

# A

## ABRASION CORROSION

See “[Erosion Corrosion.](#)”

## ABSORPTION

See also “[Sheet Linings.](#)”

Unlike metals, polymers will absorb varying quantities of the corrodents they come into contact with, especially organic liquids. This can result in swelling, cracking, and penetration to the substrate. Swelling can cause softening of the polymer. If the polymer has a high absorption rate, permeation will probably occur. An approximation of the expected permeation and/or absorption of a polymer can be based on the absorption of water. Some typical rates are shown in [Table A.1](#). [Table A.2](#) shows the absorption of selected liquids by FEP, and [Table A.3](#) shows the absorption of selected liquids by PFA.

## ACID

Any chemical compound containing hydrogen capable of being replaced by positive elements or radicals to form salts. In terms of the dissociation theory, it is a compound which on dissociation in solution yields excess hydrogen ions.

**Table A.1** Water Absorption Rates of Polymers

Polymer	Water absorption 24 h at 73°F (23°C) (%)
PVC	0.05
CPVC	0.03
PP (Homo)	0.02
PP (Co)	0.03
PE (EHMW)	<0.01
E-CTFE	<0.1
PVDF	<0.04
Saran	nil
PFA	<0.03
ETFE	0.029
PTFE	<0.01
FEP	<0.01

**Table A.2** Absorption of Selected Liquids<sup>a</sup> by FEP

Chemical	Temperature (°F/°C)	Range of weight gains (%)
Aniline	365/185	0.3–0.4
Acetophenone	394/201	0.6–0.8
Benzaldehyde	354/179	0.4–0.5
Benzyl alcohol	400/204	0.3–0.4
<i>n</i> -Butylamine	172/78	0.3–0.4
Carbon tetrachloride	172/78	2.3–2.4
Dimethyl sulfoxide	372/190	0.1–0.2
Nitrobenzene	410/210	0.7–0.9
Perchloroethylene	250/121	2.0–2.3
Sulfuryl chloride	154/68	1.7–2.7
Toluene	230/110	0.7–0.8
Tributyl phosphate	392/200 <sup>b</sup>	1.8–2.0

<sup>a</sup>168-hour exposure at their boiling points.

<sup>b</sup>Not boiling.

**Table A.3** Absorption of Representative Liquids by PFA

Liquid <sup>a</sup>	Temperature (°F/°C)	Range of weight gains (%)
Aniline	365/185	0.3–0.4
Acetophenone	394/201	0.6–0.8
Benzaldehyde	354/179	0.4–0.5
Benzyl alcohol	400/204	0.3–0.4
<i>n</i> -Butylamine	172/78	0.3–0.4
Carbon tetrachloride	172/78	2.3–2.4
Dimethyl sulfoxide	372/190	0.1–0.2
Freon 113	117/47	1.2
Isooctane	210/99	0.7–0.8
Nitrobenzene	410/210	0.7–0.9
Perchloroethylene	250/121	2.0–2.3
Sulfuryl chloride	154/68	1.7–2.7
Toluene	230/110	0.7–0.8
Tributyl phosphate	392/200 <sup>b</sup>	1.8–2.0
Bromine, anhydrous	–5/–22	0.5
Chlorine, anhydrous	248/120	0.5–0.6
Chlorosulfonic acid	302/150	0.7–0.8
Chromic acid 50%	248/120	0.00–0.01
Ferric chloride	212/100	0.00–0.01
Hydrochloric acid 37%	248/120	0.00–0.03
Phosphoric acid, concentrated	212/100	0.00–0.01
Zinc chloride	212/100	0.00–0.03

<sup>a</sup>Liquids were exposed for 168 hours at the boiling point of the solvents. The acidic reagents were exposed for 168 hours.

<sup>b</sup>Not boiling.

## ACID BRICK

Acid brick is brick made from selected clays having a higher silica content than ordinary firebrick and containing little acid-soluble components. It is used to line vessels to impart corrosion resistance against hot acid or erosion–corrosion attack. It is fired at higher temperatures and for longer periods of time than the same clay when used to make “common” brick. Acid-resistant brick is covered by ASTM Specification C-279. The two most commonly used bricks are red shale and fireclay. These are used for all applications except those where the exposure is to strong alkali or hydrofluoric acid. Of the two, the most frequently used is red shale.

### Red Shale Brick

Red shale brick is usually described as meeting type L in ASTM C-279. These bricks provide a lower absorption rate than fireclay and are usually somewhat more brittle. They are applied in those areas where lowest absorption masonry is desired.

### Fireclay

Fireclay brick is usually described as meeting type H in ASTM C-279. It contains a higher proportion of alumina and lower percentages of silica and iron than does shale brick. Fireclay bricks have a higher absorption rate than shale bricks, although some manufacturers provide a denser brick that will meet type L for absorption. These bricks are usually selected for outdoor exposures where rapid thermal changes occur, since they are less brittle than the shale brick. Since they also have a low iron content, they are used in process equipment where this characteristic is important in maintaining product purity.

### Carbon Brick

Carbon brick is used in areas exposed to strong alkali (pH 12.5+) and hydrofluoric acid, or fluoride salts in an acid medium. These bricks are more shock resistant than either red shale or fireclay brick, permitting them to be used in areas where rapid pressure changes take place, a condition that can cause shale or fireclay to spall.

### Silica Brick

All silica brick is used in very high acid concentrations, particularly in phosphoric acid. See [Ref. 1](#).

## ACID MINE WATERS

These are waters that are present in some underground coal mines. They are extremely corrosive because of their free acidity and the presence of high concentrations of ferric and sulfate ions. Their corrosiveness is a result of the aerial and microbial oxidation of pyrite sulfur present in the coal seams or related strata.

## ACID RAIN

When rain has a pH less than 5.6 it is classified as acid rain. It is the result of atmospheric moisture coming into contact with sulfur dioxide gases from industrial emissions and/or with nitrogen oxide gases from car exhausts. See “[Atmospheric Corrosion](#).”

## ACRYLATE-BUTADIENE RUBBER (ABR) AND ACRYLIC ESTER–ACRYLIC HALIDE (ACM) RUBBERS

Acrylate-butadiene and acrylic ester–acrylic halide rubbers are very similar to ethylene-acrylic rubbers.

### Physical and Mechanical Properties

The ABRs and ACM rubbers exhibit good resilience and tear resistance but poor impact resistance. Abrasion resistance and compression set are good. The maximum temperature rating is 340°F (170°C), the same as for the EA rubbers.

Table A.4 lists the physical and mechanical properties of the ACM rubbers.

### Resistance to Sun, Weather, and Ozone

Acrylate-butadiene and acrylic ester–acrylic halide rubbers exhibit good resistance to sun, weather, and ozone.

### Chemical Resistance

The acrylate-butadiene and ACM rubbers have excellent resistance to aliphatic hydrocarbons (gasoline, kerosene) and offer good resistance to water, acids, synthetic lubricants, and silicate hydraulic fluids. They are unsatisfactory for use in contact with alkali, aromatic hydrocarbons (benzene, toluene), halogenated hydrocarbons, alcohol, and phosphate hydraulic fluids.

### Applications

These rubbers are used where resistance to atmospheric conditions and heat is required.

See [Refs. 2](#) and [3](#).

## ACRYLIC ESTER–ACRYLIC HALIDE RUBBERS

See “Acrylate-Butadiene Rubber.”

**Table A.4** Physical and Mechanical Properties of Acrylic Ester–Acrylic Halide (ACM) Rubbers<sup>a</sup>

Specific gravity	1.1
Hardness range, Shore A	45–90
Tensile strength, psi	2175
Elongation, % at break	400
Compression set, %	Fair
Tear resistance	Good
Maximum temperature, continuous use	340°F (170°C)
Electrical properties	Poor to fair
Abrasion resistance	Fair to good
Permeability to gases	Low
Resistance to sunlight	Good
Resistance to heat	Excellent

<sup>a</sup>These are representative values since they may be altered by compounding.

**Table A.5** Physical and Mechanical Properties of ABS

Specific gravity	1.03
Water absorption 24 h at 73°F (23°C), %	0.2–0.4
Tensile strength at 73°F (23°C), psi	5350
Modulus of elasticity in tension at 73°F (23°C) × 10 <sup>5</sup>	2.4
Flexural strength, psi	9400
Izod impact strength, notched at 73°F (23°C)	8.5
Coefficient of thermal expansion	
in./in.–°F × 10 <sup>–5</sup>	5.6
in./10 °F/100 ft.	0.056
Thermal conductivity, Btu/h/sq ft/°F/in.	1.7
Heat distortion temperature at 66 psi, °F/°C	204/94
Resistance to heat at continuous drainage, °F/°C	140/60
Limiting oxygen index, %	19
Flame spread	Not applicable
Underwriters lab rating (Sub 94)	94 HB

## ACRYLONITRILE-BUTADIENE-STYRENE (ABS)

ABS is a vast family of compounds whose properties can be varied extensively, depending on the ratio of acrylonitrile to other components. Higher strength, better toughness, greater dimensional stability, and other properties can be obtained at the expense of other characteristics. Typical physical and mechanical properties that can be obtained are shown in Table A.5. The ABS material has limited heat tolerance, with a maximum operating temperature of approximately 195°F (90°C), with relatively low strength and limited chemical resistance. But its low price and ease of fabrication and joining make it attractive for use as distribution piping for gas, water, and waste. It also finds application for vent lines, automotive parts, and other consumer items.

ABS plastic will be attacked by oxidizing agents and strong acids, and will stress crack in the presence of certain organic compounds. The compatibility of ABS plastic with selected corrodents is shown in Table A.6. Because manufacturers can vary the properties so greatly, the corrosion resistance of the specific material to be used should be verified with the manufacturer.

## ADSORPTION

Adsorption is a surface phenomenon exhibited by solids which consists of the adhesion in an extremely thin layer of the molecules of gases, of liquids, or of dissolved substances with which they are in contact. There are two types depending on the nature of forces involved. In chemisorption, a single layer of molecules, atoms, or ions is attached to the surface by chemical bonds and is essentially irreversible. In physical adsorption, attachment is by the weaker Van der Waal's forces, whose energy levels approximate those of condensation.

Compare with “Absorption.”

Table A.6 Compatibility of ABS with Selected Corrodents<sup>a</sup>

Chemical	Maximum temp.		Chemical	Maximum temp.	
	°F	°C		°F	°C
Acetaldehyde	x	x	Benzyl chloride	x	x
Acetic acid 10%	100	38	Borax	140	60
Acetic acid 50%	130	54	Boric acid	140	60
Acetic acid 80%	x	x	Bromine liquid	x	x
Acetic acid, glacial	x	x	Butadiene	x	x
Acetic anhydride	x	x	Butyl acetate	x	x
Acetone	x	x	Butyl alcohol	x	x
Acetyl chloride	x	x	Butyric acid	x	x
Adipic acid	140	60	Calcium bisulfite	140	60
Allyl alcohol	x	x	Calcium carbonate	100	38
Allyl chloride	x	x	Calcium chlorate	140	60
Alum	140	60	Calcium chloride	140	60
Aluminum chloride, aqueous	140	60	Calcium hydroxide, sat.	140	60
Aluminum fluoride	140	60	Calcium hypochlorite	140	60
Aluminum hydroxide	140	60	Calcium nitrate	140	60
Aluminum oxychloride	140	60	Calcium oxide	140	60
Aluminum sulfate	140	60	Calcium sulfate 25%	140	60
Ammonia gas dry	140	60	Carbon bisulfide	x	x
Ammonium bifluoride	140	60	Carbon dioxide, dry	90	32
Ammonium carbonate	140	60	Carbon dioxide, wet	140	60
Ammonium chloride, sat.	140	60	Carbon disulfide	x	x
Ammonium fluoride 10%	x	x	Carbon monoxide	140	60
Ammonium fluoride 25%	x	x	Carbon tetrachloride	x	x
Ammonium hydroxide 25%	90	32	Carbonic acid	140	60
Ammonium hydroxide, sat.	80	27	Cellosolve	x	x
Ammonium nitrate	140	60	Chloracetic acid	x	x
Ammonium persulfate	140	60	Chlorine gas, dry	140	60
Ammonium phosphate	140	60	Chlorine gas, wet	140	60
Ammonium sulfate 10–40%	140	60	Chlorine, liquid	x	x
Ammonium sulfide	140	60	Chlorobenzene	x	x
Amyl acetate	x	x	Chloroform	x	x
Amyl alcohol	80	27	Chlorosulfonic acid	x	x
Amyl chloride	x	x	Chromic acid 10%	90	32
Aniline	x	x	Chromic acid 50%	x	x
Antimony trichloride	140	60	Citric acid 15%	140	60
Aqua regia 3:1	x	x	Citric acid 25%	140	60
Barium carbonate	140	60	Copper chloride	140	60
Barium chloride	140	60	Copper cyanide	140	60
Barium hydroxide	140	60	Copper sulfate	140	60
Barium sulfate	140	60	Cresol	x	x
Barium sulfide	140	60	Cyclohexane	80	27
Benzaldehyde	x	x	Cyclohexanol	80	27
Benzene	x	x	Dichloroacetic acid	x	x
Benzene sulfonic acid 10%	80	27	Dichloroethane (ethylene dichloride)	x	x
Benzoic acid	140	60	Ethylene glycol	140	60
Benzyl alcohol	x	x	Ferric chloride	140	60

Table A.6 Compatibility of ABS with Selected Corrodents<sup>a</sup> (Continued)

Chemical	Maximum temp.		Chemical	Maximum temp.	
	°F	°C		°F	°C
Ferric nitrate 10–50%	140	60	Phosphoric acid 50–80%	130	54
Ferrous chloride	140	60	Picric acid	x	x
Fluorine gas, dry	90	32	Potassium bromide 30%	140	60
Hydrobromic acid 20%	140	60	Sodium carbonate	140	60
Hydrochloric acid 20%	90	32	Sodium chloride	140	60
Hydrochloric acid 38%	140	60	Sodium hydroxide 10%	140	60
Hydrofluoric acid 30%	x	x	Sodium hydroxide 50%	140	60
Hydrofluoric acid 70%	x	x	Sodium hydroxide, concentrated	140	60
Hydrofluoric acid 100%	x	x	Sodium hypochlorite 20%	140	60
Hypochlorous acid	140	60	Sodium hypochlorite, concentrated	140	60
Ketones, general	x	x	Sodium sulfide to 50%	140	60
Lactic acid 25%	140	60	Stannic chloride	140	60
Magnesium chloride	140	60	Stannous chloride	100	38
Malic acid	140	60	Sulfuric acid 10%	140	60
Methyl chloride	x	x	Sulfuric acid 50%	130	54
Methyl ethyl ketone	x	x	Sulfuric acid 70%	x	x
Methyl isobutyl ketone	x	x	Sulfuric acid 90%	x	x
Muriatic acid	140	60	Sulfuric acid 98%	x	x
Nitric acid 5%	140	60	Sulfuric acid 100%	x	x
Nitric acid 20%	130	54	Sulfuric acid, fuming	x	x
Nitric acid 70%	x	x	Sulfurous acid	140	60
Nitric acid, anhydrous	x	x	Thionyl chloride	x	x
Oleum	x	x	Toluene	x	x
Perchloric acid 10%	x	x	White liquor	140	60
Perchloric acid 70%	x	x	Zinc chloride	140	60
Phenol	x	x			

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.

