S

SACRIFICIAL ANODE

See also "Cathodic Protection."

Use of a sacrificial anode is a means of cathodic protection. By selecting an anode constructed of a metal more active in the galvanic series than the metal to be protected, a galvanic cell may be established with the current flowing such that the metal to be protected becomes the cathode and is protected from corrosion while the anode is corroded (sacrificed). These sacrificial anodes are usually composed of magnesium or magnesium-based alloys. Occasionally, zinc and aluminum have been used.

Most sacrificial anodes in use in the United States are of magnesium construction. Approximately 10 million pounds of magnesium are used annually for this purpose. These anodes are used to protect buried pipelines and metal structures. Magnesium rods have also been placed in steel hot-water tanks to increase the life of these tanks.

See Ref. 1.

SARAN

See "Polyvinylidene Chloride."

SCAB CORROSION

Scab corrosion is the condition where the paint film remains intact but corrosion has taken place under the paint film as a result of external damage and the paint film is nonadherent to the metal substrate.

SEASON CRACKING

This is a form of stress corrosion cracking that is usually applied to the stress corrosion cracking of brass. The term originates from early in the twentieth century when cartridge shells made of 70% copper and 30% zinc were found to crack over a period of time. It was later realized that ammonia from decaying organic matter in combination with residual stresses in the brass was responsible for the crack of these shells. This phenomenon was called "season cracking" because the presence of high humidity during warm, moist climates (or seasons) promoted the stress corrosion cracking.

Stress corrosion cracking of brass commonly occurs when brass is subjected to an applied or residual tensional stress while in contact with a trace of ammonia or amine in the presence of moisture and oxygen.

See "Copper and Copper Alloys."

SELECTIVE CORROSION

See "Dezincification." Also called selective leaching.

SELECTIVE LEACHING

Removal of one element from a solid alloy by a corrosion process. See "Dezincification."

SEMIKILLED STEEL

See "Killed Carbon Steel."

SENSITIZATION

Sensitization is the term applied to the precipitation of chromium carbides in the grain boundaries of both austenitic 300 series alloys and the straight chromium grades such as types 405 and 410 stainless steel, as a result of exposure to temperatures in the range of 800 to 1600°F (425 to 870°C). This results in intergranular corrosion or cracking.

As the chromium carbides develop, the adjacent metal becomes depleted in dissolved chromium, creating a zone adjacent to the grain boundary of locally corrosion-susceptible iron-nickel alloy. The local composition of the straight chromium grades may approach that of carbon steel. This chromium-depleted zone has less corrosion resistance than the adjacent unaffected alloy and can react galvanically with the unaffected zone, accelerating corrosion rates.

There is not complete agreement over the lower threshold temperature that causes sensitization. It has been reported that cold-worked austenitic stainless steels sensitize at temperatures as low as 700°F (370°C). Solution-annealed austenitic stainless steels require extremely long exposure times to sensitize at temperatures below 850°F (455°C). In general, sensitization takes place most rapidly when the temperature is in the range of 1500°F (815°C).

Sensitization can cause two types of corrosion problems: weld rusting and intergranular corrosion. Refer to "Intergranular Corrosion."

S-GLASS

S-glass is used as a reinforcing material for thermosetting resins. See "Thermoset Reinforcing Materials."

SHEET LININGS

Designers of tanks and process vessels are faced with the problem of choosing the most reliable material of construction at reasonable cost. When handling corrosive materials, a choice must often be made between the use of an expensive metallic material of construction or the use of a low-cost material from which to fabricate the shell and then install a corrosion-resistant lining. Carbon steel has been and still is the material predominantly selected, although there has been a tendency over the past few years to use a fiberglass-reinforced plastic shell. This latter choice has the advantage of providing atmospheric corrosion protection of the shell exterior.

For many years vessels have been successfully lined with various rubber formulations, both natural and synthetic. Many such vessels have given over 20 years of reliable service.

With the development of newer synthetic elastomeric and plastic materials, the variety of lining materials available has greatly increased.

As with any material, the corrosion resistance, allowable operating values, and cost varies with each. Care must be taken when selecting the lining material that it is compatible with the corrodent being handled at the operating temperatures and pressures required.

Shell Design

In order for a lining to perform satisfactorily, the vessel shell must meet certain design configurations. Although these details may vary slightly depending upon the specific lining material to be used, there are certain basic principles that apply in all cases.

1. The vessel must be of butt-welded construction.
2. All internal welds must be ground flush.
3. All weld spatter must be removed.
4. All sharp corners must be ground to a minimum of $\frac{1}{8}$ in. radius.
5. All outlets must be of the flanged or pad type. Certain lining materials require that nozzles be no less than 2 in. (55 mm) in diameter.
6. No protrusions are permitted inside of the vessel. Once the lining has been installed, there should be no welding permitted on the exterior of the vessel.

After the fabrication has been completed, the interior surface of the vessel must be prepared to accept the lining. This is a critical step. Unless the surface is properly prepared, proper bonding of the lining to the shell will not be achieved. The basic requirement is that the surface be absolutely clean. To ensure proper bonding, all surfaces to be lined should be abrasive blasted to white metal in accordance with SSPC specification Tp5-63 or NACE specification NACE-1. A white-metal surface condition is defined as being one from which all rust, scale, paint, and the like has been removed and the surface has a uniform gray-white appearance. Streaks or stains of rust or other contaminants are not allowed. A near-white blast-cleaned finish equal to SSPC SP-10 is allowed on occasion. This is a more economical finish. In any case it is essential that the finish be as the lining contractor has specified. Some lining contractors will fabricate the vessel as well as preparing the surface. When the total responsibility is placed on the lining contractor, the problem is simplified, and usually a better-quality product will be the result.

When a vessel shell is fabricated from a reinforced thermosetting plastic (RTP), several advantages are realized. The RTPs themselves generally have a wider range of corrosion resistance but relatively low allowable operating temperatures. When a fluoropolymer type lining is applied to an RTP shell, the temperature to which the backup RTP is exposed has been reduced, in addition to preventing the RTP from becoming exposed to the chemicals in the process system. An upper temperature limit for using RTP dual laminates is 350°F (177°C).

The dual laminate construction lessens the problem of permeation through liners. If there is permeation, it is believed to pass through the RTP structure at a rate equal to or greater than through the fluoropolymer itself, resulting in no potential for collection of permeate at the thermoplastic-to-thermoset interface. If delamination does not occur, permeation is not a problem.

Considerations in Liner Selection

Before a lining material is selected, careful consideration should be given to several broad categories, specifically materials being handled, operating conditions, and conditions external to the vessel.

The following questions must be answered about the materials being handled.

1. What are the primary chemicals being handled and at what concentrations?
2. Are there any secondary chemicals, and if so at what concentrations?
3. Are there any trace impurities or chemicals?
4. Are there any solids present, and if so what is their particle size and concentration?
5. If a vessel, will there be agitation, and to what degree? If a pipeline, what are the flow rates, maximum and minimum?
6. What are the fluid purity requirements?

The answers will narrow the selection to those materials that are compatible. This next set of questions will narrow the selection still further by eliminating those materials that do not have the required physical and/or mechanical properties.

1. What is the normal operating temperature and temperature range?
2. What peak temperatures can be reached during shutdown, startup, process upset, etc.?
3. Will any mixing areas exist where exothermic or heat of mixing temperatures can develop?
4. What is the normal operating pressure?
5. What vacuum conditions and range are possible during operation, startup, shutdown, or upset conditions?
6. Will there be temperature cycling?
7. What cleaning methods will be used?

Finally, consideration should be given to the conditions external to the vessel or pipe.

1. What are the ambient temperature conditions?
2. What is the maximum surface temperature during operation?
3. What are the insulation requirements?
4. What is the nature of the external environment? This can dictate finish requirements and/or affect the selection of the shell material.
5. What are the external heating requirements?
6. Is grounding necessary?

With the answers to these questions an intelligent selection of liner and shell can be made.

Design Considerations

In addition to selecting a lining material that is resistant to the corrodent being handled, there are three other factors that must be considered in the design, namely permeation, absorption, and environmental stress cracking. Permeation and absorption can cause

1. Bond failure and blistering, resulting from the accumulation of fluids at the bond when the substrate is less permeable than the liner, or from corrosion/reaction products if the substrate is attacked by the permeant.
2. Failure of the substrate from corrosive attack.
3. Loss of contents through the substrate and liner as a result of the eventual failure of the substrate. In unbonded linings it is important that the space between the liner and substrate be vented to the atmosphere, not only to allow minute quantities of permeant vapor to escape but also to prevent entrapped air from collapsing the liner.

Permeation

Also see “Permeation.”

All materials are somewhat permeable to chemical molecules, but plastic materials tend to be an order of magnitude greater in their permeability rates than metals. Polymers can be permeated by gases, vapors, or liquids. Permeation is strictly a physical phenomenon: there is no chemical attack on the polymer. It is a molecular migration either through microvoids in the polymer (if the structure is more or less porous) or between polymer molecules.

Permeation is a function of two variables, one relating to diffusion between molecular chains and the other to the solubility of the permeant in the polymer. The driving forces of diffusion are the concentration gradients in liquids and the partial pressure gradient for gases. Solubility is a function of the affinity of the permeant for the polymer.

Material passing through cracks and voids is not related to permeation. These are two distinct happenings. They are not related in any way.

Permeation is affected by the factors

1. Temperature and pressure
2. Permeant concentration
3. Thickness of the polymer

An increase in temperature will increase the permeation rate, since the solubility of the permeant in the polymer will increase, and as the temperature rises, the polymer chain movement is stimulated, permitting more permeants to diffuse among the chain more easily. For many gases the permeant rates increase linearly with the partial pressure gradient, and the same effect is experienced with concentration gradients of liquids. If the permeant. is highly soluble in the polymer, the permeability increase may not be linear.

The thickness of the polymer affects the permeation. An increase in thickness will generally decrease permeation by the square of the thickness. However, there are disadvantages to this approach. First, as the lining thickness is increased, thermal stresses on the bond are increased, resulting in bond failure. Temperature changes and large differences in coefficients of thermal expansion are the most common causes of bond failure. The thickness and modulus of elasticity of the lining material are two of the factors that influence these stresses. In addition, as the thickness of the sheet lining material increases, it becomes more difficult to form, and heat may have to be applied. Also, the thicker sheets are more difficult to weld. Third is cost. As the thickness of the material increases, not only does the material cost more but also the labor cost increases because of the greater difficulty of working with the material. If polymers such as FEP, PTFE, or PVDF are being used, the cost may become prohibitive.

The density of the polymer, in addition to the thickness, will also have an effect on the permeation rate. The higher the specific gravity of the sheet, the fewer will be the voids present through which permeation can take place. A comparison of the specific gravity between two different polymers will not give an indication as to the relative permeation rates. However, a comparison between two liners of the same polymer will provide the difference in the relative permeation rates. The liner having the greater density will have the lower permeation rate.

Other factors affecting permeation consisting of chemical and physicoehemical properties are

1. Ease of condensation of the permeant. Chemicals that condense readily will permeate at a higher rate.
2. The higher the intermolecular chain forces (e.g., Van der Waals hydrogen bonding) of the polymer, the lower the permeation rate.
3. The higher the level of crystallinity in the polymer, the lower the permeation rate.
4. The greater the degree of cross-linking within the polymer, the lower the permeation rate.
5. Chemical similarity between the polymer and the permeant. When the permeant and polymer have similar functional groups, the permeant rate will increase.
6. The smaller the molecule of the permeant, the greater the permeation rate.

The magnitude of any of the effects will be a function of the combination of the polymer and the permeant in actual service.

Absorption

Also see “Absorption.”

Polymers have the potential to absorb varying amounts of corrodents they come into contact with, particularly organic liquids. This can result in swelling, cracking, and penetration to the substrate. Swelling can cause softening of the polymer, introduce high stresses, and cause failure of the bond. If the polymer has a high absorption rate, permeation will probably take place. An approximation of the expected permeation and/or absorption of a polymer can be based on the absorption of water. These data are usually available. Table A.1 provides the water absorption rates for the more common polymers.

The failure due to absorption can best be understood by considering the “steam cycle” test described in the ASTM standards for lined pipe. A section of lined pipe is subjected to thermal and pressure fluctuations. This is repeated for 100 cycles. The steam creates a temperature and pressure gradient through the liner, causing absorption of a small quantity of steam, which condenses to water within the inner wall. Upon pressure release, or on reintroduction of steam, the entrapped water can expand to vapor, causing an original micropore. The repeated pressure and thermal cycling enlarges the micropores, ultimately producing visible water-filled blisters within the liner.

In an actual process, the polymer may absorb process fluids, and repeated temperature or pressure cycling can cause blisters. Eventually corrodent may find its way to the substrate.

Related effects can occur when process chemicals are absorbed, which may later react, decompose, or solidify within the structure of the plastic. Prolonged retention of the chemicals may lead to their decomposition within the polymer. Although it is unusual, it is possible for absorbed monomers to polymerize.

Several steps can be taken to reduce absorption. Thermal insulation of the substrate will reduce the temperature gradient across the vessel, thereby preventing condensation and subsequent expansion of the absorbed fluids. This also reduces the rate and magnitude of temperature changes, keeping blisters to a minimum. The use of operating procedures or devices that limit the ratio of process pressure reductions or temperature increases will provide additional protection.

Environmental Stress Cracking

Stress cracks develop when a tough polymer is stressed for an extended period of time under loads that are small relative to the polymer's yield point. Cracking will occur with little elongation of the material. The higher the molecular weight of the polymer, the less likelihood of environmental stress cracking, other things being equal. Molecular weight is a function of the length of individual chains that make up the polymer. Longer-chain polymers tend to crystallize less than polymers of lower molecular weight or shorter chains and also have greater load-bearing capacity.

Crystallinity is an important factor affecting stress corrosion cracking. The less the crystallization that takes place, the less the likelihood of stress cracking. Unfortunately, the lower the crystallinity, the greater the likelihood of permeation.

Resistance to stress cracking can be reduced by the absorption of substances that chemically resemble the polymer and will plasticize it. In addition, the mechanical strength will be reduced. Halogenated chemicals, particularly those consisting of small molecules containing fluorine or chlorine, are especially likely to be similar to the fluoropolymers and should be tested for their effect.

The presence of contaminants in a fluid may act as an accelerator. For example, polypropylene can safely handle sulfuric or hydrochloric acids, but iron or copper contamination in concentrated sulfuric or hydrochloric acids can result in the stress cracking of polypropylene.

Elastomeric Linings

Elastomers, sometimes referred to as rubbers, have given many years of service in providing protection to steel vessels. Each of these materials can be compounded to improve certain of its properties. Because of this it is necessary that a complete specification for a lining using these materials include specific properties that are required for the application. These include resilience, hysteresis, static or dynamic shear and compression modulus, flex fatigue and cracking, creep resistance to oils and chemicals, permeability, and brittle point, all in the temperature range to be encountered in service. This will permit a competent manufacturer to propose lining material for the application.

Elastomeric linings are sheet applied and bonded to the steel substrate. The bonding material to be used is dependent upon the specific elastomer to be installed. Repair of these linings is relatively simple. Many older vessels with numerous repair patches are still operating satisfactorily.

