compositions are not identical and analyses cannot be used interchangeably. Foundry techniques require a rebalancing of the wrought chemical compositions. However, corrosion resistance is not greatly affected by these composition changes. Typical members of this group are CF-8, similar to type 304 stainless; CF-8M, similar to type 316; and CD-4M Cu, which has improved resistance to nitric, sulfuric, and phosphoric acids.

In addition to the C grades, there is a series of heat-resistant grades of ACI cast alloys, identified similarly to the corrosion-resistant grades, except that the first letter is H rather than C. Mention should

TABLE 28-5 Melting Temperatures of Common Alloys*

	UNS	Melting range	
		°F	°C
Aluminum alloy AA1100	A91100	1190–1215	640–660
Aluminum alloy AA5052	A95052	1125–1200	610–650
Aluminum cast alloy 43	A24430	1065–1170	570–630
Copper	C11000	1980	1083
Red brass	C23000	1810–1880	990–1025
Admiralty brass	C44300	1650–1720	900–935
Muntz Metal	C28000	1650–1660	900–905
Aluminum bronze D	C61400	1910–1940	1045–1060
Ounce metal	C83600	1510–1840	854–1010
Manganese bronze	C86500	1583–1616	862–880
90-10 copper nickel	C70600	2010–2100	1100–1150
70-30 copper nickel	C71500	2140–2260	1170–1240
Carbon steel, AISI 1020	G10200	2760	1520
Gray cast iron	F10006	2100–2200	1150–1200
4-6 Cr, ½ Mo Street	S50100	2700–2800	1480–1540
Stainless steel, AISI 410	S41000	2700–2790	1480–1530
Stainless steel, AISI 446	S44600	2600–2750	1430–1510
Stainless steel, AISI 304	S30400	2550–2650	1400–1450
Stainless steel, AISI 310	S31000	2500–2650	1400–1450
Stainless steel, ACl HK	J94224	2550	1400
Nickel alloy 200	N02200	2615–2635	1440–1450
Nickel alloy 400	N04400	2370–2460	1300–1350
Nickel alloy 600	N06600	2470–2575	1350–1410
Nickel-molybdenum alloy B-2	N10665	2375–2495	1300–1370
Nickel-molybdenum alloy C-276	N10276	2420–2500	1320–1370
Titanium, commercially pure	R50250	3100	1705
Titanium alloy T1-6Al-4V	R56400	2920–3020	1600–1660
Magnesium alloy AZ 31B	M11311	1120–1170	605–632
Magnesium alloy HK 31A	M13310	1092–1204	589–651
Chemical lead		618	326
50-50 solder	L05500	361–421	183–216
Zinc	Z13001	787	420
Tin	Z13002	450	232
Zirconium	R60702	3380	1860
Molybdenum	R03600	4730	2610
Tantalum	R05200	5425	2996

*Courtesy of National Association of Corrosion Engineers.

also be made of precipitation-hardening (PH) stainless steels, which can be hardened by heat treatments at moderate temperatures. Very strong and hard at high temperatures, these steels have but moderate corrosion resistance. A typical PH steel, containing 17 percent Cr, 7 percent Ni, and 1.1 percent Al, has high strength, good fatigue properties, and good resistance to wear and cavitation corrosion. A large number of these steels with varying compositions are commercially available. Essentially, they contain chromium and nickel with added alloying agents such as copper, aluminum, beryllium, molybdenum, nitrogen, and phosphorus.

Medium Alloys A group of (mostly) proprietary alloys with somewhat better corrosion resistance than stainless steels are called medium alloys. A popular member of this group is the **20 alloy**, made by a number of companies under various trade names. Durimet 20 is a well-known cast version, containing 0.07 percent C, 29 percent Ni, 20 percent Cr, 2 percent Mo, and 3 percent Cu. The ACI designation of this alloy is CN-7M. A wrought form is known as Carpenter 20 (Cb3). Worthite is another proprietary 20 alloy with about 24 percent Ni and 20 percent Cr. The 20 alloy was originally developed to fill the need for a material with sulfuric acid resistance superior to the stainless steels.

Other members of the medium-alloy group are **Incoloy 825** and **Hastelloy G-3** and **G-30**. Wrought Incoloy 825 has 40 percent Ni, 21 percent Cr, 3 percent Mo, and 2.25 percent Cu. Hastelloy G-3 contains 44 percent Ni, 22 percent Cr, 6.5 percent Mo, and 0.05 percent C maximum.

These alloys have extensive applications in sulfuric acid systems. Because of their increased nickel and molybdenum contents they are more tolerant of chloride-ion contamination than standard stainless steels. The nickel content decreases the risk of stress-corrosion cracking; molybdenum improves resistance to crevice corrosion and pitting.

High Alloys The group of materials called high alloys all contain relatively large percentages of nickel. **Hastelloy B-2** contains 61 percent Ni and 28 percent Mo. It is available in wrought and cast forms. Work hardening presents some fabrication difficulties, and machining is somewhat more difficult than for type 316 stainless. Conventional welding methods can be used. The alloy has unusually high resistance to all concentrations of hydrochloric acid at all temperatures in the absence of oxidizing agents. Sulfuric acid attack is low for all concentrations at 65°C (150°F), but the rate goes up with temperature. Oxidizing acids and salts rapidly corrode Hastelloy B. But alkalis and alkaline solutions cause little damage.

Chlorimet 2 has 63 percent Ni and 32 percent Mo and is somewhat similar to Hastelloy B-2. It is available only in cast form, mainly as valves and pumps. This is a tough alloy, very resistant to mechanical and thermal shock. It can be machined with carbide-tipped tools and welded with metal-arc techniques.

Hastelloy C-276 is a nickel-based alloy containing chromium (15.5 percent), molybdenum (15.5 percent), and tungsten (3 percent) as major alloying elements. It is available only in wrought form. This alloy is a low-impurity modification of Hastelloy C, which is still available in cast form. The low impurity level substantially reduces the risk of intergranular corrosion of grain-boundary precipitation in weld-heat-affected zones. This alloy is resistant to strong oxidizing chloride solutions, such as wet chlorine and hypochlorite solutions. It is one of the very few alloys which are totally resistant to seawater.

Hastelloy C-4 is almost totally immune to selective intergranular corrosion in weld-heat-affected zones with high temperature stability in the 650–1040°C (1200–1900°F) range; Hastelloy C-22 has better overall corrosion resistance and versatility than either C-4 or C-276 (in most environments).

Chlorimet 3 is an alloy, available only in cast form, which is similar in alloy content and corrosion resistance to Hastelloy C.

Inconel 600 (80 percent Ni, 16 percent Cr, and 7 percent Fe) should also be mentioned as a high alloy. It contains no molybdenum. The corrosion-resistant grade is recommended for reducing-oxidizing environments, particularly at high temperatures. When heated in air, this alloy resists oxidation up to 1,100°C (2,000°F). The alloy is outstanding in resisting corrosion by gases when these gases are essentially sulfur-free.

The alloys discussed are typical examples of the large number of proprietary high alloys used in the chemical industry. For more comprehensive lists and data, refer to the listed references.

NONFERROUS METALS AND ALLOYS

Nickel and Nickel Alloys Nickel is available in practically any mill form as well as in castings. It can be machined easily and joined by welding. Generally, oxidizing conditions favor corrosion, while reducing conditions retard attack. Neutral alkaline solutions, seawater, and mild atmospheric conditions do not affect nickel. The metal is widely used for handling alkalis, particularly in concentrating, storing, and shipping high-purity caustic soda. Chlorinated solvents and phenol are often refined and stored in nickel to prevent product discoloration and contamination.

A large number of nickel-based alloys are commercially available. Many have been mentioned in the preceding discussion of alloy castings and high alloys. One of the best known of these is **Monel 400**, 67 percent Ni and 30 percent Cu. It is available in all standard forms. This nickel-copper alloy is ductile and tough and can be readily fabricated and joined. Its **corrosion resistance** is generally superior to that of its components, being more resistant than nickel in reducing environments and more resistant than copper in oxidizing environments. The alloy can be used for relatively dilute sulfuric acid (below 80 percent), although aeration will result in increased corrosion. Monel will handle hydrofluoric acid up to 92 percent and 115°C

TABLE 28-6 Carbon and Low-Alloy Steels^a

Steel type	ASTM	UNS	Composition, % ^b	Mechanical properties ^c		
				Yield strength, kip/in ² (MPa)	Tensile strength, kip/in ² (MPa)	Elongation, %
C-Mn	A53B	K03005	0.30 C, 1.20 Mn	35 (241)	60 (415)	
C-Mn	A106B	K03006	0.30 C, 0.29–1.06 Mn, 0.10 min. Si	35 (241)	60 (415)	30
C	A285A	K01700	0.17 C, 0.90 Mn	24 (165)	45–55 (310–380)	30
HSLA	A517F	K11576	0.08–0.22 C, 0.55–1.05 Mn, 0.13–0.37 Si, 0.36–0.79 Cr, 0.67–1.03 Ni, 0.36–0.64 Mo, 0.002–0.006 B, 0.12–0.53 Cu, 0.02–0.09 V	100 (689)	115–135 (795–930)	16
HSLA	A242(1)	K11510	0.15 C, 1.00 Mn, 0.20 min Cu, 0.15 P	42–50 (290–345)	63–70 (435–480)	21
2¼ Cr, 1 Mo	A387(22)	K21590	0.15 C, 0.30–0.60 Mn, 0.5 Si, 2.00–2.50 Cr, 0.90–1.10 Mo	30 (205) ^d 45 (310) ^e	60–85 (415–585) ^d 75–100 (515–690) ^e	18 ^c 18 ^d
4–6 Cr, ½ Mo	A335 (P5)	K41545	0.15 C, 0.30–0.60 Mn, 0.5 Si, 4.00–6.00 Cr, 0.45–0.65 Mo	30 (205)	60 (415)	
9 Cr, 1 Mo	A335 (P9)	K81590	0.15 C, 0.30–0.6 Mn, 0.25–1.00 Si, 8.00–10.00 Cr, 0.90–1.10 Mo	30 (205)	60 (415)	
9 Ni	A333(8), A353(1)	K81340	0.13 C, 0.90 Mn, 0.13–0.32 Si, 8.40–9.60 Ni	75 (515)	100–120 (690–825)	20
	AISI 4130	G41300	0.28–0.33 C, 0.80–1.10 Mn, 0.15–0.3 Si, 0.8–1.10 Cr, 0.15–0.25 Mo	120 (830) ^f	140 (965) ^f	22 ^g
	AISI 4340	G43400	0.38–0.43 C, 0.60–0.80 Mn, 0.15–0.3 Si, 0.70–0.90 Cr, 1.65–2.00 Ni, 0.20–0.30 Mo	125 (860) ^g	148 (1020) ^g	20 ^g

^aCourtesy of National Association of Corrosion Engineers. To convert MPa to lbf/in², multiply by 145.04.

^bSingle values are maximum values unless otherwise noted.

^cRoom-temperature properties. Single values are minimum values.

^dClass 1.

^eClass 2.

^f1-in-diameter bars water-quenched from 1,575°F (860°C) and tempered at 1,200°F (650°C).

^g1-in-diameter bars oil-quenched from 1,550°F (845°C) and tempered at 1,200°F (650°C).

(235°F). Alkalies have little effect on this alloy, but it will not stand up against very highly oxidizing or reducing environments.

Aluminum and Alloys Aluminum and its alloys are made in practically all the forms in which metals are produced, including castings. Thermal conductivity of aluminum is 60 percent of that of pure copper, and unalloyed aluminum is used in many heat-transfer applications. Its high electrical conductivity makes aluminum popular in electrical applications. Aluminum is one of the most workable of metals, and it is usually joined by inert-gas-shielded arc-welding techniques.

Commercially pure aluminum has a tensile strength of 69 MPa (10,000 lbf/in²), but it can be strengthened by cold working. One limitation of aluminum is that strength declines greatly above 150°C (300°F). When strength is important, 200°C (400°F) is usually considered the highest permissible safe temperature for aluminum. However, aluminum has excellent low-temperature properties; it can be used at –250°C (–420°F).

Aluminum has high resistance to atmospheric conditions as well as to industrial fumes and vapors and fresh, brackish, or salt waters. Many mineral acids attack aluminum, although the metal can be used with concentrated nitric acid (above 82 percent) and glacial acetic acid. Aluminum cannot be used with strong caustic solutions.

It should be noted that a number of **aluminum alloys** are available (see Table 28-16). Many have improved mechanical properties over pure aluminum. The wrought heat-treatable aluminum alloys have tensile strengths of 90 to 228 MPa (13,000 to 33,000 lbf/in²) as annealed; when they are fully hardened, strengths can go as high as 572 MPa (83,000 lbf/in²). However, aluminum alloys usually have lower corrosion resistance than the pure metal. The **alclad** alloys have been developed to overcome this shortcoming. Alclad consists of an aluminum layer metallurgically bonded to a core alloy.

The corrosion resistance of aluminum and its alloys tends to be very sensitive to trace contamination. Very small amounts of metallic mercury, heavy-metal ions, or chloride ions can frequently cause rapid failure under conditions which otherwise would be fully acceptable.

When alloy steels do not give adequate corrosion protection—particularly from sulfidic attack—steel with an **aluminized surface coating** can be used. A spray coating of aluminum on a steel is not likely to spall or flake, but the coating is usually not continuous and

may leave some areas of the steel unprotected. Hot-dipped “aluminized” steel gives a continuous coating and has proved satisfactory in a number of applications, particularly when sulfur or hydrogen sulfide is present. It is also used to protect thermal insulation and as weather shields for equipment. The coated steel resists fires better than solid aluminum.

Copper and Alloys Copper and its alloys are widely used in chemical processing, particularly when heat and electrical conductivity are important factors. The thermal conductivity of copper is twice that of aluminum and 90 percent that of silver. A large number of cop-

TABLE 28-7 Properties of Low-Alloy AISI Steels

AISI type	Typical physical properties ^a			
	Melting temperature, °F	Thermal conductivity, Btu/[(h·ft ²)(°F/ft)] (212°F)	Coefficient of thermal expansion (0–1,200°F) per °F	Specific heat (68–212°F), Btu/(lb·°F)
13XX		27	7.9 × 10 ^{-6b}	0.10–0.11
23XX	2,600–2,620	38.3 ^c	8.0 × 10 ⁻⁶	0.11–0.12
25XX	2,610–2,620	34.5–38.5 ^c	7.8 × 10 ⁻⁶	0.11–0.12
40XX		27	8.3 × 10 ^{-6b}	0.10–0.11
41XX		24.7 ^d		0.11
43XX	2,740–2,750	21.7 ^e	8.1 × 10 ⁻⁶	0.107
46XX		27 ^d	6.3 × 10 ^{-6c}	0.10–0.11
48XX	2,750	26 ^f	8.6 × 10 ⁻⁶	
51XX	2,720–2,760	27–34 ^g	7.4 × 10 ^{-6b}	0.10–0.11
61XX		27	8.1 × 10 ^{-6b}	0.10–0.11
86, 87XX	2,745–2,755	21.7 ^e	8.2 × 10 ⁻⁶	0.107
92, 94XX		27	8.1 × 10 ^{-6b}	0.10–0.12

XX = nominal percent carbon.

^aDensity for all low-alloy steels is about 0.28 lb/in³.

^b68 to 1200°F.

^c120°F.

^d68°F.

^e0 to 200°F.

^f75°F.

^g32 to 212°F.

^h100 to 518°F.

TABLE 28-7 Properties of Low-Alloy AISI Steels (Concluded)

Typical mechanical properties ^a						
AISI type	Tensile strength, 1,000 lbf/in ²	Yield strength (0.2% offset), 1000 lbf/in ²	Elongation (in 2 in), %	Reduction of area, %	Hardness, Brinell	Impact strength (Izod), ft-lbf
1,330 ^b	122	100	19	52	248	
1,335 ^c	126	105	20	59	262	
1,340 ^c	137	118	19	55	285	
2,317 ^c	107	72	27	71	222	84
2,515 ^c	113	94	25	69	233	85
2,517 ^c	120	100	22	66	244	80
4,023 ^d	120	85	20	53	255	
4,032 ^c	210	182	11	49	415	
4,042 ^f	235	210	10	42	461	
4,053 ^g	250	223	12	40	495	
4,063 ^h	269	231	8	15	534	
4,130 ⁱ	200	170	16	49	375	25
4,140 ^j	200	170	15	48	385	16
4,150 ^k	230	215	10	40	444	12
4,320 ^l	180	154	15	50	360	32
4,337 ^k	210	140	14	50	435	18
4,340 ^k	220	200	12	48	445	16
4,615 ^d	100	75	18	52	42	42
4,620 ^d	130	95	21	65	68	68
4,640 ^j	185	160	14	52	390	25
4,815 ^d	150	125	18	58	325	44
4,817 ^d			15	52	355	36
4,820 ^j			13	47	380	28
5,120 ^l	143	114	13	45	302	6
5,130 ^m	189	175	13	51	380	
5,140 ^m	190	170	13	43	375	16
5,150 ^m	224	208	10	40	444	
6,120 ⁿ	125	94	21	56		28
6,145 ^o	176	169	16	52	429	20
6,150 ^o	187	179	13	42	444	13
8,620 ^p	122	98	21	63	245	76
8,630 ^p	162	142	14	54	325	42
8,640 ^p	208	183	13	43	420	18
8,650 ^p	214	194	12	41	423	
8,720 ^p	122	98	21	63	245	76
8,740 ^p	208	183	13	43	420	18
8,750 ^p	214	194	12	41	423	
9,255 ^p	232 ^r	215	9	21	477	6
9,261 ^p	258 ^r	226	10	30	514	12

^aProperties are for materials hardened and tempered as follows: ^bwater-quenched from 1,525°F, tempered at 1,000°F; ^coil-quenched from 1,525°F, tempered at 1,000°F; ^dpseudocarbonized 8 h at 1700°F, oil-quenched, tempered 1 h at 300°F; ^ewater-quenched from 1,525°F, tempered at 600°F; ^foil-quenched from 1,500°F, tempered at 600°F; ^goil-quenched from 1,475°F, tempered at 600°F; ^hoil-quenched from 1,450°F, tempered at 600°F; ⁱwater-quenched from 1,500 to 1,600°F, tempered at 800°F; ^joil-quenched from 1,550°F, tempered at 800°F; ^koil-quenched from 1,525°F, tempered at 800°F; ^lnormalized at 1,650°F, reheated to 1,475°F, oil-quenched, tempered at 800°F; ^mnormalized at 1,625°F, reheated to 1,550°F, water-quenched, tempered at 800°F; ⁿcarbonized 10 h at 1,680°F, pot-cooled, oil-quenched from 1,525°F, tempered at 300°F; ^onormalized at 1,600°F, oil-quenched from 1,575°F, tempered at 1,000°F; ^poil-quenched tempered at 800°F; ^qnormalized at 1,650°F, reheated to 1,625°F, quenched in agitated oil, tempered at 800°F; ^rnormalized at 1,600°F, reheated to 1,575°F, quenched in agitated oil, tempered at 800°F.

NOTE: °C = (°F - 32) × 5/9. To convert Btu/(h · ft · °F) to W/(m · °C), multiply by 0.8606; to convert Btu/(lb · °F) to kJ/(kg · °C), multiply by 0.2388; to convert lbf/in² to MPa, multiply by 0.006895; and to convert ft · lbf to J, multiply by 0.7375.

per alloys are available, including brasses (Cu-Zn), bronzes (Cu-Sn), and cupronickels.

Copper has excellent low-temperature properties and is used at -200°C (-320°F). Brazing and soldering are common joining methods for copper, although welding, while difficult, is possible. Generally, copper has high resistance to industrial and marine atmospheres, seawater, alkalis, and solvents. Oxidizing acids rapidly corrode cop-

per. However, the alloys have somewhat different properties than commercial copper.

Brasses with up to 15 percent Zn are ductile but difficult to machine. Machinability improves with increasing zinc up to 36 percent Zn. Brasses with less than 20 percent Zn have corrosion resistance equivalent to that of copper but with better tensile strengths. Brasses with 20 to 40 percent Zn have lower corrosion resistance and are subject to dezincification and stress-corrosion cracking, especially when ammonia is present.