## ALIPHATIC HYDROCARBONS

Aliphatic hydrocarbons are straight chain organic compounds that are either alkanes, alkenes, alkynes, or their derivatives. All monocyclic organic compounds are aliphatic and cyclic aliphatic compounds are alicyclic.

## ALKALINE

Alkaline describes a solution with an excess of hydroxyl ions having a pH greater than 7.

## ALLIGATORING

Alligatoring is a rupture of an organic coating film, usually caused by application of a hard brittle film over a more flexible film, having an appearance similar to an alligator hide. It is a form of checking in which the surface hardens and shrinks at a much faster rate than the body of the coating. See “[Organic Coatings](#).”

## ALLOY

An alloy is a mixture of two or more metallic elements to produce a single phase. Alloys can be either heterogeneous, where the alloy is a mixture of two or more separate phases, or they may be homogeneous, where the components are completely soluble in one another.

The term alloy is also used to describe resin, polymer, and plastic mixtures formed from two or more immiscible polymers united by another component and having improved performance properties.

## ALLOY B-2

Alloy B was originally developed to resist hydrochloric acid up to the atmospheric boiling point. However, because of the susceptibility to intergranular attack in the heat-affected zone after welding in some environments, a low-carbon variant, alloy B-2, was developed and is replacing alloy B in most applications. The chemical composition is shown in Table A.7.

This alloy is uniquely different from other corrosion-resistant alloys because it does not contain chromium. Molybdenum is the primary alloying element and provides significant corrosion resistance to reducing environments.

Alloy B-2 has improved resistance to knifeline and heat-affected zone attack. It also resists formation of grain boundary precipitation in weld heat-affected zones.

Alloy B-2 has excellent elevated-temperature (1650°F/900°C) mechanical properties because of its high molybdenum content and has been used for mechanical components in reducing environments and vacuum furnaces. Because of the formation of the intermetallic phase Ni<sub>3</sub>Mo and Ni<sub>4</sub>Mo after long aging, the use of alloy B-2 in the temperature range 1110–1560°F (600–850°C) is not recommended.

Alloy B-2 is recommended for service in handling all concentrations of hydrochloric acid in the temperature range 158–212°F (70–100°C) and for handling wet hydrogen chloride gas as shown in Fig. A.1.

Alloy B-2 has excellent resistance to pure sulfuric acid at all concentrations and temperatures below 60% acid and good resistance to 212°F (100°C) above 60% acid, as shown in Fig. A.2. The alloy is resistant to a number of phosphoric acids and numerous organic acids, such as acetic, formic, and cresylic. It is also resistant to many chloride-bearing salts (nonoxidizing), such as aluminum chloride, magnesium chloride, and antimony chloride.

Since alloy B-2 is nickel rich (approximately 70%), it is resistant to chloride-induced stress corrosion cracking. Because of its high molybdenum content, it is highly resistant to pitting attack in most acid chloride environments.

**Table A.7** Chemical Composition of Alloy B-2

Chemical	Weight percent
Molybdenum	26.0–30.0
Chromium	1.0 max.
Iron	2.0 max.
Nickel	Balance

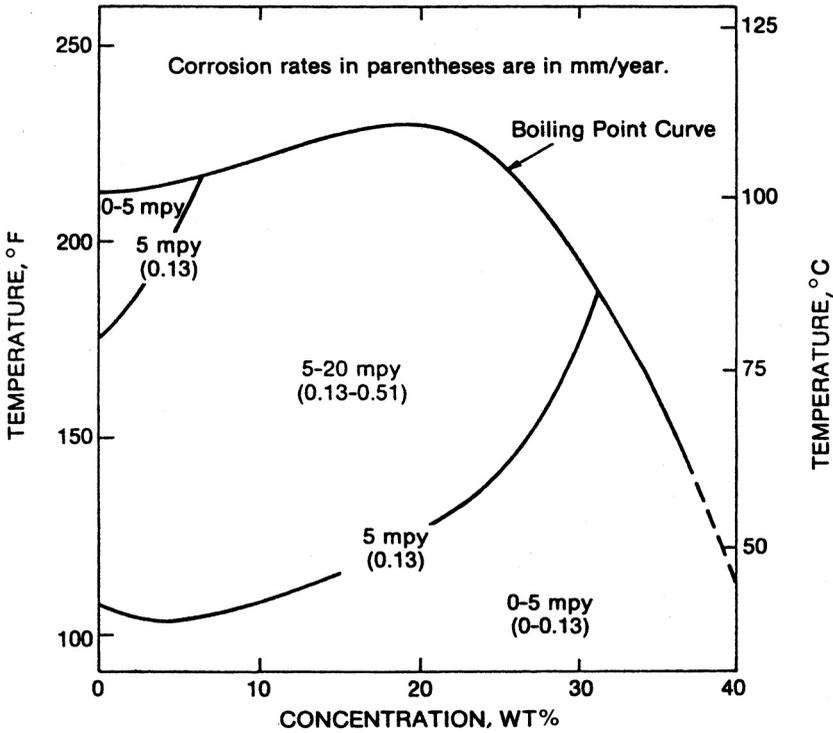


Figure A.1 Isocorrosion diagram for alloy B-2 in hydrochloric acid (from Ref. 4).

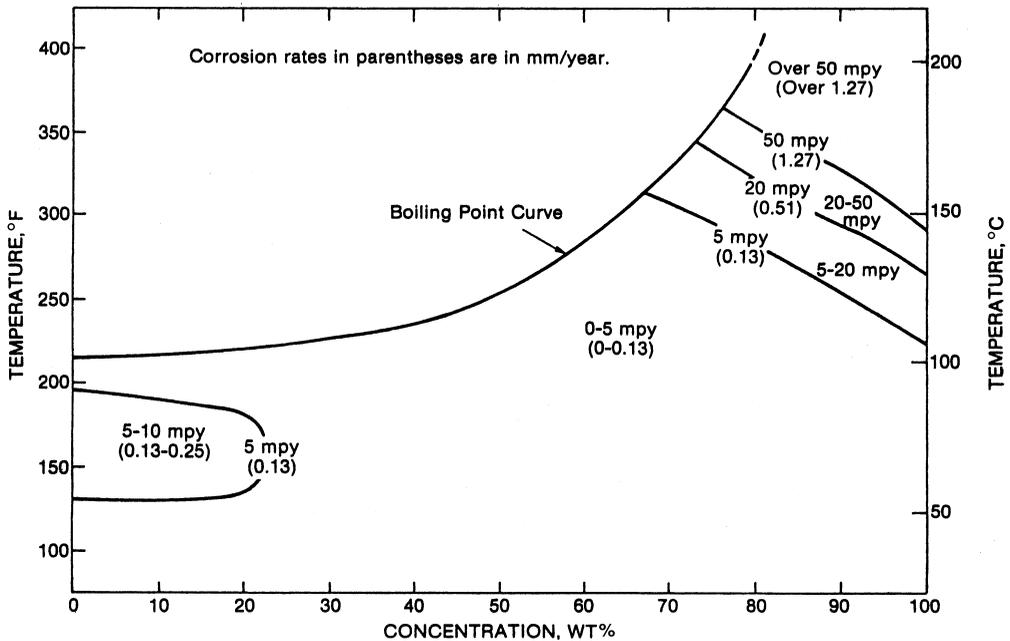


Figure A.2 Isocorrosion diagram for alloy B-2 in sulfuric acid (from Ref. 4).

Alloy B-2 is not recommended for elevated-temperature service except in very specific circumstances. Since there is no chromium in the alloy, it scales heavily at temperatures above 1400°F (760°C). A nonprotective layer of molybdenum trioxide forms and results in a heavy green oxidation scale. In a chloride-containing atmosphere alloy B-2 has demonstrated good resistance.

The major factor limiting the use of alloy B-2 is poor corrosion resistance in oxidizing environments. Alloy B-2 has virtually no corrosion resistance to oxidizing acids such as nitric and chromic or to oxidizing salts such as ferric chloride or cupric chloride. The presence of oxidizing salts in reducing acids must also be considered. Oxidizing salts such as ferric chloride, ferric sulfate, or cupric chloride, even when present in the parts-per-million range, can significantly accelerate the attack in hydrochloric or sulfuric acids as shown in Fig. A.3. Even dissolved oxygen has sufficient oxidizing power to affect the corrosion rates for alloy B-2 in hydrochloric acid. Alloy B-2 exhibits excellent resistance to pure phosphoric acid.

Stress corrosion cracking has been observed in alloy B-2 in 20% magnesium chloride solution at temperatures exceeding 500°F (260°C). Other environments in which stress corrosion cracking of this alloy has been observed include high-purity water at 350°F (170°C), molten lithium at 315°F (157°C), oxygenated de-ionized water at 400°F (204°C), 1% hydrogen iodide at 62–450°F (17–232°C), and 10% hydrochloric acid at

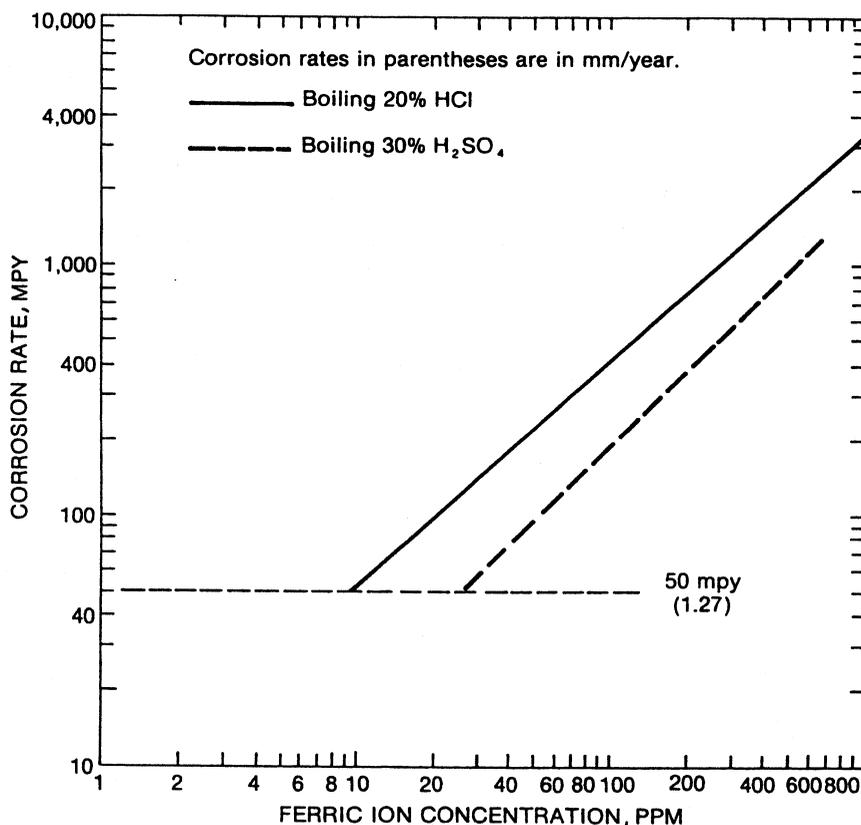


Figure A.3 Effect of ferric ions on corrosion rate of alloy B-2 (from Ref. 4).

400°F (204°C). In some environments, such as concentrated ammonia at 77–140°F (25–60°C), cracking has been observed if the alloy was aged at 1382°F (750°C) for 24 hours before the test. Precipitation of an ordered intermetallic phase Ni<sub>4</sub>Mo has been attributed as the cause of the increased embrittlement.

Table A.8 shows the compatibility of alloy B-2 with selected corrodents. Reference 3 contains a more extensive listing. Table A.9 lists the mechanical and physical properties of alloy B-2.