Natural Rubber

The maximum temperature for continuous use of natural rubber is 175°F (80°C). The degree of curing to which natural rubber is subjected will determine whether it is classified as soft, semihard, or hard. Soft rubber is the form primarily used for lining material, although some hard linings are produced.

It provides excellent resistance to most inorganic salt solutions, alkalies, and nonoxidizing acids. Hydrochloric acid will react with soft rubber to form rubber hydrochloride, and therefore it is not recommended that natural (soft) rubber be used in contact with this acid. Strong oxidizing media such as nitric acid, concentrated sulfuric acid, permanganates, dichromates, chlorine dioxide, and sodium hypochlorite will severely attack rubber. Mineral and vegetable oils, gasoline, benzene, toluene, and chlorinated hydrocarbons also affect rubber. Cold water tends to preserve natural rubber. Natural rubber offers good resistance to radiation and alcohols. Refer to Table S.1 for the compatibility of multiple-ply (soft/hard/soft) natural rubber

See also "Natural Rubber."

Table S.1 Compatibility of Multiple-Ply (Soft/Hard/Soft) Natural Rubber with Selected Corrodents[a]

	Maximum temp.			Maximum temp.	
Chemical	°F	°C	Chemical	°F	°C
Acetaldehyde	x	x	Ammonium chloride, sat.	160	71
Acetamide	x	x	Ammonium fluoride 10%	x	x
Acetic acid 10%	x	x	Ammonium fluoride 25%	x	x
Acetic acid 50%	x	x	Ammonium hydroxide 25%	100	38
Acetic acid 80%	x	x	Ammonium hydroxide, sat.	100	38
Acetic acid, glacial	x	x	Ammonium nitrate	160	71
Acetic anhydride	x	x	Ammonium persulfate		
Acetone	140	60	Ammonium phosphate	160	71
Acetyl chloride			Ammonium sulfate 10–40%	160	71
Acrylic acid			Ammonium sulfide	160	71
Acrylonitrile			Ammonium sulfite		
Adipic acid			Amyl acetate	x	x
Allyl alcohol			Amyl alcohol	100	38
Allyl chloride			Amyl chloride	x	x
Alum	160	71	Aniline	x	x
Aluminum acetate			Antimony trichloride		
Aluminum chloride, aqueous	160	71	Aqua regia 3:1	x	x
Aluminum chloride, dry	160	71	Barium carbonate	160	71
Aluminum fluoride	x	x	Barium chloride	160	71
Aluminum hydroxide			Barium hydroxide	160	71
Aluminum nitrate	x	x	Barium sulfate	160	71
Aluminum oxychloride			Barium sulfide	160	71
Aluminum sulfate	160	71	Benzaldehyde	x	x
Ammonia gas			Benzene	x	x
Ammonium bifluoride			Benzene sulfonic acid 10%	x	x
Ammonium carbonate	160	71	Benzoic acid	160	71
Ammonium chloride 10%	160	71	Benzyl alcohol	x	x
Ammonium chloride 50%	160	71	Benzyl chloride	x	x

Table S.1 Compatibility of Multiple-Ply (Soft/Hard/Soft) Natural Rubber with Selected Corrodents[a] (Continued)

Chemical	Maximum temp.		Chemical	Maximum temp.	
	°F	°C		°F	°C
Borax	160	71	Copper cyanide	160	71
Boric acid	140	60	Copper sulfate	160	71
Bromine gas, dry			Cresol	x	x
Bromine gas, moist			Cupric chloride 5%	x	x
Bromine liquid			Cupric chloride 50%	x	x
Butadiene			Cyclohexane	x	x
Butyl acetate	x	x	Cyclohexanol		
Butyl alcohol	160	71	Dichloroacetic acid		
n-Butylamine			Dichloroethane (ethylene dichloride)	x	x
Butyl phthalate			Ethylene glycol	160	71
Butyric acid	x	x	Ferric chloride	160	71
Calcium bisulfide			Ferric chloride 50% in water	160	71
Calcium bisulfite	160	71	Ferric nitrate 10–50%	x	x
Calcium carbonate	160	71	Ferrous chloride	140	60
Calcium chlorate	140	60	Ferrous nitrate	x	x
Calcium chloride	140	60	Fluorine gas, dry	x	x
Calcium hydroxide 10%	160	71	Fluorine gas, moist		
Calcium hydroxide, sat.	160	71	Hydrobromic acid, dilute	160	71
Calcium hypochlorite	x	x	Hydrobromic acid 20%	160	71
Calcium nitrate	x	x	Hydrobromic acid 50%	160	71
Calcium oxide	160	71	Hydrochloric acid 20%	x	x
Calcium sulfate	160	71	Hydrochloric acid 38%	160	71
Caprylic acid			Hydrocyanic acid 10%		
Carbon bisulfide	x	x	Hydrofluoric acid 30%	x	x
Carbon dioxide, dry			Hydrofluoric acid 70%	x	x
Carbon dioxide, wet			Hydrofluoric acid 100%	x	x
Carbon disulfide	x	x	Hypochlorous acid		
Carbon monoxide	x	x	Iodine solution 10%		
Carbon tetrachloride	x	x	Ketones, general		
Carbonic acid	160	71	Lactic acid 25%	x	x
Cellosolve	x	x	Lactic acid, concentrated	x	x
Chloracetic acid	x	x	Magnesium chloride	160	71
Chloracetic acid, 50% water	x	x	Malic acid	100	38
Chlorine gas, dry	x	x	Manganese chloride		
Chlorine gas, wet	x	x	Methyl chloride	x	x
Chlorine, liquid	x	x	Methyl ethyl ketone	x	x
Chlorobenzene	x	x	Methyl isobutyl ketone	x	x
Chloroform	x	x	Muriatic acid	140	60
Chlorosulfonic acid	x	x	Nitric acid 5%	x	x
Chromic acid 10%	x	x	Nitric acid 20%	x	x
Chromic acid 50%	x	x	Nitric acid 70%	x	x
Chromyl chloride			Nitric acid, anhydrous	x	x
Citric acid 15%	x	x	Nitrous acid, concentrated	x	x
Citric acid, concentrated	x	x	Oleum		
Copper acetate			Perchloric acid 10%		
Copper carbonate	x	x	Perchloric acid 70%		
Copper chloride	x	x	Phenol	x	x

Table S.1 Compatibility of Multiple-Ply (Soft/Hard/Soft) Natural Rubber with Selected Corrodents[a] (Continued)

Chemical	Maximum temp. °F	Maximum temp. °C	Chemical	Maximum temp. °F	Maximum temp. °C
Phosphoric acid 50–80%	160	71	Stannous chloride	160	71
Picric acid			Sulfuric acid 10%	160	71
Potassium bromide 30%	160	71	Sulfuric acid 50%	x	x
Salicylic acid			Sulfuric acid 70%	x	x
Silver bromide 10%			Sulfuric acid 90%	x	x
Sodium carbonate	160	71	Sulfuric acid 98%	x	x
Sodium chloride	160	71	Sulfuric acid 100%	x	x
Sodium hydroxide 10%	160	71	Sulfuric acid, fuming	x	x
Sodium hydroxide 50%	x	x	Sulfurous acid	x	x
Sodium hydroxide, concentrated	x	x	Thionyl chloride		
Sodium hypochlorite 20%	x	x	Toluene		
Sodium hypochlorite, concentrated	x	x	Trichloroacetic acid		
Sodium sulfide to 50%	160	71	White liquor		
Stannic chloride	160	71	Zinc chloride	160	71

[a] The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable.

Source: PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

Isoprene

Natural rubber chemically is a natural *cis*-polyisoprene. Isoprene (IR) is a synthetic *cis*-polyisoprene. The corrosion resistance of IR is the same as that of natural rubber. The major difference is that isoprene has no odor and therefore can be used in the handling of certain food products.

Neoprene

The maximum temperature under which neoprene (CR) can be used is 180–200°F (82–93°C). Excellent service is experienced in contact with aliphatic compounds (methyl and ethyl alcohols, ethylene glycols, etc.), aliphatic hydrocarbons, and most freon refrigerants. However, the outstanding property of neoprene is its resistance to attack from solvents, waxes, fats, oils, greases, and many other petroleum-based products. Dilute mineral acids, inorganic salt solutions, and alkalies can also be handled successfully.

Chlorinated and aromatic hydrocarbons, organic esters, aromatic hydroxy compounds, and certain ketones will attack neoprene, as will highly oxidizing acid and salt solutions such as nitric and concentrated sulfuric acids.

See also “Neoprene.”

Butyl Rubber

The maximum temperature to which butyl rubber (IIR) can be exposed on a continuous basis is 250–300°F (120–148°C). Butyl rubber is very nonpolar. It has exceptional resistance to dilute mineral acids, alkalies, phosphate ester oils, acetone, ethylene glycol, ethylene, and water. Resistance to concentrated acids, except nitric and sulfuric, is good. It will be attacked by petroleum oils, gasoline, and most solvents (except oxygenated solvents) but is resistant to swelling by vegetable and animal oils. Refer to “Butyl Rubber and Chlorobutyl Rubber” for more details.

Chlorsulfonated Polyethylene

The maximum temperature that Hypalon can be exposed to on a continuous basis is 250°F (121°C). Hypalon is highly resistant to attack by hydrocarbon oils and fuels, even at elevated temperatures. It is also resistant to such oxidizing chemicals as sodium hypochlorite, sodium peroxide, ferric chloride, and sulfuric, chromic, and hydrofluoric acids. Concentrated hydrochloric acid (37%) can be handled below 158°F (70°C). Below this temperature Hypalon can handle all concentrations without adverse effect. Nitric acid up to 60% concentration at room temperature can also be handled without adverse effect. Hypalon is also resistant to salt solutions, alcohols, and both weak and concentrated alkalies.

Aliphatic, aromatic, and chlorinated hydrocarbons, aldehydes, and ketones will attack Hypalon. Refer to Table C.17 for compatibility of Hypalon with selected corrodents.

Urethane Rubber

The maximum temperature to which the urethane rubbers (AU) can be exposed on a continuous basis is 250°F (121°C). The urethane rubbers are resistant to most mineral and vegetable oils, greases, and fuels. They have limited service in weak acid solutions and cannot be used in concentrated acids. Neither are they resistant to steam or caustic, aromatic hydrocarbons, polar solvents, esters, or ethers. Ketones will attack urethane. Alcohols will soften and swell the urethane rubbers.

Polyester Elastomer

The maximum temperature to which polyester elastomers (PE) can be exposed continuously is 302°F (150°C). The elastomers have excellent resistance to nonpolar materials such as oils and hydraulic fluids, even at elevated temperatures. At room temperature they are resistant to most polar fluids, such as acids, bases, amines, and glycols. Resistance is very poor at temperatures of 158°F (70°C) or above.

These elastomers are not resistant to polar fluids at elevated temperatures.

Perfluoroelastomers

The maximum temperature to which PFEs may be subjected on a continuous basis is 400°F (205°C). These materials are sold under various trade names. Three typical brands are given in the table.

Trade name	Manufacturer
Viton	DuPont
Technoflon	Ausimont
Fluorel	3M

The fluoroelastomers provide excellent resistance to oils, fuels, lubricants, most mineral acids, many aliphatic and aromatic hydrocarbons (carbon tetrachloride, benzene, toluene, xylene), gasoline, naphtha, chlorinated solvents, and pesticides.

These materials are not suitable for use with low-molecular-weight esters, ethers, ketones, certain amines, or hot anhydrous hydrofluoric or chlorosulfonic acids. Refer to Table E.3 for the compatibility of Viton with selected corrodents.

Thermoplastic Linings

Thermoplastic linings are used more extensively than any other type of lining. The most common thermoplasts used are

Polyvinyl chloride (PVC)
Chlorinated polyvinyl chloride (CPVC)
Polyvinylidene fluoride (PVDF)
Polypropylene (PP)
Polyethylene (PE)
Tetrafluoroethylene (PTFE)
Fluorinated ethylene propylene (FEP)
Perfluoralkoxy (PFA)
Ethylene-tetrafluoroethylenc (ETFE)
Ethylene-chlorotrifluorethylene (ECTFE)

These materials are capable of providing a wide range of corrosion resistance. Table S.2 lists the general area of corrosion resistance for each of the thermoplasts. This table is only a general guide. The resistance of a lining material to a specific corrodent should be checked.

These materials are used to line vessels as well as pipe and fittings. When vessels are lined, the linings, with the exception of plasticized PVC, are fabricated from sheet stock that must be cut, shaped, and joined. Joining is usually accomplished by hot gas welding. Several problems exist when a thermoplastic lining is bonded to a metal shell, due primarily to the large differences in the coefficient of thermal expansion and the difficulty of adhesion. If the vessel is to be used under ambient temperature, such as a storage vessel, the problem of thermal expansion differences is eliminated. However, the problem of adhesion is still present. Because of this, many linings are installed as loose linings in the vessel.

Techniques have been developed to overcome the problem of adhesion, making use of an intermediate bond. One approach is to heat the thermoplastic sheet, then impress into one surface a fiber cloth or nonwoven web. This provides half of the bond. Bonding to the metal surface is accomplished by the use of an epoxy adhesive that will bond to both the fiber and the metal.

Table S.2 General Corrosion Resistance of Thermoplastic Lining Materials

Material	Strong acids	Strong bases	Chlorinated solvents	Esters and ketones	Strong oxidants
PVC (type 1)	F	F	P	P	P
CPVC	F	F	F	P	P
PVDF	E	P	E	P	E
Polypropylene	G	E	P	F	P
Polyethylene	F	G	P	P	E
PTFE	E	E	E	E	E
FEP	E	E	E	E	E
ECTFE	E	E	E	E	E

E = excellent; G = good; F = fair; P = poor.

Welding techniques for joining the thermoplastic sheets are critical. Each weld must be continuous, leak tight, and mechanically strong. It is important that only qualified welders be used for this operation. Poor welding is a common cause of lining failure.

Polyvinyl Chloride

The maximum allowable temperature for continuous operation of Type 1 PVC is 140°F (60°C). Plasticized PVC can be bonded directly to a metal substrate. Unplasticized PVC cannot be bonded directly. It is bonded to a plasticized material forming a dual laminate that is then bonded to a metal substrate.

Plasticized PVC does not have the same range of corrosion resistance as the unplasticized PVC (Type 1). Unplasticized PVC is resistant to attack by most acids and strong alkalies as well as gasoline, kerosene, and aliphatic alcohols and hydrocarbons. It is subject to attack by aromatics, chlorinated organic compounds, and lacquer solvents.

See also "Polyvinyl Chloride."

Chlorinated Polyvinyl Chloride

CPVC can be operated continuously at a maximum temperature of 200°F (93°C). Chlorinated polyvinyl chloride is very similar in properties to PVC, except that it has a higher allowable operating temperature and a somewhat better resistance to chlorinated solvents. It is extremely difficult to hot weld the joints in a sheet lining. This factor should be considered when selecting this material.

CPVC is resistant to most acids, alkalies, salts, halogens, and many corrosive waters. In general, it should not be used to handle most polar organic materials including chlorinated or aromatic hydrocarbons, esters, and ketones.