Bronzes are somewhat similar to brasses in mechanical properties and to high-zinc brasses in corrosion resistance (except that bronzes are not affected by stress cracking). **Aluminum and silicon bronzes** are very popular in the process industries because they combine good strength with corrosion resistance.

Cupronickels (10 to 30 percent Ni) have become very important as copper alloys. They have the highest corrosion resistance of all copper alloys and find application as heat-exchanger tubing. Resistance to seawater is particularly outstanding.

Lead and Alloys Chemical leads of 99.9+ percent purity are used primarily in the chemical industry in environments that form thin, insoluble, and self-repairable protective films, for example, salts such as sulfates, carbonates, or phosphates. More soluble films such as nitrates, acetates, or chlorides offer little protection.

Alloys of antimony, tin, and arsenic offer limited improvement in mechanical properties, but the usefulness of lead is limited primarily because of its poor structural qualities. It has a low melting point and a high coefficient of expansion, and it is a very ductile material that will creep under a tensile stress as low as 1 MPa (145 lbf/in²).

Titanium Titanium has become increasingly important as a construction material. It is strong and of medium weight. Corrosion resistance is very superior in oxidizing and mild reducing media (Ti-Pd alloys Grade 7 and 11 have superior resistance in reducing environments, as does the Ti-Mo-Ni alloy Grade 12). Titanium is usually not bothered by impingement attack, crevice corrosion, and pitting attack in seawater. Its general resistance to seawater is excellent. Titanium is resistant to nitric acid at all concentrations except with red fuming nitric. The metal also resists ferric chloride, cupric chloride, and other hot chloride solutions. However, there are a number of disadvantages to titanium which have limited its use. Titanium is not easy to form, it has a high springback and tends to gall, and welding must be carried out in an inert atmosphere.

Zirconium Zirconium was originally developed as a construction material for atomic reactors. Reactor-grade zirconium contains very little hafnium, which would alter zirconium's neutron-absorbing properties. Commercial-grade zirconium, for chemical process applications, however, contains 2.5 percent hafnium. Zirconium resembles titanium from a fabrication standpoint. All welding must be done under an inert atmosphere. Zirconium has excellent resistance to reducing environments. Oxidizing agents frequently cause accelerated attack. It resists all chlorides except ferric and cupric. Zirconium alloys should *not* be used in concentrations of sulfuric acid above about 70 percent. There are a number of alloys of titanium and zirconium, with mechanical properties superior to those of the pure metals. The zirconium alloys are referred to as Zircalox.

Tantalum The physical properties of tantalum are similar to those of mild steel except that tantalum has a higher melting point. Tantalum is ductile and malleable and can be worked into intricate forms. It can be welded by using inert-gas-shielded techniques. The metal is practically inert to many oxidizing and reducing acids (except fuming sulfuric). It is attacked by hot alkalis and hydrofluoric acid. Its cost generally limits use to heating coils, bayonet heaters, coolers, and condensers operating under severe conditions. When economically justified, larger items of equipment (reactors, tanks, etc.) may be fabricated with tantalum liners, either loose (with proper anchoring) or explosion-bonded-clad. Since tantalum linings are usually very thin, very careful attention to design and fabrication details is required.

INORGANIC NONMETALLICS

Glass and Glassed Steel Glass is an inorganic product of fusion which is cooled to a rigid condition without crystallizing. With unique

TABLE 28-8 Cast-Iron Alloys*

Alloy	ASTM	UNS	Composition, %†	Condition	Mechanical properties‡			
					Yield strength, kip/in ² (MPa)	Tensile strength, kip/in ² (MPa)	Elongation, %	Hardness, HB
Gray cast iron	A159 (G3000)	F10006	3.1–3.4 C, 0.6–0.9 Mn, 1.9–2.3 Si	As cast		30 (207)		187–241
Malleable cast iron	A602 (M3210)	F20000	2.2–2.9 C, 0.15–1.25 Mn, 0.9–1.90 Si	Annealed	32 (229)	50 (345)	12	130
Ductile cast iron	A395 (60-40-18)	F32800	None specified	Annealed	40 (276)	60 (414)	18	170
Cast iron	A436(1)	F41000	3.0 C, 1.5–2.5 Cr, 5.5–7.5 Cu, 0.5–1.5 Mn, 13.5–17.5 Ni, 1.0–2.8 Si	As cast		25 (172)		150
Cast iron	A436(2)	F41002	3.0 C, 1.5–2.5 Cr, 0.50 Cu, 0.5–1.5 Mn, 18–22 Ni, 1.0–2.8 Si	As cast		25 (172)		145
Cast iron	A436(5)	F41006	2.4 C, 0.1 Cr, 0.5 Cu, 0.5–1.5 Mn, 34–36 Ni, 1.0–2.0 Si	As cast		20 (138)		110
Ductile austenitic cast iron	A439(D-2)	F43000	3.0 C, 1.75–2.75 Cr, 0.7–1.25 Mn, 18–22 Ni, 1.5–3.0 Si	As cast	30 (207)	58 (400)		170
Ductile austenitic cast iron	A439 (D-5)	F43006	2.4 C, 0.1 Cr, 1.0 Mn, 34–36 Ni, 1.0–2.8 Si	As cast	30 (207)	55 (379)		155
Silicon cast iron	A518	F47003	0.7–1.1 C, 0.5 Cr, 0.5 Cu, 1.50 Mn, 0.5 Mo, 14.2–14.75 Si	As cast		16 (110)		520

*Courtesy of National Association of Corrosion Engineers. To convert MPa to lbf/in², multiply by 145.04.
 †Single values are maximum values.
 ‡Typical room-temperature properties.

properties compared with metals, they require special considerations in their design and use.

Glass has excellent resistance to all acids except hydrofluoric and hot, concentrated H₃PO₄. It is also subject to attack by hot alkaline solutions. Glass is particularly suitable for piping when transparency is desirable.

The chief drawback of glass is brittleness, and it is also subject to damage by thermal shock. However, glass armored with epoxy-polyester fiberglass can readily be protected against breakage. On the other hand, glassed steel combines the corrosion resistance of glass with the working strength of steel. Accordingly, **glass linings** are resistant to all concentrations of hydrochloric acid to 120°C (250°F), to dilute concentrations of sulfuric to the boiling point, to concentrated sulfuric to 230°C (450°F), and to all concentrations of nitric

acid to the boiling point. Acid-resistant glass with improved alkali resistance (up to 12 pH) is available.

A nucleated crystalline ceramic-metal composite form of glass has superior mechanical properties compared with conventional glassed steel. Controlled high-temperature firings chemically and physically bond the ceramic to steel, nickel-based alloys, and refractory metals. These materials resist corrosive hydrogen chloride gas, chlorine, or sulfur dioxide at 650°C (1,200°F). They resist all acids except HF up to 180°C (350°F). Their impact strength is 18 times that of safety glass; abrasion resistance is superior to that of porcelain enamel. They have 3 to 4 times the thermal-shock resistance of glassed steel.

Porcelain and Stoneware Porcelain and stoneware materials are about as resistant to acids and chemicals as glass, but with the advantage of greater strength. This is offset somewhat by poor ther-

TABLE 28-9 Standard Wrought Martensitic Stainless Steels*

AISI type	UNS	Composition, %†					Mechanical properties‡			
		Cr	Ni	Mo	C	Other	Yield strength, kip/in ² (MPa)	Tensile strength, kip/in ² (MPa)	Elongation, %	Hardness, HB
403	S40300	11.5–13.0			0.15		40 (276)	75 (517)	35	155
410	S41000	11.5–13.5			0.15		35 (241)	70 (483)	30	150
414	S41400	11.5–13.5	1.25–2.5		0.15		90 (621)	115 (793)	20	235
416	S41600	12–14		0.6	0.15	0.15S§	40 (276)	75 (517)	30	155
416Se	S41623	12–14			0.15	0.15Se§	40 (276)	75 (517)	30	155
420	S42000	12–14			0.15		50 (345)	95 (655)	20	195
420F	S42020	12–14		0.6	0.15§	0.15S§	55 (379)	95 (655)	22	220
422	S42200	11–13	0.5–1.0	0.75–1.25	0.20–0.25	0.15–0.30 V, 0.75–1.25 W	125 (862)	145 (1000)	18	320
431	S43100	15–17	1.25–2.5		0.20		95 (665)	125 (862)	20	260
440A	S44002	16–18		0.75	0.6–0.75		60 (414)	105 (724)	20	210
440B	S44003	16–18.0		0.75	0.75–0.95		62 (427)	107 (738)	18	215
440C	S44004	16–18		0.75	0.95–1.20		65 (448)	110 (758)	14	220
501	S50100	4–6		0.40–0.65	0.10§		30 (207)	70 (483)	28	160
502	S50200	4–6		0.40–0.65	0.10		25 (172)	65 (448)	30	150

*Courtesy of National Association of Corrosion Engineers. To convert MPa to lbf/in², multiply by 145.04.
 †Single values are maximum values unless otherwise noted.
 ‡Typical room-temperature properties of annealed plates.
 §Minimum.

TABLE 28-10 Standard Wrought Ferritic Stainless Steels*

AISI type	Composition, %†								Mechanical properties‡			
	UNS	Cr	C	Mn	Si	P	S	Other	Yield strength, kip/in ² (MPa)	Tensile strength, kip/in ² (MPa)	Elongation, %	Hardness, HB
405	S40500	11.5–14.5	0.08	1.0	1.0	0.04	0.03	0.1–0.3 Al	40 (276)	65 (448)	30	150
409	S40900	10.5–11.75	0.08	1.0	1.0	0.045	0.045	(6 × C) Ti§	35 (241)	65 (448)	25	137
429	S42900	14–16	0.12	1.0	1.0	0.04	0.03		40 (276)	70 (483)	30	163
430	S43000	16–18	0.12	1.0	1.0	0.04	0.03		40 (276)	75 (517)	30	160
430F	S43020	16–18	0.12	1.25	1.0	0.06	0.15¶	0.6 Mo	55 (379)	80 (552)	25	170
430FSe	S43023	16–18	0.12	1.25	1.0	0.06	0.06	0.15 Se¶	55 (379)	80 (552)	25	170
434	S43400	16–18	0.12	1.0	1.0	0.04	0.03	0.75–1.25 Mo	53 (365)	77 (531)	23	160
436	S43600	16–18	0.12	1.0	1.0	0.04	0.03	0.75–1.25 Mo (5 × C)(Cb + Ta)§	53 (365)	77 (531)	23	160
442	S44200	18–23	0.20	1.0	1.0	0.04	0.03		45 (310)	80 (552)	20	185
446	S44600	23–27	0.20	1.5	1.0	0.04	0.03	0.25N	55 (379)	85 (586)	25	160

*Courtesy of National Association of Corrosion Engineers. To convert MPa to lbf/in², multiply by 145.04.

†Single values are maximum values unless otherwise noted.

‡Typical room-temperature properties of annealed plates.

§0.70 maximum.

¶Minimum.

mal conductivity, and the materials can be damaged by thermal shock fairly easily. **Porcelain enamels** are used to coat steel, but the enamel has slightly inferior chemical resistance. Some refractory coatings, capable of taking very high temperatures, are also available.

Brick Construction Brick-lined construction can be used for many severely corrosive conditions under which high alloys would fail. Common bricks are made from carbon, red shale, or acidproof refractory materials. Red-shale brick is not used above 175°C (350°F) because of spalling. Acidproof refractories can be used up to 870°C (1,600°F).

A number of **cement** materials are used with brick. Standard are phenolic and furan resins, polyesters, sulfur, silicate, and epoxy-based materials. Carbon-filled polyesters and furanes are good against nonoxidizing acids, salts, and solvents. Silica-filled resins should not be used against hydrofluoric or fluosilicic acids. Sulfur-based cements are limited to 93°C (200°F), while resins can be used to about 180°C (350°F). The sodium silicate-based cements are good against acids to 400°C (750°F).

Differential thermal expansion of the brick, its joints, and the vessel substrate necessitates an intermediate lining of lead, asphalt, rubber,

TABLE 28-11 Standard Wrought Austenitic Stainless Steels*

AISI type	UNS	Composition, %†							Mechanical properties‡			
		Cr	Ni	Mo	C	Si	Mn	Other	Yield strength, kip/in ² (MPa)	Tensile strength, kip/in ² (MPa)	Elongation, %	Hardness, HB
201	S20100	16–18	3.5–5.5		0.15	1.0	5.5–7.5	0.25 N	55 (379)	115 (793)	55	185
202	S20200	17–19	4–6		0.15	1.0	7.5–10.	0.25 N	55 (379)	105 (724)	55	185
301	S30100	16–18	6–8		0.15	1.0	2.0		40 (276)	105 (724)	55	165
302	S30200	17–19	8–10		0.15	1.0	2.0		35 (241)	90 (621)	60	150
302B	S30215	17–19	8–10		0.15	2.0–3.0	2.0		40 (276)	90 (621)	50	165
303	S30300	17–19	8–10	0.6	0.15	1.0	2.0	0.15 S, § 0.2 P	35 (241)	90 (621)	50	160
303Se	S30323	17–19	8–10		0.15	1.0	2.0	0.15 Se, § 0.2 P	35 (241)	90 (621)	50	160
304	S30400	18–20	8–10.5		0.08	1.0	2.0		35 (241)	82 (565)	60	149
304L	S30403	18–20	8–12		0.03	1.0	2.0		33 (228)	79 (545)	60	143
304N	S30451	18–20	8–10.5		0.08	1.0	2.0	0.10–0.16 N	48 (331)	90 (621)	50	180
308	S30800	19–21	10–12		0.08	1.0	2.0		30 (207)	85 (586)	55	150
309	S30900	22–24	12–15		0.20	1.0	2.0		40 (276)	95 (655)	45	170
309S	S30908	22–24	12–15		0.08	1.0	2.0		40 (276)	95 (655)	45	170
310	S31000	24–26	19–22		0.25	1.5	2.0		45 (310)	95 (655)	50	170
310S	S31008	24–26	19–22		0.08	1.5	2.0		45 (310)	95 (655)	50	170
314	S31400	23–26	19–22		0.25	1.5–3.0	2.0		50 (345)	100 (690)	45	180
316	S31600	16–18	10–14	2.0–3.0	0.08	1.0	2.0		36 (248)	82 (565)	55	149
316L	S31603	16–18	10–14	2.0–3.0	0.03	1.0	2.0		34 (234)	81 (558)	55	146
316N	S31651	16–18	10–14	2.0–3.0	0.08	1.0	2.0	0.10–0.16 N	42 (290)	90 (621)	55	180
317	S31700	18–20	11–15	3.0–4.0	0.08	1.0	2.0		40 (276)	85 (586)	50	160
317L	S31703	18–20	11–15	3.0–4.0	0.03	1.0	2.0		35 (241)	85 (586)	55	150
321	S32100	17–19	9–12		0.08	1.0	2.0	(5 × C) Ti§	30 (207)	85 (586)	55	160
329	S32900	25–30	3–6	1.0–2.0	0.10	1.0	2.0		80 (552)	105 (724)	25	230
347	S34700	17–19	9–13		0.08	1.0	2.0	(10 × C)(Cb + Ta)§	35 (241)	90 (621)	50	160
348	S34800	17–19	9–13		0.08	1.0	2.0	(10 × C)(Cb + Ta)¶ 0.20 Co	35 (241)	90 (621)	50	160

*Courtesy of National Association of Corrosion Engineers. To convert MPa to lbf/in², multiply by 145.04.

†Single values are maximum values unless otherwise noted.

‡Typical room-temperature properties of solution-annealed plates.

§Minimum.

¶Minimum except Ta = 0.1 maximum.

TABLE 28-12 Special Stainless Steels*

Alloy	UNS	Composition, %†							Mechanical properties‡			
		Cr	Ni	Mo	C	Mn	Si	Other	Yield strength, kip/ in ² (MPa)	Tensile strength, kip/ in ² (MPa)	Elongation, %	Hardness [§] HB
A-286	K66286	13.5–16	24–27	1.0–1.5	0.08	2.0	1.0	1.90–2.35 Ti, 0.1–0.5 V, 0.001–0.01 B, 8 × C–1.0 Cb	100 (690)	140 (970)	20	
20Cb-3	N08020	19–21	32–38	2.0–3.0	0.07	2.0	1.0	3.0–4.0 Cu	53 (365)	98 (676)	33	185
20Mod	N08320	21–23	25–27	4.0–6.0	0.05	2.5	1.0	(4.0 × C) Ti min.	43 (296)	84 (579)	42	160
PH13-8Mo	S13800	12.25–13.25	7.5–8.5	2.0–2.5	0.05	0.2	0.1	0.90–1.35 Al	120 (827)	160 (1100)	17	300
PH14-8Mo	S14800	13.75–15.0	7.75–8.75	2.0–3.0	0.05	1.0	1.0	0.75–1.5 Al, 0.15–45 Cb	55–210 (380–1450)	125–230 (860–1540)	2–25	200–450
15-5PH	S15500	14.0–15.5	3.5–5.5		0.07	1.0	1.0	2.5–4.5 Cu	145 (1000)	160 (1100)	15	320
PH15-7Mo	S15700	14.0–16.0	6.5–7.75	2.0–3.0	0.09	1.0	1.0	0.75–1.5 Al, 0.15–0.45 Cb	55–210 (380–1450)	130–220 (900–1520)	2–35	200–450
17-4PH	S17400	15.5–17.5	3.0–5.0		0.07	1.0	1.0	3.0–5.0 Cu, 0.4 Al	145 (1000)	160 (1100)	15	320
W	S17600	16.0–17.5	6.0–7.5		0.08	1.0	1.0	0.4–1.20 Ti	90–200 (620–1380)	135–210 (930–1450)	3–12	260–420
17-7PH	S17700	16.0–18.0	6.5–7.75		0.09	1.0	1.0	0.75–1.5 Al	40 (276)	130 (710)	10	185
216	S21600	17.5–22.0	5.0–7.0	2.0–3.0	0.08	7.5–9.0	1.0	0.25–0.5 N	70 (480)	115 (790)	45	200
Nitronic 60	S21800	16.0–18.0	8.0–9.0		0.10	7.0–9.0	3.5–4.5	0.08–0.18 N	60 (410)	103 (710)	62	210
21-6-9	S21900	18.0–21.0	5.0–7.0		0.08	8.0–10.0	1.0	0.15–0.40 N	68 (470)	112 (770)	44	220
AM350	S35000	16.0–17.0	4.0–5.0	2.5–3.25	0.07–0.11	0.5–1.25	0.5	0.07–0.13 N	60–173 (410–1200)	145–206 (1000–1420)	13.5–40	200–400
AM355	S35500	15.0–16.0	4.0–5.0	2.5–3.25	0.10–0.15	0.5–1.25	0.5		182 (1250)	216 (1490)	19	402–477
Almar 362	S36200	14.0–15.0	6.0–7.0		0.05	0.5	0.3	0.55–9.0 Ti	105–185 (124–286)	120–188 (827–1300)	15–13	250–400
18-18-2	S38100	17.0–19.0	17.5–18.5		0.08	2.0	1.5–2.5	0.20 × (C + N)	40 (280)	80 (550)	55	165
Stab. 18-2	S44400	17.5–19.5	1.0	1.75–2.5	0.025	1.0	1.0	min.–0.8 Ti + Cb 0.015 N	45 (310)	60 (414)	20	210
26-1	S44625	25.0–27.5	0.5	0.75–1.50	0.01	0.4	0.4	0.5 Ni + Cu	50 (345)	70 (480)	30	165
Stab. 26-1	S44626	25.0–27.0	0.5	0.75–1.50	0.06	0.75	0.75	7 × (C + Ni)– 1.0 Ti, 0.15 Cu	50 (345)	70 (480)	30	165
28-4	S44700	28.0–30.0	0.15	3.5–4.2	0.010	0.3	0.2	0.02 N, 0.15 Cu	70 (480)	90 (620)	25	210
28-4-2	S44800	28.0–30.0	2.0–2.5	3.5–4.2	0.010	0.3	0.2	0.02 N, 8 × C Cb min.	85 (590)	95 (650)	25	230
Custom 450	S45000	14.0–16.0	5.0–7.0	0.5–1.0	0.05	1.0	1.0	1.25–1.75 Cu	117–184 (800–1270)	144–196 (990–1350)	14	270–400
Custom 455	S45500	11.0–12.5	7.5–9.5	0.5	0.05	0.5	0.5	1.5–2.5 Cu, 0.8– 1.4 Ti	115–220 (790–1500)	140–230 (970–1600)	10–14	290–460

*Courtesy of National Association of Corrosion Engineers. To convert MPa to lbf/in², multiply by 145.04.