**Table A.8** Compatibility of Alloy B-2 and Alloy C-276 with Selected Corrodents<sup>a</sup>

Chemical	Maximum temp. (°F/°C)	
	Alloy B-2	C-276
Acetaldehyde	80/27	140/60
Acetamide		60/16
Acetic acid, 10%	300/149	300/149
Acetic acid, 50%	300/149	300/149
Acetic acid, 80%	300/149	300/149
Acetic acid, glacial	560/293	560/293
Acetic anhydride	280/138	280/138
Acetone	200/93	200/93
Acetyl chloride	80/27	
Acrylic acid	210/99	
Acrylonitrile	210/99	210/99
Adipic acid		210/99
Allyl alcohol		570/299
Allyl chloride	200/93	
Alum	150/66	150/66
Aluminum acetate	60/16	60/16
Aluminum chloride, aqueous	300/149	210/99
Aluminum chloride, dry	210/99	210/99
Aluminum fluoride	80/27	80/27
Aluminum sulfate	210/99	210/99
Ammonia gas	200/93	200/93
Ammonium bifluoride		380/193
Ammonium carbonate	300/149	300/149
Ammonium chloride, 10%	210/99	210/99
Ammonium chloride, 50%	210/99	210/99
Ammonium chloride, sat.	570/299	570/299
Ammonium fluoride, 10%	210/99	210/99
Ammonium fluoride, 25%		210/99
Ammonium hydroxide, 25%	210/99	570/299
Ammonium hydroxide, sat.	210/99	570/299
Ammonium persulfate	x	
Ammonium sulfate, 10–40%	80/27	200/93
Ammonium sulfite		100/38
Amyl acetate	340/171	340/171
Amyl alcohol		180/82
Amyl chloride	210/99	90/32

**Table A.8** Compatibility of Alloy B-2 and Alloy C-276 with Selected Corrodents<sup>a</sup> (Continued)

Chemical	Maximum temp. (°F/°C)	
	Alloy B-2	C-276
Aniline	570/299	570/299
Antimony trichloride	210/99	210/99
Aqua regia, 3:1	x	x
Barium carbonate	570/299	570/299
Barium chloride	570/299	210/99
Barium hydroxide	270/132	270/132
Barium sulfate	80/27	
Benzaldehyde	210/99	210/99
Benzene	210/99	210/99
Benzene sulfonic acid, 10%	210/99	210/99
Benzoic acid	210/99	
Benzyl alcohol	210/99	210/99
Benzyl chloride	210/99	
Borax	120/49	120/49
Boric acid	570/299	570/299
Bromine gas, dry	60/16	60/16
Bromine gas, moist		60/16
Bromine liquid		180/82
Butadiene	300/149	300/149
Butyl acetate	200/93	200/93
Butyl alcohol	210/99	200/93
<i>n</i> -Butylamine	210/99	210/99
Butyric acid	280/138	280/138
Calcium bisulfite		80/27
Calcium carbonate	210/99	210/99
Calcium chlorate		210/99
Calcium chloride	350/177	350/177
Calcium hydroxide, 10%	210/99	170/177
Calcium hydroxide, sat.	210/99	
Calcium hypochlorite	x	
Calcium nitrate	210/99	210/99
Calcium oxide		90/32
Calcium sulfate, 10%	320/160	320/160
Caprylic acid	300/149	300/149
Carbon bisulfide	180/82	210/99
Carbon dioxide, dry	570/299	570/299
Carbon dioxide, wet	570/299	200/93
Carbon disulfide	180/82	300/149
Carbon monoxide	570/299	570/299
Carbon tetrachloride	300/149	300/149
Carbonic acid	80/27	80/27
Cellosolve	210/99	210/99
Chloracetic acid, 50% water		210/99
Chloracetic acid	370/188	300/149
Chlorine gas, dry	200/93	570/299

**Table A.8** Compatibility of Alloy B-2 and Alloy C-276 with Selected Corrodents<sup>a</sup> (Continued)

Chemical	Maximum temp. (°F/°C)	
	Alloy B-2	C-276
Chlorine gas, wet	x	220/104
Chlorine, liquid		110/43
Chlorobenzene	350/177	350/177
Chloroform	210/99	210/99
Chlorosulfonic acid	230/110	230/110
Chromic acid, 10%	130/54	210/99
Chromic acid, 50%	x	210/99
Chromyl chloride	210/99	210/99
Citric acid, 15%	210/99	210/99
Citric acid, conc.	210/99	210/99
Copper acetate	100/38	100/38
Copper carbonate	90/32	90/32
Copper chloride	200/93	200/93
Copper cyanide	150/66	150/66
Copper sulfate	210/99	210/99
Cresol	210/99	210/99
Cupric chloride, 5%	60/16	210/99
Cupric chloride, 50%	210/99	210/99
Cyclohexane	210/99	210/99
Cyclohexanol	80/27	80/27
Dichloroethane	230/110	230/110
Ethylene glycol	570/299	570/299
Ferric chloride	90/32	90/32
Ferric chloride, 50% in water	x	
Ferric nitrate, 10–50%	x	
Ferrous chloride	280/138	280/138
Fluorine gas, dry	80/27	150/66
Fluorine gas, moist		570/299
Hydrobromic acid, dilute	210/99	
Hydrobromic acid, 20%	210/99	90/32
Hydrobromic acid, 50%	260/127	90/32
Hydrochloric acid, 20%	140/60	150/66
Hydrochloric acid, 38%	140/60	90/32
Hydrofluoric acid, 30%	140/60	210/99
Hydrofluoric acid, 70%	110/43	200/93
Hydrofluoric acid, 100%	80/27	210/99
Hypochlorous acid	90/32	80/27
Iodine solution, 10%		180/82
Ketones, general	180/82	100/38
Lactic acid, 25%	250/121	210/99
Lactic acid, conc.	250/121	210/99
Magnesium chloride	300/149	300/149
Malic acid	210/99	210/99
Manganese chloride, 40%	210/99	210/99

**Table A.8** Compatibility of Alloy B-2 and Alloy C-276 with Selected Corrodents<sup>a</sup> (Continued)

Chemical	Maximum temp. (°F/°C)	
	Alloy B-2	C-276
Methyl chloride	210/99	90/32
Methyl ethyl ketone	210/99	210/99
Methyl isobutyl ketone	200/93	200/93
Muriatic acid	90/32	90/32
Nitric acid, 5%	x	210/99
Nitric acid, 20%	x	160/71
Nitric acid, 70%	x	200/93
Nitric acid, anhydrous	x	80/27
Nitrous acid, conc.	x	x
Oleum, to 25%	110/43	140/60
Perchloric acid, 70%		220/104
Phenol	570/299	570/299
Phosphoric acid, 50–80%	210/99	210/99
Picric acid	220/104	300/149
Potassium bromide, 30%	90/32	90/32
Salicylic acid	80/27	250/121
Silver bromide, 10%	90/32	90/32
Sodium carbonate	570/299	210/99
Sodium chloride, to 30%	210/99	210/99
Sodium hydroxide, 10% <sup>b</sup>	240/116	230/110
Sodium hydroxide, 50%	250/121	210/99
Sodium hydroxide, conc.	200/93	120/49
Sodium hypochlorite, 20%	x	x
Sodium hypochlorite, conc.	x	x
Sodium sulfide, to 50%	210/99	210/99
Stannic chloride, to 50%	210/99	210/99
Stannous chloride <sup>c</sup>	570/299	210/99
Sulfuric acid, 10%	210/99	200/93
Sulfuric acid, 50%	230/110	230/110
Sulfuric acid, 70%	290/143	290/143
Sulfuric acid, 90%	190/88	190/88
Sulfuric acid, 98%	280/138	210/99
Sulfuric acid, 100%	290/143	190/88
Sulfuric acid, fuming	210/99	90/32
Sulfurous acid	210/99	370/188
Toluene	210/99	210/99
Trichloroacetic acid	210/99	210/99
White liquor	100/38	100/38
Zinc chloride	60/16	250/121

<sup>a</sup>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. When compatible, corrosion rate is <20 mpy.

<sup>b</sup>Alloy B-2 is subject to stress cracking.

<sup>c</sup>Alloy B-2 is subject to pitting.

Source: Ref. 3.

**Table A.9** Mechanical and Physical Properties of Alloy B-2

Modulus of elasticity $\times 10^6$ , psi	31.4
Tensile strength $\times 10^3$ , psi	110
Yield strength 0.2% offset $\times 10^3$ , psi	60
Elongation in 2 in., %	60
Hardness, Brinell	210
Density, lb/in. <sup>3</sup>	0.333
Specific gravity	9.22
Specific heat, at 212°F, Btu/lb °F	0.093
Thermal conductivity, Btu/ft <sup>2</sup> /in. h °F	
at 32°F	77
at 212°F	85
at 392°F	93
at 572°F	102
at 752°F	111
at 932°F	120
at 1112°F	130
Coefficient of thermal expansion, in./in. °F $\times 10^{-6}$	
at 68–200°F	5.7
at 68–600°F	6.2
at 68–1000°F	6.5

**ALLOY C-276**

Hastelloy alloy C-276 is a low-carbon (0.01% maximum), low-silicon (0.08% maximum) version of Hastelloy alloy C. The chemical composition is given in Table A.10. Alloy C-276 was developed to overcome the corrosion problems associated with the welding of alloy C. When used in the as-welded condition, alloy C was often susceptible to serious intergranular corrosion attack in many oxidizing and chloride-containing environments. The low carbon and silicon content of alloy C-276 prevents continuous grain boundary precipitates in the weld heat-affected zone. Thus alloy C-276 can be used in most applications in the as-welded condition without suffering severe intergranular attack.

Alloy C-276 is extremely versatile because it possesses good resistance to both oxidizing and reducing media, including conditions with ion contamination. In dealing

**Table A.10** Chemical Composition of Alloy C-276 (N10276)

Chemical	Weight percent
Carbon	0.01 max.
Manganese	0.5
Silicon	0.08 max.
Chromium	15.5
Nickel	57
Molybdenum	16
Tungsten	3.5
Iron	5.5

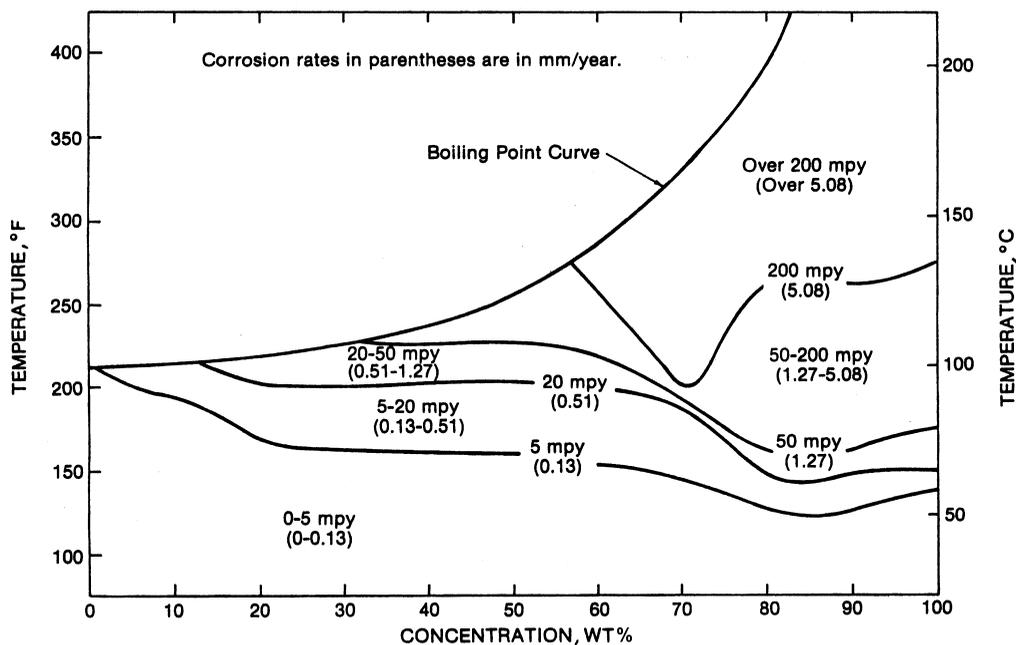


Figure A.4 Isocorrosion diagram for Hastelloy C-276 in sulfuric acid (from Ref. 3).

with acid chloride salts, the pitting and crevice corrosion resistance of the alloy make it an excellent choice.

Alloy C-276 has exceptional resistance to many process materials, including highly oxidizing, neutral, and acid chlorides; solvents; chlorine; formic and acetic acids; and acetic anhydride. It also resists highly corrosive agents such as wet chlorine gas, hypochlorite, and chlorine solutions.

Exceptional corrosion resistance is exhibited in the presence of phosphoric acid at all temperatures below the boiling point of phosphoric acid, when concentrations are less than 65% weight. Corrosion rates of less than 5 mpy were recorded. At concentrations above 65% by weight and up to 85%, alloy C-276 displays similar corrosion rates, except at temperatures between 240°F (116°C) and the boiling point, where corrosion rates may be erratic and may reach 25 mpy.

Isocorrosion diagrams for alloy C-276 have been developed for a number of inorganic acids, for example, sulfuric (see Fig. A.4). Rather than having one or two acid systems in which the corrosion resistance is exceptional, as with alloy B-2, alloy C-276 is a good compromise material for a number of systems. For example, in sulfuric acid coolers handling 98% acid from the absorption tower, alloy C-276 is not the optimal alloy for the process-side corrosion, but it is excellent for the water-side corrosion and allows the use of brackish water or seawater. Concentrated sulfuric acid is used to dry chlorine gas. The dissolved chlorine will accelerate the corrosion of alloy B-2, but alloy C-276 has performed quite satisfactorily in a number of chlorine-drying applications.

Alloy C-276 has been indicated as a satisfactory material for scrubber construction, where problems of localized attack have occurred with other alloys because of pH,

**Table A.11** Mechanical and Physical Properties of Alloy C-276

Modulus of elasticity $\times 10^6$ (psi)	29.8
Tensile strength $\times 10^3$ (psi)	100
Yield strength 0.2% offset $\times 10^3$ (psi)	41
Elongation in 2 in. (%)	40
Brinell hardness	190
Density (lb/in. <sup>3</sup> )	0.321
Specific gravity	8.89
Specific heat (Btu/lb °F)	0.102
Thermal conductivity (Btu/ft <sup>2</sup> /hr °F/in.)	
at -270°F	50
at 0°F	65
at 100°F	71
at 200°F	77
at 400°F	90
at 600°F	104
at 800°F	117
at 1000°F	132
at 1200°F	145
Coefficient of thermal expansion $\times 10^{-6}$ (in./in. °F)	
at 75–200°F	6.2
at 75–400°F	6.7
at 75–600°F	7.1
at 75–800°F	7.3
at 75–1000°F	7.4
at 75–1200°F	7.8
at 75–1400°F	8.3
at 75–1600°F	8.8

temperature, or chloride content. Refer to [Table A.8](#) for the compatibility of alloy C-276 with selected corrodents. The mechanical and physical properties are shown in [Table A.11](#).

See [Refs. 3](#) and [4](#).