See also "Chlorinated Polyvinyl Chloride."

Polyvinylidene Fluoride

This material may be operated continuously at a maximum temperature of 275°F (135°C). PVDF is one of the most popular lining materials because of its range of corrosion resistance and high allowable operating temperature. Unless a dual laminate is used, linings of PVDF will be loose.

PVDF is resistant to most acids, bases, and organic solvents. It also has the ability to handle wet or dry chlorine, bromine, and other halogens.

It is not resistant to strong alkalies, fuming acids, polar solvents, amines, ketones, and esters. When used with strong alkalies, it stress cracks.

See also "Vinylidene Fluoride Elastomers."

Polypropylene

The maximum allowable temperature under which PP can be operated continuously is 180°F (82°C). PP must be attached to a backing sheet in order to be secured as a lining. If a backing sheet is not used, the lining will be loose.

PP is resistant to sulfur-bearing compounds, caustics, solvents, acids, and other organic chemicals. It is not resistant to oxidizing-type acids, detergents, low-boiling hydrocarbons, alcohols, aromatics, and some chlorinated organic materials.

See also "Polypropylene."

Polyethylene

The maximum allowable temperature, at continuous contact, at which polyethylene (PE) can be used is 120°F (49°C). PE is the least expensive of all the plastic materials.

PE has a wide range of corrosion resistance ranging from potable water to corrosive wastes. It exhibits excellent resistance to strong oxidizing chemicals, alkalies, acids, and salt solutions.

See also "Polyethylene."

Tetrafluorethylene

PTFE can be used continuously at 500°F (260°C). It cannot be bonded directly to metal substrates but can be bonded by using a laminated fiberglass sheet as a backing.

The material tends to creep under stress at elevated temperatures. When the vessel is designed, provisions should be made to retain the PTFE. PTFE liners are subject to permeation by some corrodents. Table P.5 provides the vapor permeation of PTFE by selected materials.

PTFE is chemically inert in the presence of most corrodents. There are very few chemicals that will attack it within normal use temperatures. These reactants are among the most violent oxidizers and reducing agents known. Elemental sodium in intimate contact with fluorocarbons removes fluorine from the polymer molecule. The other alkali metals (potassium, lithium, etc.) react in a similar manner.

Fluorine and related compounds (e.g., chlorine trifluoride) are absorbed into the PTFE resin with such intimate contact that the mixture becomes sensitive to a source of ignition such as impact.

The handling of 80% sodium hydroxide, aluminum chloride, ammonia, and certain amines at high temperatures may produce the same effect as elemental sodium. Also, slow oxidative attack can be produced by 70% nitric acid under pressure at 480°F (250°C).

See also "Permeation" and "Polytetrafluorethylene."

Fluorinated Ethylene Propylene

FEP has a lower maximum operating temperature than PTFE. It exhibits changes in physical strength after prolonged exposure above 400°F (204°C), so the recommended maximum continuous operating temperature is 375°F (190°C).

Permeation of FEP liners can pose a problem. Table P.6 provides some permeation data relating to the more common chemicals. There is also some absorption of chemicals by FEP. This absorption can also lead to problems. Table A.2 is a listing of the absorption of selected liquids by FEP.

FEP basically has the same corrosion-resistant properties as PTFE but at a lower maximum temperature. It is resistant to practically all chemicals, the exception being extremely potent oxidizers such as chlorine trifluoride and related compounds. Some chemicals will attack FEP when present in high concentrations, at or near the service temperature limit.

See also "Fluorinated Ethylene Propylene."

Perfluoralkoxy

PFA can be used continuously at 500°F (260°C). It is subject to permeation by certain gases and will absorb liquids. Table P.7 illustrates the permeability of PFA and Table A.3 lists the absorption of representative liquids by PFA.

Perfluoralkoxy is inert to strong mineral acids, inorganic bases, inorganic oxidizers, aromatics, some aliphatic hydrocarbons, alcohols, aldehydes, ketones, esters, ethers, chlorocarbons, fluorocarbons, and mixtures of these compounds.

PFA will be attacked by certain halogenated complexes containing fluorine. These include chlorine trifluoride, bromine trifluoride, iodine pentafluoride, and fluorine. PFA can also be attacked by such metals as sodium or potassium, particularly in the molten state.

See also "Perfluoralkoxy."

Ethylene-Tetrafluoroethylene

ETFE has a maximum continuous service temperature of 300°F (140°C). It is fairly inert to strong mineral acids, halogens, inorganic bases, and metal salt solutions. Under most conditions ETFE is resistant to alcohols, ketones, ethers, and chlorinated hydrocarbons.

Strong oxidizers (e.g., nitric acid), organic bases (e.g., amines), and sulfonic acid will attack ETFE.

See also "Ethylene-Tetrafluoroethylene."

Ethylene-Chlorotrifluorethylene

The maximum service temperature of ECTFE is 340°F (170°C). ECTFE is very similar to PTFE as far as corrosion resistance is concerned, but it does not have the permeation problems associated with PTFE. It is resistant to strong mineral and oxidizing acids, alkalies, metal etchants, liquid oxygen, and essentially all organic solvents *except* hot amine (e.g., aniline, dimethylamine). ECTFE will be attacked by metallic sodium and potassium.

See also "Ethylene-Chlorotrifluoroethylene."

Causes of Lining Failure

Linings, if properly selected, installed, and maintained, and if the vessel has been properly designed, fabricated, and prepared to accept the lining, will usually give many useful years of service. However, on occasion there have been lining failures, which can be attributed to one or more of the following causes.

Liner Selection

This is the first step. Essential to this step is a careful analysis of the materials to be handled, their concentrations, and operating conditions as outlined in the beginning of this section. Consideration must also be given to the physical and mechanical properties of the liner to ensure that they meet the specified operating conditions. If there is any doubt, corrosion testing should be undertaken to guarantee the resistance of the liner material.

Inadequate Surface Preparation

Surface preparation is extremely important. All specifications for surface preparation must be followed. If surface preparation is not done properly, poor bonding can result and/or mechanical damage to the liner is possible.

Thermal Stresses

If sheet linings are not properly designed, thermal stresses produced by thermal cycling can eventually result in bond failure.

Permeation

Certain lining materials are subject to permeation when in contact with specific corrodents. When the possibility of permeation exists, an alternative lining material should be selected. Permeation can result in debonding resulting from corrosion products of fluids accumulating at the interface between the liner and the substrate. In addition, corrosion of the substrate can result, leading to leakage problems and eventual failure of the substrate.

Absorption

As with permeation, absorption of the corrodent by the liner material can result in swelling of the liner, cracking, and eventual penetration to the substrate. This can lead to high stresses and debonding.

Welding Flaws

It is essential that qualified personnel perform the welding and that only qualified and experienced contractors be used to install the linings. A welding flaw is a common cause of lining failure.

Debonding

Debonding can also occur as a result of the use of the wrong bonding agent. Care should be taken that the proper bonding agent is employed for the specific lining being used.

Operation

Lined vessels should be properly identified when installed, with the allowable operating characteristics of the liner posted to avoid damage to the liner during cleaning or repair operations. Most failures from this cause result while vessels are being cleaned or repaired. If live steam is used to clean the vessel, allowable operating temperatures may be exceeded. If the vessel is solvent cleaned, chemical attack may occur.

See Ref. 2.

SHELTERED CORROSION

Corrosion taking place in locations where moisture condenses or accumulates and does not dry out for long periods of time is known as sheltered corrosion. Typical locations are the inside surfaces of automobile doors, storage tanks, etc. Also see "Atmospheric Corrosion."

SHOT PEENING

Since cracks will not initiate or propagate in an area of compressive stress, stress corrosion cracking cannot occur. After all manufacturing operations on metals are completed, residual stresses remain in the finished part. These stresses can be either tensile or compressive. High residual tensile stresses will be present in the heat-affected zone adjacent to a welded joint, while compressive stresses may be present on the surface of induction-hardened components.

Shot peening is a cold-working process in which the surface of a part is bombarded with small spherical media called shot. Each piece of shot upon striking the metal part imparts a small indentation or dimple on the surface. For the dimple to form, the surface fibers of the material must be yielded in tension. The fibers below the surface try to restore the surface to its original shape, thereby producing, below the dimple, an area of cold worked material highly stressed in compression. By overlapping the dimples an even area of residual compressive stress is produced.

Materials typically used for shot peening are small spheres of cast steel, conditioned cut wire (both carbon and stainless steel), and ceramic and glass beads. Normally, cast steel is used, but in cases where iron contamination on the surface is a concern, stainless steel cut wire, glass, or ceramic beads are employed.

The effects of the compressive stress and the cold working induced by shot peening are responsible for the benefits derived. Compressive stresses are beneficial in increasing resistance to fatigue failure, corrosion fatigue, stress corrosion cracking, hydrogen-assisted cracking, fretting, galling, and erosion caused by cavitation. Benefits received due to cold working include work hardening, intergranular corrosion resistance, surface texturing, closing of porosity, and testing the bond of coatings.

Fretting can develop when the relative motion of microscopic amplitude occurs between two metal surfaces. Fine abrasive oxides form as a result of this rubbing. These oxides contribute to the scoring of the surfaces. Fretting gives rise to one or more forms of damage, such as fretting corrosion, fretting wear, or fretting fatigue. (See "Fretting Corrosion.") Shot peening has proven to be successful in retarding fretting by increasing the surface hardness and providing residual compressive stresses at the fretting surfaces.

Stress corrosion cracking is the failure of metal by cracking as a result of the combined action of corrosion and static tensile stress (either externally applied or internal, i.e., residual). Cracking may be either intergranular or transgranular depending on the metal and the corrodent. Refer to "Stress Corrosion Cracking." Most metals such as aluminum, copper, magnesium, nickel, steel, and stainless steel alloys are susceptible to stress corrosion cracking when a tensile stress at or above their threshold limits exists and they are exposed to specific corrosive environments.

The primary sources of stress contributing to SCC are applied as a result of pressure, poor fit-up, residual resulting from heat treatment, welding, machining, or forming. Shot peening produces compressive stresses that retard and in many cases prevent SCC.

Hydrogen-assisted cracking, or hydrogen embrittlement, is the result of atomic hydrogen penetrating and reacting with the metal, reducing the metal's ductility and ability to withstand cyclic loads. (See "Hydrogen Damage.") Shot peening retards the migration of hydrogen through the metal. It not only increases the time it takes hydrogen to migrate through the metal but also lowers the steady-state permeation rate of hydrogen by as much as 24%.

When austenitic stainless steels are subjected to heating in the range of 900 to 1500°F (482 to 815°C), such as in welding, there is a preferential precipitation of chromium carbides in the grain boundaries. This results in a depletion of chromium in the areas adjacent to these grain boundaries, reducing the corrosion resistance of such regions and making the alloy susceptible to intergranular corrosion. (See "Intergranular Corrosion.")

Shot peening prior to exposure to this sensitization temperature range breaks up grains and grain boundaries and provides many nucleation sites for chromium carbide precipitation. Since the chromium carbides precipitate randomly in the peened surface rather than preferentially along the grain boundaries, there is no continuous path for corrosion to follow, and intergranular corrosion does not occur.

See Refs. 3–10.

SILICON CARBIDE

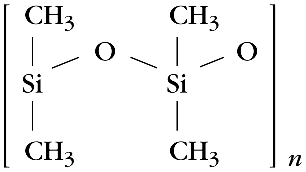
Silicon carbide fibers are used as a reinforcing material for thermosetting resins. See "Thermoset Reinforcing Materials."

SILICON CARBIDE FIBERS

Silicon carbide fibers are produced by a chemical vapor deposition process in which a heated carbon monofilament approximately 33 μm in diameter reacts with a mixture of hydrogen and chlorinated alkyl silicones. These fibers have been used on a development basis for reinforcing aluminum and titanium and to some extent for ceramic and organic matrices.

SILICONE

Silicon is in the same chemical group as carbon but is a more stable element. The silicones are a family of synthetic polymers that are partly organic and partly inorganic. They have a backbone of alternating silicon and oxygen atoms rather than a backbone of carbon-carbon atoms. The basic structure is



Typically the silicon atoms will have one or more organic side groups attached to them, generally phenol (C_6H_5–), methyl (CH_3–), or vinyl ($CH_2 = CH$–) units. These groups impart properties such as solvent resistance, lubricity, and reactivity with organic chemicals and polymers. Silicone polymers may be filled or unfilled depending upon the properties required and the application.

Silicone polymers possess several properties that distinguish them from their organic counterparts:

1. Chemical inertness
2. Weather resistance
3. Extreme water repellency
4. Uniform properties over a wide temperature range
5. Excellent electrical properties over a wide range of temperature and frequencies
6. Low surface tension
7. High degree of slip or lubricity
8. Excellent release properties
9. Inertness and compatibility, both physiologically and in electronic applications

Silicone resins and composites produced with silicone resins exhibit outstanding long-term thermal stability at temperatures approaching 572°F/300°C and excellent moisture resistance and electrical properties. These materials are also useful in the cryogenic temperature range. Table S.3 shows the effect of cryogenic temperatures on the physical properties of silicone glass fabric laminates. Refer to Table S.4 for the physical and mechanical properties of mineral- and/or glass-filled silicones.

Table S.3 Strength of Silicone Glass Fabric Laminate at Cryogenic Temperatures

Transformation (°F/°C)	Tensile strength (psi × 10^3)	Flexural strength (psi × 10^3)	Compressive strength (psi × 10^3)
72/22	30	38	21
–110/–79	47	46	39
–320/–201	70	67	43
–424/–253	76	65	46

Table S.4 Physical and Mechanical Properties of Silicone Laminates

Property	
Specific gravity	1.8–2.03
Water absorption (24 h at 73°F/23°C) (%)	0.15
Dielectric strength, short-term (V/mil)	200–550
Tensile strength at break (psi)	500–1500
Tensile modulus (psi × 10^3)	
Elongation at break (%)	80–800
Compressive strength (psi)	21,000
Flexural strength (psi)	38,000
Compressive modulus (psi × 10^3)	
Flexural modulus (psi × 10^3) at	
73°F/23°C	
200°F/93°C	
250°F/121°C	
Izod impact (ft-lb/in., of notch)	
Hardness, Shore	A10–80
Coefficient of thermal expansion (10^{-6} in./in./°F)	20–50
Thermal conductivity (10^{-4} cal-cm/s-cm^2 °C or Btu/h/ft^2/°F/in.)	7–18
Deflection temperature at	
264 psi (°F)	>500
66 psi (°F)	
Max. operating temperature (°F/°C)	>550/288
Limiting oxygen index (%)	
Flame spread	
Underwriters lab rating (Sub. 94)	

As discussed previously, the silicone atoms may have one or more organic side groups attached. The addition of these side groups has an effect on the corrosion resistance. Therefore, it is necessary to check with the supplier as to the properties of the silicone laminate being supplied. Table S.5 lists the compatibility of a silicone laminate (with methyl groups appended to the silicon atoms) with selected corrodents.