†Single values are maximum values unless otherwise noted.

‡Typical room-temperature properties.

TABLE 28-13 Standard Cast Heat-Resistant Stainless Steels^a

ACI	Equivalent AISI	UNS	Composition, % ^b							Mechanical properties at 1600°F			
										Short term		Stress to rupture in 1000 h	
										Tensile strength, kip/in ² (MPa)	Elonga- tion, %	kip/in ²	MPa
HA			8-10		0.2	0.35-0.65	1.0	0.9-1.2 Mo	44 (303) ^c	36 ^c	27	186 ^d	
HC	446	J92605	26-30	4	0.5	1.0	2.0				1.3	9.0	
HD	327	J93005	26-30	4-7	0.5	1.5	2.0		23 (159)	18	7.0	48 ^e	
HE		J93403	26-30	8-11	0.2-0.5	2.0	2.0						
HF	302B	J92603	18-23	9-12	0.2-0.4	2.0	2.0		21 (145)	16	4.4	30	
HH ^f		J93503	24-28	11-14	0.2-0.5	2.0	2.0	0.2 N	18.5 (128)	30	3.8	26	
HH ^g	309	J93503	24-28	11-14	0.2-0.5	2.0	2.0	0.2 N	21.5 (148)	18	3.8	26	
HI		J94003	26-30	14-18	0.2-0.5	2.0	2.0		26 (179)	12	4.8	33	
HK	310	J94224	24-28	18-22	0.2-0.6	2.0	2.0		23 (159)	16	6.0	41	
HL		J94604	28-32	18-22	0.2-0.6	2.0	2.0		30 (207)				
HN		J94213	19-23	23-27	0.2-0.5	2.0	2.0		20 (138)	37	7.4	51	
HP		J95705	24-28	33-37	0.35-0.75	2.0	2.5		26 (179)	27	7.5	52	
HT	330	J94605	13-17	33-37	0.35-0.75	2.0	2.5		19 (131)	26	5.8	40	
HU		J95405	17-21	37-41	0.35-0.75	2.0	2.5		20 (138)	20	5.2	36	
HW			10-14	58-62	0.35-0.75	2.0	2.5		19 (131)		4.5	31	
HX			15-19	64-68	0.35-0.75	2.0	2.5		20.5 (141)	48	4.0	28	

^a Courtesy of National Association of Corrosion Engineers. To convert MPa to lbf/in², multiply by 145.04.

^b Single values are maximum values; S and P are 0.04 maximum; Mo is 0.5 maximum.

^c At 1100°F (593°C).

^d At 1000° (538°C).

^e At 1400°F (760°C).

^f Type I; partially ferritic.

^g Type II; wholly austenitic.

TABLE 28-14 Standard Cast Corrosion-Resistant Stainless Steels^a

ACI	Equivalent AISI	UNS	Composition, % ^b							Mechanical properties ^c				
										Yield strength, kip/in ² (MPa)	Tensile strength, kip/in ² (MPa)	Elonga- tion, %	Hardness ^d HB	
										Cr	Ni	Mo	C	Mn
Ca-15	410	J91150	11.5-14	1.0	0.5	0.15	1.00	1.50			150 (1034) ^d	200 (1379) ^d	7 ^d	390 ^d
CA-15M		J91151	11.5-14	1.0	0.15-1.0	0.15	1.00	1.50			150 (1034) ^d	200 (1379) ^d	7 ^d	390 ^d
CA-6NM		J91540	11.5-14	3.5-4.5	0.4-1.0	0.06	1.00	1.00			100 (690) ^e	120 (827) ^e	4 ^e	269 ^e
CA-40	420	J91153	11.5-14	1.0	0.5	0.20-0.40	1.00	1.50			165 (1138) ^d	220 (1517) ^d	1 ^d	470 ^d
CB-30	431	J91803	18.21	2.0		0.30	1.00	1.50			60 (414) ^f	95 (655) ^f	15 ^f	195 ^f
CC-50	446	J92615	26-30	4.0		0.50	1.00	1.50			65 (448) ^g	97 (669) ^g	18 ^g	210 ^g
CE-30	312	J93423	26-30	8-11		0.30	1.50	2.00			63 (434)	97 (669)	18	190
CB-7Cu	(17-4PH)		(16)	(4)		0.07			(3) Cu		165 (1138)		3	418
CD-4MCu			25-26.5	4.75-6.0	1.75-2.25	0.04	1.00	1.00	2.75-3.25 Cu		82 (565)	108 (745)	25	253
CF-3	304L	J92500	17-21	8-12		0.03	1.50	2.00			36 (248)	77 (531)	60	140
CF-8	304	J92600	18-21	8-11		0.08	1.50	2.00			37 (255)	77 (531)	55	140
CF-20	302	J92602	18-21	8-11		0.20	1.50	2.00			36 (248)	77 (531)	50	163
CF-3M	316L	J92800	17-21	9-13	2.0-3.0	0.03	1.50	1.50			38 (262)	80 (552)	55	150
CF-8M	316	J92900	18-21	9-12	2.0-3.0	0.08	1.50	2.00			42 (290)	80 (552)	50	160
CF-12M			18-21	9-12	2.0-3.0	0.12	1.50	2.00			42 (290)	80 (552)	50	160
CG-12	317	J93000	18-21	9-13	3.0-4.0	0.08	1.50	1.50			44 (303)	83 (572)	45	170
CF-8C	347	J92710	18-21	9-12		0.08	1.50	2.00	(8 × C) Cb ^h		38 (262)	77 (531)	39	149
CF-16F	303	J92701	18-21	9-12	1.50	0.16	1.50	2.00			40 (276)	77 (531)	52	150
CG-12		J93001	20-23	10-13		0.12	1.50	2.00			28 (193)		35	
CH-20	309	J93402	22-26	12-15		0.20	1.50	2.00			50 (345)	88 (607)	38	190
CK-20	310	J94202	23-27	19-22		0.20	1.50	2.00			38 (262)	76 (524)	37	144
CN-7M		J95150	19-22	27.5-30.5	2.0-3.0	0.07	1.50	1.50	3-4 Cu		32 (221)	69 (476)	48	130

^a Courtesy of National Association of Corrosion Engineers. To convert MPa to lbf/in², multiply by 145.04.

^b Single values are maximum values except those in parentheses, which are minimum values. P and S values are 0.04 maximum.

^c Typical room-temperature properties for solution-annealed material unless otherwise noted.

^d For material air-cooled from 1800°F and tempered at 600°F.

^e For material air-cooled from 1750°F and tempered at 1100 to 1150°F.

^f For material annealed at 1450°F, furnace-cooled to 1000°F, then air-cooled.

^g Air-cooled from 1900°F.

^h 1.0 maximum.

TABLE 28-15 Nickel Alloys*

Alloy	UNS	Composition, %†						Mechanical properties‡				
		Ni(+Co)§	Cr	Fe	Mo	C	Other	Condition	Yield strength, kip/in ² (MPa)	Tensile strength, kip/in ² (MPa)	Elongation, %	Hardness HB
200	N02200	99.		0.4		0.15		Annealed	15–30 (103–207)	55–80 (379–552)	55–40	90–120
201	N02201	99.		0.4		0.02		Annealed	10–25 (69–172)	50–60 (345–414)	60–40	75–102
400	N04400	63–70		1.0–2.5		0.3	28–34 Cu	Annealed	25–50 (172–345)	70–90 (483–621)	60–35	110–149
K-500	N05500	63–70		2.0		0.25	2.3–3.15 Al 0.35–0.85 Ti, 30 Cu	Age-hardened Annealed	85–120 (586–827)	130–165 (896–1138)	35–20	250–315
600	N06600	72.	14–17	6–10		0.15		Annealed	30–50 (207–345)	80–100 (552–690)	55–35	120–170
601	N06601	58–63	21–25	Bal.		0.10	1.0–1.7 Al	Annealed	30–60 (207–414)	80–115 (552–793)	70–40	110–150
625	N06625	Bal.	20–23	5	8–10	0.10	3.15–4.15 (Cb + Ta)	Annealed	60–95 (414–655)	120–150 (827–1034)	60–30	145–220
706	N09706	39–44	14.5–17.5	Bal.		0.06		Solution-treated and aged	161 (1110)	193 (1331)	20.	371.
718	N07718	50–55	17–21	Bal.	2.8–3.3	0.08	4.75–5.5 (Cb + Ta)	Special heat treatment	171 (1180)	196 (1351)	17.	382.
X-750	N07750	70	14–17	5–9		0.08	0.65–1.15 Ti, 0.2–0.8 Al 0.7–1.2 (Cb + Ta) 2.25–2.75 Ti, 0.4–1.0 Al	Special heat treatment	115–142 (793–979)	162–193 (1117–1331)	30–15	300–390
800	N08800	30–35	19–23	Bal.		0.10	0.15–0.6 Al, 0.15–0.6 Ti	Annealed	30–60 (207–414)	75–100 (517–690)	60–30	120–184
800H	N08800	30–35	19–23	Bal.		0.05–0.10	0.15–0.6 Al, 0.15–0.6 Ti	Solution-treated	20–50 (138–345)	65–95 (448–655)	50–30	100–184
801	N08801	30–34	19–22	Bal.		0.10	0.75–1.5 Ti	Special heat treatment	79.5 (548)	129 (889)	29.5	
825	N08825	38–46	19.5–23.5	Bal.	2.5–3.5	0.05	1.5–3.0 Cu, 0.6–1.2 Ti	Annealed	35–65 (241–448)	85–105 (586–724)	50–30	120–180
B-2	N10665	Bal.	1.0	2	26–30	0.02		Annealed	76 (524)	139 (958)	53.	210
C-276	N10276	Bal.	14.5–16.5	4–7	15–17	0.02	3.0–4.5 W	Annealed	52 (358)	115 (793)	61.	194
C-4	N06455	Bal.	14–18	3	14–17	0.015	0.7 Ti	Annealed	61 (421)	116 (800)	54.	194
G	N06007	Bal.	21–23	18–21	5.5–7.5	0.05	1.0–2.0 Mn, 1.5–2.5 Cu 1.75–2.5 (Cb + Ta)	Annealed	46 (317)	102 (703)	61.	161
X	N06002	Bal.	20.5–23	17–20	8–10	0.05–0.15	0.2–1.0 W	Annealed	56 (386)	110 (758)	45.	178

*Courtesy of National Association of Corrosion Engineers. To convert MPa to lbf/in², multiply by 145.04.

†Single values are maximum unless otherwise noted.

‡Typical room-temperature properties.

§Single values are minima.

TABLE 28-16 Aluminum Alloys

AA designation	UNS	Composition, %°						Condition‡	Mechanical properties†				
		Cr	Cu	Mg	Mn	Si	Other		Yield strength, kip/in ² (MPa)	Tensile strength, kip/in ² (MPa)	Elongation in 2 in, %	Hardness [§] HB	
Wrought													
1060	A91060							99.6 Al min.	0	4 (28)	10 (69)	43	19
1100	A91100		0.05–0.2					99.0 Al min.	0	5 (34)	13 (90)	45	23
2024	A92024	0.1	3.8–4.9	1.2–1.8	0.3–0.9	0.5			T4	47 (324)	68 (469)	19	120
3003	A93003		0.05–0.2		1.0–1.5	0.6			H14	21 (145)	22 (152)	16	40
5052	A95052	0.15–0.35	0.1	2.2–2.8	0.1				0	13 (90)	2.8 (193)	30	47
5083	A95083	0.05–0.25	0.1	4.0–4.9	0.4–1.0	0.4			0	21 (145)			
5086	A95086	0.05–0.25	0.1	3.5–4.5	0.2–0.7	0.4			0	17 (117)	38 (262)	30	
5154	A95154	0.05–0.35	0.1	3.1–3.9	0.1	0.25			0	17 (117)	35 (241)		58
6061	A96061	0.04–0.35	0.15–0.4	0.8–1.2	0.15	0.4–0.8			T6	40 (276)	45 (310)	17	95
6063	A96063	0.1	0.1	0.45–0.9	0.1	0.2–0.6			T6	31 (214)	35 (241)	18	73
7075	A97075	0.18–0.28	1.2–2.0	2.1–2.9	0.3	0.40		5.1–6.1 Zn	T6	73 (503)	63 (572)	11	150
Cast													
242.0	A02420	0.25	3.5–4.5	1.2–1.8	0.35	0.7	1.7–2.3 Ni	S-T571			29 (200)		
295.0	A02950		4.0–5.0	0.03	0.35	0.7–1.5		S-T4			29 (200)	6	
A332.0	A13320		0.5–1.5	0.7–1.3	0.35	11–13	2.0–3.0 Ni	P-T551			31 (214)		
B443.0	A24430		0.15	0.05	0.35	4.5–6.0		S-F			17 (117)	3	
514.0	A05140		0.15	3.5–4.5	0.35	0.35		S-F			22 (152)	6	
520.0	A05200		0.25	9.5–10.6	0.15	0.25		S-T4			42 (290)	12	

°Single values are maximum values.

†Typical room-temperature properties.

‡S = sand-cast; P = permanent-mold-cast; other = temper designations.

SOURCE: Aluminum Association. Courtesy of National Association of Corrosion Engineers. To convert MPa to lbf/in², multiply by 145.04.

or plastic. This membrane functions as a barrier to protect the substrate from corrosion damage. A special prestressed-brick design that maintains the brick in compression by using a controlled-expansion resinous mortar and brick bedding material precludes the use of an elastomeric membrane.

Cement and Concrete Concrete is an aggregate of inert reinforcing particles in an amorphous matrix of hardened cement paste. Concrete made of portland cement has limited resistance to acids and bases and will fail mechanically following absorption of crystal-forming solutions such as brines and various organics. Concretes made of corrosion-resistant cements (such as calcium aluminate) can be selected for specific chemical exposures.

Soil Clay is the primary construction material for settling basins and waste-treatment evaporation ponds. Since there is no single type of clay even within a given geographical area, shrinkage, porosity, absorption characteristics, and chemical resistance must be checked for each application.

ORGANIC NONMETALLICS

Plastic Materials In comparison with metallic materials, the use of plastics is limited to relatively moderate temperatures and pressures [230°C (450°F) is considered high for plastics]. Plastics are also less resistant to mechanical abuse and have high expansion rates, low strengths (thermoplastics), and only fair resistance to solvents. However, they are lightweight, are good thermal and electrical insulators, are easy to fabricate and install, and have low friction factors.

Generally, plastics have excellent resistance to weak mineral acids and are unaffected by inorganic salt solutions—areas where metals are not entirely suitable. Since plastics do not corrode in the electrochemical sense, they offer another advantage over metals: most metals are affected by slight changes in pH, or minor impurities, or oxygen content, while plastics will remain resistant to these same changes.

The important thermoplastics used commercially are polyethylene, acrylonitrile butadiene styrene (ABS), polyvinyl chloride (PVC), cellulose acetate butyrate (CAB), vinylidene chloride (Saran), fluorocarbons (Teflon, Halar, Kel-F, Kynar), polycarbonates, polypropylene, nylons, and acetals (Delrin). Important thermosetting plastics are

general-purpose polyester glass reinforced, bisphenol-based polyester glass, epoxy glass, vinyl ester glass, furan and phenolic glass, and asbestos reinforced.

THERMOPLASTICS

The most chemical-resistant plastic commercially available today is **tetrafluoroethylene** or **TFE** (Teflon). This thermoplastic is practically unaffected by all alkalis and acids except fluorine and chlorine gas at elevated temperatures and molten metals. It retains its properties up to 260°C (500°F). **Chlorotrifluoroethylene** or **CTFE** (Kel-F, Plaskon) also possesses excellent corrosion resistance to almost all acids and alkalis up to 180°C (350°F). A Teflon derivative has been developed from the copolymerization of tetrafluoroethylene and hexafluoropropylene. This resin, **FEP**, has similar properties to TFE except that it is not recommended for continuous exposures at temperatures above 200°C (400°F). Also, FEP can be extruded on conventional extrusion equipment, while TFE parts must be made by complicated powder-metallurgy techniques. Another version is **polyvinylidene fluoride**, or **PVF₂** (Kynar), which has excellent resistance to alkalis and acids to 150°C (300°F). It can be extruded. A more recent development is a copolymer of CTFE and ethylene (Halar). This material has excellent resistance to strong inorganic acids, bases, and salts up to 150°C. It also can be extruded.

Perfluoroalkoxy, or **PFA** (Teflon), has the general properties and chemical resistance of FEP at a temperature approaching 300°C (600°F).

Polyethylene is the lowest-cost plastic commercially available. Mechanical properties are generally poor, particularly above 50°C (120°F), and pipe must be fully supported. Carbon-filled grades are resistant to sunlight and weathering.

Unplasticized polyvinyl chlorides (type I) have excellent resistance to oxidizing acids other than concentrated and to most nonoxidizing acids. Resistance is good to weak and strong alkaline materials. Resistance to chlorinated hydrocarbons is not good. Polyvinylidene chloride, known as **Saran**, has good resistance to chlorinated hydrocarbons.

Acrylonitrile butadiene styrene (ABS) polymers have good resistance to nonoxidizing and weak acids but are not satisfactory with oxidizing acids. The upper temperature limit is about 65°C (150°F).

TABLE 28-17 Copper Alloys*

Alloy	CDA	UNS	Composition, %†						Mechanical properties‡			
			Cu	Zn	Sn	Al	Ni	Other	Yield strength, kip/in ² (MPa)	Tensile strength, kip/in ² (MPa)	Elongation in 2 in, %	
Wrought												
Copper	110	C11000	99.90							10 (69)	32 (221)	55
Commercial bronze	220	C22000	89-91	Rem.						10 (69)	37 (255)	50
Red brass	230	C23000	84-86	Rem.						10 (69)	40 (276)	55
Cartridge brass	260	C26000	68.5-71.5	Rem.						11 (76)	44 (303)	66
Yellow brass	270	C27000	63-68.5	Rem.						14 (97)	46 (317)	65
Muntz Metal	280	C28000	59-63	Rem.						21 (145)	54 (372)	52
Admiralty brass	443	C44300	70-73	Rem.	0.9-1.2				0.02-0.1 As	18 (124)	48 (331)	65
Admiralty brass	444	C44400	70-73	Rem.	0.9-1.2				0.02-0.1 Sb	18 (124)	48 (331)	65
Admiralty brass	445	C44500	70-73	Rem.	0.9-1.2				0.02-0.1 P	18 (124)	48 (331)	65
Naval brass	464	C46400	59-62	Rem.	0.5-1.0					25 (172)	58 (400)	50
Phosphor bronze	510	C51000	Rem.	0.3	4.2-5.8				0.03-0.35 P	19 (131)	47 (324)	64
Phosphor bronze	524	C52400	Rem.	0.2	9.0-11.0				0.03-0.35 P	28 (193)	66 (455)	70
Aluminum bronze	613	C61300	86.5-93.8		0.2-0.5		6-8	0.5	3.5 Fe	30 (207)	70 (483)	42
Aluminum bronze D	614	C61400	88.0-92.5	0.2			6-8		1.5-3.5 Fe, 1.0 Mn	33 (228)	76 (524)	45
Nickel-aluminum bronze	630	C63000	78-85	0.3	0.2		9-11	4.0-5.5	2.0-4.0 Fe, 1.5 Mn, 0.25 Si	36 (248)	90 (620)	10
High-silicon bronze	655	C65500	94.8	1.5				0.6	0.8 Fe, 0.5-1.3 Mn, 2.8-3.8 Si	21 (145)	56 (386)	63
Manganese bronze	675	C67500	57-60	Rem.	0.5-1.5	0.25			0.05-0.5 Mn, 0.8-2.0 Fe	30 (207)	65 (448)	33
Aluminum brass	687	C68700	76-79	Rem.			1.8-2.5		0.02-0.1 As	27 (186)	60 (414)	55
90-10 copper nickel	706	C70600	86.5	1.0				9.0-11.0	1.0-1.8 Fe, 1.0 Mn	16 (110)	44 (303)	42
70-30 copper nickel	715	C71500	Rem.	1.0				29-33	0.4-1.0 Fe, 1.0 Mn	20 (138)	54 (372)	45
65-18 nickel silver	752	C75200	63-66.5	Rem.				16.5-19.5	0.25 Fe, 0.5 Mn	25 (172)	56 (386)	45
Cast												
Ounce metal	836	C83600	84-86	4-6	4-6	0.005	1.0		4-6 Pb	17 (117)	37 (255)	30
Manganese bronze	865	C86500	55-65	36-42	1.0	0.5-1.5	1.0		0.4-2.0 Fe, 0.1-1.5 Mn	28 (193)	71 (490)	30
G bronze	905	C90500	86-89	1.0-3.0	9-11	0.005	1.0			22 (152)	45 (310)	25
M bronze	922	C92200	86-90	3.0-5.0	5.5-6.5	0.005	1.0		1.0-2.0 Pb	20 (138)	40 (276)	30
Ni-Al-Mn bronze	957	C95700	71			7.0-8.5	1.5-3.0		2.0-4.0 Fe, 11-14 Mn	45 (310)	95 (665)	26
Ni-Al bronze	958	C95800	79			8.5-9.5	4.0-5.0		3.5-4.5 Fe, 0.8-1.5 Mn	38 (262)	95 (655)	25
Copper nickel	964	C96400	65-69					28-32	0.5-1.5 Cb, 0.25-1.5 Fe, 1.5 Mn	37 (255)	68 (469)	28

*Courtesy of National Association of Corrosion Engineers. To convert MPa to lbf/in², multiply by 145.04.