## ALLOY C-22 (N06022)

Hastelloy alloy C-22 is a versatile nickel-chromium-molybdenum alloy with better overall corrosion resistance than other nickel-chromium-molybdenum alloys, including alloys C-276, C-4, and 625. The chemical composition is as follows:

Alloy C-22 resists the formation of grain boundary precipitates in the weld heat-affected zone. Consequently, it is suitable for most chemical process applications in the as-welded condition.

Although alloy C-276 is a versatile alloy, its main limitations are in oxidizing environments containing low amounts of halides and in environments containing nitric acid. In addition, the thermal stability of the alloy is not sufficient to enable it to be used as a casting.

Alloy C-22 was invented to improve the resistance to oxidizing environments, such as nitric acid, and also to improve the thermal stability sufficiently to enable it to be used

Chemical	Weight percent
Carbon	0.015 max.
Manganese	0.50 max.
Phosphorous	0.025 max.
Sulfur	0.010 max.
Chromium	20.0–22.5
Molybdenum	12.5–14.5
Cobalt	2.5 max.
Tungsten	2.5–3.5
Iron	2.0–6.0
Silicon	0.08 max.
Vanadium	0.35 max.
Nickel	Balance

for casting. The higher chromium level in this alloy not only makes it superior in oxidizing environments containing nitric acid, but also improves the pitting resistance over that of alloy C-276.

Alloy C-22 has outstanding resistance to pitting, crevice corrosion, and stress corrosion cracking. It has excellent resistance to oxidizing aqueous media, including acids with oxidizing agents, wet chlorine, and mixtures containing nitric or oxidizing acids with chloride ions. The alloy also has outstanding resistance to both reducing and oxidizing media and, because of its versatility, can be used where “upset” conditions are likely to occur or in multi purpose plants.

Alloy C-22 has exceptional resistance to a wide variety of chemical process environments, including strong oxidizers such as ferric and cupric chlorides, hot contaminated media (organic and inorganic), chlorine, formic, and acetic acids, acetic anhydride, seawater, and brine solutions. The compatibility of alloy C-22 with selected corrodents can be found in [Table A.12](#).

The areas of application of alloy C-22 are the same as many of those for alloy C-276. It is being used in pulp and paper bleaching systems, pollution control systems, and various areas in the chemical process industry.

The mechanical and physical properties of alloy C-22 are shown in [Table A.13](#).

## ALLOYS G (N06007), G-3 (N06985), AND G-30 (N06030)

Alloy G is a high-nickel austenitic stainless steel having the following chemical composition:

Chemical	Weight percent
Chromium	22
Nickel	45
Iron	20
Molybdenum	6.5
Copper	2.0
Carbon	0.05 max.
Niobium	2.0

Table A.12 Compatibility of Alloy C-22 with Selected Corrodents

Corrodent	Weight percent	Temperature (°F/°C)	Average corrosion rate (mpy)
Acetic acid	99	Boiling	Nil
Ferric chloride	10	Boiling	1.0
Formic acid	88	Boiling	0.9
Hydrochloric acid	1	Boiling	2.5
Hydrochloric acid	1.5	Boiling	11
Hydrochloric acid	2	194/90	Nil
Hydrochloric acid	2	Boiling	61
Hydrochloric acid	2.5	194/90	0.3
Hydrochloric acid	2.5	Boiling	84
Hydrochloric acid	10	Boiling	400
Hydrofluoric acid	2	158/70	9.4
Hydrofluoric acid	5	158/70	19
Phosphoric acid, reagent grade	55	Boiling	12
Phosphoric acid, reagent grade	85	Boiling	94
Nitric acid	10	Boiling	0.8
Nitric acid	65	Boiling	5.3
Nitric acid + 1% HCl	5	Boiling	0.5
Nitric acid + 2.5% HCl	5	Boiling	1.6
Sulfuric acid	10	Boiling	11
Sulfuric acid	20	150/66	0.2
Sulfuric acid	20	174/79	1.2
Sulfuric acid	20	Boiling	33
Sulfuric acid	30	150/66	0.6
Sulfuric acid	30	174/79	3.3
Sulfuric acid	30	Boiling	64
Sulfuric acid	40	100/38	0.1
Sulfuric acid	40	150/66	0.5
Sulfuric acid	40	174/79	6.4
Sulfuric acid	50	100/38	0.2
Sulfuric acid	50	150/66	1.0
Sulfuric acid	50	174/79	16
Sulfuric acid	60	100/38	0.1
Sulfuric acid	70	100/38	Nil
Sulfuric acid	80	100/38	Nil

Alloy G is intended for use in the as-welded condition, even in the circumstance of multipass welding. The niobium addition provides better resistance than titanium additions in highly oxidizing environments. Because of the nickel base, the alloy is resistant to chloride-induced stress corrosion cracking. The 2% copper addition improves the corrosion resistance of the alloy in reducing acids, such as sulfuric and phosphoric. Alloy G will also resist combinations of sulfuric acid and halides.

**Table A.13** Mechanical and Physical Properties of Alloy C-22 (N06022)

Modulus of elasticity $\times 10^6$ (psi)	29.9
Tensile strength $\times 10^3$ (psi)	115
Yield strength 0.2% offset $\times 10^3$ (psi)	60
Elongation (%)	55
Rockwell hardness	B-87
Density (lb/in. <sup>3</sup> )	0.314
Specific gravity	8.69
Thermal conductivity (Btu/ft <sup>2</sup> hr °F)	
at 70°F (20°C)	5.8
at 1500°F (816°C)	12.3

Alloy G resists pitting, crevice corrosion, and intergranular corrosion. Uses include heat exchangers, pollution control equipment, and various applications in the manufacture of phosphoric and sulfuric acids.

Alloy G-3 was developed with a lower carbon content than alloy G to prevent precipitation at the welds. Its chemical composition is as follows:

Chemical	Weight percent
Chromium	22–23.5
Molybdenum	6.0–8.0
Tungsten	1.5 max.
Iron	18–21
Copper	1.5–2.5
Carbon	0.015 max.
Niobium	0.8
Nickel	44
Silicon	1.0 max.

Although niobium stabilized alloy G from the formation of chromium-rich carbides in the heat-affected zones of the welds, secondary carbide precipitation still occurred when the primary niobium carbides dissolved at high temperatures, and the increased carbon in the matrix increases the tendency of the alloy to precipitate intermetallic phases. Alloy G-3 has a lower carbon content (0.015% maximum versus 0.05% maximum for alloy G) and a lower niobium content (0.8% maximum versus 2% for alloy G). The alloy also possesses a slightly higher molybdenum content (7% versus 5% for alloy G).

The corrosion resistance of alloy G-3 is about the same as that of alloy G; however, the thermal stability is much better. Refer to [Table A.14](#) for the compatibility of alloys G and G-3 with selected corrodents.

Alloy G-30 has a higher chromium content than alloy G, which gives it a higher resistance to oxidizing environments compared with other alloys in this series. It has the following composition:

Chemical	Weight percent
Chromium	28.0–31.5
Molybdenum	4.0–6.0
Tungsten	1.5–4.0
Iron	13.0–17.0
Copper	1.0–2.4
Niobium	0.30–1.50
Nickel + Cobalt	Balance

Alloy G-30 possesses excellent corrosion resistance in the as-welded condition. In acid mixtures such as nitric plus hydrofluoric and sulfuric plus nitric, alloy G-30 has the highest resistance of this class of alloys.

Applications include pipe and tubing in phosphoric acid manufacture, sulfuric acid manufacture, and fertilizer and pesticide manufacture. The alloy is also used in the evaporators of commercial wet-process phosphoric manufacturing systems. This process contains complex mixtures of phosphoric, sulfuric, and hydrofluoric acids and various oxides. Under these conditions the corrosion rate for alloy G-30 was 6 mpy as compared with 16 mpy for alloy G-3 and alloy 625.

The mechanical and physical properties of alloys G and G-3 can be found in [Table A.15](#).

**Table A.14** Compatibility of Alloy G and Alloy G-3 with Selected Corrodents

Chemical	Temperature (°F/°C)	Chemical	Temperature (°F/°C)
Ammonium chloride, 28%	180/82	Nitric acid, 50%	180/82
Calcium carbonate	120/49	Nitric acid, 70%	180/82
Calcium chloride, 3–20%	220/104	Nitrous oxide	560/293
Chlorine gas, wet	80/27	Oleum	240/116
Chlorobenzene, 3–60%	100/38	Phosphoric acid, 50–80%	210/99
Fluorosilicic acid, 3–12%	180/82	Potassium chloride, 10%	230/110
Hydrofluoric acid	x	Sodium chlorate	80/27
Hydrofluosilicic acid, 10–50%	160/71	Sodium chloride	210/99
Kraft liquor	80/27	Sodium hydroxide, conc.	x
Lime slurry	140/60	Sodium hypochlorite, conc.	90/32
Lithium chloride, 30%	260/127	Sodium sulfide, 3–20%	120/49
Magnesium hydroxide	210/99	Sodium dioxide, wet	130/54
Magnesium sulfate	210/99	Sulfuric acid, 10%	250/121
Mercury	250/121	Sulfuric acid, 30%	210/99
Nitric acid, 10%	250/121	Sulfuric acid, 70%	x
Nitric acid, 20%	250/121	Sulfuric acid, 98%	270/131
Nitric acid, 40%	250/121		

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 less than 20 mpy.

**Table A.15** Mechanical and Physical Properties of Alloy G and Alloy G-3

Property	G	G-3
Modulus of elasticity $\times 10^6$ , psi	27.8	27.8
Tensile strength $\times 10^3$ , psi	90	90
Yield strength 0.2% offset $\times 10^3$ , psi	35	35
Elongation in 2 in., %	35	45
Hardness, Brinell	169	885(Rb)
Density, lb/in. <sup>3</sup>	0.30	0.30
Specific gravity	8.31	8.31
Specific heat, J/kg K	456	464
Thermal conductivity, W/mK	10.1	10.0
Coefficient of thermal expansion, in./in. $^{\circ}\text{F} \times 10^{-6}$		
at 70–200 $^{\circ}\text{F}$	7.5	7.5
at 70–400 $^{\circ}\text{F}$	7.7	7.7
at 70–600 $^{\circ}\text{F}$	7.9	7.9
at 70–800 $^{\circ}\text{F}$	8.3	8.3
at 70–1000 $^{\circ}\text{F}$	8.7	8.7
at 70–1200 $^{\circ}\text{F}$	9.1	9.1

**ALLOY 600 (N06600)**

Alloy 600, also known as Inconel, is a nickel base alloy with about 16% chromium and 7% iron that is used primarily to resist corrosive atmospheres at elevated temperatures. The chemical composition will be found in Table A.16.

Alloy 600 has excellent mechanical properties and a combination of high strength and good workability. It performs well in temperatures from cryogenic to 1200 $^{\circ}\text{F}$  (649 $^{\circ}\text{C}$ ) and is readily fabricated and welded.

Although alloy 600 is resistant to oxidation, the presence of sulfur in the environment can significantly increase the rate of attack. The mode of attack is generally intergranular, and therefore the attack proceeds more rapidly and the maximum use temperature is restricted to about 600 $^{\circ}\text{F}$  (315 $^{\circ}\text{C}$ ).

Inconel has excellent resistance to dry halogens at elevated temperatures and has been used successfully for chlorination equipment at temperatures up to 1000 $^{\circ}\text{F}$

**Table A.16** Chemical Composition of Alloy 600 (N06600)

Chemical	Weight percent
Nickel	72.0 min.
Chromium	14.0–17.0
Iron	6.0–10.0
Carbon	0.15 max.
Copper	0.50 max.
Manganese	1.0 max.
Sulfur	0.015 max.
Silicon	0.5 max.

(538°C). Where arrangements can be made for cooling the metal surface, the alloy can be used at even higher gas temperatures.

Resistance to stress corrosion cracking is imparted to alloy 600 by virtue of its nickel base. The alloy therefore finds considerable use in handling water environments where stainless steels fail by cracking. Because of its resistance to corrosion in high-purity water, it has a number of uses in nuclear reactors, including steam generator tubing and primary water piping. The lack of molybdenum in the alloy precludes its use in applications where pitting is the primary mode of failure.

In certain high-temperature caustic applications where sulfur is present, alloy 600 is substituted for alloy 201 because of its improved resistance. Inconel is, however, subject to stress corrosion cracking in high-temperature, high-concentration alkalis. For that reason the alloy should be stress relieved prior to use and the operating stresses kept to a minimum. Alloy-600 is almost entirely resistant to attack by solutions of ammonia over the complete range of temperatures and concentrations.

The alloy exhibits greater resistance to sulfuric acid under oxidizing conditions than either nickel 200 or alloy 400. The addition of oxidizing salts to sulfuric acid tends to passivate alloy 600, which makes it suitable for use with acid mine waters or brass pickling solutions, where alloy 400 cannot be used. Table A.17 provides the compatibility of alloy 600 with selected corrodents. Reference 3 provides a more comprehensive listing.

The mechanical and physical properties of alloy 600 can be found in [Table A.18](#).