Table S.5 Compatibility of Methyl Appended Silicone Laminate with Selected Corrodents[a]

	Maximum temp.	
Chemical	°F	°C
Acetic acid 10%	90	32
Acetic acid 50%	90	32
Acetic acid 80%	90	32
Acetic acid, glacial	90	32
Acetone	100	43
Acrylic acid 75%	80	27
Acrylonitrile	x	x
Alum	220	104
Aluminum sulfate	410	210
Ammonium chloride 10%	x	x
Ammonium chloride 50%	80	27
Ammonium chloride, sat.	80	27
Ammonium fluoride 25%	80	27
Ammonium hydroxide 25%	x	x
Ammonium nitrate	210	99
Amyl acetate	80	27
Amyl alcohol	x	x
Amyl chloride	x	x
Aniline	x	x
Antimony trichloride	80	27
Aqua regia 3:1	x	x
Benzene	x	x
Benzyl chloride	x	x
Boric acid	390	189
Butyl alcohol	80	27
Calcium bisulfide	400	204
Calcium chloride	300	149
Calcium hydroxide 30%	200	93
Calcium hydroxide, sat.	400	204
Carbon bisulfide	x	x
Carbon disulfide	x	x
Carbon monoxide	400	204
Carbonic acid	400	204
Chlorobenzene	x	x
Chlorosulfonic acid	x	x
Ethylene glycol	400	204
Ferric chloride	400	204
Hydrobromic acid 50%	x	x
Hydrochloric acid 20%	90	32
Hydrochloric acid 38%	x	x
Hydrofluoric acid 30%	x	x
Lactic acid, all conc.	80	27
Lactic acid, concd.	80	27
Magnesium chloride	400	204
Methyl alcohol	410	210
Methyl ethyl ketone	x	x
Methyl isobutyl ketone	x	x
Nitric acid 5%	80	23
Nitric acid 20%	x	x
Nitric acid 70%	x	x
Nitric acid, anhydrous	x	x
Oleum	x	x
Phenol	x	x
Phosphoric acid 50–80%	x	x
Propyl alcohol	400	204
Sodium carbonate	300	149
Sodium chloride 10%	400	204
Sodium hydroxide 10%	90	27
Sodium hydroxide 50%	90	27
Sodium hydroxide, concd.	90	27
Sodium hypochlorite 20%	x	x
Sodium sulfate	400	204
Stannic chloride	80	27
Sulfuric acid 10%	x	x
Sulfuric acid 50%	x	x
Sulfuric acid 70%	x	x
Sulfuric acid 90%	x	x
Sulfuric acid 98%	x	x
Sulfuric acid 100%	x	x
Sulfuric acid, fuming	x	x
Sulfurous acid	x	x
Tartaric acid	400	204
Tetrahydrofuran	x	x
Toluene	x	x
Tributyl phosphate	x	x
Turpentine	x	x
Vinegar	400	204
Water, acid mine	210	99
Water, demineralized	210	99
Water, distilled	210	99
Water, salt	210	99
Water, sea	210	99
Xylene	x	x
Zinc chloride	400	204

[a] The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x.

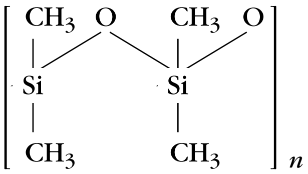
Source: PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

However, in general, silicone laminates can be used in contact with dilute acids and alkalies, alcohols, and animal and vegetable oils. They are also resistant to aliphatic hydrocarbons, but aromatic solvents such as benzene, toluene, gasoline, and chlorinated solvents will cause excessive swelling. Although they have excellent resistance to water and weathering, they are not resistant to high pressure, high-temperature steam.

Silicone laminates find application as radar domes, structures in electronics, heaters, rocket components, slot wedges, ablator shields, coil forms, and terminal boards.

SILICONE AND FLUOROSILICONE RUBBERS

The silicone rubbers (SI), also known as polysiloxanes, are a series of compounds whose polymer structure consists of silicone and oxygen atoms rather than the carbon structures of most other elastomers. The silicones are derivatives of silica, SiO_2 or $O = Si = O$. When the atoms are combined so that the double linkages are broken and methyl groups enter the linkages, silicone rubber is produced:



Silicone is in the same chemical group as carbon but is a more stable element, and therefore more stable compounds are produced from it. The basic structure can be modified with vinyl or fluoride groups, which improve such properties as tear resistance, oil resistance, and chemical resistance. This results in a family of silicones that covers a wide range of physical and environmental requirements.

Physical and Mechanical Properties

The silicones are some of the most heat-resistant elastomers available and the most flexible at low temperatures. Their effective operating temperature range is from –60 to 450°F (–51 to 232°C). They exhibit excellent properties even at the lowest temperature.

The fluorosilicones have an effective operating temperature range of –100 to 375°F (–73 to 190°C).

Silicone rubbers possess outstanding electrical properties, superior to those of most elastomers. The decomposition product of carbon-based elastomers is conductive carbon black, which can sublime and thus leave nothing for insulation, whereas the decomposition product of the silicone rubbers is an insulating silicone dioxide. This property is taken advantage of in the insulation of electric motors. The polysiloxanes have poor abrasion resistance, tensile strength, and tear resistance, but they exhibit good compression set resistance and rebound properties in both cold and hot environments. Their resistance to flame is good.

The physical and mechanical properties of silicone rubbers are given in Table S.6.

Table S.6 Physical and Mechanical Properties of Silicone (SI) Rubbers[a]

Specific gravity	1.05–1.94
Brittle point	–75°F (–6°C)
Water absorption, %/24 h	0.02–0.6
Dielectric strength, V/mil	350–590
Dissipation (power) factor	
at 60 Hz	0.0007
at 1 MHz	8.5×10^{-3}–2.6×10^{-3}
Dielectric constant	
at 60 Hz	2.91
at 1 MHz	2.8–3.94
Volume resistivity, ohm-cm	1×10^{14}–1×10^{16}
Water absorption, %/24 h	0.02–0.1
Tensile strength, psi	1200–6000
Elongation % at break	800
Hardness, Shore A	20–90
Abrasion resistance	Poor
Maximum temperature, continuous use	450°F (232°C)
Tear resistance	Fair to good
Compression set, %	10–15
Impact resistance, notch $\frac{1}{8}$ -in, specimen, ft-lb/in.	0.25–0.30
Resistance to sunlight	Excellent
Effect of aging	Nil
Resistance to heat	Excellent

[a]These are representative values since they may be altered by compounding.

The fluorosilicones (FSIs) have essentially the same physical and mechanical properties as the silicones but with some improvement in adhesion to metals and impermeability.

Table S.7 lists the physical and mechanical properties of the fluorosilicones.

Table S.7 Physical and Mechanical Properties of FluorosiIicones[a]

Specific gravity	1.4
Hardness, Shore A	40–75
Tensile strength, psi	1000–5400
Elongation, % at break	100–500
Compression set, %	15
Tear resistance	Poor to fair
Maximum temperature, continuous use	375°F (190°C)
Abrasion resistance	Poor
Resistance to sunlight	Excellent
Effect of aging	Nil
Resistance to heat	Excellent

[a]These are representative values since they may be altered by compounding.

Resistance to Sun, Weather, and Ozone

The silicone and fluorosilicone rubbers display excellent resistance to sun, weathering, and ozone. Their properties are virtually unaffected by long-term exposure.

Chemical Resistance

Silicone rubbers can be used in contact with dilute acids and alkalies, alcohols, animal and vegetable oils, and lubricating oils. They are also resistant to aliphatic hydrocarbons, but aromatic solvents such as benzene, toluene, gasoline, and chlorinated solvents will cause excessive swelling. Although they have excellent resistance to water and weathering, they are not resistant to high-pressure, high-temperature steam.

The fluorosilicone rubbers have better chemical resistance than the silicone rubbers. They have excellent resistance to aliphatic hydrocarbons and good resistance to aromatic hydrocarbons, oil and gasoline, animal and vegetable oils, dilute acids and alkalies, and alcohols; and fair resistance to concentrated alkalies. Table S.8 provides the compatibility of the silicone rubbers with selected corrodents.

Table S.8 Compatibility of Silicone Rubbers with Selected Corrodents[a]

Chemical	Maximum temp. °F	Maximum temp. °C
Acetamide	80	27
Acetic acid 10%	90	32
Acetic acid 20%	90	32
Acetic acid 50%	90	32
Acetic acid 80%	90	32
Acetic acid vapors	90	32
Acetic acid, glacial	90	32
Acetone	110	43
Acetone, 50% water	110	43
Acetophenone	x	x
Acrylic acid 75%	80	27
Acrylonitrile	x	x
Aluminum acetate	x	x
Aluminum phosphate	400	204
Aluminum sulfate	410	210
Ammonia gas	x	x
Ammonium chloride 10%	80	27
Ammonium chloride 28%	80	27
Ammonium chloride, sat.	80	27
Ammonium hydroxide 10%	210	99
Ammonium hydroxide, sat.	400	204
Ammonium nitrate	80	27
Amyl acetate	x	x
Amyl alcohol	x	x
Aniline	80	27
Aqua regia 3:1	x	x
Barium sulfide	400	204
Benzene	x	x
Benzyl chloride	x	x
Boric acid	390	189
Butyl alcohol	80	27
Calcium acetate	x	x
Calcium bisulfite	400	204
Calcium chloride, all concentrations	300	149
Calcium hydroxide to 30%	210	99
Calcium hydroxide, sat.	400	204
Carbon bisulfide	x	x
Carbon monoxide	400	204
Carbonic acid	400	204
Chlorobenzene	x	x
Chlorosulfonic acid	x	x
Dioxane	x	x
Ethane	x	x
Ethers, general	x	x
Ethyl acetate	170	77
Ethyl alcohol	400	204
Ethyl chloride	x	x
Ethylene chloride	x	x
Ethylene diamine	400	204
Ethylene glycol	400	204
Ferric chloride	400	204
Fluosilicic acid	x	x
Formaldehyde, all concentrations	200	93
Fuel oil	x	x

Table S.8 Compatibility of Silicone Rubbers with Selected Corrodents[a] (Continued)

	Maximum temp.			Maximum temp.	
Chemical	°F	°C	Chemical	°F	°C
Gasoline	x	x	Phenol	x	x
Glucose (corn syrup)	400	204	Phosphoric acid	x	x
Glycerine	410	210	Picric acid	x	x
Green liquor	400	204	Potassium chloride 30%	400	204
Hexane	x	x	Potassium cyanide 30%	410	210
Hydrobromic acid	x	x	Potassium dichromate	410	210
Hydrochloric acid dilute	90	32	Potassium hydroxide to 50%	210	99
Hydrochloric acid 20%	90	32	Potassium hydroxide 90%	80	27
Hydrochloric acid 35%	x	x	Potassium nitrate to 80%	400	204
Hydrofluoric acid	x	x	Potassium sulfate 10%	400	204
Hydrogen peroxide, all concentrations	200	93	Potassium sulfate, pure	400	204
Lactic acid, all concentrations	80	27	Propane	x	x
Lead acetate	x	x	Propyl acetate	x	x
Lime sulfur	400	204	Propyl alcohol	400	204
Linseed oil	x	x	Propyl nitrate	x	x
Magnesium chloride	400	204	Pyridine	x	x
Magnesium sulfate	400	204	Silver nitrate	410	210
Mercury	80	27	Sodium acetate	x	x
Methyl alcohol	410	210	Sodium bisulfite	410	210
Methyl cellosolve	x	x	Sodium borate	400	204
Methyl chloride	x	x	Sodium carbonate	300	149
Methyl ethyl ketone	x	x	Sodium chloride 10%	400	204
Methylene chloride	x	x	Sodium hydroxide, all concentrations	90	32
Mineral oil	300	149	Sodium peroxide	x	x
Naphtha	x	x	Sodium sulfate	400	204
Nickel acetate	x	x	Sodium thiosulfate	400	204
Nickel chloride	400	204	Stannic chloride	80	27
Nickel sulfate	400	204	Styrene	x	x
Nitric acid 5%	80	27	Sulfite liquors	x	x
Nitric acid 10%	80	27	Sulfuric acid	x	x
Nitric acid 20%	x	x	Sulfurous acid	x	x
Nitric acid, anhydrous	x	x	Tartaric acid	400	204
Nitrobenzene	x	x	Tetrahydrofuran	x	x
Nitrogen	400	204	Toluene	x	x
Nitromethane	x	x	Tributyl phosphate	x	x
Nitrous acid–sulfuric acid 50:50	x	x	Turpentine	x	x
Oils, vegetable	400	204	Vinegar	400	204
Oleic acid	x	x	Water, acid mine	210	99
Oleum	x	x	Water, demineralized	210	99
Oxalic acid to 50%	80	27	Water, distilled	210	99
Ozone	400	204	Water, salt	210	99
Palmitic acid	x	x	Water, sea	210	99
Parrafin	x	x	Xylene	x	x
Peanut oil	400	204	Zinc chloride	400	204
Perchloric acid	x	x			

[a] The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x.

Source: Extracted from PA Schweitzer. *Corrosion Resistance Tables,* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

Applications

Because of their unique thermal stability and their insulating values, the silicone rubbers find many uses in the electrical industries, primarily in appliances, heaters, furnaces, aerospace devices, and automotive parts.

Their excellent weathering qualities and wide temperature range have also resulted in their employment as caulking compounds.

When silicone or fluorosilicone rubbers are infused with a high-density conductive filler, an electric path is created. These conductive elastomers are used as part of an EMI/RFI/EMP shielding process in forms such as O-rings and gaskets to provide

1. Shielding for containment to prevent the escape of EMI internally generated by the device
2. Shielding for exclusion to prevent the intrusion of EMI/RFI/EMP created by outside sources into the protected device
3. Exclusion or containment plus pressure or vacuum sealing to provide EMI/EMP attenuation and pressure containment and/or weatherproofing
4. Grounding and contacting to provide a dependable low-impedance connection to conduct electric energy to ground, often used where mechanical mating is imperfect or impractical

The following equipment is either capable of generating EMI or susceptible to EMI:

Aircraft and aerospace electronics
Digital instrumentation and process control systems
Analog instrumentation
Automotive electronics
Communication systems
Radio-frequency instrumentation and radar
Medical electronics
Security systems (military and commercial)
Home appliances
Business machines
Military and marine electronics

Table S.9 lists some typical properties of these infused elastomers.

Table S.9 Typical Properties of Conductive Elastomers[a]

Property	SI	FSI
Volume resistivity, ohm-cm	0.002–0.01	0.002–0.01
Shielding effectiveness, dB		
at 200 kHz (H field)	30–75	60–75
at 100 kHz (E field)	70–120	95–1 20
at 500 kHz (E field)	60–120	90–120
at 2 GHz (plane wave)	40–120	80–115
at 10 GHz (plane wave)	30–120	75–120
Heat aging, ohm-cm	0.006–0.012	0.006–0.015
Electrical stability after break, ohm-cm	0.003–0.015	0.003–0.015
Vibration resistance, ohm-cm		
during	0.004–0.008	0.004–0.008
after	0.002–0.010	0.002–0.005

Table S.9 Typical Properties of Conductive Elastomers[a] (Continued)

Property	SI	FSI
EMP survivability, kA/in. perimeter	0.9	0.9
Specific gravity	1.9–4.5	2.1–4.1
Hardness, Shore A	50–85	70–85
Tensile strength, psi	175–600	200–500
Elongation, % at break	20–300	70–300
Tear strength, psi	20–75	40–50
Compression set, %	22–40	24–29
Operating temperature		
min, °F/°C	–85/–65	–85/–65
max, °F/°C	392/200	392/200

[a] These are typical values since they may be altered by compounding. SI = silicone; FSI = fluorosilicone.