†Single values are maximum values except for Cu, which is minimum.

‡Typical room-temperature properties of annealed or as-cast material.

Acetals have excellent resistance to most organic solvents but are not satisfactory for use with strong acids and alkalis.

Cellulose acetate butyrate is not affected by dilute acids and alkalis or gasoline, but chlorinated solvents cause some swelling. **Nylons** resist many organic solvents but are attacked by phenols, strong oxidizing agents, and mineral acids.

Polypropylene has a chemical resistance about the same as that of polyethylene, but it can be used at 120°C (250°F). **Polycarbonate** is a relatively high-temperature plastic. It can be used up to 150°C (300°F). Resistance to mineral acids is good. Strong alkalis slowly decompose it, but mild alkalis do not. It is partially soluble in aromatic solvents and soluble in chlorinated hydrocarbons. **Polyphenylene oxide** has good resistance to aliphatic solvents, acids, and bases but poor resistance to esters, ketones, and aromatic or chlorinated solvents.

Polyphenylene sulfide (PPS) has no known solvents below 190 to 205°C (375 to 400°F); mechanical properties of PPS are unaffected by exposures in air at 230°C (450°F). It is resistant to aqueous inorganic salts and bases.

Polysulfone can be used to 170°C (340°F); it is highly resistant to mineral acid, alkali, and salt solutions as well as to detergents, oils, and alcohols. It is attacked by such organic solvents as ketones, chlorinated hydrocarbons, and aromatic hydrocarbons.

Polyamide or polyimide polymers are resistant to aliphatic, aromatic, and chlorinated or fluorinated hydrocarbons as well as to many acidic and basic systems but are degraded by high-temperature caustic exposures.

Thermosetting Plastics Among the thermosetting materials are phenolic plastics filled with asbestos, carbon or graphite, glass, and silica. Relatively low cost, good mechanical properties, and chemical resistance (except against strong alkalis) make phenolics popular for chemical equipment. Furan plastics filled with asbestos and glass have much better alkali resistance than phenolic resins. They are more expensive than the phenolics but also offer somewhat higher strengths.

Polyester resins, reinforced with fiberglass, have good strength and good chemical resistance except to alkalis. Some special materials in this class, based on bisphenol and vinyl esters are more alkali-

TABLE 28-18 Typical Mechanical Properties of Selected Materials

Material	Tensile modulus, GPa	Tensile strength, yield, MPa	Tensile strength, ultimate, MPa	Elongation, %	Poisson's ratio	Fracture toughness, MPa√m
High-nickel gray cast iron	79–130		170–310			
20°C						
500°C						
700°C			130–212			
Medium-silicon ductile cast iron		210–240	415–690	0.2		
295°C				In 50 mm		
Low-carbon steel sheet						
20°C Hot rolled		27–48	40–66	25–43		
20°C Cold rolled		23–37	43–56	30–44		
SA-335P12 (ASME) ferritic steel				In 50 mm		
20°C	200	207	415	30(L), 20(T)	0.288	
540°C	155	170	345		0.303	
Type 4330V low-alloy steel				In 50 mm		
Oil-quenched plate						
20°C	200	1150	1330	13		130
Type 301 stainless steel				In 50 mm		
–100°C Annealed	196	410	1300			
20°C	190	205	515	30		214
650°C	80	100	260	34		225
Type 304 stainless steel				In 50 mm		
–200°C Annealed bar	204	280	1400–1520	32–45		
20°C	190	350–560	660–770	45–72	0.26	
400°C	168	245–475	525–610	26–48	0.32	
800°C	120	210–280	245–350	22–60		
Type 316 stainless steel				In 50 mm		
–200°C Annealed	232		1440	60 (25 mm)	0.281	
20°C	196	250	560	64	0.294	
400°C	167	170	500	48	0.331	
800°C	130	120	200	42	0.265	
Type 347 stainless steel				In 50 mm		
–200°C Annealed bar		430	1500	43		
20°C	200	380	670	50	0.30	
400°C	170	150–180	460	34	0.32	
800°C	105	110	160	42	0.25	
Alloy 42 (Fe + 42Ni)						
20°C	143	286	492	33.5	0.34	
100°C	150	222	445	41.3	0.33	
175°C	165	182	408	29.6	0.32	
250°C	174	152	388	34.6	0.30	
Kovar (Fe + 29Ni + 17Co)						
20°C	134	372	526	31.5	0.37	
100°C	139	295	454	30	0.36	
175°C	149	235	418	36	0.35	
250°C	153	192	396	35	0.33	
63Sn + 37Pb						
–70°C	34	60	85			
20°C	31	38	53	35		
125°C		18	25	48		
150°C		15	15	105		
Aluminum						
–200°C Annealed	76	61	184	13	0.34	
20°C	70	37	184	19.5	0.35	
400°C	58	5.5	18	19.5	0.36	
600°C	49		9.2		0.38	
Antimony						
20°C	77.7		11.40			
Beryllium, grade S-200 F						
20°C	303	262–269	380–413	2–5		9–13
400°C		255–262	317–331	11–26		
1000°C		138–145	186–200	6–10		
Bismuth						
20°C	32					
Cadmium						
20°C	55		69–83	In 25 mm	0.33	
50						
Chromium (electrolytic)				In 25 mm		
20°C	248		83	0		
400°C	227	140	225	51		
800°C	255	97	180	47		
Cobalt				In 50 mm		
20°C	211		255.1			
Annealed		758.5	944.6			
Zone-refined						
Annealed strip		310–345		15–22		

TABLE 28-18 Typical Mechanical Properties of Selected Materials (Continued)

Material	Tensile modulus, GPa	Tensile strength, yield, MPa	Tensile strength, ultimate, MPa	Elongation, %	Poisson's ratio	Fracture toughness, MPa√m
Copper						
-200°C						
Annealed	137	96	360	46	0.336	
20°C	128	71	212	51	0.344	
100°C	125	71	181	53	0.346	
300°C		70	128	56		
400°C	112				0.353	
500°C	107				0.358	
-200°C						
Cold worked		200	390-517			
20°C		170	230-393			
100°C		160	205-381			
200°C		140	175-350			
600°C			46			
20°C			145			
100°C			120			
200°C			98			
600°C			37			
Gold						
20°C	78		103	30		
Iron						
-200°		320-480				
20°C	208.2	70-140			0.291	
Lead						
-200°C						
Annealed	24					
20°C	18.8		12	68		
100°C	16.7		8	74		
150°C			5.5	86		
Magnesium (annealed sheet)						
20°C	40	90-105	160-195	In 50 mm 3-15		
Manganese (γ phase)						
20°C	191	241	496	40		
Molybdenum						
-100°C		650-750				
20°C	315	310-385	550-650			
500°C	285	110	250-315			
1200°C	215		100-140			
Tin						
-200°C						
Annealed	61					
20°C	50		24-38	33	0.33	
100°C	43.5		12-19	41		
150°C			8-10	50		
Titanium						
20°C	105	140	235	In 50 mm 54		
400°C	80		105	41		
Tungsten, annealed						
20°C	407-410					
400°C	393-396	75-130	275-355	33-58		
1800°C	322-325	6-42	35-85	19-43		
Teflon (PTFE)						
-200°C	5.5	111	112			
20°C	0.86	13	30			
100°C	0.23	7	10			
250°C		3	1.2			
Kapton						
-200°C	5.2	236 (L)	360		0.275	
20°C	3.9	105	212	72	0.365	8-10
100°C	3.1	87	161		0.441	6.3-8.8
200°C	1.3	80	117		0.568	
Kevlar 49	L T					
20°C	126,6.9		3480	2.9	0.36	
100°C	114,16.6		3200	2.8	0.36	
200°	110		2800			
Amoco P75/ERLX 1962 [0] _s unidirectional laminate						
20°C	46		120	Strain-to- Failure 0.26		
S-glass/Epoxy 2D (0)	Hercules 3501-6		Shell Epon (828 & 1031)			
-100°C	60					
20°C	57-80		1600			
100°C	50-62		1350-1600			
20°C	12-22					
100°C	5-19					

TABLE 28-18 Typical Mechanical Properties of Selected Materials (Concluded)

Material	Tensile modulus, GPa	Tensile strength, yield, MPa	Flexural strength, MPa	Poisson's ratio	Fracture toughness, MPa√m
Alumina (>99%)					
20°C	401	275-1030	520	0.24	3.2-4.0
600°C	343		360	0.25	
1200°C			340	0.35	
1400°C			260		
Silicon nitride					
20°C Sintered	248 (195-315)		415 (275-840)	0.28	4.66 (4.40-5.40)
1400°C			70 (0-700)	0.26	4.70 (3.40-6.80)
20°C Hot pressed	314 (250-325)	375	750 (450-1100)		
1000°C	300		600		
1400°C	175 (175-250)	150	300 (0-600)		
Silicon carbide					
20°C Hot pressed	450 (430-450)	200	470	0.17	3.85 (3-4)
800°C			412		
1000°C			227		3.59
1200°C			324		3.52
1400°C	380	35-150	175 (175-525)		2.81
20°C Sintered	411 (375-420)		460	0.16	3.01 (2.5-6.5)
800°C			326	0.165	
1000°C			353	0.170	
1200°C			377	0.192	
1400°C	372		240		
Boron nitride (H)	L T		L T		
20°C Hot pressed	92,36		120,51		
100°C	84,34		116,50		
400°C	61,27		105,44		
400°C	24,10		60,12		
Aluminum nitride					
20°C Hot pressed	345		390		2.90 (2.90-3.40)
700°C	343		375		2.80
1050°C			267		3.30
Silicon					
20°C	130 [100]	2900	2800-3100		0.76
400°C		200			
800°C		23			
1000°C		7.5			
1200°C		2.5			
Silica					
-200°C Fused	68				
20°C	71	49	66	0.17	
400°C	76				
900°C	82				

SOURCE: Center for Information and Numerical Data Analysis and Synthesis (CINDAS), Purdue University, West Lafayette, Ind.

resistant. The temperature limit for polyesters is about 90 to 150°C (200 to 300°F), depending upon exposure conditions.

Epoxyes reinforced with fiberglass have very high strengths and resistance to heat. The chemical resistance of the epoxy resin is excellent in nonoxidizing and weak acids but not good against strong acids. Alkaline resistance is excellent in weak solutions. Resistance is poor to such organic solvents as ketones, chlorinated hydrocarbons, and aromatic hydrocarbons.

The thermoset polyimides are a family of heat-resistant polymers with acceptable properties up to 260°C (500°F). They are unaffected by dilute acids, aromatic and aliphatic hydrocarbons, esters, ethers, and alcohols but are attacked by dilute alkalis and concentrated inorganic acids.

Chemical resistance of thermosetting-resin-glass-reinforced laminates may be affected by any exposed glass in the laminate.

Phenolic asbestos, general-purpose polyester glass, Saran, and CAB are adversely affected by alkalis. And thermoplastics generally show poor resistance to organics.

The lack of homogeneity and the friable nature of FRP composite structures dictate that caution be followed in mechanical design, vendor selection, inspection, shipment, installation, and use.

FRP code vessels for pressure service over 0.1 MPA (15 lbf/in²) may be designed and built under ASME Sec. X. Equipment for service from full vacuum through 0.1-MPA (15-lbf/in²) pressure, while not

presently covered by an ASME code designation, can be designed or fabricated in accordance with the SPI-MTI Quality Assurance Practices and Procedures Report for RTP equipment.

Rubber and Elastomers Rubber and elastomers are widely used as lining materials. To meet the demands of the chemical industry, rubber processors are continually improving their products. A number of synthetic rubbers have been developed, and while none has all the properties of natural rubber, they are superior in one or more ways. The isoprene and polybutadiene synthetic rubbers are duplicates of natural.

The ability to bond natural rubber to itself and to steel makes it ideal for lining tanks. Many of the synthetic elastomers, while more chemically resistant than natural rubber, have very poor bonding characteristics and hence are not well suited for lining tanks.

Natural rubber is resistant to dilute mineral acids, alkalis, and salts, but oxidizing media, oils, and most organic solvents will attack it. **Hard rubber** is made by adding 25 percent or more of sulfur to natural or synthetic rubber and, as such, is both hard and strong. **Chloroprene** or **neoprene rubber** is resistant to attack by ozone, sunlight, oils, gasoline, and aromatic or halogenated solvents but is easily permeated by water, thus limiting its use as a tank lining. **Styrene rubber** has chemical resistance similar to that of natural. **Nitrile rubber** is known for resistance to oils and solvents. **Butyl rubber's** resistance to dilute mineral acids and alkalis is exceptional; resistance to concen-

TABLE 28-19 Miscellaneous Alloys*

Alloy	Designation	UNS	Composition, %‡	Condition	Mechanical properties†			
					Yield strength, kip/in ² (MPa)	Tensile strength, kip/in ² (MPa)	Elongation, %	Hardness, HB
Refractory alloys								
Niobium R04210 (columbium)		204-210	99.6 Cb	Annealed	37 (255)	53 (365)	26	80
Molybdenum		R03600	0.01-0.04 C					
Molybdenum, low C		R03650	0.01 C					
Molybdenum alloy		R03630	0.01-0.04 C, 0.40-0.55 Ti, 0.06-0.12 Zn					
Tantalum		R05200	99.8 min. Ta	Annealed		50 (345)	40	45
Tungsten		R07030	99.9 min. W	Annealed		270 (1862)		
Zirconium		R60702	4.5 Hf, 0.2 Fe + Cr, 99.2 Zr + Hf	Annealed	16 (110)	36 (248)	31	77
Precious metals and alloys								
Gold		P00020	99.95 min. Au	Annealed		19 (131)	45	25
Silver		P07015	99.95 min. Ag	Annealed	8 (55)	18 (124)	54	27
Sterling silver			7.5 Cu, 92.5 Ag	Annealed	20 (138)	41 (283)	26	65
Platinum		P04955	99.95 min. Pt	Annealed		18 (124)	38	39
Palladium		P03980	99.80 min. Pd	Annealed		25 (172)	27	38
Lead alloys								
Chemical lead			99.9 min. Pb	Rolled	1.9 (13)	2.5 (17)	50	5
Antimonial lead			90 Pb, 10 Sb	Rolled		4.1 (28)	47	13
Tellurium lead			99.85 Pb, 0.04 Te, 0.06 Cu	Rolled	2.2 (15)	3 (21)	45	6
50-50 solder		L05500	50 Pb, 50 Sn, 0.12 max. Sb	Cast		6.8 (47)	50	14
Magnesium alloys								
Wrought alloy	AZ31B	M11311	2.5-3.5 Al, 0.20 min. Mn, 0.6-1.4 Zn	Annealed	15-18 (103-124)	32 (220)	9-12	56
Cast alloy	AZ91C	M11914	8.1-9.3 Al, 0.13 min. Mn, 0.4-1.0 Zn	As cast	11 (76)	23 (159)		60
Cast alloy	EZ33A	M12330	2.0-3.1 Zn, 0.5-1.0 Zr	Aged	14 (97)	20 (138)	2	50
Wrought alloy	HK31A	M13310	0.3 Zn, 2.5-4.0 Th, 0.4-1.0 Zr	Stress hard-annealed	24-26 (165-179)	33-34 (228-234)	4	57
Titanium alloys								
Commercial pure	Gr. 1	R50250	0.20 Fe, 0.18 O	Annealed	35 (241)	48 (331)	30	120
Commercial pure	Gr. 2	R50400	0.30 Fe, 0.25 O	Annealed	50 (345)	63 (434)	28	200
Ti-Pd	Gr. 7	R52400	0.30 Fe, 0.25 O, 0.12-0.25 Pd	Annealed	50 (345)	63 (434)	28	200
Ti-6Al-4V	Gr. 5	R56400	5.5-5.6 Al, 0.40 Fe, 0.20 O, 3.5-4.5 V	Annealed	134 (924)	144 (993)	14	330
Low alloy	Gr. 12		0.2-0.4 Mo, 0.6-0.9 Ni	Annealed	65 (448)	75 (517)	25	
Cobalt alloys								
	N-155	R30155	0.08-0.16 C, 0.75-1.25 Cb, 18.50-21.0 Co, 20.0-22.5 Cr, 1.0-2.0 Mn, 2.5-3.5 Mo, 19-21 Ni, 1.0 Si, 2.0-3.0 W					
	MP35N	R30036	0.025 C, 19-21 Cr, 1.0 Fe, 0.15 Mn, 9.0-10.5 Mo, 33.37 Ni, 0.15 Si, 1.0 Ti	Annealed	60 (414)	135 (931)	70	
	Stellite 6	R30006	0.9-1.4 C, 27-31 Cr, 3 Fe, 1.0 Mn, 1.5 Mo, 3.0 Ni, 1.5 Si, 3.5-5.5 W	As cast		105 (724)	1	

*Courtesy of National Association of Corrosion Engineers. To convert MPa to lbf/in², multiply by 145.04.

†Typical room-temperature properties.

‡Single values are maximum values unless otherwise noted.

TABLE 28-20 Properties of Glass and Silica*

	Pyroceram	96% silica	Borosilicate	Glass lining
Specific gravity, 77°F	2.60	2.18	2.23	2.56
Water absorption, %	0.00	0.00	0.00	
Gas permeability	Gastight	Gastight	Gastight	
Softening temperature, °F (°C)	2282 (1250)	2732 (1500)	1508 (1820)	
Specific heat, 77°F Btu/(lb·°F)[J/(kg·K)]	0.185 (775)	0.178 (746)	0.186 (779)	
Mean specific heat (77–752°F)	0.230	0.224	0.233	
Thermal conductivity, mean temperature, 77°F, Btu/(ft ² ·h·°F)/in [W/(m·K)]	25.2 (3.6)		7.5 (1.1)	
Linear thermal expansion, per °F (77–572°F); (per °C), × 10 ⁻⁶	3.2 (5.8)	0.44 (0.79)	1.8 (3.2)	
Modulus of elasticity, kip/in ² (MPa) × 10 ³	17.3 (119)	9.6 (66)	9.5 (66)	6–9 (40–60)
Poisson's ratio	0.245	0.17	0.20	
Modulus of rupture, kip/in ²	20 (140)	5–9 (35–63)	6–10 (42–70)	
Knoop hardness, 100 g	698	532	481	480
Knoop hardness, 500 g	619	477	442	
Adhesion strength kip/in ² (MPa)				5–10 (35–70)
Maximum operating temperature, °F (°C)				500 (260)
Thermal shock resistance, temperature difference, °F (°C)				305 (152)

*Courtesy of National Association of Corrosion Engineers.

trated acids, except nitric and sulfuric, is good. **Silicone rubbers**, also known as polysiloxanes, have outstanding resistance to high and low temperatures as well as against aliphatic solvents, oils, and greases. **Chlorosulfonated polyethylene**, known as **Hypalon**, has outstanding resistance to ozone and oxidizing agents except fuming nitric and sulfuric acids. Oil resistance is good. **Fluoroelastomers (Viton A, Kel-F, Kalrez)** combine excellent chemical and temperature resistance. **Polyvinyl chloride elastomer (Koroseal)** was developed to overcome some of the limitations of natural and synthetic rubbers. It has excellent resistance to mineral acids and petroleum oils.