**Table A.17** Compatibility of Alloy 600 and Alloy 625 with Selected Corrodents<sup>a</sup>

Chemical	Maximum temp.		Chemical	Maximum Temp.	
	°F	°C		°F	°C
Acetaldehyde	140	60	Ammonium fluoride 10%	90	32
Acetic acid 10%	80	27	Ammonium fluoride 25%	90	32
Acetic acid 50%	x	x	Ammonium hydroxide 25%	80	27
Acetic acid 80%	x	x	Ammonium hydroxide, sat.	90	32
Acetic acid, glacial	220	104	Ammonium nitrate	x	x
Acetic anhydride	200	93	Ammonium persulfate	80	27
Acetone	190	88	Ammonium phosphate 10%	210	99
Acetyl chloride	80	27	Ammonium sulfate 10-40%	210	99
Acrylonitrile	210	99	Ammonium sulfide		
Adipic acid	210	99	Ammonium sulfite	90	32
Allyl alcohol	200	93	Amyl acetate	300	149
Allyl chloride	150	66	Amyl chloride	x	x
Alum	200	93	Aniline	210	99
Aluminum acetate	80	27	Antimony trichloride	90	32
Aluminum chloride, aqueous	x	x	Aqua regia 3:1	x	x
Aluminum chloride, dry	x	x	Barium carbonate	80	27
Aluminum fluoride	80	27	Barium chloride	570	299
Aluminum hydroxide	80	27	Barium hydroxide	90	32
Aluminum sulfate	x	x	Barium sulfate	210	99
Ammonium carbonate	190	88	Benzaldehyde	210	99
Ammonium chloride 10% <sup>b</sup>	230	110	Benzene	210	99
Ammonium chloride 50%	170	77	Benzoic acid 10%	90	32
Ammonium chloride, sat.	200	93	Benzyl alcohol	210	99

Table A.17 Compatibility of Alloy 600 and Alloy 625 with Selected Corrodents<sup>a</sup> (Continued)

Chemical	Maximum temp.		Chemical	Maximum Temp.	
	°F	°C		°F	°C
Benzyl chloride	210	99	Ethylene glycol	210	99
Borax	90	52	Ferric chloride	x	x
Boric acid	80	27	Ferric chloride 50% in water	x	x
Bromine gas, dry	60	16	Ferric nitrate 10–50%	x	x
Bromine gas, moist	x	x	Ferrous chloride	x	x
Butadiene	80	27	Fluorine gas, dry	570	299
Butyl acetate	80	27	Fluorine gas, moist	60	16
Butyl alcohol	80	27	Hydrobromic acid, dilute	90	32
<i>n</i> -Butylamine			Hydrobromic acid 20%	80	27
Butyl phthalate	210	99	Hydrobromic acid 50%	x	x
Butyric acid	x	x	Hydrochloric acid 20%	80	27
Calcium bisulfite	x	x	Hydrochloric acid 38%	x	x
Calcium carbonate	90	32	Hydrofluoric acid 30%	x	x
Calcium chlorate	80	27	Hydrofluoric acid 70%	x	x
Calcium chloride	80	27	Hydrofluoric acid 100%	120	49
Calcium hydroxide 10%	210	99	Lactic acid 25%	210	99
Calcium hydroxide, sat.	90	32	Lactic acid, concentrated	90	32
Calcium hypochlorite	x	x	Magnesium chloride 50%	130	54
Calcium sulfate <sup>c</sup>	210	99	Malic acid	210	99
Caprylic acid	230	110	Manganese chloride 37%	x	x
Carbon bisulfide	80	27	Methyl chloride	210	99
Carbon dioxide, dry	210	99	Methyl ethyl ketone	210	99
Carbon dioxide, wet	200	93	Methyl isobutyl ketone	200	93
Carbon disulfide	80	27	Muriatic acid	x	x
Carbon monoxide	570	299	Nitric acid 5%	90	32
Carbon tetrachloride	210	99	Nitric acid 20%	80	27
Carbonic acid	210	99	Nitric acid 70%	x	x
Cellosolve	210	99	Nitric acid, anhydrous	x	x
Chloroacetic acid	x	x	Nitrous acid, concentrated	x	x
Chlorine gas, dry	90	32	Oleum	x	x
Chlorine gas, wet	x	x	Phenol	570	299
Chlorobenzene	210	99	Phosphoric acid 50–80%	190	88
Chloroform	210	99	Picric acid	x	x
Chromic acid 10%	130	54	Potassium bromide 30%	210	99
Chromic acid 50%	90	32	Salicylic acid	80	27
Chromyl chloride	210	99	Sodium carbonate to 30%	210	99
Citric acid 15%	210	99	Sodium chloride to 30%	210	99
Citric acid, concentrated	210	99	Sodium hydroxide 10%	300	149
Copper acetate	100	38	Sodium hydroxide 50% <sup>b</sup>	300	149
Copper carbonate	80	27	Sodium hydroxide, concentrated	80	27
Copper chloride	x	x	Sodium hypochlorite 20%	x	x
Copper cyanide	80	27	Sodium hypochlorite, concentrated	x	x
Copper sulfate	80	27	Sodium sulfide to 50%	210	99
Cresol	100	38	Stannic chloride	x	x
Cupric chloride 5%	x	x	Stannous chloride, dry	570	299
Cupric chloride 50%	x	x	Sulfuric acid 10%	x	x
Cyclohexanol	80	27	Sulfuric acid 50%	x	x
Dichloroethane (ethylene dichloride)	200	93	Sulfuric acid 70%	x	x

**Table A.17** Compatibility of Alloy 600 and Alloy 625 with Selected Corrodents<sup>a</sup> (Continued)

Chemical	Maximum temp.		Chemical	Maximum Temp.	
	°F	°C		°F	°C
Sulfuric acid 90%	x	x	Sulfurous acid	90	32
Sulfuric acid 98%	x	x	Toluene	210	99
Sulfuric acid 100%	x	x	Trichloroacetic acid	80	27
Sulfuric acid, fuming	x	x	Zinc chloride, dry	80	27

<sup>a</sup>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, when compatible corrosion rate is <20 mpy.

<sup>b</sup>Material is subject to stress cracking.

<sup>c</sup>Material subject to pitting.

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

**Table A.18** Mechanical and Physical Properties of Alloy 600

Modulus of elasticity $\times 10^6$ (psi)	30–31
Tensile strength $\times 10^3$ (psi)	80
Yield strength 0.2% offset $\times 10^3$ (psi)	30–35
Elongation in 2 in. (%)	40
Rockwell hardness	B-120–170
Density (lb/in. <sup>3</sup> )	0.306
Specific gravity	8.42
Specific heat (Btu/lb °F)	0.106
Thermal conductivity (Btu/h/ft <sup>2</sup> /°F/in.)	
at 70°F	103
at 200°F	109
at 400°F	121
at 600°F	133
at 800°F	145
at 1000°F	158
at 1200°F	172
Coefficient of thermal expansion $\times 10^6$ (in./in./°F)	
at 70–200°F	7.4
at 70–400°F	7.7
at 70–600°F	7.9
at 70–800°F	8.1
at 70–1000°F	8.4
at 70–1200°F	8.6

## ALLOY 625 (N06625)

Alloy 625, also known as Inconel alloy 625, is used both for its high strength and for its aqueous corrosion resistance. The strength of alloy 625 is primarily a solid-solution effect from molybdenum and niobium. Alloy 625 has excellent weldability. The chemical composition is shown in [Table A.19](#).

Because of its combination of chromium, molybdenum, carbon, and niobium + tantalum, the alloy retains its strength and oxidation resistance at elevated temperatures.

**Table A.19** Chemical Composition of Alloy 625 (N06625)

Chemical	Weight percent
Chromium	20.0–23.0
Molybdenum	8.0–10.0
Cobalt	1.00 max.
Columbium + tantalum	3.15–4.15
Aluminum	0.40 max.
Titanium	0.40 max.
Carbon	0.10 max.
Iron	5.00 max.
Manganese	0.50 max.
Silicon	0.50 max.
Phosphorus	0.015 max.
Sulfur	0.015 max.
Nickel	Balance

This alloy finds application where strength and corrosion resistance are required. It exhibits exceptional fatigue strength and superior strength and toughness at temperatures ranging from cryogenic to 2000°F (1093°C). The niobium and tantalum stabilization makes the alloy suitable for corrosion service in the as-welded condition. It has excellent resistance to chloride stress corrosion cracking.

Field operating experience has shown that alloy 625 exhibits excellent resistance to phosphoric acid solutions, including commercial grades that contain fluorides, sulfates, and chlorides that are used in the production of superphosphoric acid (72% P<sub>2</sub>O<sub>5</sub>).

Refer to [Table A.17](#) for the compatibility of alloy 625 with selected corrodents.

Elevated-temperature applications include ducting systems, thrust reverser assemblies, and afterburners. Use of this alloy has been considered in the high-temperature, gas-cooled reactor; however, after long aging in the temperature range of 1100–1400°F (590–760°C), the room temperature ductility is significantly reduced.

Alloy 625 has been used in preheaters for sulfur dioxide scrubbing systems in coal-fired power plants and bottoms of electrostatic precipitators that are flushed with seawater.

[Table A.20](#) lists the mechanical and physical properties of alloy 625.

## ALLOY 686 (N06686)

Inconel alloy 686 is an austenitic nickel-chromium-molybdenum-tungsten alloy. The chemical composition can be found in [Table A.21](#).

This highly alloyed material has good mechanical strength. It is most often used in the annealed condition. Since alloy 686 is a solid-solution alloy, it cannot be strengthened by heat treatment, but strain hardening by cold work will greatly increase the strength of the alloy. Exposure to high temperatures for long periods of time can have an embrittling effect on the alloy.

The alloy's composition provides resistance to general corrosion, stress corrosion cracking, pitting, and crevice corrosion in a broad range of aggressive environments. The

**Table A.20** Mechanical and Physical Properties of Alloy 625

Modulus of elasticity $\times 10^6$ (psi)	30.1
Tensile strength $\times 10^3$ (psi)	100–120
Yield strength 0.2% offset $\times 10^3$ (psi)	60
Elongation in 2 in. (%)	30
Brinell hardness	192
Density ((lb/in. <sup>3</sup> )	0.305
Specific gravity	8.44
Specific heat (Btu/lb °F)	0.098
Thermal conductivity (Btu-in./ft <sup>2</sup> h °F)	
at -250°F	50
at -100°F	58
at 0°F	64
at 70°F	68
at 100°F	70
at 200°F	75
at 400°F	87
at 600°F	98
at 1000°F	121
at 1400°F	144
Coefficient of thermal expansion $\times 10^6$ in./in. °F	
at 70–200°F	7.1
at 70–400°F	7.3
at 70–600°F	7.4
at 70–800°F	7.6
at 70–1000°F	7.8
at 70–1200°F	8.2
at 70–1400°F	8.5
at 70–1600°F	8.8

**Table A.21** Chemical Composition of Alloy 686 (N06686)

Chemical	Weight percent
Chromium	19.0–23.0
Molybdenum	15.0–17.0
Tungsten	3.0–4.0
Titanium	0.02–0.25
Iron	5.0 max.
Carbon	0.01 max.
Manganese	0.75 max.
Sulfur	0.02 max.
Silicon	0.08 max.
Phosphorus	0.04 max.
Nickel	Balance

high nickel and molybdenum contents provide good corrosion resistance in reducing environments, while the high chromium level imparts resistance to oxidizing media. The molybdenum and tungsten also aid resistance to localized corrosion, such as pitting, while the low carbon content and other composition controls help minimize grain boundary precipitation to maintain resistance to corrosion in heat-affected zones of welded joints.

The ability of alloy 686 to resist pitting is evident from its pitting resistance equivalent, which is 51.

Alloy 686 has excellent resistance to mixed acids as well as reducing and oxidizing acids and to mixed acids containing high concentrations of halides. Good resistance has been shown to mixed acid media having pH levels of 1 or less and chloride levels in excess of 100,000 ppm.

The mechanical and physical properties are shown in Table A.22.

## ALUMINUM AND ALUMINUM ALLOYS

Aluminum is one of the most prevalent metallic elements in the solid portion of the earth's crust, comprising approximately 8%. It is always present in a combined form, usually a hydrated oxide, of which bauxite is the primary ore. Metallic aluminum is very active thermodynamically and seeks to return to the natural oxidized state through the process of corrosion.

Aluminum alloys possess a high resistance to corrosion by most atmospheres and waters, many chemicals, and other materials. Their salts are nontoxic, allowing applications with beverages, foods, and pharmaceuticals; are white or colorless, permitting applications with chemicals and other materials without discoloration, and are not damaging to the ecology. Other desirable properties of aluminum and its alloys include high electrical conductivity, high thermal conductivity, high reflectivity, and noncatalytic action. They are also nonmagnetic.

### Classifications and Designations

Wrought aluminum and aluminum alloys are classified based on their major alloying element via a four-digit numbering system as shown in Table A.23. These alloy numbers and their respective tempers are covered by the American National Standards Institute (ANSI) standard H35.1. In the 1XXX group the second digit indicates the purity of the aluminum used to

**Table A.22** Mechanical and Physical Properties of Alloy 686 (N06686) at 70°F/20°C

Modulus of elasticity $\times 10^6$ (psi)	30
Tensile strength $\times 10^3$ (psi)	104
Yield strength 0.2% $\times 10^3$ (psi)	52.8
Elongation in 2 in. (%)	71
Density (lb/in. <sup>3</sup> )	0.315
Specific heat (Btu/lb °F)	0.089
Coefficient of thermal expansion $\times 10^{-6}$ (in./in.°F)	6.67
Impact strength (ft-lb)	299

**Table A.23** Wrought Aluminum and Aluminum Alloy Designation

Series designation	Alloying materials
1XXX	99.9% min. Al
2XXX	Al-Cu, Al-Cu-Mg, Al-Cu-Mg-Li, Al-Cu-Mg-Si
3XXX	Al-Mn, Al-Mn-Mg
4XXX	Al-Si
5XXX	Al-Mg, Al-Mg-Mn
6XXX	Al-Mg-Si, Al-Mg-Si-Mn, Al-Mg-Si, Cu
7XXX	Al-Zn, Al-Zn-Mg, Al-Zn-Mg-Mn, Al-Zn-Mg-Cu

**Table A.24** Major Alloying Ingredients

Series designation	Major alloying ingredient
1XXX	Aluminum $\geq$ 99.0%
2XXX	Copper
3XXX	Manganese
4XXX	Silicon
5XXX	Magnesium
6XXX	Magnesium and silicon
7XXX	Zinc
8XXX	Other elements
9XXX	Unused series

manufacture this particular grade. The zero in the 10XX group indicates that the aluminum is essentially of commercial purity, while a second digit of 1 through 9 indicates special control of one or more individual impurity elements. In the 2XXX through 7XXX alloy groups the second digit indicates an alloy modification. If the second digit is zero, the alloy is the original alloy; numbers 1 through 9 are assigned consecutively as the original alloy becomes modified. The last two digits serve only to identify the different alloys in the group and have no numerical significance. The classification shown in Table A.23 is based on the major alloying ingredients as shown in Table A.24.

The Unified Numbering System (UNS), used for other metals, is also used for aluminum. A comparison for selected aluminum alloys between the Aluminum Association designation and the UNS designation is shown in Table A.25.