See Refs. 2 and 11.

SILOXIRANE

Siloxirane is the registered trademark for Tankinetics homopolymerized polymer with an ether cross-linking (carbon–oxygen–carbon) having a very dense, highly cross-linked molecular structure. The end products are extremely resistant to material abrasion, have a wide range of chemical resistance, and have an operating temperature range of –80 to 500°F (–62 to 260°C). The specific maximum operating temperature will be dependent upon the material being handled.

Following is a list of some of the chemicals with which Siloxirane is compatible.

Acetamide
Acetic acid, glacial
Acetic anhydride
Acetone
Aluminum chloride
Ammonium chloride
Ammonium hydroxide
Aqua regia
Benzene
Benzene sulfonic acid
Black liquor (paper)
Bromine water
Calcium hypochlorite
Carbon tetrachloride
Chloric acid
Chlorine water
Chloroacetic acid
Chlorobenzene
Chromic acid 10%
Chromic acid 50%
Dibutylphthalate
Dichlorobenzene
Dimethyl formamide
Ethanol
Ethyl acetate
Ferric chloride
Formaldehyde
Furan
Furfural alcohol
Gasohol
Gasoline
Green liquor
Hydraulic oil
Hydrazine
Hydrochloric acid 0–37%
Hydrochloric acid 1%
Hydrofluoric acid 40%
Hydrofluoric acid 52%
Iodine
Jet fuel
Kerosene
Ketones
Latex
Methanol

Methyl ethyl ketone
Methyl isobutyl ketone
Methylene chloride
Molten sulfur
Monochloroacetic acid
Nickel plating
Nitrous oxide
Phosphoric acid
Phosphoric acid 85%
Sodium chloride
Sodium dichromate
Sodium hydroxide
Sodium hypochlorite 17%
Sodium hypochlorite, aged
Sulfite liquor (paper)
Sulfur trioxide
Sulfuric acid 1–70%
Sulfuric acid 70–90%
Sulfuric acid 90–98%
Sulfuric acid, fuming oleum
Tallow
Thionyl chloride
Toluene
Trichloroethylene
Tricresylphosphate
Water, deionized
Water, salt
White liquor (paper)

SOIL CORROSION

When soil is dry it is not corrosive. It becomes corrosive as a result of its water content and related water-soluble salts that permit it to act as an electrolyte. Moisture received by the soil from the atmosphere contains specific contaminants and picks up specific water-soluble materials from the soil. Such materials include salts of aluminum, calcium, magnesium, and sodium, sulfates, chlorides, carbonates, phosphates, and silicates. This subjects construction materials to a wide variety of corrosive conditions.

In addition to the problem of localized cells, buried pipelines are also subject to macrocell action. Because of the differences in soil chemistry, soil compaction, thermal effects, and bacterial action, long sections of pipeline may become anodic to other long sections. Stray DC currents will cause electrolysis. Corrosion of buried structures can also be caused by telluric currents, which are a result of fluctuations in the earth's magnetic field as well as stray currents from AC power lines.

The corrosivity of soil is influenced by three factors: resistivity, chemistry, and physical characteristics.

Resistivity

Resistivity is the property of a material, as opposed to resistance, which is the resultant property of a physical entity. For example, copper has a certain resistivity, but a piece of copper wire has resistance.

Many physical and chemical aspects of the soil give it its resistivity. It is determined by passing a known current I through a known volume of soil (volume = depth × width × length) and measuring the difference in voltage E due to current flow. From Ohm's Law we have

$$R = \frac{E}{I}$$

and resistivity is

$$P = R \times \frac{W \times d}{L}$$

where W is width, d is depth, and L is length.

Resistivity is expressed in ohm-centimeters (Ω cm) when R is expressed in ohms (Ω), area ($W \times d$) in square centimeters, and length (L) in centimeters. For example, sea water has a resistivity of 25 to 75 Ω cm, while a specific volume of seawater has so many ohms resistance. The lower the value of the resistivity, the more highly corrosive a material is.

Soil is considered highly corrosive if its resistivity is 2000 Ω cm or less. It is considered mildly corrosive when its resistivity is between 2000 and 10,000 Ω cm, while at 10,000 to 20,000 Ω cm it is considered only slightly corrosive. If the resistivity of the soil is below 25,000 Ω cm, cathodic protection is recommended.

Soil Chemistry

Different types of soils can contain a wide variety of chemical species. These not only influence the electrolytic nature of the soil but will also have specific ion effects (for example, chlorides for pitting or stress corrosion cracking or sulfides for stress corrosion cracking). Varying amounts of water may be available from the water table or atmospheric ingress.

Composition and Condition

Sand, clay, loam, and rock are four major categories of soil. With the exception of nonporous rock, any of these categories can have varying degrees of moisture and varying chemical contaminants. Dry desert sand is totally different from wet salty sand.

Ordinary earth will have different degrees of compaction. Freshly excavated and filled trenches will be more apt to absorb moisture and oxygen than undisturbed soil.

Overall Corrosivity

Resistivity alone is not the only criterion for judging a soil's corrosivity. Besides resistivity, the other factors that must be taken into account are pH, chloride content, redox potential, and type of soil. Overall rating of soil as to its corrosivity can be made by use of the different arithmetical point values from the following table.

Factor	Points	Factor	Points
1. pH		4. Soil type	
0–2	5	clay (blue gray)	10
2–4	3	clay/stone	5
4–8.5	0	clay	3
8.5+	3	silt	2
		clean sand	0
2. Chlorides, ppm		5. Soil resistivity	
1000+	10	<1000	10
500–1000	6	1000–1500	8
200–500	4	1500–2500	6
50–200	2	2500–5000	4
0–50	0	5000–10,000	2
		10,000+	0
3. Redox, mV (vs. copper; copper sulfate)			
negative	5		
0–50	4		
50–100	3.5		
100+	0		

Based on the above factors, the overall rating of the corrosivity of the soil is as follows:

Point total	Rating
15+	Severe
10–15	Appreciable
5–10	Moderate
0–5	Mild

Reaction of Specific Materials

Depending upon the specific chemistry of the soil, different materials will react in different ways. However, some generalizations can be made and specific problems highlighted.

Concrete

Portland cement–type concrete is suitable for soil contact if a type appropriate to the sulfate concentration and chlorides and other chemical variants is used. Most important are the pH and sulfate effects.

Steels

Steel should not be exposed to soil unless some type of corrosion control is employed, such as a barrier coating, cathodic protection, or environmental control (mixing of extraneous materials in the soil such as lime, sand, or water repellents to reduce the corrosivity). The most effective approach is to use a combination of a coating and cathodic protection.

Cast Iron

Cast iron is more resistant than steel because of the adherent nature of the rust formed under normal conditions. In soils of low pH or those saturated with soft aggressive waters it can be subject to graphitic corrosion. Corrosion can also be aggravated by bacterial action. Underground cast iron pipe is usually protected by a barrier coating. Because of the difficulty of establishing continuity across the mechanical joints of cast iron pipe, cathodic protection is not often used.

Zinc

Specific soil chemistry will determine the suitability of zinc. In general, galvanized steel is not recommended for underground service since the zinc coating is very thin and anodically active to every metallic structure in the area. However, galvanized steel structured legs for power lines and such can be used provided they are protected by a coating.

Aluminum

If protected from galvanic demands and specific ion effects (chlorides), aluminum can provide satisfactory underground service. Because of the possibility of generating high alkali concentrations when using cathodic protection, care must be taken, since such alkali concentrations can corrode aluminum.

Stainless Steels

High chloride concentrations and/or oxygen concentration cells will pit all stainless steels. Austenitic stainless steel underground piping should be coated and cathodically protected, since corrosive conditions can arise, and localized attack can lead to rapid penetration.

Lead

Lead is generally resistant but can be corroded by stray electrical currents and specific chemical contaminants.

Copper Alloys

Sulfate-bearing bacteria in soils can cause corrosion by sulfides. If ammonia is present from the rotting of nitrogenous compounds, corrosion or stress corrosion cracking can take place. However, copper is usually satisfactory. Copper pipe was used by the Egyptian pharaoh Cheops to transport water to the royal bath. Several years ago a remnant of this pipe was unearthed still in usable condition, a testimony to copper's durability and resistance to corrosion.

Plastics

Plastic is an ideal material for underground service, provided temperature and pressure otherwise permit. Major concerns are mechanical damage from rock fill and other foreign objects, due to ground subsidence or surface traffic imposing a loading force against the pipe or vessel wall.

SOLEF

See "Polyvinylidene Fluoride."

SOLUTION QUENCHING

See "Quench Annealing."

SPHERADIZING

See "Annealing."

STAINLESS STEELS

Probably the most widely known and most widely used metallic material for corrosion resistance is stainless steel. For many years this was the only material available.

Stainless steel is not a single material, as its name might imply, but rather a broad group of alloys, each of which exhibits its own physical and corrosion-resistant properties. Stainless steels are alloys of iron to which a minimum of 11% chromium has been added to provide a passive film to resist "rusting" when the material is exposed to weather. This film is self-forming and self-healing in environments where the stainless steel is resistant. As more chromium is added to the alloy, improved corrosion resistance results. Consequently, there are stainless steels with chromium contents of 15%, 17%, 20%, and even higher. Chromium provides resistance to oxidizing environments such as nitric acid and also provides resistance to pitting and crevice attack.

Other alloying ingredients are added to further improve the corrosion resistance and mechanical strength. Molybdenum is extremely effective in improving pitting and crevice corrosion resistance.

By the addition of copper, improved resistance to general corrosion in sulfuric acid is obtained. This will also strengthen some precipitation-hardenable grades. In sufficient amounts, though, copper will reduce the pitting resistance of some alloys.

The addition of nickel will provide improved resistance to reducing environments and stress corrosion cracking. Nitrogen can also be added to improve corrosion resistance to pitting and crevice attack, and to improve strength.

Columbium and titanium are added to stabilize carbon. They form carbides and reduce the amount of carbon available to form chromium carbides, which can be deleterious to corrosion resistance.

As a result of these alloying possibilities, more than 70 stainless steels are available. These can be divided into four major categories depending upon their microstructure. The classifications are

Austenitic
Ferritic
Martensitic
Duplex

Refer to these headings for specific information about each type.

See Refs. 12–14.

STRESS CORROSION CRACKING (SCC)

Certain alloys (or alloy systems) in specific environments may be subject to stress corrosion cracking (SCC). Stress corrosion cracking occurs at points of stress. Usually the metal or alloy is visually free of corrosion over most of its surface, yet fine cracks penentrate through the surface at the points of stress. Depending upon the alloy system and corrodent combination, the cracking can be intergranular or transgranular. The rate of propagation can vary greatly and is affected by stress levels, temperature, and concentration of the corrodent. This type of attack takes place in certain media. All metals are potentially subject to SCC. The conditions necessary for stress corrosion cracking are

1. Suitable environment
2. Tensile stress
3. Sensitive metal
4. Appropriate temperature and pH values

An ammonia-containing environment can induce SCC in copper-containing alloys, while with low-alloy austenitic stainless steels a chloride-containing environment is necessary. It is not necessary to have a high concentration of corrodent to cause SCC. A solution containing only a few parts per million of the critical ion is all that is necessary. Temperature and pH are also factors. There is usually a threshold temperature below which SCC will not take place and a maximum or minimum pH value before cracking will start.

Normally, SCC will not occur if the part is in compression. Failure is triggered by a tensile stress that must approach the yield stress of the metal. The stresses may be induced by faulty installation or they may be residual stresses from welding, straightening, bending, or accidental denting of the component. Pits, which act as stress concentration sites, will often initiate SCC.

The alloy content of stainless steels, particularly nickel, determines the sensitivity of the metal to SCC. Ferritic stainless steels that are nickel free, and the high nickel alloys are not subject to stress corrosion cracking. An alloy with a nickel content greater than 30% is immune to SCC. The most common grades of stainless steel (304, 304L, 316, 316L, 321, 347, 303, and 301) have nickel contents in the range of 7–10% and are the most susceptible to stress corrosion cracking.

Examples of stress corrosion cracking include the cracking of austenitic stainless steels in the presence of chlorides, caustic embrittlement cracking of steel in caustic solutions, cracking of cold-formed brass in ammonia environments, and cracking of Monel in hydrofluorosilicic acid. Table S.10 is a partial listing of alloy systems subject to SCC.

Table S.10 Alloy-Environment Combinations Causing Stress Corrosion Cracking

Alloy	Environment
Aluminum alloys	Air with water vapor
	Potable waters
	Seawater
	NaCl solutions
	NaCl–H_2O_2 solutions
Carbon steels	Caustic NaOH solutions
	Calcium, ammonium, and sodium nitrate solutions
	HCN solutions
	Acidified H_2S solutions
	Anhydrous liquid ammonia
	Carbonate/bicarbonate
	CO/CO_2 solutions
	Seawater
Copper alloys	Ammoniacal solutions
	Amines
	Nitrites
Nickel alloys	Caustic alkaline solutions
	High-temperature chloride solutions
	High-purity steam
	Hydrofluoric acid
	Acidic fluoride solutions
Stainless steels	
Austenitic	Hot acid chloride solutions
	NaCl–H_2O_2 solutions
	NaOH–H_2S solutions
	Seawater
	Concentrated caustic solutions
	Neutral halides, Br^-, I^-, F^-

Table S.10 Alloy-Environment Combinations Causing Stress Corrosion Cracking (Continued)

Alloy	Environment
Austenitic (sensitized)	Polythionic acids Sulfurous acid Pressurized hot water containing 2 ppm dissolved oxygen
Ferritic	H_2S, NH_4Cl, NH_4NO_3 Hypochlorite solutions
Martensitic	Caustic NaOH solutions
Titanium alloys	Red fuming nitric acid Hot salts, molten salts N_2O_4 Methanol/halide

In severe combinations, such as type 304 stainless steel in a boiling magnesium chloride solution, extensive cracking can be generated in a matter of hours.

Fortunately, in most industrial applications the progress of SCC is much slower. However, because of the nature of the cracking, it is difficult to detect until extensive corrosion has developed, which can lead to unexpected failure.

Tensile stresses can assist in other corrosion processes, such as the simple mechanical fatigue process. Corrosion fatigue is difficult to differentiate from simple mechanical fatigue, but is recognized as a factor when the environment is believed to have accelerated the normal fatigue process. Such systems can also have the effect of lowering the endurance limit such that fatigue will occur at a stress level below which it would normally be expected.

It is important that any stresses that may have been induced during the fabrication be removed by an appropriate stress relief operation. The design should also avoid stagnant areas that could lead to pitting and the initiation of stress concentration sites.