The **cis-polybutadiene**, **cis-polyisoprene**, and **ethylene-propylene** rubbers are close duplicates of natural rubber. The newer ethylene-propylene rubbers (EPR) have excellent resistance to heat and oxidation.

Asphalt Asphalt is used as a flexible protective coating, as a brick-lining membrane, and as a chemical-resisting floor covering and road surface. Resistant to acids and bases, asphalt is soluble in organic solvents such as ketones, most chlorinated hydrocarbons, and aromatic hydrocarbons.

Carbon and Graphite The chemical resistance of impervious carbon and graphite depends somewhat on the type of resin impregnant used to make the material impervious. Generally, impervious graphite is completely inert to all but the most severe oxidizing conditions. This property, combined with excellent heat transfer, has made impervious carbon and graphite very popular in heat exchangers, as brick lining, and in pipe and pumps. One limitation of these materials is low tensile strength. Threshold oxidation temperatures are 350°C (660°F) for carbon and 400°C (750°F) for graphite.

TABLE 28-21 Chemical Resistance of Important Plastics

	Polypropylene polyethylene	CAB°	ABS†	PVC‡	Saran§	Polyester glass¶	Epoxy glass	Phenolic asbestos	Fluoro-carbons	Chlorinated polyether (Penton)	Poly-carbonate
10% H ₂ SO ₄	Excel.	Good	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.
50% H ₂ SO ₄	Excel.	Poor	Excel.	Excel.	Excel.	Good	Excel.	Excel.	Excel.	Excel.	Excel.
10% HCl	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.
10% HNO ₃	Excel.	Poor	Good	Excel.	Excel.	Good	Good	Fair	Excel.	Excel.	Excel.
10% Acetic	Excel.	Good	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.
10% NaOH	Excel.	Fair	Excel.	Good	Fair	Fair	Excel.	Poor	Excel.	Excel.	Excel.
50% NaOH	Excel.	Poor	Excel.	Excel.	Fair	Poor	Good	Poor	Excel.	Excel.	Excel.
NH ₄ OH	Excel.	Poor	Excel.	Excel.	Poor	Fair	Excel.	Poor	Excel.	Excel.	Excel.
NaCl	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.
FeCl ₃	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.
CuSO ₄	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.
NH ₄ NO ₃	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Good	Excel.	Excel.	Excel.
Wet H ₂ S	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.
Wet Cl ₂	Poor	Poor	Excel.	Good	Poor	Poor	Poor	Excel.	Excel.	Excel.	Excel.
Wet SO ₂	Excel.	Poor	Excel.	Excel.	Good	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.
Gasoline	Poor	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.
Benzene	Poor	Poor	Poor	Poor	Fair	Good	Excel.	Excel.	Excel.	Fair	Fair
CCl ₄	Poor	Poor	Poor	Fair	Fair	Excel.	Good	Excel.	Excel.	Fair	Poor
Acetone	Poor	Poor	Poor	Poor	Fair	Poor	Good	Poor	Excel.	Good	Good
Alcohol	Poor	Poor	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.

NOTE: Ratings are for long-term exposures at ambient temperatures [less than 38°C (100°F)].

°Cellulose acetate butyrate.

†Acrylonitrile butadiene styrene polymer.

‡Polyvinyl chloride, type I.

§Chemical resistance of Saran-lined pipe is superior to extruded Saran in some environments.

¶Refers to general-purpose polyesters. Special polyesters have superior resistance, particularly in alkalis.

Several types of resin impregnates are employed in manufacturing impervious graphite. The standard impregnant is a phenolic resin suitable for service in most acids, salt solutions, and organic compounds. A modified phenolic impregnant is recommended for service in alkalies and oxidizing chemicals. Furan and epoxy thermosetting resins are also used to fill structural voids. The chemical resistance of the impervious graphite is controlled by the resin used. However, no type of impervious graphite is recommended for use in over 60 percent hydrofluoric, over 20 percent nitric, and over 96 percent sulfuric acids and in 100 percent bromine, fluorine, or iodine.

Wood While fairly inert chemically, wood is readily dehydrated by concentrated solutions and hence shrinks badly when subjected to the action of such solutions. It is also slowly hydrolyzed by acids and alkalies, especially when hot. In tank construction, if sufficient shrinkage once takes place to allow crystals to form between the staves, it becomes very difficult to make the tank tight again.

A number of manufacturers offer wood impregnated to resist acids or alkalies or the effects of high temperatures.

HIGH- AND LOW-TEMPERATURE MATERIALS

LOW-TEMPERATURE METALS

The low-temperature properties of metals have created some unusual problems in fabricating cryogenic equipment.

Most metals lose their ductility and impact strength at low temperatures, although in many cases yield and tensile strengths increase as the temperature goes down.

Materials selection for low-temperature service is a specialized area. In general, it is necessary to select materials and fabrication methods which will provide adequate toughness at all operating conditions. It is frequently necessary to specify Charpy V-notch (or other appropriate) qualification tests to demonstrate adequate toughness of carbon and low-alloy steels at minimum operating temperatures.

Stainless Steels Chromium-nickel steels are suitable for service at temperatures as low as -250°C (-425°F). Type 304 is the most popular. The original cost of stainless steel may be higher than that of another metal, but ease of fabrication (no heat treatment) and welding, combined with high strength, offsets the higher initial cost. Sensitization or formation of chromium carbides can occur in several stainless steels during welding, and this will affect impact strength. However, tests have shown that impact properties of types 304 and 304L are not greatly affected by sensitization but that the properties of 302 are impaired at -185°C (-300°F).

Nickel Steel Low-carbon 9 percent nickel steel is a ferritic alloy developed for use in cryogenic equipment operating as low as -195°C (-320°F). ASTM specifications A 300 and A 353 cover low-carbon 9 percent nickel steel (A 300 is the basic specification for low-temperature ferritic steels). Refinements in welding and (ASME code-approved) elimination of postweld thermal treatments make 9 percent steel competitive with many low-cost materials used at low temperatures.

Aluminum Aluminum alloys have unusual ability to maintain strength and shock resistance at temperatures as low as -250°C (-425°F). Good corrosion resistance and relatively low cost make these alloys very popular for low-temperature equipment. For most welded construction the 5000-series aluminum alloys are widely used. These are the aluminum-magnesium and aluminum-magnesium-manganese materials.

Copper and Alloys With few exceptions the tensile strength of copper and its alloys increases quite markedly as the temperature goes down. However, copper's low structural strength becomes a problem when constructing large-scale equipment. Therefore, alloy must be used. One of the most successful for low temperatures is silicon bronze, which can be used to -195°C (-320°F) with safety.

HIGH-TEMPERATURE MATERIALS

Metals Successful applications of metals in high-temperature process service depend on an appreciation of certain engineering factors. The important alloys for service up to $1,100^{\circ}\text{C}$ ($2,000^{\circ}\text{F}$) are shown in Table 28-35. Among the most important properties are creep, rupture, and short-time strengths (see Figs. 28-23 and 28-24).

Creep relates initially applied stress to rate of plastic flow. **Stress**

is another important consideration at high temperatures since it relates stress and time to produce rupture. As the figures show, ferritic alloys are weaker than austenitic compositions, and in both groups molybdenum increases strength. Austenitic castings are much stronger than their wrought counterparts. And higher strengths are available in the superalloys. Other properties which become important at high temperatures include thermal conductivity, thermal expansion, ductility at temperature, alloy composition, and stability.

Actually, in many cases strength and mechanical properties become of secondary importance in process applications, compared with resistance to the corrosive surroundings. All common heat-resistant alloys form oxides when exposed to **hot oxidizing environments**. Whether the alloy is resistant depends upon whether the oxide is stable and forms a protective film. Thus, mild steel is seldom used above 480°C (900°F) because of excessive scaling rates. Higher temperatures require **chromium** (see Fig. 28-25). Thus, type 502 steel, with 4 to 6 percent Cr, is acceptable to 620°C ($1,150^{\circ}\text{F}$). A 9 to 12 percent Cr steel will handle 730°C ($1,350^{\circ}\text{F}$); 14 to 18 percent Cr extends the limit to 800°C ($1,500^{\circ}\text{F}$); and 27 percent Cr to $1,100^{\circ}\text{C}$ ($2,000^{\circ}\text{F}$).

The well-known austenitic stainless steels have excellent oxidation resistance: up to 900°C ($1,650^{\circ}\text{F}$) for 18-8; and up to $1,100^{\circ}\text{C}$ ($2,000^{\circ}\text{F}$) for 25-12 (and Inconel 600 and Incoloy 800). The cobalt-

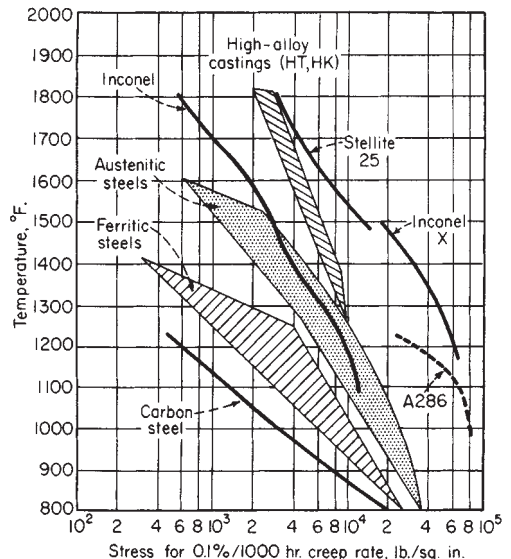


FIG. 28-23 Effect of creep on metals for high-temperature use. $^{\circ}\text{C} = (^{\circ}\text{F} - 32) \times \frac{5}{9}$; to convert lbf/in² to MPa, multiply by 6.895×10^{-3} . [Chem. Eng., 139 (Dec. 15, 1958).]

TABLE 28-22 Typical Property Ranges for Plastics

Thermosets ^a	Specific gravity	Tensile strength		Modulus of elasticity, tension		Impact strength, Izod ^b		Maximum use temperature (no load)		HDT at 254 lbf/in ² ^c		Chemical resistance ^d						
		kip	MPa	10 ³ kip/in ²	10 ² MPa	ft-lb	J	°F	°C	°F	°C	Weather resistance	Weak acid	Strong acid	Weak alkali	Strong alkali	Solvents	
Alkyds																		
Glass-filled	2.12–2.15	4–9.5	28–66	20–28	138–193	0.6–10	0.8–14	450	230	400–500	200–260	R	A	A	A	A	A	
Mineral-filled	1.60–2.30	3–9	21–62	5–30	34–207	0.3–0.5	0.4–0.7	300–450	150–230	350–500	180–260	R	R	A	A	D	A	
Asbestos-filled	1.65	4.5–7	31–48			0.4–0.5	0.6–0.7	450	230	315	160	R	R	S	R	S	R	
Synthetic fiber-filled	1.24–2.10	4.5–7	31–48	20	138	0.5–4.5	0.7–6.1	300–430	150–220	245–430	120–220	R	R	S	R	S	A	
Alkyl diglycol carbonate	1.30–1.40	5–6	34–41	3.0	21	0.2–0.4	0.3–0.5	212	100	140–190	60–90	R	R	A ^e	R	R-S	R	
Diallyl phthalates																		
Glass-filled	1.61–1.78	6–11	41–76	14–22	97–152	0.4–15	0.5–20	300–400	150–200	330–540	165–280	R	R	S	R-S	S	R	
Mineral-filled	1.65–1.68	5–9	34–62	12–22	83–152	0.3–0.5	0.4–1	300–400	150–200	320–540	160–280	R	R	S	R-S	S	R	
Asbestos-filled	1.55–1.65	7–8	48–55	12–22	83–152	0.4–0.5	0.5–0.7	300–400	150–200	320–540	160–280	R	R	S	R-S	S	R	
Epoxies (<i>bis-A</i>)																		
No filler	1.06–1.40	4–13	28–90	2.15–5.2	15–36	0.2–1.0	0.3–1.4	250–500	120–260	115–500	45–260	R	R	A	R	S	R-S	
Graphite-fiber reinforced	1.37–1.38	185–200	1280–1380	118–120	814–827							S	R	R	R	R	R-S	
Mineral-filled	1.6–2.0	5–15	34–103			0.3–0.4	0.4–0.5	300–500	150–260	250–500	120–260	S	R	R	R	R	R-S	
Glass-filled	1.7–2.0	10–30	69–207	30	207	10–30	14–41	300–500	150–260	250–500	120–260	S	R	R-S	R	R	R-S	
Epoxies (novolac): no filler	1.12–1.24	5–11	34–76	2.15–5.2	15–36	0.3–0.7	0.4–0.9	400–500	200–260	450–500	230–260	R	R	R	R	R	R	
Epoxies (cycloaliphatic): no filler	1.12–1.18	10–17.5	69–121	5–7	34–48			480–550	250–290	500–550	260–290	R	R	R-A	R	R-A	R	
Melamines																		
Cellulose-filled	1.45–1.52	5–9	34–62	11	76	0.2–0.4	0.3–0.5	250	120	270	130	S	R-S	D	R	D	R	
Flock-filled	1.50–1.55	7–9	48–62			0.4–0.5	0.5–0.7	250	120	270	130	S	R-S	D	R	D	R-S	
Asbestos-filled	1.70–2.0	5–7	34–48	20	138	0.3–0.4	0.4–0.5	250–400	120–200	265	130	S	R-S	D	S	S	R	
Fabric-filled	1.5	8–11	55–76	14–16	97–110	0.6–1.0	0.8–1.4	250	120	310	150	S	R	D	R	A	R-S	
Glass-filled	1.8–2.0	5–10	34–69	24	165	0.6–1.8	0.8–2.4	300–400	150–200	400	200	S	R	D	R	R-S	R	
Phenolics																		
Wood-flour-filled	1.34–1.45	5–9	34–62	8–17	55–117	0.2–0.6	0.3–0.8	300–350	150–180	300–370	150–190	S	R-S	S-D	S-D	A	R-S	
Asbestos-filled	1.45–2.00	4.5–7.5	31–52	10–30	69–207	0.2–0.4	0.3–0.5	350–500	180–260	300–500	150–260	S	R-S	S-D	S-D	A	R-S	
Mica-filled	1.65–1.92	5.5–7	38–48	25–50	172–345	0.3–0.4	0.4–0.5	250–300	120–150	300–350	150–180	S	R-S	S-D	S-D	A	R-S	
Glass-filled	1.69–1.95	5–18	34–124	19–33	131–228	0.3–1.8	0.4–2.4	350–550	180–290	300–600	150–320	S	R-S	S-D	S-D	A	R-S	
Fabric-filled	1.36–1.43	3–9	21–62	9–14	62–97	0.8–8	1.1–11	220–250	100–120	250–330	120–170	S	R-S	S-D	S-D	A	R-S	
Polybutadienes																		
Very high vinyl (no filler)	1.00	8	55	2	14	1.1	1.5	500	260			S	R	R	R	R	R	
Polyesters																		
Glass-filled BMC	1.7–2.3	4–10	28–69	16–25	110–172	1.5–16	2.0–22	300–350	150–180	400–450	200–230	R-E	R-A	S-A	S-A	S-D	A-D	
Glass-filled SMC	1.7–2.1	8–20	55–138	16–25	110–172	8–22	11–30	300–350	150–180	400–450	200–230	R-E	R-A	S-A	S-A	S-D	A-D	
Glass-cloth reinforced	1.3–2.1	25–50	172–345	19–45	131–310	5–30	7–41	300–350	150–180	400–450	200–230	R-E	R-A	S-A	S-A	S-D	A-D	
Silicones																		
Glass-filled	1.7–2.0	4–6.5	28–45	10–15	69–103	3–15	4–20	600	320	600	320	R-S	R-S	R-S	S	S-A	R-A	
Mineral-filled	1.8–2.8	4–6	28–41	13–18	90–124	0.3–0.4	0.4–0.5	600	320	600	320	R-S	R-S	R-S	S	S-A	R-A	
Ureas																		
Cellulose-filled	1.47–1.52	5.5–13	38–90	10–15	69–103	0.2–0.4	0.3–0.5	170	80	260–290	130–140	S	R-S	A-D	S-A	D	R-S	
Urethanes																		
No filler	1.1–1.5	0.2–10	1–69	1–10	7–69	5–NB	7	129–250	90–120			R-S	S	A	S	S-A	R-S	

TABLE 28-22 Typical Property Ranges for Plastics (Concluded)

Thermosets ^c	Specific gravity	Tensile strength		Modulus of elasticity, tension		Impact strength, Izod ^b		Maximum use temperature (no load)		HDT at 66 lb/in ²		HDT at 264 lb/in ²		Chemical resistance ^d					
		kip/in ²	MPa	10 ³ kip/in ²	10 ³ MPa	ft-lb	J	°F	°C	°F	°C	°F	°C	Weather resistance	Weak acid	Strong acid	Weak alkali	Strong alkali	Solvents
ABS																			
GP	1.05–1.07	5.9	41	3.1	21	6	8	160–200	70–90	210–225	100–110	190–206	90–95	R-E	R	A ^c	R	R	A/R
High-impact	1.01–1.06	4.8	33	2.4	17	7.5	10	140–210	60–100	210–225	100–110	188–211	85–100	R-E	R	A ^f	R	R	A/R
Heat-resistant	1.06–1.08	7.4	51	3.9	27	2.2	3.0	190–230	90–110	225–252	110–120	226–240	110–115	R-E	R	A ^f	R	R	A/R
Trans.	1.07–1.20	5.6	39	2.9	20	5.3	7.1	130–180	55–80	180–220	80–105	165–195	75–90	R-E	R	A ^f	R	R	A/R
Acetals																			
Homopolymers	1.42	10	69	5.2	36	1.4	1.9	195	90	338	170	255	125	R	R	A	R	A-D	R
Copolymers	1.41	8.8	61	4.1	28	1.2–1.6	1.6–2.2	212	100	316	160	230	110	R	R	A	R	R	R
Acrylics																			
GP	1.11–1.19	5.6–11.0	39–76	2.25–4.65	16–32	0.3–2.3	0.4–3.1	130–230	55–110	175–225	80–110	165–210	75–100	R	R	A ^c	R	A	A/R
High-impact	1.12–1.16	5.8–8.0	40–55	2.3–3.3	16–23	0.8–2.3	1.1–3.1	140–195	60–90	180–205	80–95	165–190	75–90	R	R	A ^c	R	R	A/R
	1.21–1.28	8.0–12.5	55–86	3.5–4.8	24–33	0.3–0.4	0.4–0.5	125–200	50–90	170–200	75–95	155–205	70–95	R	R	A ^c	R	A	A/R
Cast	1.18–1.28	9.0–12.5	62–86	3.7–5.0	26–34	0.4–1.5	0.5–2.0	140–200	60–90	165–235	75–115	160–215	70–100	R	R	A ^c	R	A	A/R
Multipolymer	1.09–1.14	6–8	41–55	3.1–4.3	21–30	1–3	1–4	165–175	75–80			185–195	85–90	E	R	A ^c	H	S	A ^f
Cellulosics																			
Acetate	1.23–1.34	3.0–8.0	21–55	1.05–2.55	7–18	1.1–6.8	1.5–9	140–220	60–105	120–209	50–100	111–195	45–90	S	S	D	S	D	D-S
Butyrate	1.15–1.22	3.0–6.9	21–48	0.7–1.8	5–12	3.0–10.0	4–14	140–220	60–105	130–227	55–110	113–202	45–95	S	S	D	S	D	D-S
E cellulose	1.10–1.17	3–8	21–55	0.5–3.5	3–24	1.7–7.0	2.3–9.5	115–185	45–85			115–190	45–90	S	S	D	R	S	D
Nitrate	1.35–1.40	7–8	48–55	1.9–2.2	13–15	5–7	7–9	140	60			140–160	60–70	E	S	D	S	D	D
Propionate	1.19–1.22	4.0–6.5	28–45	1.1–1.8	8–12	1.7–9.4	2.3–13	155–220	70–105	147–250	65–120	111–228	45–110	S	S	D	S	D	D-S
Chloro polyether																			
Ethylene copolymers	1.4	5.4	37	1.5	10	0.4	0.5	290	140	285	140			R-S	R	A ^c	R	R	R
EVA	0.93	2.0	14	0.05	0.3	NB	NB	190	90					S	R	A ^c	R	R	A-D
EVA	0.94	3.6	25	0.02–0.12	0.14–0.8	NB	NB			140–147	60–65	93	35	S	R	A	R	R	A-D
Fluoropolymers																			
FEP	2.14–2.17	2.5–3.9	17–27	0.5–0.7	3–5	NB	NB	400	208	158	70			R	R	R	R	R	R
PTFE	2.1–2.3	1.4	7–28	0.38–0.65	2.6–4.5	2.5–4.0	3.4–5.4	550	290	250	120			R	R	R	R	R	R
CTFE	2.10–2.15	4.6–5.7	32–39	1.8–2.0	12–14	3.5–3.6	4.7–4.9	350–390	180–200	258	125			R	R	R	R	R	S ^c
PVF ₂	1.77	7.2	50	1.7	12	3.8	5.2	300	150	300	150	195	90	S	R	A ^b	R	R	R
ETFE and ECTFE	1.68–	6.5–7.0	45–48	2–2.5	14–17	NB	NB	300	150	220	105	160	70	R	R	R	R	R	R
Methylpentene	0.83	3.3–3.6	23–25	1.3–1.9	10–13	0.95–3.8	1.3–5.2	275	135					E	R	A ^b	R	R	A
Nylons																			
6/6	1.13–1.15	9–12	62–83	3.85	27	2.0	27	180–300	80–150	360–470	180–240	150–220	165–105	R	R	A	R	R	R-D ^f
6	1.14	12.5	86			1.2	1.6	180–250	80–170	300–365	150–185	140–155	60–70	R	R	A	R	R	R-A ^f
6/10	1.07	7.1	49	2.8	19	1.6	2.2	180	80	300	150			R	R	A	R	R	R-A ^f