### Chemical Composition

The word aluminum can be misleading since it is used for both the pure metal and for the alloys. Practically all commercial products are composed of aluminum alloys.

For aluminum to be considered “unalloyed” it must have a minimum content of 99.0% aluminum. Most unalloyed specifications range from 99.00% to 99.75% minimum aluminum.

To assist in the smelting process, elements such as bismuth and titanium are added, while chromium, manganese, and zirconium are added for grain control during solidification of large ingots. Elements such as copper, magnesium, manganese, nickel, and zinc

**Table A.25** Aluminum Association Designation System and UNS Equivalencies for Aluminum Alloys

Aluminum Association designation	UNS designation
1050	A91050
1080	A91080
1100	A91100
1200	A91200
2014	A92014
2024	A92024
3003	A93003
3004	A93004
4043	A94043
4047	A94047
5005	A95005
5052	A95052
5464	A95464
6061	A96061
6063	A96063
6463	A96463
7005	A97005
7050	A97050
7075	A97075

are added to impart properties such as strength, formability, and stability at elevated temperature and other extreme conditions. Some unintentional impurities are present, coming from trace elements contained in the ore, from pickup from ceramic furnace linings, or from the use of scrap metal in recycling.

There are three types of composition listings in use. First there is the nominal, or target, composition of the alloy. This is used in discussing the generic types of alloys and their uses. Second are the alloy limits registered with the Aluminum Association, which are the specification limits against which alloys are produced. In these limits intentional alloying elements are defined as an allowable range. The usual impurity elements are listed as the maximum amount allowed. Rare trace elements are grouped into an “each other” category. A trace element cannot exceed a specified “each” amount, and the total of all trace elements cannot exceed the slightly higher “total” amount. The third listing consists of the elements actually present as found in an analyzed sample. Examples of all three types of these compositions for unalloyed aluminum (1160), a heat-treatable alloy (2024), and a non-heat-treatable alloy (3004) are shown in [Table A.26](#).

When the melt is analyzed, the intentional elements must be within the prescribed range, but not necessarily near the midpoint if the range is wide. For example, as shown in [Table A.26](#), copper in alloy 2024 can be skewed to a high content (sample 2) to improve strength or a low content to improve toughness (sample 3). The producer will target for the nominal composition when the allowable range is only about half a percentage point or less.

**Table A.26** Comparison of Composition Listings of Aluminum and Aluminum Alloys

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Others	
										Each	Total
Nominal (target) chemical composition of wrought alloys (%) <sup>a</sup>											
1160	(99.6% min. Al; all other elements 0.040%)										
2024	—	—	4.4	0.6	1.5	—	—	—	—		
3004	—	—	1.2	1.0	—	—	—	—	—		
Registered chemical composition limits of wrought alloys (%) <sup>b</sup>											
1160	0.25	0.35	0.05	0.03	0.03	—	—	0.05	0.03	0.03	
2024	0.50	0.40	3.8–4.9	0.30–0.9	1.2–1.8	0.10	—	0.25	0.05	0.05	0.15
3004	0.30	0.70	0.25	1.0–1.5	0.8–1.3	—	—	0.25	0.05	0.05	0.15
Analysis of aluminum samples alloying elements present (%) <sup>c</sup>											
1160 sample 1	0.080	0.100	0.00	0.00	0.00	0.00	0.00	0.000	0.020		
2024 sample 2	0.25	0.32	4.77	0.61	1.77	0.00	0.00	0.025	0.03		
2024 sample 3	0.10	0.12	4.40	0.55	1.45	0.00	0.00	0.00	0.02		
3004 sample 4	0.030	0.42	0.00	1.25	1.10	0.00	0.00	0.00	0.03		

<sup>a</sup>Aluminum and normal impurities constitute remainder.

<sup>b</sup>Alloying elements shown as a required range; impurity elements are the maximum tolerable. Aluminum and trace impurities constitute remainder.

<sup>c</sup>Remainder is aluminum.

Specified impurity elements must be at or below the maximum limit. Individual non-specified impurities should be less than the “0.05% each” level, with the total less than 0.15%. It should be recognized that, as shown in Table A.26, some impurity elements will be present, but usually well below the allowed limit. Every sample will not contain all of the impurity elements, but some amounts of iron and silicon are usually present except in ultra-refined pure aluminum. Certain alloys are produced in several levels of purity, with the less pure levels being less expensive and the higher purity levels improving some property. For example, when the iron and silicon levels are both less than 0.10%, toughness is improved.

It is important to know that other metallic elements are present and necessary for desired properties. Many elements combine with one another and with aluminum to produce intermetallic compounds that are either soluble or insoluble in the aluminum matrix. The presence of second-phase particles is normal, and they can be seen and identified by metallographic examination.

The nominal chemical composition of representative aluminum wrought alloys are given in Table A.27.

There are two types of wrought alloys: non-heat-treatable of the 1XXX, 3XXX, 4XXX, and 5XXX series, and heat-treatable of the 2XXX, 6XXX, and 7XXX series.

A high resistance to general corrosion is exhibited by all of the non-heat-treatable alloys. Because of this, selection is usually based on other factors. Alloys of the 1XXX series have relatively low strength. Alloys of the 3XXX series have the same desirable properties as those of the 1XXX series but with higher strength.

Magnesium added to some alloys in the series provides additional strength, but the amount is low enough that the alloys still behave more like those with manganese alone than like the stronger Al-Mg alloys of the 5XXX series. Alloys of the 4XXX series are low-strength alloys used for brazing and welding products and for cladding in architectural products.

**Table A.27** Nominal Chemical Compositions of Representative Aluminum Wrought Alloys

Alloy	Percent of alloying elements								
	Si	Cu	Mn	Mg	Cr	Zn	Ti	V	Zr
<i>Non-heat-treatable alloys</i>									
1060	99.60% min. Al								
1100	99.00% min. Al								
1350	99.50% min. Al								
3003		0.12	1.2						
3004			1.2	1.0					
5052				2.5	0.25				
5454			0.8	2.7	0.12				
5456			0.8	5.1	0.12				
5083			0.7	4.4	0.15				
5086			0.45	4.0	0.15				
7072 <sup>a</sup>						1.0			
<i>Heat-treatable alloys</i>									
2014	0.8	4.4	0.8	0.50					
2219		6.3	0.30				0.06	0.10	0.18
2024		4.4	0.6	1.5					
6061	0.6	0.28		1.0	0.20				
6063	0.4			0.7					
7005			0.45	1.4	0.13	4.5	0.04		0.14
7050		2.3		2.2		6.2			
7075		1.6		2.5	0.23	5.6			

<sup>a</sup>Cladding for Alclad products.

The strongest non-heat-treatable alloys are those of the 5XXX series, and in most products they are more economical than alloys of the IXXX and 3XXX series in terms of strength per unit cost.

Alloys of the 5XXX series have the same high resistance to general corrosion as the other non-heat-treatable alloys in most environments. In addition, they exhibit a better resistance in slightly alkaline solutions than any other aluminum alloy. These alloys are widely used because of their high as-welded strength when welded with a compatible 5XXX series filler wire.

Of the heat-treatable alloys those of the 6XXX series exhibit a high resistance to general corrosion, equal to or approaching that of the non-heat-treatable alloys. A high resistance to corrosion is also exhibited by alloys of the 7XXX series that do not contain copper as an alloying ingredient. All other heat-treatable alloys have a lower resistance to general corrosion. [Table A.28](#) shows the mechanical and physical properties of aluminum.

### Corrosion of Aluminum

The resistance of aluminum to corrosion is dependent on the passivity of a protective oxide film. The thermodynamic conditions under which this film forms in aqueous solutions are expressed by the potential-pH diagram according to Pourbaix (refer to [Fig. A.5](#)).

Table A.28 Mechanical and Physical Properties of Aluminum Alloys

Property	Aluminum alloy			
	3003-3	5052-0	6061-T6	6063-T6
Modulus of elasticity $\times 10^6$ , psi	10	10.2	10	10
Tensile strength $\times 10^3$ , psi	17	41	45	35
Yield strength 0.2% offset $\times 10^3$ , psi	8	36	40	31
Elongation in 2 in., %	40	25	12	12
Density, lb/in. <sup>3</sup>	0.099	0.097		0.098
Specific gravity	2.73	2.68		2.70
Specific heat, Btu/h °F	0.23	0.23		
Thermal conductivity, Btu/h/ft <sup>2</sup> /°F/in.	1070	960	900	1090
Coefficient of thermal expansion, in./°F/in. $\times 10^{-6}$				
at 58–68 °F	12		12.1	12.1
at 68–212 °F	12.9	13.2	13.0	13.0
at 68–392 °F	13.5		13.5	13.6
at 68–572 °F	13.9		14.1	14.2

Note from the diagram that aluminum is passive only in the pH range of 4 to 9. The limits of passivity depend on the form of oxide present, the temperature, and the low dissolution of aluminum that must be assumed for inertness. (Theoretically, this value cannot be zero for any metal.) At a pH of about 5 the various forms of aluminum oxide all exhibit a minimum solubility.

When the protective oxide film is formed in water and atmospheres at ambient temperatures, it is only a few nanometers thick and structureless. Thicker films are formed at higher temperatures. These may consist of a thin structureless barrier layer next to the aluminum and a thicker crystalline layer next to the barrier layer. Highly protective films of boehmite (aluminum oxide hydroxide, A100H) are formed in water near its boiling point, particularly if it is made slightly alkaline. In water or steam at still higher temperatures, thicker, more protective films are formed.

A protective film in water or steam ceases to develop starting at a temperature of about 445°F/230°C, and the reaction progresses rapidly until eventually all the aluminum exposed to this medium is converted to oxide. Special alloys containing iron and nickel retard this reaction. These alloys have an allowable operating temperature of 680°F/360°C without excessive attack.

As shown in Fig. A.5, aluminum corrodes under both acidic and alkaline conditions. In the first case trivalent  $\text{Al}^{3+}$  ions are formed and in the latter case  $\text{Al}_2\text{O}_3$  ions are formed. There are a few exceptions, either when the oxide film is not soluble in an acidic or alkaline solution, or when it is maintained by the oxidizing nature of the solution. Exceptions include acetic acid, ammonium hydroxide above 30% concentration by weight, nitric acid above 80% concentration by weight, and sulfuric acid in the concentration range of 98% to 100%.

It is possible for aluminum to corrode as a result of defects in its protective oxide film. As purity is increased, resistance to corrosion improves, but the oxide film on even the purest aluminum still contains a few defects where minute corrosion can develop. The presence of second phases in the less pure aluminums of the 1XXX series and in aluminum alloys becomes the more important factor. These phases are present as an

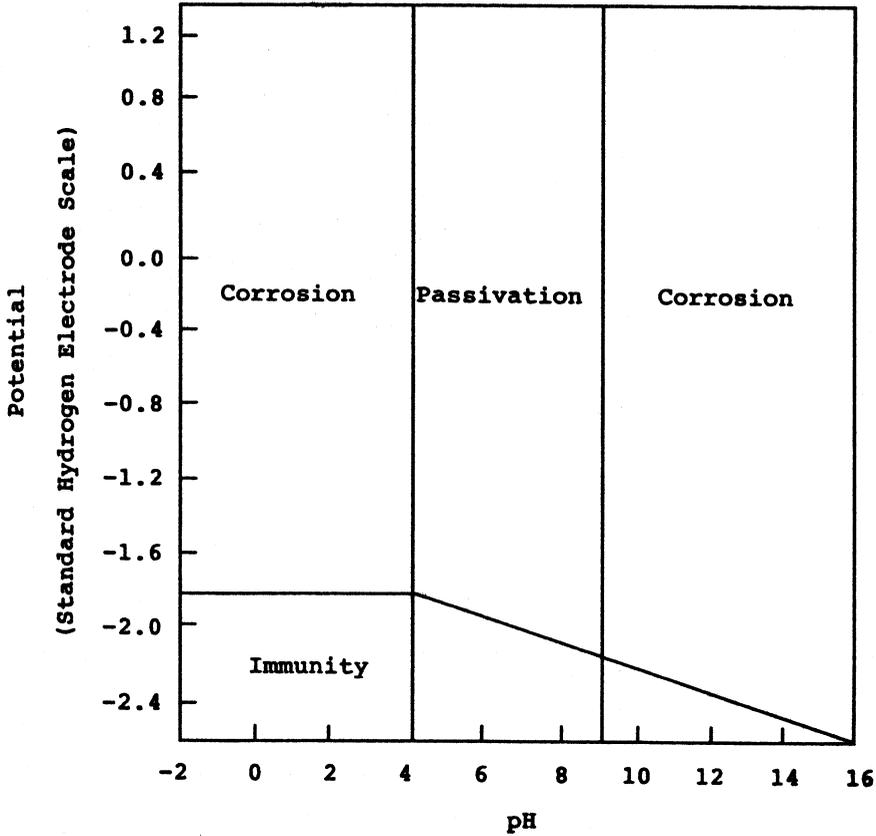


Figure A.5 Potential-pH diagram according to Pourbaix for aluminum at 77°F (25°C) with an oxide film of hydrargillite (from Ref. 5).

insoluble constituent of intermetallic compounds produced primarily from iron, silicon, and other impurities plus a smaller precipitate of compounds produced primarily from soluble alloying elements. While most of the phases are cathodic to aluminum, a few are anodic. In either case, they produce galvanic cells because of the potential difference between them and the aluminum matrix.

### Pitting Corrosion

As with other passive metals, any corrosion of aluminum in its passive range may be of the pitting type. This type of corrosion is produced primarily by halide ions, notably chloride, which is the one most frequently encountered in service.

Pitting of aluminum is reduced as the acidity or alkalinity is increased beyond the passive range of aluminum, at which point the corrosion attack becomes more nearly uniform.

Pits that are almost invisible to the naked eye will develop in polluted outdoor atmospheres. Their growth is relatively rapid during the first few years of exposure, but it eventually stops and seldom exceeds 200  $\mu\text{m}$ . These pits have no effect on the mechanical strength of the structure, but the bright appearance of the surface is gradually replaced

by a gray patina of corrosion products. If soot is present, it will become absorbed by the corrosion products and the patina will become dark. Exterior areas exposed to rain will generally age uniformly, but areas sheltered from the washing action of the rain will corrode and produce an uneven gray discoloration. By regularly washing these sections, this condition can be prevented.