See Ref. 15.

STRESS RELIEF

Fabrication processes, such as rolling or forging, uneven heating or cooling, or welding are all capable of inducing residual stresses in a metal. The magnitude of these stresses is usually on the order of the yield strength of the metal, but in some cases it approaches the tensile strength of the metal.

Carbon and low-alloy steels are heated to a temperature in the range of 1000 to 1350°F (595 to 730°C) to be stress relieved. They are held at this temperature for a period of time, then air cooled. The minimum holding time is specified by the appropriate engineering code. The holding temperature must be less than the lower transformation temperature of the steel, which is the lowest temperature at which austenite forms. For plain carbon steels this temperature is 1333°F (720°C).

As metals and alloys are heated, their yield strengths decrease. Residual stresses in excess of the reduced yield strength are eliminated. Upon cooling, the maximum residual stress possible is the yield strength at the holding temperature. For carbon steels, this heat treatment process reduces residual stresses by approximately two-thirds.

Austenitic stainless steels are not usually stress relieved or postweld heat treated. When such treatments are given to austenitic stainless steels, they are held at a temperature of 1600 to 1650°F (870 to 900°C) followed by rapid cooling. The rapid cooling is necessary to prevent sensitization. If austenitic stainless steels are exposed to heat treating operation at less than 1600°F (870°C), they can be sensitized. For this reason, local stress relief of unstabilized austenitic stainless steel is usually impractical, since the runout areas immediately adjacent to the region being heat treated will be sensitized.

SUPERAUSTENITIC STAINLESS STEELS

The classification of superaustenitic stainless steels came about during the 1970s and 1980s. Carpenter Steel's introduction of alloy 20 in 1951 as a cast material was the foundation for this class of materials. In 1965 Carpenter introduced the wrought product 20Cb3. This alloy became popular as an intermediate step between 316 stainless steel and the more highly alloyed nickel-base materials. It was a cost-effective way to combat chloride stress cracking.

Because of the high nickel content of 20Cb3, it received a nickel-base alloy UNS designation as UNS N08020. However, since the main constituent is iron, it is truly a stainless steel.

The term superaustenitic is derived from the fact that the composition plots high above the austenite–ferrite boundary on the Schaeffler diagram. Unlike the 300 series stainless alloys, there is no chance of developing ferrite in this material. Many of the superaustenitic alloys have been assigned nickel-base identification numbers, but they are truly stainless steels.

The initial alloys that were developed exhibited good general corrosion resistance to strong acids, but their pitting resistance was only slightly better than that of type 316L. In order to improve the pitting resistance and crevice corrosion resistance, the molybdenum content was increased. One of the first to be introduced was 904L (UNS N08904), which increased the molybdenum content to 4% and reduced the nickel content to 25%. The reduction in nickel content was a cost-saving factor, with a minimal loss in general corrosion resistance and maintenance of sufficient resistance to chloride stress corrosion cracking.

Improvements continued with the alloying addition of nitrogen to offset the tendency for the formation of the sigma phase and an increase of the molybdenum content to 6%. This concept was introduced with two alloys, 254SMO (S31254) and Al-6XN (N08367).

Alloy 20Cb3

This alloy has the following composition:

Chemical	Weight percent
Chromium	20.0
Nickel	33.5
Silicon	1.00 max.
Manganese	0.75 max.
Carbon	0.07 max.
Niobium/tantalum	8 × % carbon min.
Iron	Balance

The alloy is stabilized with niobium and tantalum.

Alloy 20Cb3 was originally developed to provide improved corrosion resistance to sulfuric acid. However, it has found wide application throughout the chemical process industry.

This alloy is weldable, machinable, and cold formable and has minimal carbide precipitation due to welding. It is particularly useful in the handling of sulfuric acid. It is resistant to stress corrosion cracking in sulfuric acid at a variety of temperatures and concentrations. The resistance of 20Cb3 to chloride stress corrosion cracking is also increased over type 304 and type 316 stainless steels. The alloy also exhibits excellent resistance to sulfide stress cracking and consequently finds many applications in the oil industry.

In high concentrations of chlorides, alloy 20Cb3 is vulnerable to pitting and crevice attack. For improved resistance to these types of corrosion the 2% molybdenum must be increased to 4% or 6% as has been done in alloy 20Mo4 and 20Mo6. Table S.11 lists the compatibility of alloy 20Cb3 with selected corrodents.

Table S.11 Compatibility of Type 20Cb3 Stainless Steel with Selected Corrodents[a]

	Maximum temp.			Maximum temp.	
Chemical	°F	°C	Chemical	°F	°C
Acetaldehyde	200	93	Ammonium fluoride, 25%	90	32
Acetamide	60	16	Ammonium hydroxide, 25%	90	32
Acetic acid, 10%	220	104	Ammonium hydroxide, sat.	210	99
Acetic acid, 50%	300	149	Ammonium nitrate[b]	210	99
Acetic acid, 80%	300	149	Ammonium persulfate	210	99
Acetic acid, glacial	300	149	Ammonium phosphate	210	99
Acetic anhydride	180	82	Ammonium sulfate, 10–40%	210	99
Acetone	220	104	Ammonium sulfide	210	99
Acetyl chloride	210	99	Ammonium sulfite	210	99
Acrylonitrile	210	99	Amyl acetate	310	154
Adipic acid	210	99	Amyl alcohol	160	71
Allyl alcohol	300	149	Amyl chloride	130	54
Allyl chloride	200	93	Aniline	500	260
Alum	200	93	Antimony trichloride	200	93
Aluminum acetate	60	16	Aqua regia, 3:1	x	x
Aluminum chloride, aqueous	120	43	Barium carbonate	90	32
Aluminum chloride, dry	120	43	Barium chloride, 40%	210	99
Aluminum fluoride	x	x	Barium hydroxide, 50%	230	110
Aluminum hydroxide	80	27	Barium sulfate	210	99
Aluminum nitrate	80	27	Barium sulfide	210	99
Aluminum sulfate	210	99	Benzaldehyde	210	99
Ammonia gas	90	32	Benzene	230	110
Ammonium bifluoride	90	32	Benzene sulfonic acid, 10%	210	99
Ammonium carbonate	310	154	Benzoic acid	400	204
Ammonium chloride, 10%	230	110	Benzyl alcohol	210	99
Ammonium chloride, 50%	170	77	Benzyl chloride	230	110
Ammonium chloride, sat.[b]	210	99	Borax	100	38
Ammonium fluoride, 10%	90	32	Boric acid	130	54

Table S.11 Compatibility of Type 20Cb3 Stainless Steel with Selected Corrodents^a (Continued)

	Maximum temp.			Maximum temp.	
Chemical	°F	°C	Chemical	°F	°C
Bromine gas, dry	80	27	Ferric chloride	x	x
Bromine gas, moist	x	x	Ferric chloride, 50% in water	x	x
Butadiene	180	82	Ferric nitrate, 10–50%	210	99
Butyl acetate	300	149	Ferrous chloride	x	x
Butyl alcohol	90	32	Fluorine gas, dry	570	299
Butyl phthalate	210	99	Fluorine gas, moist	x	x
Butyric acid	300	149	Hydrobromic acid, dilute	x	x
Calcium bisulfide	300	149	Hydrobromic acid, 20%	x	x
Calcium carbonate	210	99	Hydrobromic acid, 50%	x	x
Calcium chlorate	90	32	Hydrochloric acid, 20%	x	x
Calcium chloride	210	99	Hydrochloric acid, 38%	x	x
Calcium hydroxide, 10%	210	99	Hydrocyanic acid, 10%	210	99
Calcium hydroxide, sat.	210	99	Hydrofluoric acid, 30%	190	88
Calcium hypochlorite	90	32	Hydrofluoric acid, 70%	x	x
Calcium oxide	80	27	Hydrofluoric acid, 100%	80	27
Calcium sulfate	210	99	Iodine solution, 10%	x	x
Caprylic acid	400	204	Ketones, general	100	38
Carbon bisulfide	210	99	Lactic acid, 25%^{b}	210	49
Carbon dioxide, dry	570	299	Lactic acid, conc., air free	300	149
Carbon dioxide, wet	400	204	Magnesium chloride	200	93
Carbon disulfide	210	99	Malic acid, 50%	160	71
Carbon monoxide	570	299	Manganese chloride, 40%	210	99
Carbon tetrachloride	210	99	Methyl chloride	210	99
Carbonic acid	570	299	Methyl ethyl ketone	200	93
Cellosolve	210	99	Methyl isobutyl ketone	210	99
Chloracetic acid	80	27	Muriatic acid	x	x
Chlorine gas, dry	400	204	Nitric acid, 5%	200	93
Chlorine gas, wet	x	x	Nitric acid, 20%	210	99
Chlorobenzene, dry	100	38	Nitric acid, 70%	210	99
Chloroform	210	99	Nitric acid, anhydrous	80	27
Chlorosulfonic acid	130	54	Nitrous acid, conc.	90	32
Chromic acid, 10%	130	54	Oleum	110	43
Chromic acid, 50%	140	60	Perchloric acid, 10%	100	38
Chromyl chloride	210	99	Perchloric acid, 70%	110	43
Citric acid, 15%	210	99	Phenol	570	299
Citric acid, conc.	210	99	Phosphoric acid, 50–80%	210	99
Copper acetate	100	38	Picric acid	300	149
Copper carbonate	90	32	Potassium bromide, 30%	210	99
Copper chloride	x	x	Salicylic acid	210	99
Copper cyanide	210	99	Silver bromide, 10%	90	32
Copper sulfate	210	99	Sodium carbonate	570	299
Cupric chloride, 5%	60	16	Sodium chloride, to 30%^{b}	210	99
Cupric chloride, 50%	x	x	Sodium hydroxide, 10%	300	149
Cyclohexane	200	93	Sodium hydroxide, 50%^{c}	300	149
Cyclohexanol	80	27	Sodium hydroxide, conc.	200	93
Dichloroethane (ethylene dichloride)	210	99	Sodium hypochlorite, 30%	90	32
Ethylene glycol	210	99	Sodium sulfide, to 50%	200	93

Table S.11 Compatibility of Type 20Cb3 Stainless Steel with Selected Corrodents[a] (Continued)

Chemical	Maximum temp. °F	Maximum temp. °C	Chemical	Maximum temp. °F	Maximum temp. °C
Stannic chloride	x	x	Sulfuric acid, 100%	300	149
Stannous chloride, 10%	90	32	Sulfuric acid, fuming	210	99
Sulfuric acid, 10%	200	93	Sulfurous acid	360	182
Sulfuric acid, 50%	110	43	Toluene	210	99
Sulfuric acid, 70%	120	49	White liquor	100	38
Sulfuric acid, 90%	100	38	Zinc chloride	210	99
Sulfuric acid, 98%	300	149			

[a] The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. When compatible the corrosion rate is <20 mpy.

[b] Material subject to intergranular corrosion.

[c] Material subject to stress cracking.

Source: Ref. 2.

Alloy 20Mo-4 (N08024)

This alloy is similar to alloy 20Cb3 but with 4% molybdenum content instead of the 2% providing improved pitting and crevice corrosion resistance over alloy 20Cb3. The chemical composition is as follows:

Chemical	Weight percent
Nickel	35–40
Chromium	22.5–25.0
Molybdenum	3.5–5.0
Copper	0.5–1.5
Niobium	0.15–0.35
Carbon	0.03 max.
Iron	Balance

Alloy 20Mo-4 has outstanding corrosion resistance to chloride pitting and crevice corrosion with good resistance to sulfuric acid and various other acid environments. Applications include heat exchangers, chemical process equipment, and wet-process phosphoric acid environments.

Alloy 20Mo-6 (N08026)

Of the three grades of alloy 20 this offers the highest level of pitting and crevice corrosion resistance. Alloy 20Mo-6 is resistant to corrosion in hot chloride environments and is also resistant to oxidizing media. This alloy is designed for applications where better pitting and crevice corrosion resistance is required than 20Cb3 offers.

Alloy 20Mo-6 is melted with low carbon to provide a high level of resistance to intergranular corrosion. It also possesses excellent resistance to chloride stress corrosion cracking. When in contact with sulfuric acid, excellent resistance is shown at 176°F

(80°C) with the exception of concentrations in the range of 75–97 wt%. In boiling sulfuric acid 20Mo-6 stainless has good resistance to general corrosion only in relatively dilute solutions. At approximately 10% concentration of boiling sulfuric acid, the corrosion rate becomes excessive.

The alloy is highly resistant to phosphoric acid, both wet-process plant acid and reagent-grade concentrated phosphoric acid.

Alloy 20Mo-6 has the following composition:

Chemical	Weight percent
Chromium	22.00–26.00
Nickel	33.00–37.20
Molybdenum	5.00–6.70
Silicon	0.03–0.50
Manganese	1.00
Phosphorus	0.03
Carbon	0.03
Iron	Balance

25-6Mo (N08925)

Alloy 25-6Mo is produced by Inco International. It is also known as 1925 hMo. Typical and specified compositions of this alloy are as follows:

	Weight percent	
Chemical	Alloy 25-6Mo	UNS N08926
Carbon	0.02 max.	0.02 max.
Chromium	19.0–21.0	20.0–21.0
Nickel	24.0–26.0	24.5–25.5
Molybdenum	6.0–7.0	6.0–6.8
Nitrogen	0.15–0.25	0.18–0.20
Copper	0.5–1.5	0.8–1.0
Manganese	2.0 max.	2.0 max.
Phosphorus	0.03 max.	0.03 max.
Sulfur	0.010 max.	0.010 max.
Silicon	0.050 max.	0.050 max.
Iron	Balance	Balance

This alloy is especially suited for applications in high-chloride environments such as brackish water, seawater, caustic chlorides, and pulp mill bleach systems.

In brackish and wastewater systems, microbially influenced corrosion can occur, especially in systems where equipment has been idle for extended periods. A 6% molybdenum alloy offers protection from manganese-bearing, sulfur-bearing, and generally reducing types of bacteria. Because of its resistance to microbially influenced corrosion, alloy 25-6Mo is being used in wastewater piping systems of power plants.

In saturated sodium chloride environments and for pH values of 6–8, alloy 25-6Mo maintains a corrosion rate of less than 1 mpy and shows no pitting even at temperatures up to boiling.

Alloy 904L (N08904)

This is a fully austenitic low-carbon chromium stainless steel with additives of molybdenum and copper. It has a chemical composition as follows:

Chemical	Weight percent
Carbon	0 .02
Chromium	21.0
Nickel	25.5
Molybdenum	4.7
Copper	1.5
Iron	Balance

Its high nickel and chromium contents make alloy 904L resistant to corrosion in a wide variety of both oxidizing and reducing environments. Molybdenum and copper are included in the alloy for increased resistance to pitting and crevice corrosion and to general corrosion in reducing acids. Other advantages of the alloy's composition are sufficient nickel for resistance to chloride ion stress corrosion cracking and low carbon content for resistance to intergranular corrosion.

The alloy's outstanding attributes are resistance to nonoxidizing acids along with resistance to pitting, crevice corrosion, and stress corrosion cracking in such media as stack gas condensate and brackish water.