TABLE 28-22 Typical Property Ranges for Plastics (Concluded)

Thermosets ^a	Specific gravity	Tensile strength		Modulus of elasticity, tension		Impact strength, Izod ^b		Maximum use temperature (no load)			HDT at 66 lb/in ²		HDT at 264 lb/in ²		Chemical resistance ^d				
		kip/in ²	MPa	10 ³ kip/in ²	10 ³ MPa	ft-lb	J	°F	°C	°F	°C	°F	°C	Weather resistance	Weak acid	Strong acid	Weak alkali	Strong alkali	Solvents
8	1.09	3.9	27			>16	>22							R	R	A	R	R	R-A'
12	1.01	6.5-8.5	45-59	1.7-2.1	12-14	1.2-4.2	1.6-5.7	175-260	80-125					R	R	A	R	R	R-A'
Copolymers	1.08-1.14	7.5-11.0	52-76			1.5-19	2-26	180-250	80-120					R	R	A	R	R	R-A'
Polyesters																			
PET	1.37	10.4	72			0.8	1.1	175	80	240	115	185	85	R	R	A ^c	R	A	R-A'
PBT	1.31	8.0-8.2	55-57	3.6	25	1.2-1.3	1.6-1.8	280	140	310	155	130	55	R	R	R	R	A	R
PTMT	1.31	8.2	57			1.0	1.4	270	130	302	150	122	50	R	R	R	R	A	R
Copolymers	1.2	7.3	50			1.0	1.4					154	70						
Polyaryl ether	1.14	7.5	52	3.2	22	10	14	250	120	320	100	300	150	E	R	R	R	R	A
Polyaryl sulfone	1.36	13	90	3.7	26	2	2.7	500	260			525	275	Darkens	R	R	R	R	R
Polybutylene	0.910	3.8	26	0.26	1.8	NB		225	105	215	100	130	55	E	R	A ^c	R	R	R
Polycarbonate	1.2	9	62	3.45	24	12-16	16-22	250	120	270-290	130-145	265-285	130-140	R	R	A ^c	A	A	A
PC-ABS	1.14	8.2	57	3.7	26	10	14	220	105	235	115	220	105	R-E	R	A ^c	R	S	A
Polyethylenes																			
LD	0.91-0.93	0.9-2.5	6-17	0.20-0.27	1.4-1.9	NB		180-212	80-100	100-120	40-50	90-105	30-40	E	R	A ^c	R	R	R
HD	0.95-0.96	2.9-5.4	20-37			0.4-1.4	0.5-1.9	175-250	80-120	140-190	60-90	110-130	45-55	E	R	R-A ^c	R	R	R
HMW Ionomer	0.945-0.95	2.5-3.4-4.5	17-23-31	1-0.3-0.7	7-2-5	NB-6-NB	8	160-180	70-80	155-180-110	70-80-45	105-180-100-120	40-80-40-50	E-E	R-A	A ^c -A ^c	R-R	R-R	R-R
Phenylene oxide-based materials	1.06-1.10	7.8-9.6	54-66	3.5-3.8	24-26	5.0	68	175-220	80-105	230-280	110-140	212-265	100-130	R	R	R	R	R	R-A
Polyphenylene sulfide	1.34	10	69	4.8	33	0.3	0.4	500	260			278	135	R	R	A ^c	R	R	R
Polyimide	1.43	5-7.5	34-52	5.4	37	5-7	7-9	500	260			680	360		R	R	A	A	R
Polypropylenes																			
GP	0.90-0.91	4.8-5.5	33-38	1.6-2.2	11-15	0.4-2.2	0.5-3.0	225-300	105-150	200-230	95-110	125-140	50-60	E	R	A ^c	R	R	R
High-impact	0.90-0.91	3-5	21-34	1.3	9	1.5-1.2	2-1.6	200-250	95-120	160-200	70-95	120-135	50-60	E	R	A ^c	R	R	A
Propylene copolymer	0.91	4	28	1.0-1.7	7-12	1.1	1.5	190-240	90-115	185-230	85-110	115-140	45-60	E	R	A ^c	R	R	R
Polystyrenes																			
GP	1.04-1.07	6.0-7.3	41-50	4.5	31	0.3	0.4	150-170	65-80			180-220	80-105	S	R	A ^c	R	R	D
High-impact	1.04-1.07	2.8-4.6	20-32	2.9-4.0	20-28	0.7-1.0	0.9-1.4	140-175	60-80			175-210	80-100	S	R	A ^c	R	R	D
Polysulfone	1.24	10.2	70	3.6	25	1.2	1.6	300	150	360	180	345	175	S	R	R	R	R	R-A
Polyurethanes	1.11-1.25	4.5-8.4	31-58	0.1-3.5	0.7-2.4	NB		190	90					R-S	S-D	S-D	S-D	S-D	R
Vinyl, rigid	1.3-1.5	5-8	34-55	3-5	21-34	0.5-2.0	0.7-2.7	150-175	65-80	135-180	60-80	130-175	55-80	R	R	R-S	R	R	R-A
Vinyl, flexible	1.2-1.7	1-4	7-28			0.5-2.0	0.7-2.7	140-175	60-80					S	R	R-S	R	R	R-A
Rigid CPVC	1.49-1.58	7.5-9.0	52-62	3.6-4.7	25-32	1.0-5.6	1.4-7.6	230	110	215-245	100-120	200-235	95-115	R	R	R	R	R	R
PVC-acrylic	1.30-1.35	5.5-6.5	38-45	2.75-3.35	19-23	15	20			180	80	170	80	R	R	S	R	R	A
PVC-ABS	1.10-1.21	2.6-6.0	18-41	0.8-3.4	6-23	10-15	14-20							S	R	R-S	R	R	R-D
SAN	1.08	10-12	69-83	5.0-5.6	34-39	0.4-0.5	0.5-0.7	140-200	60-95			190-220	90-105	S-E	R	A	R	R	A

^aAll values at room temperature unless otherwise listed.

^bNotched samples.

^cHeat-deflection temperature.

^dAc = acid, and Al = alkali; R = resistant; A = attached; S = slight effects; E = embrittles; D = decomposes.

^eBy oxidizing acids.

^fBy ketones, esters, and chlorinated and aromatic hydrocarbons.

^gHalogenated solvents cause swelling.

^hBy fuming sulfuric.

ⁱDissolved by phenols and formic acid.

SOURCE: *Plastics Engineering Handbook*, 4th ed., Van Nostrand Reinhold, New York, 1976. Courtesy of National Association of Corrosion Engineers. To convert MPA to lb/in², multiply by 145.04.

TABLE 28-23 Chemical Resistance of Coatings for Immersion Service (Room Temperatures)

	Asphalt, unmodified	Coal tar		Coal tar— epoxy	Coal tar— urethanes	Epoxy: phenolic- baked	Epoxy: amine- cured	Epoxy ester	Furfuryl alcohol	Phenolics, baked	Polyesters (unsatu- rated)	Polyvinyl chloracetates	Vinyl ester	Urethanes		Vinylidene chloride	Chlorinated rubber
		Hot- applied	Cold- applied											Air-dried	Baked		
Water Distilled R R R R LR R R R R R R R R LR LR R R Salt water R R R R LR R R R R R R R R LR LR R R																	
Alkalies Sodium hydroxide, 10% R R LR R R R R NR R NR R R LR LR LR R R Sodium hydroxide, 70% NR NR NR LR R R R NR NR LR R LR LR LR NR R R Ammonium hydroxide, 10% R R LR R R R LR LR R R R LR R R NR NR R R Sodium carbonate, 5% R R R R R R R R R R R R R R R R R R																	
Gases Chlorine R NR NR LR NR LR LR LR NR NR R LR R LR R LR R LR Ammonia LR LR NR LR LR LR R R NR LR R LR R NR NR NR NR Hydrogen sulfide R R R R R R R R R R R LR R R R R R R																	
Organics Alcohols R LR LR NR NR R R LR R R R R R R NR R R LR Aliphatic hydrocarbons NR LR LR LR LR LR R R R R R R R R R R R LR Aromatic hydrocarbons NR NR NR NR NR LR R R R R R NR LR R R LR NR Ketones NR NR NR NR NR LR LR NR LR R NR NR NR R NR NR NR Ethers NR NR NR NR LR LR NR LR R R NR NR R R NR NR Esters NR NR NR NR NR LR LR NR R R LR NR LR NR R NR NR Chlorinated hydrocarbons NR NR NR NR LR LR LR NR LR R R NR LR LR R LR NR																	
Maximum temperature (dry conditions), °F 150 200 200 250 250 250 300 250-300 160 350 160																	
Maximum temperature (wet conditions), °F 120 120 150 150 150 150 190 160-250 250 150 210 150 140																	

NOTE: Chemical resistance data are for coatings only. Thin coatings generally are not suitable for substrates such as carbon steel which are corroded significantly (e.g., >20 mils/year) in the test environment. R = recommended; LR = limited recommendation; NR = no recommendation.

SOURCE: NACE TPC-2, *Coatings and Linings for Immersion Service*. Courtesy of National Association of Corrosion Engineers.

TABLE 28-24 Properties of Coatings for Atmospheric Service

	Physical properties	Water resistance	Acid resistance	Alkali resistance	Solvent resistance	Temperature resistance	Weathering	Recoating
Alkyd								
Short-oil alkyd	Hard	Fair	Fair	Poor	Fair	Good	Fair	Easy
Long-oil alkyd	Flexible	Fair	Poor	Poor	Poor	Good	Good	Easy
Silicone alkyd	Tough	Good	Fair	Poor	Fair	Best of group	Very good	Fair
Vinyl alkyd	Tough	Good	Best of group	Poor	Fair	Fair	Very good	Difficult
Vinyl								
Polyvinyl chloride acetate copolymers	Tough	Very good	Excellent	Excellent	(Aliphatic hydrocarbon, good; aromatic hydrocarbon, poor)	Fair, 150°F	Very good	Easy
Vinyl acrylic copolymers	Tough	Good	Very good	Very good	(Aliphatic, good; aromatic, poor)	Fair, 150°F	Excellent	Easy
Chlorinated rubber								
Resin-modified	Hard	Very good	Very good	Very good	(Aliphatic, good; aromatic, poor)	Fair	Good	Easy
Alkyd-modified	Tough	Good	Fair	Fair	(Aliphatic, good; aromatic, poor)	Fair	Very good	Easy
Water base								
Polyvinyl acetate	Scrub-resistant	Poor	Poor	Poor	Poor	Fair	Very good	Easy
Acrylic polymers	Scrub-resistant	Poor	Poor	Poor	Poor	Fair	Excellent	Easy
Epoxy	Tough	Good	Good	Good	Good	Good	Fair	Difficult
Epoxy								
Epoxyamine	Hard	Good	Good	Good	Very good	Very good	Fair; chalks	Difficult
Epoxy polyamide	Tough	Very good	Fair	Excellent	Fair	Good	Good; chalks	Difficult
Epoxy coal tar	Hard	Excellent	Good	Good	Poor	Good	Poor	Difficult
Epoxyester	Flexible	Good	Fair	Poor	Fair	Good	Good; chalks	Reasonable
Polyurethane								
Air-drying polyurethane varnish	Very tough	Fair	Fair	Fair	Fair	Good	Yellowing	Requires care
Two-package-reactive polyurethane	Tough; hard	Good	Fair	Fair	Good	Good	Some yellowing and chalking	Difficult
Moisture-reactive polyurethane	Very tough; abrasion-resistant	Fair	Fair	Fair	Good	Good	Fades in light; yellows in shade	Difficult
Nonyellowing polyurethane	Fairly hard to rubbery	Good	Fair	Fair	Good	Good	Very good	Difficult
Inorganic zinc								
Water base (sodium or potassium silicate)	Tough; abrasion-resistant; excellent chemical bond	Good	Poor	Poor	Excellent	Excellent	Excellent; unaffected by weather	Easy
Organic base (ethyl silicate)	Tough; hard; excellent bond	Good	Poor	Poor	Good	Excellent	Excellent	Easy

SOURCE: F. L. LaQue, *Marine Corrosion; Causes and Prevention*, Wiley, New York, 1975, pp. 302–305. Courtesy of National Association of Corrosion Engineers.

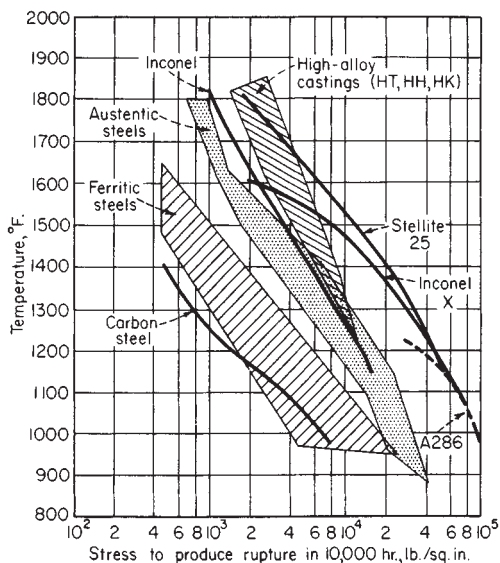


FIG. 28-24 Rupture properties of metals as a function of temperature. °C = (°F - 32) × 5/9; to convert lbf/in² to MPa, multiply by 6.895 × 10⁻³. [Chem. Eng., 139 (Dec. 15, 1958).]

based alloys, of which Stellite 25 is an example, show excellent strengths up to 1,100°C (2,000°F).

Another useful element in imparting oxidation resistance to steel is **silicon** (complementing the effects of chromium). In the lower-chromium ranges, silicon in the amounts of 0.75 to 2 percent is more effective than chromium on a weight-percentage basis. The influence of 1 percent silicon in improving the oxidation rate of steels with varying chromium contents is shown in Fig. 28-26.

Aluminum also improves the resistance of iron to oxidation as well as sulfidation. But use as an alloying agent is limited because the amount required interferes with the workability and high-temperature

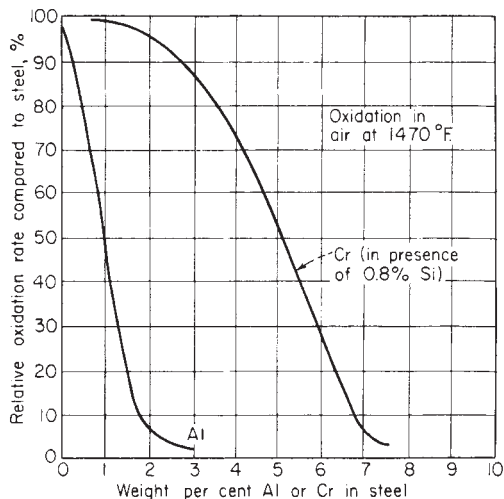


FIG. 28-25 How chromium and aluminum reduce steel oxidation. °C = (°F - 32) × 5/9.

strength properties of the steel. However, development of high-aluminum surface layers by spraying, dipping, and cementation is a feasible means of improving the heat resistance of low-alloy steels.

Hydrogen Atmospheres Austenitic stainless steels, by virtue of their high chromium contents, are usually resistant to hydrogen atmospheres.

Sulfur Corrosion Chromium is the most important material in imparting resistance to sulfidation (formation of sulfidic scales similar to oxide scales). The austenitic alloys are generally used because of their superior mechanical properties and fabrication qualities, despite the fact that nickel in the alloy tends to lessen resistance to sulfidation somewhat.

Halogens (Hot, Dry Cl₂, HCl) Pure nickel and nickel alloys are useful with dry halogen gases. But even with the best materials, cor-

TABLE 28-25 Typical Physical Properties of Surface Coatings for Concrete

	Concrete	Polyester		Epoxy		Urethane*
		Isophthalic	Bisphenol	Polyamide	Amine	
Tensile strength (ASTM C307), lbf/in ²	200-400	1200-2500	1200-2500	600-4000	1200-2500	200-1200
MPa	1.4-2.8	8.3-17	8.3-17	4.0-28	8.3-17	1.4-8.3
Thermal coefficient of expansion (ASTM C531)						
Maximum in/(in.°F)	6.5 × 10 ⁶	20 × 10 ⁶	20 × 10 ⁶	40 × 10 ⁶	40 × 10 ⁶	†
Maximum mm/(mm.°C)	11.7 × 10 ⁶	36 × 10 ⁶	36 × 10 ⁶	72 × 10 ⁶	72 × 10 ⁶	
Compressive strength, (ASTM) C579), lbf/in ²	3500	10,000	10,000	4000	6000	†
MPa	24	70	70	28	42	
Abrasion resistance, Taber abraser—weight loss, mg, 1000-g load/1000 cycles		15-27	15-27	15-27	15-27	†
Shrinkage, ASTM C531, %		2-4	2-4	0.25-0.75	0.25-0.75	0-2
Work life, min		15-45	15-45	30-90	30-90	15-60
Traffic limitations, h after application		16	16	24	24	24
	Light	36	36	48	48	48
	Heavy	48	48	72	72	72
	Ready for service					
Adhesion characteristics‡		Poor	Fair	Excellent	Good	Fair
Flexural strength (ASTM C580), lbf/in ²		1500	1500	1000	1500	†
MPa		10	10	7	10	

NOTE: All physical values depend greatly on reinforcing. Values are for ambient temperatures.

*Type of urethane used is one of three: (1) Type II, moisture-cured; (2) Type IV, two-package catalyst; or (3) Type V, two-package polyol. (Ref. ASTM C16.)

†Urethanes not shown because of great differences in physical properties, depending on formulations. Adhesion characteristics should be related by actual test data. Any system which shows concrete failure when tested for surfacing adhesion should be rated excellent with decreasing rating for systems showing failure in cohesion or adhesion below concrete failure.

‡Adhesion to concrete: primers generally are used under polyesters and urethanes to improve adhesion.

SOURCE: NACE RP-03-76, *Monolithic Organic Corrosion Resistant Floor Surfacing*, 1976. Courtesy of National Association of Corrosion Engineers.