### Galvanic Relations

The galvanic series of aluminum alloys and other metals representative of their electrochemical behavior in seawater and in most natural waters and atmospheres is shown in [Table A.29](#). The effect of alloying elements in determining the position of aluminum alloys in the series is shown in Fig. A.6. These elements, primarily copper and zinc, affect electrode potential only when they are in solid solution.

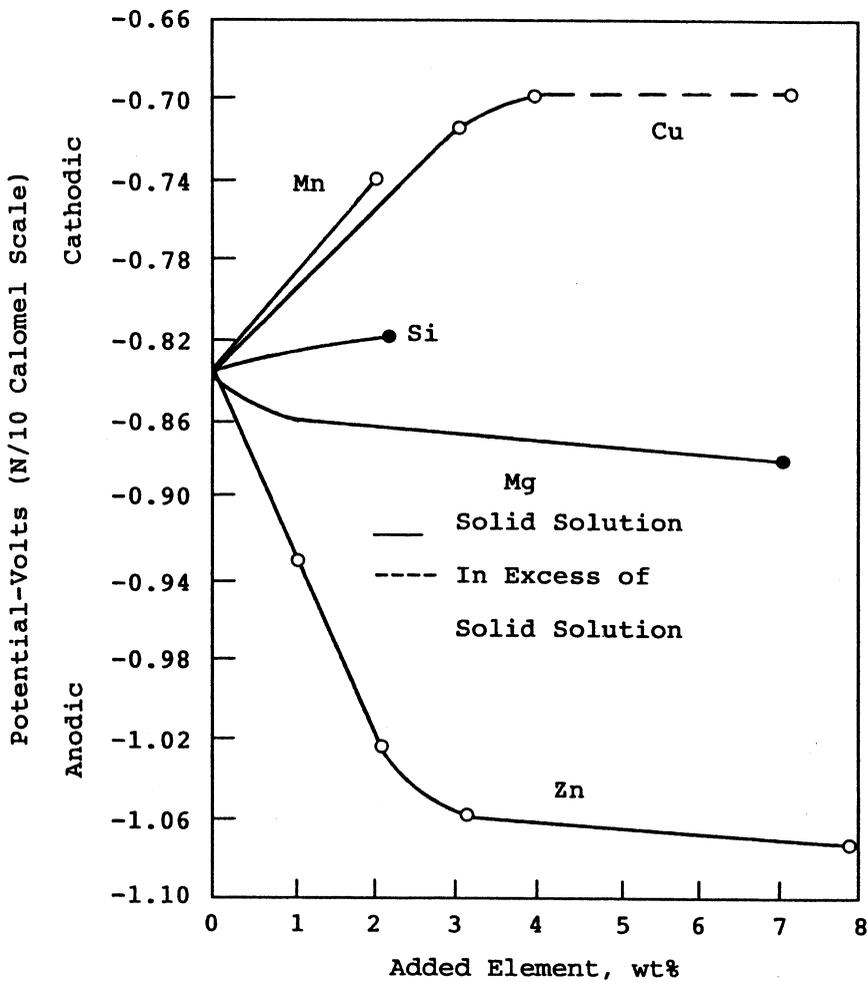


Figure A.6 Effect of alloying elements on the electrode potential of aluminum.

**Table A.29** Electrode Potentials of Representative Aluminum Alloys and Other Metals<sup>a</sup>

Aluminum alloy or other metal <sup>b</sup>	Potential (V)
Chromium	+0.18 to -0.40
Nickel	-0.07
Silver	-0.08
Stainless steel (300 series)	-0.09
Copper	-0.20
Tin	-0.49
Lead	-0.55
Mild carbon steel	-0.58
2219-T3, T4	-0.64 <sup>c</sup>
2024-T3, T4	-0.69 <sup>c</sup>
295.O-T4 (SC or PM)	-0.70
295.O-T6 (SC or PM)	-0.71
2014-T6, 355.O-T4 (SC or PM)	-0.78
355.O-T6 (SC or PM)	-0.79
221 9-T6, 6061-T4	-0.80
2024-T6	-0.81
2219-T8, 2024-T8, 356.O-T6 (SC or PM)	-0.82
443.O-F (PM), cadmium	
1100, 3003, 6061-T6, 6063-T6, 7075-T6 <sup>c</sup>	-0.83
443.O-F (SC)	
1060, 1350, 3004, 7050-T73 <sup>c</sup> , 7075-T73 <sup>c</sup>	-0.84
5052, 5086	-0.85
5454	-0.86
5456, 5083	-0.87
7072	-0.96
Zinc	-1.10
Magnesium	-1.73

<sup>a</sup>Measured in an aqueous solution of 53 g of NaCl and 3 g of H<sub>2</sub>O<sub>2</sub> per liter at 25°C; 0.1 N calomel reference electrode.

<sup>b</sup>The potential of an aluminum alloy is the same in all tempers where ever the temper is not designated.

<sup>c</sup>The potential varies  $\pm 0.01$  to 0.02 V with quenching rate.

As can be seen in Table A.29, aluminum or its alloy becomes the anode in galvanic cells with most metals and corrodes sacrificially to protect them. Only magnesium and zinc are more anodic and corrode to protect aluminum. Neither aluminum nor cadmium corrodes sacrificially in a galvanic cell because the two have nearly the same electrode potential. The degree to which aluminum is polarized in a galvanic cell will determine the degree to which aluminum corrodes when coupled to a more cathodic metal. Contact with copper and its alloys should be avoided because of the low degree of polarization of these metals. Aluminum may be used in contact with stainless steel and chromium in atmospheric and other mild environments with only a slight increase of corrosion. In these environments the two metals polarize highly; therefore, the additional corrosion current impressed onto the aluminum with them in the galvanic cell is small.

When in contact with other metals, the ratio of exposed aluminum to the more cathodic metal should be kept as high as possible. This reduces the current density on the aluminum. In order to minimize corrosion, paints and other coatings may be applied to both the aluminum and the cathodic metal, or to the cathodic metal alone, but never applied to only the aluminum since it is very difficult to apply and maintain the coatings free of defects.

Cathodic metals in nonhalide salt solutions usually corrode aluminum to a lesser degree than in solutions of halide salts. This is because the aluminum is less likely to be polarized to its pitting potential. Galvanic corrosion is reduced in any solution when the cathodic reactant is removed. Therefore, the corrosion rate of aluminum coupled with copper in seawater is reduced greatly when the seawater is de-aerated.

### Reduction of Ions of Other Metals by Aluminum

The metals most commonly encountered are copper, cobalt, lead, mercury, nickel, and tin. The corrosive action is twofold since a chemical equivalent of aluminum is oxidized for each equivalent of ion reduced, but galvanic cells are set up because the metal reduced from the ions plates onto the aluminum. Acidic solutions with reducible metallic ions are of most concern. In alkaline solutions they are less of a concern because of their greatly reduced solubilities.

Rainwater entering aluminum gutters from roofs with copper flashing is a common source of copper ions. A threshold concentration of 0.02 ppm of copper is generally accepted for the reduction of copper ions. If more than 0.25% copper is present as an alloying ingredient, the corrosion resistance of the aluminum alloy is reduced because the alloys reduce the copper ions in any corrosion product from them.

Whenever stress is present, mercury, whether reduced from its ions or introduced directly in the metallic form, can be severely damaging to aluminum. This results from the amalgamation of mercury with aluminum, which, once started, progresses for long periods since the aluminum in the amalgam oxidizes immediately in the presence of water, continuously regenerating the mercury. Any concentration in a solution of more than a few parts per billion is susceptible to attack. Under no circumstances should metallic mercury be allowed to come into contact with aluminum.

### Stress Corrosion Cracking

Stress corrosion cracking (SCC) is experienced only in aluminum alloys having appreciable amounts of copper, magnesium, silicon, and zinc as alloying elements. The cracking is normally intergranular and may be produced whenever alloying ingredients precipitate along grain boundaries, depleting the regions adjacent to them of these ingredients. Metallurgical treatment of these alloys can improve or prevent stress corrosion cracking in aluminum alloys. The process of stress corrosion cracking can be retarded greatly, if not completely eliminated, by cathodic protection.

Stress corrosion cracking of an aluminum alloy in a susceptible temper is determined by the magnitude and duration of a tensile stress acting on its surface. Resistance to SCC is highest for stressing parallel to the longitudinal direction of grains and lowest for stressing across the minimum thickness of grains. Therefore, in wrought alloys having an elongated grain structure, and in products thick enough for stressing in all directions, resistance to SCC in the short transverse direction may be the controlling factor in applying these alloys.

For SCC to take place, water or water vapor must be present; otherwise cracking will not occur. The presence of halides will accelerate cracking further.

Sufficient amounts of alloying elements are present in wrought alloys of the 2XXX, 5XXX, 6XXX, and 7XXX series to make them subject to SCC. Special treatment can cause SCC in 6XXX series, but cracking has never been experienced in commercial alloys. Tempers have been developed to provide a very high resistance to stress corrosion cracking in the other three alloy series.

### **Exfoliation Corrosion**

Exfoliation corrosion is a leafing or delamination of the product. Wrought aluminum products, in certain tempers, are subject to this type of corrosion. Alloys of the 2XXX, 5XXX, and 7XXX series are the most prone to this type of corrosion. Both exfoliation corrosion and stress corrosion cracking in alloys of this series are associated with decomposition of solid solution selectively along boundaries. Consequently, metallurgical treatment that improves resistance to SCC also improves resistance to exfoliation corrosion; however, resistance to the latter is usually achieved first.

Exfoliation corrosion is infrequent and less severe in wrought alloys of the non-heat-treatable type.

### **Weathering**

Aluminum alloys, except those containing copper as a major alloying element, have a high resistance to weathering in most atmospheres. After an initial period of exposure, the depth of attack decreases to a low rate. The loss in strength decreases in the same manner after the initial period, but not to as low a rate.

This “self-limiting” characteristic of corrosive attack during weathering also occurs with aluminum alloys in many other environments.

### **Waters**

Wrought alloys of the 1XXX, 3XXX, and 5XXX series exhibit excellent resistance to high-purity water. When first exposed a slight reaction takes place, producing a protective oxide film on the alloys within a few days, after which pickup of aluminum by water becomes negligible. The presence of carbon dioxide or oxygen dissolved in the water does not appreciably affect the corrosion resistance of these alloys; neither is the corrosion resistance affected by the chemicals added to the water to minimize the corrosion of steel because of the presence of these gases.

These same alloys are also resistant to many natural waters, their resistance being greater in neutral or slightly alkaline waters and less in acidic waters.

Resistance to corrosion by seawater is also high. General corrosion is minimal. Corrosion of these alloys in seawater is primarily of the pitting type. The rates of pitting usually range from 3 to 6  $\mu\text{m}/\text{year}$  during the first year and from 0.8 to 1.5  $\mu\text{m}/\text{year}$  averaged over a 10-year period. The lower rate for the longer period indicates the tendency of older pits to become inactive.

Alloys of the 5XXX series have the highest resistance to seawater and are widely used for marine applications.

### **General Corrosion Resistance**

All of the non-heat-treatable alloys have a high degree of corrosion resistance. These alloys, which do not contain copper as a major alloying ingredient, have a high resistance

to corrosion by many chemicals. They are compatible with dry salts of most inorganic chemicals and, within their passive range of pH 4–9 in aqueous solutions, with most halide salts, under conditions at which most alloys are polarized to their pitting potentials. In most other solutions where conditions are less likely to occur that will polarize the alloys to these potentials, pitting is not a problem.

Aluminum alloys are not compatible with most inorganic acids, bases, and salts with pH outside the passive range of 4–9.

Aluminum alloys are resistant to a wide variety of organic compounds, including most aldehydes, esters, ethers, hydrocarbons, ketones, mercaptans, other sulfur-containing compounds, and nitro compounds. They are also resistant to most organic acids, alcohols, and phenols, except when these compounds are nearly dry and near their boiling points. Carbon tetrachloride also exhibits this behavior.

Aluminum alloys are most resistant to organic compounds halogenated with chlorine, bromine, and iodine. They are also resistant to highly polymerized compounds.

It should be noted that the compatibility of aluminum alloys with mixtures of organic compounds cannot always be predicted from their compatibility with each of the compounds. For example, some aluminum alloys are corroded severely in mixtures of carbon tetrachloride and methyl alcohol, even though they are resistant to each compound alone. Caution should be exercised in using data for pure organic compounds to predict performance of the alloys with commercial grades that may contain contaminants. Ions of halides and reducible metals, commonly copper and chloride, frequently have been found to be the cause of excessive corrosion of aluminum alloys in commercial grades of organic chemicals that would not have been predicted from their resistance to pure compounds.

Regardless of environment, pure aluminum has the greatest corrosion resistance, followed by the non-heat-treatable alloys and finally the heat treatable alloys. The two most frequently used alloys are 3003 and 3004. The 3XXX series of alloys are not susceptible to the more drastic forms of localized corrosion. The principal type of corrosion encountered is pitting corrosion. With a low copper content of <0.05% the 3003 and 3004 alloys are almost as resistant as pure aluminum.

Large quantities of aluminum are used for household cooking utensils and for the commercial handling and processing of foods. Aluminum and aluminum alloys such as foil, foil laminated to plastics, and cans are used for the packaging of foods and beverages. For most applications, lacquers and plastically laminated coatings are applied to the alloys because of the long periods of exposure, where only the smallest amount of corrosion can be tolerated.

Refer to [Table A.30](#) for the compatibility of aluminum with selected corrodents. Reference 3 provides a more detailed listing.

See also [Refs. 5–7](#).

## ALUMINUM BRONZE

See “[Copper-Aluminum Alloys](#).”

## AMBIENT TEMPERATURE

Ambient temperature is the temperature of the surrounding medium coming into contact with a material or apparatus. It is not necessarily room temperature.