Alloy 904L is especially suited for handling sulfuric acid. Hot solutions at moderate concentrations represent the most corrosive conditions. It also has excellent resistance to phosphoric acid.

At high temperatures 904L may be subject to stress corrosion cracking.

Alloy 904L finds applications in piping systems, pollution control equipment, heat exchangers, and bleaching systems.

Alloy 800 (N08800)

The composition of alloy 800 is as follows:

Chemical	Weight percent
Nickel	30.0–35.0
Chromium	19.0–23.0
Aluminum	0.15–0.6
Titanium	0.15–0.6
Carbon	0.10 max.
Iron	Balance

This alloy is used primarily for its oxidation resistance and strength at elevated temperatures. It is particularly useful for high-temperature applications be cause the alloy does not form the embrittling sigma phase after long exposures at 1200–1600°F (649–871°C). High creep and rupture strengths are other factors contributing to its performance in many other applications. It resists sulfidation, internal oxidation, scaling, and carburization.

At moderate temperatures the general corrosion resistance of alloy 800 is similar to that of the other austenitic nickel–iron–chromium alloys. However, as the temperature increases, alloy 800 continues to exhibit good corrosion resistance, while other austenitic alloys are unsatisfactory for the service.

Alloy 800 has excellent resistance to nitric acid at concentrations up to about 70%. It resists a variety of oxidizing salts, but not halide salts. It also has good resistance to organic acids, such as formic, acetic, and propionic. Alloy 800 is particularly suited for the handling of hot corrosive gases such as hydrogen sulfide.

In aqueous service alloy 800 has general resistance that falls between type 304 and type 316 stainless steels. Thus the alloy is not widely used for aqueous service. While not immune, alloy 800 has a stress corrosion cracking resistance better than that of the 300 series of stainless steels and may be substituted on that basis. Table S.12 provides the compatibility of alloy 800 with selected corrodents.

Table S.12 Compatibility of Alloy 800 and Alloy 825 with Selected Corrodents[a]

	Maximum temp.	
Chemical	°F	°C
Acetic acid 10%[b]	200	93
Acetic acid 50%[b]	220	104
Acetic acid 80%[b]	210	99
Acetic acid, glacial[b]	220	104
Acetic anhydride	230	110
Acetone	210	99
Acetyl chloride	210	99
Aluminum acetate	60	16
Aluminum chloride, aqueous	60	16
Aluminum fluoride 5%	80	27
Aluminum hydroxide	80	27
Aluminum sulfate	210	99
Ammonium carbonate	190	88
Ammonium chloride 10%[b]	230	110
Ammonium chloride, sat.	200	93
Ammonium hydroxide, sat.	110	43
Ammonium nitrate	90	32
Ammonium persulfate	90	32
Ammonium sulfate 10–40%	210	99
Ammonium sulfite	210	99
Amyl acetate[b]	200	93
Amyl chloride	90	32
Aniline	90	32
Antimony trichloride	90	32
Barium carbonate	90	32
Barium sulfate	90	32
Benzene	190	88
Benzoic acid 5%	90	32
Borax	190	88
Boric acid 5%	210	99
Bromine gas, dry[b]	90	32
Butyl acetate[b]	90	32
Butyric acid 5%	90	32
Calcium carbonate	90	32
Calcium chlorate	80	27
Calcium chloride[b,c]	60	16
Calcium hydroxide 10%	200	93
Calcium hypochlorite	x	x
Calcium sulfate	90	32
Carbon monoxide	570	299
Carbon tetrachloride	90	32
Carbonic acid	90	32
Chloracetic acid	x	x
Chlorine gas, dry[b]	90	32
Chlorine gas, wet	x	x
Chlorobenzene	90	32
Chloroform	90	32
Chlorosulfonic acid	x	x
Chromic acid 10%[b]	210	99
Chromic acid 50%	x	x
Citric acid 15%	210	99
Citric acid, concentrated[b]	210	99

Table S.12 Compatibility of Alloy 800 and Alloy 825 with Selected Corrodents[a] (Continued)

	Maximum temp.			Maximum temp.	
Chemical	°F	°C	Chemical	°F	°C
Copper acetate	90	32	Nitric acid 5%	90	32
Copper carbonate	90	32	Nitric acid 20%	60	16
Copper chloride 5%[b]	80	27	Nitric acid, anhydrous	210	99
Copper cyanide	210	99	Phenol	90	32
Copper sulfate	210	99	Picric acid	90	32
Cupric chloride 5%	x	x	Potassium bromide 5%	90	32
Ferric chloride	x	x	Salicylic acid	90	32
Ferric chloride 50% in water	x	x	Silver bromide 10%[b]	90	32
Ferric nitrate 10–50%	90	32	Sodium carbonate	90	32
Ferrous chloride[b,c]	90	32	Sodium chloride[c]	200	93
Fluorine gas, dry	x	x	Sodium hydroxide I0%	90	32
Fluorine gas, moist	x	x	Sodium hydroxide, concentrated	90	32
Hydrobromic acid 20%	x	x	Sodium sulfide to 50%	90	32
Hydrobromic acid 50%	x	x	Stannic chloride	x	x
Hydrochloric acid 20%[b]	90	32	Stannous chloride 5%	90	32
Hydrochloric acid 38%	x	x	Sulfuric acid 10%[b]	230	110
Hydrocyanic acid 10%	60	16	Sulfuric acid 50%[b]	210	99
Hydrofluoric acid 30%	x	x	Sulfuric acid 70%[b]	150	66
Hydrofluoric acid 70%	x	x	Sulfuric acid 90%[b]	180	82
Hydrofluoric acid 100%	x	x	Sulfuric acid 98%[b]	220	104
Magnesium chloride 10–50%	170	77	Sulfuric acid 100%[b]	230	110
Malic acid	170	77	Sulfuric acid, fuming	x	x
Manganese chloride 10–50%	210	99	Sulfurous acid[b]	370	188
Muriatic acid[b]	90	32	Zinc chloride 5%	140	60

[a] The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. When compatible, corrosion rate is < 20 mpy.

[b] Applicable to alloy 825 only.

[c] Material subject to pitting.

Source: Ref. 2.

Applications include heat exchangers, process piping, steam generators, and heating element cladding.

Alloy 800H is a controlled version of alloy 800. The carbon content is maintained between 0.05% and 0.1% to provide the alloy with better elevated temperature creep and stress rupture properties. It is solution annealed to ensure the improved creep and stress-to-rupture properties.

Applications include superheater and reheater tubing, headers, and furnace tubing, as well as applications in the refining and heat treatment industries.

Alloy 800AT is similar to alloy 800 but has higher levels of aluminum and titanium. It is used for thermal processing applications, chemical and petrochemical piping, pigtails, and outlet manifolds.

Alloy 825 (N08825)

Alloy 825 is very similar to alloy 800, but the composition has been modified to improve its aqueous corrosion resistance. Its chemical composition is as follows:

Chemical	Weight percent
Nickel	38–46
Chromium	19.5–23.5
Molybdenum	2.3–3.5
Copper	1.5–3.0
Titanium	0.6–1.2
Aluminum	0.2 max
Iron	Balance

The higher nickel content of alloy 825 compared with alloy 800 makes it resistant to chloride stress corrosion cracking. The addition of molybdenum and copper gives resistance to pitting and to corrosion in reducing acid environments, such as sulfuric or phosphoric acid solutions. Alloy 825 is resistant to pure sulfuric acid solutions up to 40% weight at boiling temperatures, and at all concentrations at a maximum temperature of 150°F (60°C). In dilute solutions the presence of oxidizing salts, such as cupric or ferric, actually reduces the corrosion rate. It has limited use in hydrochloric or hydrofluoric acids.

The chromium content of alloy 825 gives it resistance to various oxidizing environments such as nitrates, nitric acid solutions, and oxidizing salts. The alloy is not fully resistant to stress corrosion cracking when tested in magnesium chloride, but it has good resistance in neutral chloride environments.

If localized corrosion is a problem with the 300 series stainless steels, alloy 825 may be substituted. Alloy 825 also provides excellent resistance to corrosion by seawater. The compatibility of alloy 825 with selected corrodents is shown in Table S.12.

Applications include the nuclear industry, chemical processing, and pollution control systems.

Type 330 (N08330)

This is a nickel–chromium iron alloy with the addition of silicon. Its chemical composition is as follows:

Chemical	Weight percent
Carbon	0.08 max.
Manganese	2.00 max.
Silicon	1.5–3.0
Chromium	17.00–20.00
Nickel	34.00–37.00
Tantalum	0.10
Niobium	0.20
Iron	Balance

Type 330 stainless steel has good strength at elevated temperatures, good thermal stability, and excellent resistance to carburizing and oxidizing atmospheres. It is weldable and machinable. This alloy has been used in low-stress applications to temperatures as high as 2250°F (1230°C) and has moderate resistance to creep to 1600°F (870°C).

Type 330 stainless resists the absorption of carbon and nitrogen, making it an excellent choice for furnace components. Overall it exhibits good corrosion resistance.

Al-6XN (N08367)

Alloy Al-6XN is the registered trademark of Allegheny Ludlum Industries Inc. The typical and specified chemical compositions are as follows:

Chemical	Typical Al-6N alloy	UNS N08367 specification
Carbon	0.02	0.03 max.
Manganese	0.0	2.00 max.
Phosphorus	0.020	0.040 max.
Sulfur	0.001	0.030 max.
Silicon	0.40	1.00 max.
Chromium	20.5	20.00–22.00
Molybdenum	6.2	6.00–7.00
Nitrogen	0.22	0.18–0.25
Copper	0.2	0.75 max.
Iron	Balance	Balance

Alloy A1-6XN was originally designed to resist seawater. However, it has proven also to be resistant to a wide range of corrosive environments.

The high strength and corrosion resistance of this alloy makes it a better choice than the more expensive nickel-base alloys in applications where excellent formability, weldability, strength, and corrosion resistance are essential.

It is also a cost-effective alternative to less expensive alloys, such as type 316, that do not have the strength or corrosion resistance required to minimize life cycle costs in certain applications.

The high nickel and molybdenum contents provide improved resistance to chloride stress corrosion cracking. Copper has been kept to a residual level for improved performance in seawater. The high alloy composition resists crevice corrosion and pitting in oxidizing chloride solutions.

The low carbon content of the alloy defines it as an L grade, providing resistance to intergranular corrosion in the as-welded condition.

The corrosion-resistant properties of alloy Al-6XN show exceptional resistance to pitting, crevice attack, and stress cracking in high chlorides and general resistance in various acid, alkaline, and salt solutions found in chemical processing and other industrial environments. Excellent resistance is shown to oxidizing chlorides, reducing solutions, and seawater corrosion. Sulfuric, nitric, phosphoric, acetic, and formic acids can be handled at various concentrations and a variety of temperatures. The material is also approved for contact with foods. Refer to Table S.13 for the compatibility of alloy Al-6XN with selected corrodents.

Table S.13 Compatibility of Al-6XN Stainless Steel with Selected Corrodents[a]

Chemical	Maximum temperature (°F/°C)
Acetic acid 20%	210/99
Acetic acid 80%	217/103
Formic acid 45%	220/104
Formic acid 50%	220/104
Nitric acid 10%	194/90
Nitric acid 65%	241/116
Oxalic acid 10%	210/99
Phosphoric acid 20%	210/99
Phosphoric acid 85%	158/76
Sulfamic acid 10%	210/99
Sulfuric acid 10%	x/x
Sulfuric acid 60%	122/50
Sulfuric acid 95%	86/30
Sodium bisulfate 10%	210/99
Sodium hydroxide 50%	210/99

[a] Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. When compatible, the corrosion rate is <20 mpy.

Alloy Al-6XN finds applications as chemical process vessels and pipeline condensers, heat exchangers, power plant flue gas scrubbers, distillation columns, service water piping in nuclear plants, and food processing equipment.

254SMo (S31254)

This alloy is designed for maximum resistance to pitting and crevice corrosion. It has the following composition:

Chemical	Weight percent
Carbon	0.02
Chromium	19.5–20.5
Nickel	17.5–18.5
Molybdenum	6.0–6.5
Nitrogen	0.18–0.22
Copper	0.50–1.00
Iron	Balance

A PREN value above 33 is considered necessary for pitting and crevice resistance to ambient seawater. Alloy 254SMo has a PREN value of 45.8. With its high levels of chromium, molybdenum, and nitrogen, S31254 is especially suited for environments such as brackish water, seawater, pulp mill bleach plants, and other high-chloride process streams.

Alloy 31 (N08031)

This alloy has the following composition:

Chemical	Weight percent
Carbon	0.02 max.
Nickel	31
Chromium	27
Molybdenum	6.5
Copper	1.8
Nitrogen	0.20
Iron	Balance

With a PREN value of 54.45, this alloy exhibits excellent resistance to pitting and crevice corrosion in neutral and acid solutions. The high chromium content of 27% imparts superior resistance to corrosive attack by oxidizing media.

654SMo (S32654)

This alloy contains 7+% of molybdenum, which provides it with corrosion resistance associated with nickel-based alloys. The composition is as follows:

Chemical	Weight percent
Carbon	0.02
Chromium	24.0
Nickel	22.0
Molybdenum	7.3
Nitrogen	0.5
Copper	0.5
Manganese	3.0
Iron	Balance

Alloy 654 has better resistance to localized corrosion than other superaustenitic alloys. Indications are that alloy 654 is as corrosion resistant as alloy C-276, based on tests in filtered seawater, bleach plants, and other aggressive chloride environments. It is intended to compete with titanium in the handling of high-chloride media.

STYRENE-BUTADIENE-STYRENE (SBS) RUBBER

Styrene-butadiene-styrene (SBS) rubbers are either pure or oil-modified block copolymers. They are most suitable as performance modifiers in blends with thermoplastics or as a base rubber for adhesive, sealant, or coating formulations. SBS compounds are formulations containing block copolymer rubber and other suitable ingredients. These compounds have a wide range of properties and provide the benefits of rubberiness and easy processing on standard thermoplastic processing equipment.

Physical and Mechanical Properties

Since the physical and mechanical properties vary greatly depending upon the formulation, this discussion of these properties is based on the fact that proper formulation will provide a material having the desired combination of properties.

The degree of hardness will determine the flexibility of the final product. With a Shore A hardness range from 37 to 74, SBS rubbers offer excellent impact resistance and low-temperature flexibility. Their maximum service temperature is 150°F (65°C). They also exhibit good abrasion resistance and good resistance to water absorption and heat aging. Their resistance to compression set and tear is likewise good, as is their tensile strength.

The electrical properties of SBS rubber are only fair, and resistance to flame is poor.

The physical and mechanical properties of SBS rubber are given in Table S.14.

Resistance to Sun, Weather, and Ozone

The SBS rubbers are not resistant to ozone, particularly when they are in a stressed condition. Neither are they resistant to prolonged exposure to sun or weather.

Chemical Resistance

The chemical resistance of SBS rubbers is similar to that of natural rubber. They have excellent resistance to water, acids, and bases. Prolonged exposure to hydrocarbon solvents and oils will cause deterioration; however, short exposures can be tolerated.