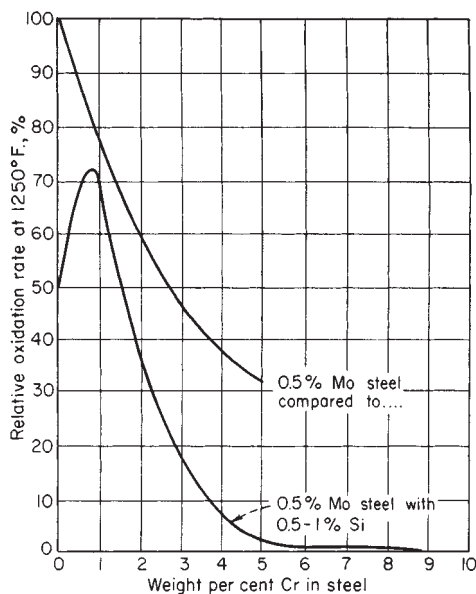


FIG. 28-26 Effect of silicon on oxidation resistance. $^{\circ}\text{C} = (^{\circ}\text{F} - 32) \times 5/9$.

rosion rates are relatively high at high temperature. There are cases in which equipment for high-temperature halogenation has used platinum-clad nickel-base alloys. These materials have high initial cost but long life. Platinum and gold have excellent resistance to dry HCl even at $1,100^{\circ}\text{C}$ ($2,000^{\circ}\text{F}$).

Refractories Refractories are selected to accomplish four objectives:

1. Resist heat
2. Resist high-temperature chemical attack
3. Resist erosion by gas with fine particles
4. Resist abrasion by gas with large particles

Refractories are available in three general physical forms: solids in the form of brick and monolithic castable ceramics and as ceramic fibers.

The primary method of selection of the type of refractory to be used is by gas velocity:

- <7.5 m/s (25 ft/s): fibers
- 7.5–60 m/s (25–200 ft/s): monolithic castables
- >60 m/s (200 ft/s): brick

Within solids the choice is a trade-off because, with brick, fine particles in the gas remove the mortar joints and, in the monolithic castables, while there are no joints, the refractory is less dense and less wear-resistant.

Internal Insulation The practice of insulating within the vessel (as opposed to applying insulating materials on the equipment exterior) is accomplished by the use of fiber blankets and lightweight aggregates in ceramic cements. Such construction frequently incorporates a thin, high-alloy shroud (with slip joints to allow for thermal expansion) to protect the ceramic from erosion. In many cases this design is more economical than externally insulated equipment because it allows use of less expensive lower-alloy structural materials.

Refractory Brick Nonmetallic refractory materials are widely used in high-temperature applications in which the service permits the appropriate type of construction. The more important classes are described in the following paragraphs.

Fireclays can be divided into plastic clays and hard flint clays; they may also be classified as to alumina content. **Firebricks** are usually made of a blended mixture of flint clays and plastic clays which is formed, after mixing with water, to the required shape. Some or all of the flint clay may be replaced by highly burned or calcined clay, called

TABLE 28-26 Chemical Resistance of Rubbers

Type of rubber	Features
Butadiene styrene	General-purpose; poor resistance to hydrocarbons, oils, and oxidizing agents
Butyl	General-purpose; relatively impermeable to air; poor resistance to hydrocarbons and oils
Chloroprene	Good resistance to aliphatic solvents; poor resistance to aromatic hydrocarbons and many fuels
Chlorosulfonated polyethylene	Excellent resistance to oxidation, chemicals, and heat; poor resistance to aromatic oils and most fuels
<i>cis</i> -Polybutadiene	General-purpose; poor resistance to hydrocarbons, oils, and oxidizing agents
<i>cis</i> -Polyisoprene	General-purpose; poor resistance to hydrocarbons, oils, and oxidizing agents
Ethylene propylene	Excellent resistance to heat and oxidation
Fluorinated	Excellent resistance to high temperature, oxidizing acids, and oxidation; good resistance to fuels containing up to 30% aromatics
Natural	General-purpose; poor resistance to hydrocarbons, oils, and oxidizing agents
Nitrile (butadiene acrylonitrile)	Excellent resistance to oils, but not resistant to strong oxidizing agents; resistance to oils proportional to acrylonitrile content
Polysulfide	Good resistance to aromatic solvents; unusually high impermeability to gases; poor compression set and poor resistance to oxidizing acids
Silicone	Excellent resistance over unusually wide temperature range [-100 to 260°C (-150 to 500°F)]; fair oil resistance; poor resistance to aromatic oils, fuels, high-pressure steam, and abrasion
Styrene	Synonymous with butadiene-styrene

grog. A large proportion of modern brick production is molded by the dry-press or power-press process, in which the forming is carried out under high pressure and with a low water content. Extruded and hand-molded bricks are still made in large quantities.

The dried bricks are burned in either periodic or tunnel kilns at temperatures ranging between $1,200$ and $1,500^{\circ}\text{C}$ ($2,200$ and $2,700^{\circ}\text{F}$). Tunnel kilns give continuous production and a uniform burning temperature.

Fireclay bricks are used in kilns, malleable-iron furnaces, incinerators, and many portions of metallurgical furnaces. They are resistant to spalling and stand up well under many slag conditions but are not generally suitable for use with high-lime slags or fluid-coal-ash slags or under severe load conditions.

High-alumina bricks are manufactured from raw materials rich in alumina, such as diaspore. They are graded into groups with 50, 60, 70, 80, and 90 percent alumina content. When well fired, these bricks contain a large amount of mullite and less of the glassy phase than is present in firebricks. Corundum is also present in many of these bricks. High-alumina bricks are generally used for unusually severe temperature or load conditions. They are employed extensively in lime kilns and rotary cement kilns, in the ports and regenerators of glass tanks, and for slag resistance in some metallurgical furnaces; their price is higher than that of firebrick.

Silica bricks are manufactured from crushed ganister rock containing about 97 to 98 percent silica. A bond consisting of 2 percent lime is used, and the bricks are fired in periodic kilns at temperatures of $1,500$ to $1,540^{\circ}\text{C}$ ($2,700$ to $2,800^{\circ}\text{F}$) for several days until a stable volume is obtained. They are especially valuable when good strength is required at high temperatures. Superduty silica bricks are finding some use in the steel industry. They have a lowered alumina content and often a lowered porosity.

Silica bricks are used extensively in coke ovens, the roofs and walls of open-hearth furnaces, and the roofs and sidewalls of glass tanks and as linings of acid electric steel furnaces. Although silica brick is readily spalled (cracked by a temperature change) below red heat, it is very stable if the temperature is kept above this range and for this reason

TABLE 28-27 Properties of Elastomers

Property	NR Natural rubber (<i>cis</i> - polyisoprene)	SBR Butadiene styrene (GR-S)	IR Synthetic (polyisoprene)	COX Butadiene acrylonitrile (nitrile)	CR Chloroprene (neoprene)	ITR Butyl (isobutylene isoprene)	BR Polybutadiene	T Polysulfide	Silicone (polysiloxane)
Physical properties									
Specific gravity (ASTM D 792)	0.93	0.91	0.93	0.98	1.25	0.90	0.91	1.35	1.1–1.6
Thermal conductivity, Btu [(h-ft ²)(°F/ft)] (ASTM C 177)	0.082	0.143	0.082	0.143	0.112	0.053			0.13
Coefficient of thermal expansion (cubical), 10 ⁻⁵ /°F (ASTM D 696)	37	37		39	34	32	37.5		45
Electrical insulation	Good	Good	Good	Fair	Fair	Good	Good	Fair	Excellent
Flame resistance	Poor	Poor	Poor	Poor	Good	Poor	Poor	Poor	Good
Minimum, recommended service temperature, °F	-60	-60	-60	-60	-40	-50	-150	-60	-178
Maximum, recommended service temperature, °F	180	180	180	300	240	300	200	250	600
Mechanical properties									
Tensile strength, lbf/in ²									
Pure gum (ASTM D 412)	2500–3500	200–300	2500–3500	500–900	3000–4000	2500–3000	200–1000	250–400	600–1300
Black (ASTM D 412)	3500–4500	2500–3500	3500–4500	3000–4500	3000–4000	2500–3000	2000–3000	>1000	
Elongation, %									
Pure gum (ASTM D 412)	750–850	400–600		300–700	800–900	750–950	400–1000	450–650	100–500
Black (ASTM D 412)	550–650	500–600	300–700	300–650	500–600	650–850	450–600	150–450	
Hardness (durometer)	A30–90	A40–90	A40–80	A40–95	A20–95	A40–90	A40–90	A40–85	A30–90
Rebound									
Cold	Excellent	Good	Excellent	Good	Very good	Bad	Excellent	Good	Very good
Hot	Excellent	Good	Excellent	Good	Very good	Very good	Excellent	Good	Very good
Tear resistance	Excellent	Fair	Excellent	Good	Fair to good	Good	Fair	Poor	Fair
Abrasion resistance	Excellent	Good to excellent	Excellent	Good to excellent	Good	Good to excellent	Excellent	Poor	Poor
Chemical resistance									
Sunlight aging	Poor	Poor	Fair	Poor	Very good	Very good	Poor	Very good	Excellent
Oxidation	Good	Good	Excellent	Good	Excellent	Excellent	Good	Very good	Excellent
Heat aging	Good	Very good	Good	Excellent	Excellent	Excellent	Good	Fair	Excellent
Solvents									
Aliphatic hydrocarbons	Poor	Poor	Poor	Excellent	Good	Poor	Poor	Excellent	Fair
Aromatic hydrocarbons	Poor	Poor	Poor	Good	Fair	Poor	Poor	Excellent	Poor
Oxygenated, alcohols	Good	Good	Good	Good	Very good	Very good		Very good	Excellent
Oil, gasoline	Poor	Poor	Poor	Excellent	Good	Poor	Poor	Excellent	Poor
Animal, vegetable oils	Poor to good	Poor to good		Excellent	Excellent	Excellent	Poor to good	Excellent	Excellent
Acids									
Dilute	Fair to good	Fair to good	Fair to good	Good	Excellent	Excellent		Good	Very good
Concentrated	Fair to good	Fair to good	Fair to good	Good	Good	Excellent		Good	Good
Permeability to gases	Low	Low	Low	Very low	Low	Very low	Low	Very low	High
Water-swell resistance	Fair	Excellent	Excellent	Excellent	Fair to excellent	Excellent	Excellent	Excellent	Excellent

stands up well in regenerative furnaces. Any structure of silica brick should be heated up slowly to the working temperature; a large structure often requires 2 weeks or more.

Magnesite bricks are made from crushed magnesium oxide, which is produced by calcining raw magnesite rock to high temperatures. A rock containing several percent of iron oxide is preferable, as this permits the rock to be fired at a lower temperature than if pure materials were used. Magnesite bricks are generally fired at a comparatively high temperature in periodic or tunnel kilns. A large proportion of magnesite brick made in the United States uses raw material extracted from seawater.

Magnesite bricks are basic and are used whenever it is necessary to resist high-lime slags, as in the basic open-hearth steel furnace. They also find use in furnaces for the lead- and copper-refining industries. The highly pressed unburned bricks find extensive use as linings for cement kilns. Magnesite bricks are not so resistant to spalling as fire-clay bricks.

Chrome bricks are manufactured in much the same way as magnesite bricks but are made from natural chromite ore. Commercial ores always contain magnesia and alumina. Unburned hydraulically pressed chrome bricks are also available.

Chrome bricks are very resistant to all types of slag. They are used as separators between acid and basic refractories, also in soaking pits and floors of forging furnaces. The unburned hydraulically pressed bricks now find extensive use in the walls of the open-hearth furnace. Chrome bricks are used in sulfite-recovery furnaces and to some extent in the refining of nonferrous metals. Basic bricks combining various properties of magnesite and chromite are now made in large quantities and have advantages over either material alone for some purposes.

The **insulating firebrick** is a class of brick that consists of a highly porous fire clay or kaolin. Such bricks are light in weight (about one-half to one-sixth of the weight of fireclay), low in thermal conductivity, and yet sufficiently resistant to temperature to be used successfully on

TABLE 28-27 Properties of Elastomers (Concluded)

Property	ECO, CO Epichlorohydrin homopolymer and copolymer	Fluorosilicone	EPDM Ethylene propylene	CSM Chlorosulfonated polyethylene	FPM Fluorocarbon elastomers
Physical properties					
Specific gravity	1.32–1.49	1.4	0.86	1.1–1.26	1.4–1.95
Thermal conductivity, Btu/ [(h-ft) ²](°F/ft)]		0.13		0.065	0.13
Coefficient of thermal expansion, 10 ⁻⁵ /°F		45		27	8.8
Flame resistance	Fair	Poor	Poor	Good	Excellent
Colorability	Good	Good	Excellent	Excellent	Good
Mechanical properties					
Hardness (Shore A)	30–95	40–70	30–90	45–95	65–90
Tensile strength, kip/in ²					
Pure gum		1	<1	4	<2
Reinforced	2–3	<2	0.8–3.2	1.5–2.5	1.5–3
Elongation, % reinforced	320–350	200–400	200–600	250–500	100–450
Resiliency	Poor to excellent	Good to fair	Good	Good	Fair
Compression-set resistance	Very good		Good	Fair to good	Good to excellent
Hysteresis resistance	Good	Good	Good	Good	Good
Flexcracking resistance	Very good	Good	Good	Good	Good
Slow rate	Very good	Good	Good	Good	Good
Fast rate	Good	Good	Good	Good	Good
Tear strength	Good	Fair	Poor to fair	Fair to good	Poor to fair
Abrasion resistance	Fair to good	Poor	Good	Excellent	Good
Electrical properties					
Dielectric strength	Fair	Good	Excellent	Excellent	Good
Electrical insulation	Fair	Good	Very good	Good	Fair to good
Thermal properties					
Service temperature, °F					
Minimum, for continuous use	-15 to -80	-90	-60	-40	-10
Maximum, for continuous use	300	400	<350	<325	<500
Corrosion resistance					
Weather	Excellent	Excellent	Excellent	Excellent	Excellent
Oxidation	Very good	Excellent	Excellent	Excellent	Outstanding
Ozone	Good to excellent	Excellent	Excellent	Excellent	Excellent
Radiation		Good	Excellent	Fair to good	Fair to good
Water	Good	Excellent	Good to excellent	Good	Good
Acids	Good	Very good to excellent	Good to excellent	Excellent	Good to excellent
Alkalies	Good	Very good	Good to excellent	Excellent	Poor to good
Aliphatic hydrocarbons	Excellent	Excellent	Poor	Fair	Excellent
Aromatic hydrocarbons	Very good	Excellent	Fair	Poor to fair	Excellent
Halogenated hydrocarbons	Good		Poor	Poor to fair	Good
Alcohol	Good		Good	Very good	Excellent
Synthetic lubricants (diester)	Fair to good	Excellent	Poor to fair	Poor	Fair to good
Hydraulic fluids					
Silicates	Very good	Excellent	Fair to good	Good	Good
Phosphates	Poor to fair	Excellent	Good to excellent	Poor to fair	Poor

SOURCE: C. H. Harper, *Handbook of Plastics and Elastomers*, McGraw-Hill, New York, 1975, Table 35. Courtesy of National Association of Corrosion Engineers. °C = (°F - 32) × 5/9; to convert Btu/(h-ft²·°F) to W/(m²·°C), multiply by 0.861; to convert lb/in² to MPa, multiply by 6.895 × 10⁻³.

the hot side of the furnace wall, thus permitting thin walls of low thermal conductivity and low heat content. The **low heat content** is particularly valuable in saving fuel and time on heating up, allows rapid changes in temperature to be made, and permits rapid cooling. These bricks are made in a variety of ways, such as mixing organic matter with the clay and later burning it out to form pores; or a bubble structure can be incorporated in the clay-water mixture which is later preserved in the fired brick. The insulating firebricks are classified into several groups according to the maximum use limit; the ranges are up to 870, 1,100, 1,260, 1,430, and above 1,540°C (1,600, 2,000, 2,300, 2,600, and above 2,800°F).

Insulating refractories are used mainly in the heat-treating industry for furnaces of the periodic type. They are also used extensively in stress-relieving furnaces, chemical-process furnaces, oil stills or heaters, and the combustion chambers of domestic-oil-burner furnaces. They usually have a life equal to that of the heavy brick that they replace. They are particularly suitable for constructing experi-

mental or laboratory furnaces because they can be cut or machined readily to any shape. They are not resistant to fluid slag.

There are a number of types of special brick obtainable from individual producers. **High-burned kaolin refractories** are particularly valuable under conditions of severe temperature and heavy load or severe spalling conditions, as in the case of high-temperature oil-fired boiler settings or piers under enameling furnaces. Another brick for the same uses is a high-fired brick of Missouri aluminous clay.

There are on the market a number of bricks made from **electrically fused materials**, such as fused mullite, fused alumina, and fused magnesite. These bricks, although high in cost, are particularly suitable for certain severe conditions.

Bricks of **silicon carbide**, either recrystallized or clay-bonded, have a high thermal conductivity and find use in muffle walls and as a slag-resisting material.

Other types of refractory that find use are forsterite, zirconia, and zircon. Acid-resisting bricks consisting of a dense body like stoneware

TABLE 28-28 Important Properties of Gasket Materials

Material	Maximum service temperature, °F	Important properties
Rubber (straight)		
Natural	225	Good mechanical properties. Impervious to water. Fair to good resistance to acids, alkalies. Poor resistance to oils, gasoline. Poor weathering, aging properties.
Styrene-butadiene (SBR)	250	Better water resistance than natural rubber. Fair to good resistance to acids, alkalies. Unsuitable with gasoline, oils and solvents.
Butyl	300	Very good resistance to water, alkalies, many acids. Poor resistance to oils, gasoline, most solvents (except oxygenated).
Nitrile	300	Very good water resistance. Excellent resistance to oils, gasoline. Fair to good resistance to acids, alkalies.
Polysulfide	150	Excellent resistance to oils, gasoline, aliphatic and aromatic hydrocarbon solvents. Very good water resistance, good alkali resistance, fair acid resistance. Poor mechanical properties.
Neoprene	250	Excellent mechanical properties. Good resistance to nonaromatic petroleum, fatty oils, solvents (except aromatic, chlorinated, or ketone types). Good water and alkali resistance. Fair acid resistance.
Silicone	600	Excellent heat resistance. Fair water resistance; poor resistance to steam at high pressures. Fair to good acid, alkali resistance. Poor (except fluorosilicone rubber) resistance to oils, solvents.
Acrylic	450	Good heat resistance but poor cold resistance. Good resistance to oils, aliphatic and aromatic hydrocarbons. Poor resistance to water, alkalies, some acids.
Chlorosulfonated polyethylene (Hypalon)	250	Excellent resistance to oxidizing chemicals, ozone, weathering. Relatively good resistance to oils, grease. Poor resistance to aromatic or chlorinated hydrocarbons. Good mechanical properties.
Fluoroelastomer (Viton, Fluorel 2141, Kel-F)	450	Can be used at high temperatures with many fuels, lubricants, hydraulic fluids, solvents. highly resistant to ozone, weathering. Good mechanical properties.
Asbestos		
Compressed asbestos-rubber sheet	To 700	Large number of combinations available; properties vary widely depending on materials used.
Asbestos-rubber woven sheet	To 250	Same as above.
Asbestos-rubber (beater addition process)	400	Same as above.
Asbestos composites	To 1000	Same as above.
Asbestos-TFE	500	Combines heat resistance and sealing properties of asbestos with chemical resistance of TFE.
Cork compositions	250	Low cost. Truly compressible materials which permit substantial deflections with negligible side flow. Conform well to irregular surfaces. High resistance to oils; good resistance to water, many chemicals. Should not be used with inorganic acids, alkalies, oxidizing solutions, live steam.
Cork rubber	300	Controlled compressibility properties. Good conformability, fatigue resistance. Chemical resistance depends on kind of rubber used.
Plastics		
TFE (solid) (Tetrafluoroethylene, Teflon)	500	Excellent resistance to almost all chemicals and solvents. Good heat resistance; exceptionally good low-temperature properties. Relatively low compressibility and resilience.
TFE (filled)	To 500	Selectively improved mechanical and physical properties. However, fillers may lower resistance to specific chemicals.
TFE composites	To 500	Chemical and heat resistance comparable with solid TFE. Inner gasket material provides better resiliency and deformability.
CFE (Chlorotrifluoroethylene, Kel-F)	350	Higher cost than TFE. Better chemical resistance than most other gasket materials, although not quite so good as TFE.
Vinyl	212	Good compressibility, resiliency. Resistant to water, oils, gasoline, and many acids and alkalies. Relatively narrow temperature range.
Polyethylene	150	Resists most solvents. Poor heat resistance.
Plant fiber		
Neoprene-impregnated wood fiber	175	Nonporous; recommended for glycol, oil, and gasoline to 175°F.
SBR-bonded cotton	230	Good water resistance.
Nitrile rubber-cellulose fiber		Resists oil at high temperatures.
Vegetable fiber, glue binder	212	Resists oil and water to 212°F.
Vulcanized fiber		Low cost, good mechanical properties. Resists gasoline, oils, greases, waxes, many solvents.
Inorganic fibers	To 2200°F	Excellent heat resistance, poor mechanical properties.
Felt		
Pure felt		Resilient, compressible and strong, but not impermeable. Resists medium-strength mineral acids and dilute mineral solutions if not intermittently dried. Resists oils, greases, waxes, most solvents. Damaged by alkalies.
TFE-impregnated	300	Good chemical and heat resistance.
Petrolatum or paraffin-impregnated		High water repellency.
Rubber-impregnated		Many combinations available; properties vary widely depending on materials used.
Metal		
Lead	500	Good chemical resistance. Best conformability of metal gaskets.
Tin		Good resistance to neutral solutions. Attacked by acids, alkalies.
Aluminum	800	High corrosion resistance. Slightly attacked by strong acids, alkalies.
Copper, brass		Good corrosion resistance at moderate temperatures.
Nickel	1400	High corrosion resistance.
Monel	1500	High corrosion resistance. Good against most acids and alkalies, but attacked by strong hydrochloric and strong oxidizing acids.
Inconel	2000	Excellent heat, oxidation resistance.
Stainless steel		High corrosion resistance. Properties depend on type used.