Applications

The specific formulation will determine the applicability of various products. Applications include a wide variety of general-purpose rubber items and use in the footwear industry. These rubbers are used primarily in blends with other thermoplastic materials and as performance modifiers.

See Refs. 2, 11, and 17.

STYRENE-ETHYLENE-BUTYLENE-STYRENE (SEBS) RUBBER

Styrene-ethylene-butylene-styrene (SEBS) rubbers are either pure or oil-modified block copolymer rubbers. These rubbers are used as performance modifiers in blends with thermoplastics or as the base rubber for adhesive, sealant, or coating formulations. Formulations

Table S.14 Physical and Mechanical Properties of Styrene-Butadiene-Styrene (SBS) Rubber[a]

Specific gravity	0.92–1.09
Tear resistance	Good
Tensile strength, psi	625–4600
Elongation, % at break	500–1400
Hardness, Shore A	37–74
Abrasion resistance	Good
Maximum temperature, continuous use	150°F (65°C)
Impact resistance	Good
Compression set at 74°F (23°C), %	10–15
Machining qualities	Can be ground
Resistance to sunlight	Poor
Effect of aging	Little
Resistance to heat	Fair

[a] These are representative values since they may be altered by compounding.

of SEBS compounds provide a wide range of properties with the benefits of rubberiness and easy processing on standard thermoplastic processing equipment.

Physical and Mechanical Properties

The SEBS rubbers offer excellent impact resistance and low-temperature flexibility, are highly resistant to oxidation and ozone, and do not require vulcanization. Their degree of flexibility is a function of hardness, with their Shore A hardness ranging from 37 to 95. These rubbers are serviceable from –120 to 220°F (–75 to 105°C). They have excellent resistance to very low-temperature impact and bending. Their thermal life and aging properties are excellent, as is their abrasion resistance.

The electrical properties of SEBS rubbers are extremely good. Although the SEBS rubbers have poor flame resistance, compounding can improve their flame retardancy. This compounding reduces the operating temperature slightly.

The physical and mechanical properties of SEBS rubbers are given in Table S.15.

Resistance to Sun, Weather, and Ozone

The SEBS rubbers and compounds exhibit excellent resistance to ozone. For prolonged outdoor exposure the addition of an ultraviolet absorber or carbon black pigment or both is recommended.

Table S.15 Physical and Mechanical Properties of Styrene-Ethylene-Butylene-Styrene (SEBS) Rubbers[a]

Specific gravity	0.885–1.17
Brittle point	–58 to –148°F (–50 to –100°C)
Tear strength, psi	275–470
Moisture absorption, mg/in.^{2}	1.2–3.3
Dielectric strength, at 77°F (25°C)	
at 60 Hz	2.1–2.8
at 1 kHz	2.1–2.8
at 1 MHz	2.1–2.35
Dissipation factor at 77°F (25°C)	
at 60 Hz	0.0001–0.002
at 1 kHz	0.0001–0.003
at 1 MHz	0.0001–0.01
Dielectric strength, V/mil	625–925
Volume resistivity, ohm/cm	9×10^5–9.1×10^{16}
Surface resistivity, ohm	2×10^{16}–9.5×10^{16}
Insulation resistance constant at 60°F (15.6°C) and 500 V DC	6.8×10^4–2.5×10^6
Insulation resistance at 60°F (15.6°C), megohms/1000 ft	2.1×10^4–1×10^6
Tensile strength, psi	1600–2700
Elongation, % at break	500–675
Hardness, Shore A	65–95
Abrasion resistance	Good
Maximum temperature, continuous use	220°F (105°C)
Impact resistance	Good
Resistance to sunlight	Good
Effect of aging	Small
Resistance to heat	Good

[a] These are representative values since they may be altered by compounding.

Chemical Resistance

The chemical resistance of the SEBS rubbers is similar to that of natural rubber. They have excellent resistance to water, acids, and bases. Soaking in hydrocarbon solvents and oils will deteriorate the rubber, but short exposures can be tolerated.

Applications

The SEBS rubbers find applications for a wide variety of general-purpose rubber items as well as in automotive, sporting goods, and other products. Many applications are found in the electrical industry for such items as flexible cords, welding and booster cables, flame-resistant appliance wiring materials, and automotive primary wire insulation.

See Refs. 2, 11, and 17.

SULFATE-REDUCING BACTERIA

These bacteria are widespread in seawater, fresh water, soil, and muddy sediments. When they are present and there is an abundance of sulfate, and the surface of the substrate has a pH of between 5.5 and 8.5, they may cause anaerobic corrosion of iron and steel. The usual by-product of this metabolic process is hydrogen sulfide, which tends to retard cathodic reactions, particularly hydrogen evolution, and to accelerate anodic dissolution, thereby increasing corrosion. The corrosion product is iron sulfide, which precipitates when ferrous and sulfide ions are in contact.

SULFIDATION

Also see “High-Temperature Corrosion.” Sulfidation is oxidation by sulfur forming a sulfide film on the metal surface similar to an oxide film but less protective than a corresponding oxide film.

SULFIDIC CORROSION

Sulfidic corrosion is most often found in petroleum refining. It is caused by a variety of sulfur compounds originating in the crude oils, including hydrogen sulfide, aliphatic sulfides, mercaptans, disulfides, polysulfides, and thiophenes. Corrosion takes place at process temperatures between 500 and 1000°F (260 and 540°C). The corrosion products are metal sulfides.

SULFIDE STRESS CRACKING

Sulfide stress cracking is a form of hydrogen-assisted cracking and refers to the cracking of metals when hydrogen sulfide environments generate the hydrogen. The term is used primarily in the petroleum industry. See “Hydrogen Damage.”

SUPER PRO 230

See “Polyvinylidene Fluoride.”

SUPERFERRITIC STAINLESS STEELS

Ferritic stainless alloys are noted for their ability to resist chloride stress corrosion cracking, which is one of their most useful features in terms of corrosion resistance. Consequently, development efforts were undertaken during the 1970s to produce ferritic stainlesses that would possess a high level of general and localized pitting resistance as well.

The first significant alloy developed commercially to meet these requirements contained 26% chromium and 1% molybdenum. In order to obtain the desired corrosion resistance and acceptable fabrication characteristics, the material had to have very low interstitial element content. To achieve these levels the material was electron beam refined under a vacuum. It was known as E-Brite alloy. Carbon plus nitrogen levels were maintained below 0.02%.

The E-Brite alloy was termed superferritic because of its high level of corrosion resistance for a ferritic material and partly because it is located far into the ferritic zone on the Schaeffler diagram. For a period of years the usage of this alloy grew. Finally its benefits for the construction of pressure vessels were overshadowed by the difficult nature of fabrication and a concern over its toughness. Due to a very low level of interstitial elements the alloy has a tendency to absorb these elements during welding processes. Increases in oxygen plus nitrogen levels much over 100 ppm resulted in poor toughness. Even without these effects the alloy could exhibit a ductile-to-brittle transition temperature around room temperature. Other superferritic alloys were developed. The chemical compositions of selected superferritic alloys are shown in Table S.16.

Type XM-27 (S44627

This alloy is also manufactured under the trade name of E-Brite by Allegheny Ludlum Industries Inc. It is a high-chromium specialty alloy. Refer to Table S-16 for the chemical composition.

In general, E-Brite has good general corrosion resistance in most oxidizing acids, organic acids, and caustics. It is resistant to pitting and crevice corrosion and free from chloride stress corrosion cracking. Refer to Table S.17 for the compatibility of alloy S44627 with selected corrodents.

Table S.16 Chemical Composition of Selected Superferritic Stainless Steels[a]

Alloy	C	Cr	Ni	Mo	N	Other
S44627	0.002	26.0	—	1.0	0.010	
S44660	0.02	26.0	2.5	3.0	0.025	Ti + Cb 0.5
S44800	0.005	29.0	2.2	4.0	0.01	

[a] Values are in wt%.

Table S.17 Compatibility of E-Brite Alloy S44627 with Selected Corrodents[a]

	Maximum temp.			Maximum temp.	
Chemical	°F	°C	Chemical	°F	°C
Acetic acid, 10%	200	93	Acetic anhydride*	300	149
Acetic acid, 20%	200	93	Ammonium chloride, 10%*	200	93
Acetic acid, 50%	200	93	Aqua regia, 3:1	x	x
Acetic acid, 80%	130	54	Beer	160	71
Acetic acid, glacial	140	60	Beet sugar liquors	120	49

Table S.17 Compatibility of E-Brite Alloy S44627 with Selected Corrodents[a] (Continued)

Chemical	Maximum temp. °F	Maximum temp. °C	Chemical	Maximum temp. °F	Maximum temp. °C
Benzaldehyde*	210	99	Nitric acid, 40%*	200	93
Bromine water, 1%	80	27	Nitric acid, 50%*	200	93
Calcium hydroxide, 50%*	210	99	Nitric acid, 70%*	200	93
Chromic acid, 10%	130	54	Oxalic acid, 10%	x	x
Chromic acid, 30%	90	32	Phosphoric acid, 25–50%*	210	99
Chromic acid, 40%	80	27	Sodium chlorite	90	32
Chromic acid, 50%	x	x	Sodium hydroxide, 10%	200	93
Citric acid, 10%	200	93	Sodium hydroxide, 15%	200	93
Citric acid, 25%	210	99	Sodium hydroxide, 30%	200	93
Copper chloride, 5%	100	38	Sodium hydroxide, 50%	180	82
Ethylene chloride*	210	99	Sodium hypochlorite, 30%*	90	32
Ferric chloride	80	27	Stearic acid	210	99
Fluosilicic acid	x	x	Sulfamic acid	100	38
Formic acid, 80%	210	99	Sulfur dioxide, wet	550	293
Hydrochloric acid	x	x	Sulfuric acid, 10%	x	x
Lactic acid, 80%	200	93	Sulfuric acid, 30–90%	x	x
Methylene chloride	x	x	Sulfuric acid, 95%	150	66
Nitric acid, 5%*	310	154	Sulfuric acid, 98%	280	138
Nitric acid, 10%*	310	154	Sulfurous acid, 5%*	210	99
Nitric acid, 20%*	320	160	Tartaric acid, 50%	210	99
Nitric acid, 30%*	320	160	Toluene	210	99

[a] The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. When compatible, corrosion rate is <2 mpy except for those marked with an *, whose corrosion rate is <20 mpy.

Source: Ref. 2.

This alloy also resists intergranular corrosion and is approved for use in contact with foods.

Applications include heat exchanger tubing, overhead condensers, reboilers, feed heaters (petroleum refining), pulp and paper liquid heaters, organic acid heaters and condensers, and nitric acid cooler condensers.

Alloy S44660 (Sea-Cure)

Sea-Cure is the trademark of Trent Tube. It is a chromium–nickel–molybdenum super ferritic alloy. The chemical composition is shown in Table S.16.

Because of its chromium–nickel–molybdenum content it possesses excellent resistance to chloride-induced pitting, crevice corrosion, and stress corrosion cracking. It has better resistance than austenitic stainless steel to general corrosion in diverse conditions. Good to excellent resistance is shown to organic acids, alkalies, salts, and seawater, with good resistance shown to sulfuric, phosphoric, and nitric acids.

Sea-Cure is used in electric power plant condensers and feedwater heaters, and heat exchangers in chemical, petrochemical, and refining applications.

Alloy S44735 (29-40)

The chemical composition of alloy 29-40 is as follows:

Chemical	Weight percent
Carbon	0.03 max.
Manganese	0.30 max.
Silicon	1.00 max.
Chromium	28.0–30.0
Nickel	1.0
Phosphorus	0.03
Molybdenum	3.60–4.20
Titanium + niobium	6.0–0.45 niobium, min.
Iron	Balance

This alloy has improved general corrosion resistance and improved resistance to chloride pitting and stress corrosion cracking in some environments. The absence of nickel reduces the cost.

Applications are found in the utility industry, chemical processing equipment, household condensing furnaces, and vent pipes.

Alloy S44800 (29-4-Z)

The chemical composition of alloy 29-4-Z is shown in Table S.16. This alloy has improved resistance to chloride pitting and stress corrosion cracking and improved general corrosion resistance in some environments.

Applications are found in chemical processing equipment and the utility industry for use in corrosive environments.

Alloy S44700 (29-4)

This is a chromium–nickel–molybdenum alloy with the composition shown below:

Chemical	Weight percent
Carbon	0.010 max.
Manganese	0.30 max.
Chromium	28.0–30.0
Nickel	0.15
Molybdenum	3.50–4.20
Silicon	0.02 max.
Copper	0.15
Nitrogen	0.02
Iron	Balance

Alloy 29-4 has excellent resistance to chloride pitting and stress corrosion cracking. Applications are found in the chemical processing and utility industries.

REFERENCES

1. PA Schweitzer. Cathodic protection. In: PA Schweitzer, ed. Corrosion and Corrosion Protection Handbook. 2nd ed. New York: Marcel Dekker, 1989, pp 33–45.
2. PA Schweitzer. Corrosion Resistance Tables. 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.
3. PB Waterhouse and DA Saunders. The effect of shot peening on the fretting fatigue behavior of austenitic stainless steel and a mild steel. Wear 53:381–386, 1979.
4. WH Friske. Shot peening to prevent corrosion of austenitic stainless steels. Rockwell International Report No. A1-75-52.
5. DO Sprowls and RH Brown. What every engineer should know about stress corrosion of aluminum. Metal Progress, April/May, 1962.
6. FP Vaccaro et al. Effect of shot peening on transition stress corrosion cracking of alloy 600 steam generator tubing. Corrosion 87, paper No. 87.
7. RD Gillespie. Controlled shot peening can help prevent stress corrosion cracking. Third International Conference of Shot Peening, Garmisch-Partenkirchen, Germany, October 12–16, 1987.
8. CS Lin et al. Stress corrosion cracking of high strength bolting. 69th Annual Meeting of the American Society for Testing and Materials. Atlantic City, June 27–July 1.
9. JJ Daly. Controlled shot peening prevents stress corrosion cracking. Chemical Engineering, Feb. 16, 1976.
10. Stress corrosion cracking prevented by shot peening. Chemical Processing, March 1976.
11. PA Schweitzer. Corrosion Resistance of Elastomers. New York: Marcel Dekker, 1990.
12. PA Schweitzer. Stainless steels. In: PA Schweitzer, ed. Corrosion and Corrosion Protection Handbook. 2nd ed. New York: Marcel Dekker, 1989, pp 69–85.
13. CP Dillon. Corrosion Resistance of Stainless Steels. New York: Marcel Dekker, 1995.
14. CP Dillon. Corrosion Control in the Chemical Process Industry. 2nd ed. St. Louis: Materials Technology Institute of the Chemical Process Industries, 1994.
15. RC Newman. Stress corrosion cracking mechanisms. In: P Marcus and J Oudar, eds. Corrosion Mechanisms in Theory and Practice. New York: Marcel Dekker, 1995, pp 311–372.
16. HH Uhlig. Corrosion and Corrosion Control. New York: John Wiley, 1963.
17. PA Schweitzer. Mechanical and Corrosion Resistant Properties of Plastics and Elastomers. New York: Marcel Dekker, 2000.