TABLE 28-28 Important Properties of Gasket Materials (Concluded)

Material	Maximum service temperature, °F	Important properties
Metal composites Leather	220	Many combinations available; properties vary widely depending on materials used. Low cost. Limited chemical and heat resistance. Not recommended against pressurized steam, acid or alkali solutions.
Glass fabric		High strength and heat resistance. Can be impregnated with TFE for high chemical resistance.
Packing and sealing materials		
Rubber (straight)	To 600	See Gasket Materials for properties. Mainly used for ring-type seals, although some types are available as spiral packings.
Rubber composites: Cotton-reinforced	350	High strength. Chemical resistance depends on type of rubber used; however, most types are noted for high resistance to water, aqueous solutions.
Asbestos-reinforced	450	High strength combined with good heat resistance.
Asbestos: Plain, braided asbestos	500	Heat resistance combined with resistance to water, brine, oil, many chemicals. Can be reinforced with wire.
Impregnated asbestos	To 750	Environmental properties vary widely depending on type of asbestos and impregnant used. Neoprene-cemented type resists hot oils, gasoline, and solvents. Oil and wax-impregnated type resists caustics. Wax-impregnated blue asbestos type has high acid resistance. TFE-impregnated type has good all-around chemical resistance.
Asbestos composites	To 1200	End properties vary widely depending on secondary material used.
Metals Copper	To 1500	Properties depend on other construction materials and form of copper used. Packing made of copper foil over asbestos core resists steam and alkalis to 1000°F. Packing of braided copper tinsel resists water, steam, and gases to 1500°F.
Aluminum	To 1000	Resists hot petroleum derivatives, gases, footstuffs, many organic acids.
Lead	550	Many types are available.
Organic fiber Flax	300	Good water resistance.
Jute	300	Good water resistance.
Ramie	300	Good resistance to water, brine, cold oil.
Cotton	300	Good resistance to water, alcohol, dilute aqueous solutions.
Rayon	300	Good resistance to water, dilute aqueous solutions.
Felt	300	See Gasket Materials.
Leather	To 210	Good mechanical properties for sealing. Resistant to alcohol, gasoline, many oils and solvents, synthetic hydraulic fluids, water.
TFE	To 500	Available in many forms, all of which have high chemical resistance.
Carbon-graphite	700	Good bearing and self-lubricating properties. Good resistance to chemicals, heat.

TABLE 28-29 Properties of Graphite and Silicon Carbide

	Graphite	Impervious graphite	Impervious silicon carbide
Specific gravity	1.4–1.8	1.75	3.10
Tensile strength, lbf/in ² (MPa)	400–1400 (3–10)	2,600 (18)	20,650 (143)
Compressive strength, lbf/in ² (MPa)	2000–6000 (14–42)	10,500 (72)	150,000 (1000)
Flexural strength, lbf/in ² (MPa)	750–3000 (5–21)	4,700 (32)	
Modulus of elasticity ($\times 10^5$), lbf/in ² (MPa)	0.5–1.8 (0.3–12 $\times 10^4$)	2.3 (1.6 $\times 10^4$)	56 (39 $\times 10^4$)
Thermal expansion, in/(in \cdot °F $\times 10^{-6}$) [mm/(mm \cdot °C)]	0.7–2.1 (1.3–3.8)	2.5 (4.5)	1.80 (3.4)
Thermal conductivity, Btu/[(h \cdot ft ²)(°F/ft)] [(W)/(m \cdot K)]	15–97 (85–350)	85 (480)	60 (340)
Maximum working temperature (inert atmosphere), °F (°C)	5000 (2800)	350 (180)	4,200 (2300)
Maximum working temperature (oxidizing atmosphere), °F (°C)	660 (350)	350 (180)	3,000 (1650)

SOURCE: Carborundum Co. Courtesy of National Association of Corrosion Engineers.

TABLE 28-30 Properties of Stoneware and Porcelain

	Stoneware	Porcelain
Specific gravity	2.2-2.7	2.4-2.9
Hardness, Mohs scale	6.5	7.5
Modulus of rupture, lb/in ²	3-7,000	8-15,000
Modulus of elasticity, lb/in ²	5-10 × 10 ⁶	10-15 × 10 ⁶
Compressive strength, lb/in ²	40-60,000	60-90,000
Pore volume, %	1.5	0.2-0.5
Water absorption, %	0.5-4.0	0-0.5
Linear thermal expansion, per °F	2.4 × 10 ⁻⁶	2.5 × 10 ⁻⁶
Thermal conductivity, Btu/(ft ² -h-°F-in ⁻¹)	8-22	8-10

are used for lining tanks and conduits in the chemical industry. Carbon blocks are used as linings for the crucibles of blast furnaces, very extensively in a number of countries and to a limited extent in the United States. Fusion-cast bricks of mullite or alumina are largely used to line glass tanks.

Ceramic-Fiber Insulating Linings Ceramic fibers are produced by melting the same alumina-silica china (kaolin) clay used in conventional insulating firebrick and blowing air to form glass fibers. The fibers, 50.8 to 101.6 mm (2 to 4 in) long by 3 μm in diameter, are interlaced into a mat blanket with no binders or chopped into shorter fibers and vacuum-formed into blocks, boards, and other shapes. Ceramic-fiber linings, available for the temperature range of 650 to 1,430°C (1,200 to 2,600°F), are more economical than brick in the 650- to 1,230°C- (1,200- to 2,250°F-) range. Savings come from reduced first costs, lower installation labor, 90 to 95 percent less weight, and a 25 percent reduction in fuel consumption.

Because of the larger surface area (compared with solid-ceramic refractories) the chemical resistance of fibers is relatively poor. Their acid resistance is good, but they have less alkali resistance than solid materials because of the absence of resistant aggregates. Also, because they have less bulk, fibers have lower gas-velocity resistance. Besides

TABLE 28-32 Comparison of Properties of Refractory Metals

Melting point, °F	Element	Advantages	Disadvantages
6180	Tungsten	Highest melting point; nonvolatile oxide to at least 2500°F	Highest density; oxidizing rapidly; brittle at low temperatures
5425	Tantalum	Very high melting point; nonvolatile oxide; ductile	High density; oxidizing rapidly; least abundant
4730	Molybdenum	High melting point; less dense than tungsten or tantalum; moderately ductile at room temperature	Extremely high oxidation rate (volatile oxide)
4380	Niobium (columbium)	High melting point; nonvolatile oxide; ductile; moderate density	Oxidizing rapidly
3435	Chromium	Extremely oxidation-resistant; lightest of refractory metals	Lowest melting point of refractory metals, brittle at low temperatures

the advantage of lower weight, since they will not hold heat, fibers are more quickly cooled and present no thermal-shock structural problem.

Castable Monolithic Refractories Standard portland cement is made of calcium hydroxide. In exposures above 427°C (800°F) the hydroxyl ion is removed from portland (water removed); below 427°C (800°F), water is added. This cyclic exposure results in spalling. Castables are made of calcium aluminate (rather than portland); without the hydroxide they are not subject to that cyclic spalling failure.

Castable refractories are of three types:

1. *Standard.* 40 percent alumina for most applications at moderate temperatures.

TABLE 28-31 Wood for Chemical Equipment

	Condition of woods after 31 d immersion in cold solutions Examined after 7 d drying							
	Fir	Oak	Oregon pine	Yellow pine	Spruce	Redwood	Maple	Cypress
Hydrochloric acid, 5%	NAC	NAC	NAC	SS	SS	SS	NAC	NAC
Hydrochloric acid, 10%	NAC	NAC	NAC	SS	SS	SS	NAC	NAC
Hydrochloric acid, 50%	SS,SB,SWF	SS,WF	S,WF	S,WF	S,WF	S,WF	S,WF	S,WF
Sulfuric acid, 1%	NAC	NAC	NAC	SS	SS	NAC	NAC	SS,SB
Sulfuric acid, 5%	SS	SS	SS	SS	SS,SB	SS,SB	NAC	SS,SB
Sulfuric acid, 10%	S,FSD	S,FSD	S,FSD	S,FSD	S,FSD	S,FSD	S,FSD	S,FSD
Sulfuric acid, 25%	SSp,FSD	SSp,FSD	SSp,FSD	SSp,FSD	SSp,FSD	SSp,FSD	SSp,FSD	SSp,FSD
Caustic soda, 5%	S,NAC	MSh,SWp	SS	SS,FSD	SSp,FSD	SSp,FSD	MSh	SSp,FSD
Caustic soda, 10%	S,FSD	MSh,WF,Horny	SS	SS,SB,FSD	SS,SB,FSD	SS,SB,FSD	MSh	S,SB,FSD
Alum, 13%	NAC	NAC	NAC	NAC	NAC	NAC	NAC	NAC
Sodium carbonate, 10%	SB,GC	NAC	GC	SB,GC	SB,GC	SB,GC	GC	SB,GC
Calcium chloride, 25%	NAC	NAC	NAC	NAC	NAC	NAC	NAC	NAC
Common salt, 25%	NAC	NAC	NAC	SS,GC	SS,GC	SS,GC	NAC	NAC
Water	NAC	NAC	NAC	NAC	NAC	NAC	NAC	NAC
Sodium sulfide	SS,SB	MSh,WF	SB	SB	SB	SB	MSh,FSD	FSD

	Condition of woods after 8 h boiling in solutions Examined after 7 d drying							
	Fir	Oak	Oregon pine	Yellow pine	Spruce	Redwood	Maple	Cypress
Hydrochloric acid, 10%	SB,S	FSD	FSD	FSD	FSD	FSD	FSD	FSD
Hydrochloric acid, 50%	FD,Ch,B,S,NG	FD,Ch,B,S,NG	FD,Ch,B,S,NG	FD,Ch,B,S,NG	FD,Ch,B,S,NG	FD,Ch,B,S,NG	FD,Ch,B,S,NG	FD,Ch,B,S,NG
Sulfuric acid, 4%	SB,GC	SB,GC	SB,GC	SB,GC	SB,GC	SB,GC	SB,GC	SB,GC
Sulfuric acid, 5%	SS,GC	SB,GC	SB,GC	SB,GC	SB,FSD	SB,GC	SB,GC	SB,FSD
Sulfuric acid, 10%	SS,GC	BFD,Wpd,NG	Sp,FD,NG	B,Sp,FD,NG	B,Sp,FD,NG	SB,FSD	SB,FSD	B,FD
Caustic soda, 5%	SS	MSh	S	GC	GC	S,GC	Sh	SSp
Alum, 13%	SB,GC	NAC	NAC	SB,GC	SB,GC	SB,GC	NAC	SB,GC
Sodium carbonate, 10%	SB,GC	GC	GC	GC	GC	GC	GC	SB,GC
Calcium chloride, 25%	SB,GC	SB,SS,GC	NAC	SB,GC	SB,GC	NAC	NAC	SB,GC
Common salt, 25%	NAC	NAC	NAC	SB,GC	NAC	SB,GC	NAC	NAC
Water	NAC	NAC	NAC	SB,GC	NAC	NAC	NAC	NAC

TABLE 28-33 General Physical and Chemical Characteristics of Refractory Brick*

Type of brick	Typical composition	Approx. bulk density, lb/ft ³	Fusion point, °F.	Chemical nature	Deformation under hot loading	Apparent porosity, %	Permeability	Hot strength	Thermal shock resistance	Chemical resistance	
										To acid	To alkali
Silica	SiO ₂ , 95%	115	3100	Acid	Excellent	21	High	Excellent	Poor‡	Good	Good at low temperatures
High-duty fire clay	SiO ₂ , 54% Al ₂ O ₃ , 40%	134	3125	Acid	Fair	18	Moderate	Fair	Fair	Good	Good at low temperatures
Superduty fire clay	SiO ₂ , 52% Al ₂ O ₃ , 42%	140	3170	Acid	Good	15	High	Fair	Good	Good	Good at low temperatures
Acid-resistant (type H)	SiO ₂ , 59% Al ₂ O ₃ , 34%	142	3040	Acid	Poor	7	Low	Poor	Good	Insoluble in acids except HF and boiling phosphoric	Very resistant in moderate concentrations
Insulating brick	Varies	30–75	Varies		Poor	65–85	High	Poor	Excellent	Poor	Poor
High-alumina	Al ₂ O ₃ , 50–85%	170	3200–3400	Slightly acid	Good	20	Low	Good	Good	Good except for HF and aqua regia	Very slight attack with hot solutions
Extra-high-alumina	Al ₂ O ₃ , 90–99%	185	3000–3650	Neutral	Excellent	23	Low	Excellent	Good		
Mullite	Al ₂ O ₃ , 71%	153	3290	Slightly acid	Excellent	20	Low	Good	Good	Insoluble in most acids	Slight reaction
Chrome-fired	Chrome ore, 100%	195	Varies	Neutral	Fair	20	Low	Good	Poor	Fair to good	Poor
Magnesite-chrome bonded§	MgO, 50–80%	190			Good	12	Very low	Good	Excellent		
Magnesite-chrome fired	Cr ₂ O ₃ , 5–18% Fe ₂ O ₃ , 3–13% Al ₂ O ₃ , 6–11%	180	Varies	Basic	Excellent	20	High	Good	Excellent	Fair except to strong acids	Fair resistance at low temperatures
Magnesite-chrome high-fired	SiO ₂ , 1.2–5%	180			Excellent	18	High	Excellent	Excellent		
Magnesite-bonded§	MgO, 95%	181	3900	Basic	Good	11	Low	Good	Good	Soluble in most acids	Good resistance at low temperatures
Magnesite-fired		178			Good	19	Moderate	Good	Good		
Zircon	ZrO ₂ , 67% SiO ₂ , 33%	200	3100†	Acid	Excellent	25	Very low	Excellent	Good	Very slight	Very slight
Zirconia (stabilized)	ZrO ₂ , 94% CaO, 4%	245	4800	Slightly acid	Excellent	23	Low	Excellent	Excellent	Very slight	Very slight
Silicon-carbide	SiC, 80–90%	160	4175	Slightly acid	Excellent	15	Very low	Excellent	Excellent	Slight reaction with HF	Attacked at high temperatures
Graphite	C, 97%	105	6400	Neutral	Excellent	16	Low	Excellent	Excellent	Insoluble	Insoluble

*From *Chem. Eng.*, 100 (July 31, 1967). To convert lbm/ft³ to kg/m³, multiply by 0.0624; °C = (°F – 32) × 5/9.

†Dissociates above 1700°C (3100°F).

‡Good above 650°C (1200°F).

§Chemically bonded.

TABLE 28-34 Minimum Temperature without Excessive Scaling in Air (Continuous Service)*

Alloy	°F	°C
Carbon steel	1050	565
½Mo steel	1050	565
1Cr ½Mo steel	1100	595
2¼Cr 1Mo steel	1150	620
5Cr ½Mo steel	1200	650
9Cr 1Mo steel	1300	705
AISI 410	1300	705
AISI 304	1600	870
AISI 321	1600	870
AISI 347	1600	870
AISI 316	1600	870
AISI 309	2000	1090
AISI 310	2100	1150

*Courtesy of National Association of Corrosion Engineers.

2. *Intermediate purity.* 50 to 55 percent alumina. The anorthite (needle-structure) form is more resistant to the action of steam exposure.

3. *Very pure.* 70 to 80 percent alumina for high temperatures. Under reducing conditions the iron in the ceramic is controlling, as it acts as a catalyst and converts the CO to CO₂ plus carbon, which results in spalling. The choice among the three types of castables is generally made by economic considerations and the temperature of the application.

Compared with brick, castables are less dense, but this does not really mean that they are less serviceable, as their cements can hydrate and form gels which can fill the voids in castables. Extra-large voids do indicate less strength regardless of filled voids and dictate a lower allowable gas velocity. If of the same density as a given brick, a castable will result in less permeation.

Normally, castables are 25 percent cements and 75 percent aggregates. The aggregate is the more chemically resistant of the two components. The highest-strength materials have 30 percent cement, but too much cement results in too much shrinkage. The standard insulating refractory, 1:2:4 LHV castable, consists of 1 volume of cement, 2 volumes of expanded clay (Haydite), and 4 volumes of vermiculite.

Castables can be modified by a clay addition to keep the mass intact, thus allowing application by air-pressure gunning (gunite). Depending upon the size and geometry of the equipment, many castable linings must be reinforced; wire and expanded metal are commonly used.

TABLE 28-35 Important Commercial Alloys for High-Temperature Process Service

	Nominal composition, %			
	Cr	Ni	Fe	Other
Ferritic steels				
Carbon steel			Bal.	
2¼ chrome	2¼		Bal.	Mo
Type 502	5		Bal.	Mo
Type 410	12		Bal.	
Type 430	16		Bal.	
Type 446	27		Bal.	
Austenitic steels				
Type 304	18	8	Bal.	
Type 321	18	10	Bal.	Ti
Type 347	18	11	Bal.	Cb
Type 316	18	12	Bal.	Mo
Type 309	24	12	Bal.	
Type 310	25	20	Bal.	
Type 330	15	35	Bal.	
Nickel-base alloys				
Nickel		Bal.		
Incoloy 800	21	32	Bal.	
Hastelloy B		Bal.	6	Mo
Hastelloy C	16	Bal.	6	W, Mo
60-15	15	Bal.	25	
Inconel 600	15	Bal.	7	
80-20	20	Bal.		
Hastelloy X	22	Bal.	19	Co, Mo
Multimet	21	20	Bal.	Co
Rene 41	19	Bal.	5	Co, Mo, Ti
Cast irons				
Ductile iron			Bal.	C, Si, Mg
Ni-Resist, D-2	2	20	Bal.	Si, C
Ni-Resist, D-4	5	30	Bal.	Si, C
Cast stainless (ACI types)				
HC	28	4	Bal.	
HF	21	11	Bal.	
HH	26	12	Bal.	
HK	15	20	Bal.	
HT	15	35	Bal.	
HW	12	Bal.	28	
Superalloys				
Inconel X	15	Bal.	7	Ti, Al, Cb
A 286	15	25	Bal.	Mo, Ti
Stellite 25	20	10	Co-base	W
Stellite 21 (cast)	27.3	2.8	Co-base	Mo
Stellite 31 (cast)	25.2	10.5	Co-base	W