Table A.30 Compatibility of Aluminum Alloys with Selected Corrodents<sup>a</sup>

Chemical	Maximum temp.		Chemical	Maximum temp.	
	°F	°C		°F	°C
Acetaldehyde	360	182	Benzene	210	99
Acetamide	340	171	Benzene sulfonic acid 10%	x	x
Acetic acid 10%	110	43	Benzoic acid 10%	400	204
Acetic acid 50%	130	54	Benzyl alcohol	110	43
Acetic acid 80%	90	32	Benzyl chloride	x	x
Acetic acid, glacial	210	99	Borax	x	x
Acetic anhydride	350	177	Boric acid	100	38
Acetone	500	260	Bromine gas, dry	60	16
Acetyl chloride	x	x	Bromine gas, moist	x	x
Acrylonitrile	210	99	Bromine liquid	210	99
Adipic acid	210	99	Butadiene	110	43
Allyl alcohol	150	66	Butyl acetate	110	43
Allyl chloride	x	x	Butyl alcohol	210	99
Alum	110	43	<i>n</i> -Butylamine	90	32
Aluminum acetate	60	16	Butyl phthalate	x	x
Aluminum chloride, aqueous	x	x	Butyric acid	180	82
Aluminum chloride, dry	60	16	Calcium bisulfite	x	x
Aluminum fluoride	120	49	Calcium carbonate	x	x
Aluminum hydroxide	80	27	Calcium chlorate	140	60
Aluminum nitrate	110	43	Calcium chloride 20%	100	38
Aluminum sulfate	x	x	Calcium hydroxide 10%	x	x
Ammonia gas	x	x	Calcium hydroxide, sat.	x	x
Ammonium carbonate	350	177	Calcium hypochlorite	x	x
Ammonium chloride 10%	x	x	Calcium nitrate	170	77
Ammonium chloride 50%	x	x	Calcium oxide	90	32
Ammonium chloride, sat.	x	x	Calcium sulfate <sup>b</sup>	210	99
Ammonium fluoride 10%	x	x	Caprylic acid	300	149
Ammonium fluoride 25%	x	x	Carbon bisulfide	210	99
Ammonium hydroxide 25%	350	177	Carbon dioxide, dry	570	299
Ammonium hydroxide, sat.	350	177	Carbon dioxide, wet	170	77
Ammonium nitrate	350	177	Carbon disulfide	210	99
Ammonium persulfate	350	177	Carbon monoxide	570	299
Ammonium phosphate	x	x	Carbon tetrachloride	x	x
Ammonium sulfate 10–40%	x	x	Carbonic acid	80	27
Ammonium sulfide	170	77	Cellosolve	210	99
Ammonium sulfite	x	x	Chloracetic acid, 50% water	x	x
Amyl acetate	350	177	Chloracetic acid	x	x
Amyl alcohol	170	77	Chlorine gas, dry	210	99
Amyl chloride	90	32	Chlorine gas, wet	x	x
Aniline <sup>b</sup>	350	177	Chlorobenzene	150	66
Antimony trichloride	x	x	Chloroform, dry	170	77
Aqua regia 3:1	x	x	Chlorosulfonic acid, dry	170	77
Barium carbonate	x	x	Chromic acid 10%	200	93
Barium chloride 30%	180	82	Chromic acid 50%	100	38
Barium hydroxide	x	x	Chromyl chloride	210	99
Barium sulfate	210	99	Citric acid 15%	210	99
Barium sulfide	x	x	Citric acid, concentrated	70	21
Benzaldehyde	120	49	Copper acetate	x	x

Table A.30 Compatibility of Aluminum Alloys with Selected Corrodents<sup>a</sup> (Continued)

Chemical	Maximum temp.		Chemical	Maximum temp.	
	°F	°C		°F	°C
Copper carbonate	x	x	Nitric acid 20%	x	x
Copper chloride	x	x	Nitric acid 70%	x	x
Copper cyanide	x	x	Nitric acid, anhydrous	90	32
Copper sulfate	x	x	Nitrous acid, concentrated	x	x
Cresol	150	66	Oleum	100	38
Cupric chloride 5%	x	x	Perchloric acid 10%	x	x
Cyclohexane	180	81	Perchloric acid 70%	x	x
Cyclohexanol	x	x	Phenol	210	99
Dichloroethane (ethylene dichloride)	110	43	Phosphoric acid 50–80%	x	x
Ethylene glycol	100	38	Picric acid	210	99
Ferric chloride	x	x	Potassium bromide 30% <sup>b</sup>	80	27
Ferric chloride 50% in water	x	x	Salicylic acid	130	54
Ferric nitrate 10–50%	x	x	Silver bromide 10%	x	x
Ferrous chloride	x	x	Sodium carbonate	x	x
Fluorine gas, dry	470	243	Sodium chloride	x	x
Fluorine gas, moist	x	x	Sodium hydroxide 10%	x	x
Hydrobromic acid, dilute	x	x	Sodium hydroxide 50%	x	x
Hydrobromic acid 20%	x	x	Sodium hydroxide, concentrated	x	x
Hydrobromic acid 50%	x	x	Sodium hypochlorite 20%	80	27
Hydrochloric acid 20%	x	x	Sodium hypochlorite, concentrated	x	x
Hydrochloric acid 38%	x	x	Sodium sulfide to 50%	x	x
Hydrocyanic acid 10%	100	38	Stannic chloride	x	x
Hydrofluoric acid 30%	x	x	Stannous chloride, dry	x	x
Hydrofluoric acid 70%	x	x	Sulfuric acid 10%	x	x
Hydrofluoric acid 100%	x	x	Sulfuric acid 50%	x	x
Hypochlorous acid	x	x	Sulfuric acid 70%	x	x
Iodine solution 10%	x	x	Sulfuric acid 90%	x	x
Ketones, general	100	38	Sulfuric acid 98%	x	x
Lactic acid 25%	80	27	Sulfuric acid 100%	x	x
Lactic acid, concentrated <sup>c</sup>	100	38	Sulfuric acid, fuming	90	32
Magnesium chloride	x	x	Sulfurous acid	370	188
Malic acid	210	99	Thionyl chloride	x	x
Methyl chloride	x	x	Toluene	210	99
Methyl ethyl ketone	150	66	Trichloroacetic acid	x	x
Methyl isobutyl ketone	150	66	White liquor	100	38
Muriatic acid	x	x	Zinc chloride	x	x
Nitric acid 5%	x	x			

<sup>a</sup>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.

<sup>b</sup>Material subject to pitting.

<sup>c</sup>Material subject to intergranular corrosion.

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

## ANAEROBIC CORROSION

Anaerobic corrosion is usually caused by the sulfide metabolic reaction products (biogenic sulfides) of sulfate-reducing bacteria. It occurs where there is an abundance of sulfate and the reaction of the metal substrate is between pH 5.5 and 8.5.

Corroded steel is characterized by a coating of strongly reduced black-sulfide-containing corrosion products. Cast iron migrates from the metal, leaving a soft residue of largely carbon.

## ANNEALING

Annealing is a heating and cooling operation of a metal or alloy that usually implies relatively slow cooling. The purpose of such a heat treatment may be (a) to induce softness; (b) to remove stress; (c) to alter ductility, toughness, electrical, magnetic, or other physical properties; (d) to refine the crystalline structure; (e) to remove gases; or (f) to produce a definite microstructure. The temperature of the operation and the rate of cooling depend upon the material being heat treated and the purpose of the treatment. Certain specific heat treatments coming under the comprehensive term annealing are as follows.

### Process Annealing

Heating iron-based alloys to a temperature below or close to the lower limit of the critical temperature, generally 1000 to 1300°F (540 to 750°C).

### Normalizing

Heating iron-based alloys to approximately 100°F (50°C) above the critical temperature range, followed by cooling to below that range in still air at ordinary temperatures.

### Patenting

Heating iron-based alloys above the critical temperature range followed by cooling below that range in air, molten lead, or a mixture of nitrates and nitrites maintained at a temperature usually between 800 and 1050°F (425 to 555°C), depending on the carbon content of the steel and the properties required in the finished product. This treatment is applied in the wire industry to medium or high carbon steel as a treatment to precede further wire drawing.

### Spheradizing

Any process of heating and cooling steel that produces a rounded or globular form of carbide. The following spheradizing methods are used: (a) prolonged heating at a temperature just below the lower critical temperature, usually followed by relatively slow cooling; (b) for small objects of high carbon steels, the spheradizing result is achieved more rapidly by prolonged heating to temperatures alternately within and slightly below the critical temperature range; (c) tool steel is generally spheradized by heating to a temperature of 1380 to 1480°F (750 to 805°C) for carbon steels and higher for many alloy tool steels, holding at heat from 1 to 4 h and cooling slowly in the furnace.

### Tempering (Drawing)

Reheating carbon steel to a temperature below the lower critical temperature followed by any desired rate of cooling. Although the terms tempering and drawing are practically synonymous as used in commercial practice, the term tempering is preferred.

The term annealing is also applied to the heat treatment of polymer alloys to effect similar benefits.

See [Ref. 8](#).

## ANODE

An anode is an electrode of an electrolytic cell where oxidation is the principal reaction. It is also the electrode where corrosion usually occurs and from where metal ions enter into solution.

A sacrificial anode is a chemically active metal that when electrically connected will provide energy needed to cathodically protect a less anodic metal. Zinc, aluminum, and magnesium are commonly used as sacrificial anodes. See “[Cathodic Protection](#).”

## ANODIC PROTECTION

Anodic protection is a technique used to reduce the corrosion rate of a metal by polarizing it into its passive region. For its corrosion resistance the anodic metal is dependent upon an insoluble film that can be reinforced and maintained by the anodic effect of an impressed anodic polarization.

A typical example of anodic protection is found in steel storage tanks used to store sulfuric acid. Anodic protection systems require careful supervision, because if the proper potentials are not maintained continuously, corrosion by electrolysis may take place.

See [Refs. 9 and 10](#).

## ANODIC UNDERMINING

Anodic undermining is a form of corrosion that takes place underneath an organic coating. A typical example is the dissolution of the tin coating between the organic coating and the steel substrate in a food container. A cathodic reaction develops that may involve a component in the foodstuff, or a defect in the tin coating that may expose iron, which then serves as a cathode. Under these circumstances the tin is selectively dissolved and the coating separates from the metal and loses its protective character.

## ANODIZING

Anodizing is one commercial method whereby a conversion coating is formed by electrolytic methods. By means of anodic oxidation a thin, dense, and durable oxide film is formed on a metal surface. The predominant application is for the protection of aluminum.

Two types of oxide films have been produced on aluminum by anodic oxidation. They are porous and nonporous films. The porous oxide films are widely used for corrosion protection. They consist of a duplex layered structure having an outer porous layer and an inner nonporous layer (barrier type).

The porous structure has a strong adsorbing ability permitting the surface of an anodic film to be dyed, but it may be contaminated. Since this property of a porous layer causes the formation of corrosion cells, a process to seal the pore is a very important posttreatment.

Sealing is accomplished using hot water or steam. This process seals the pores of the aluminum by formation of boehmite ( $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$ ) or bayerite ( $\text{Al}_2\text{O}_3\text{-3H}_2\text{O}$ ). In practice sealing is conducted after dyeing, since the sealed film will not absorb dye.

An anodized coating has desirable protective, decorative, or functional properties. Titanium, stainless steel, and zirconium are also subject to anodizing.

See [Ref. 9](#).

## ARAMID FIBERS

Aramid fibers are high-strength fibers used as reinforcing in FRP structures. See “[Thermoset Reinforcing Materials](#).”

## ATMOSPHERIC CORRODENTS

See “Atmospheric Corrosion.”

## ATMOSPHERIC CORROSION

Atmospheric corrosion, though not a separate form of corrosion, has received considerable attention because of the staggering associated costs that result. With the large number of outdoor structures such as buildings, fences, bridges, towers, automobiles, ships, and innumerable other applications exposed to the atmospheric environment, it is no wonder that so much attention has been given to the subject.

Atmospheric corrosion is a complicated electrochemical process taking place in corrosion cells consisting of base metal, metallic corrosion products, surface electrolyte, and the atmosphere. Many variables influence the corrosion characteristics of an atmosphere. Relative humidity, temperature, sulfur dioxide content, hydrogen sulfide content, chloride content, amount of rainfall, dust, and even position of the exposed metal exhibit marked influences on corrosion behavior. Geographical location is also another factor.

Because this is an electrochemical process, an electrolyte must be present on the surface of the metal for corrosion to occur. In the absence of moisture, which is the common electrolyte associated with atmospheric corrosion, metals corrode at a negligible rate. For example, carbon steel parts left in a desert remain bright and tarnish free over long periods. Also in climates where the air temperature is below the freezing point of water or of aqueous condensation on the metal surface, rusting is negligible because ice is a poor conductor and does not function effectively as an electrolyte.

Atmospheric corrosion depends not only on the moisture content present but also on the dust content and the presence of other impurities in the air, all of which have an effect on the condensation of moisture on the metal surface and the resulting corrosiveness. Air temperature can also be a factor.

### Atmospheric Types

Since corrosion rates are affected by local conditions, atmospheres are generally divided into rural, industrial, and marine.

Additional subdivisions such as urban, arctic, and tropical (wet or dry) can also be included. But the three major categories are of main concern.

For all practical purposes, the more rural the area, with little or no heavy manufacturing operations, or with very dry climatic conditions, the less will be the problems of atmospheric corrosion.

In an industrial atmosphere, all types of contamination by sulfur in the form of sulfur dioxide or hydrogen sulfide are usually the most important. The burning of fossil fuels generates large amounts of sulfur dioxide, which is converted to sulfuric and sulfurous acids in the presence of moisture. Theoretically the combustion of these fossil fuels and hazardous waste products should produce only carbon dioxide, water vapor, and

inert gas as combustion products. This is seldom the case, however. Depending upon the impurities contained in the fossil fuel, the chemical composition of the hazardous waste materials incinerated, and the combustion conditions encountered, a multitude of other compounds may be formed.

In addition to the most common contaminants, previously mentioned pollutants such as hydrogen chloride, chlorine, hydrogen fluoride, and hydrogen bromide are produced as combustion products from the burning of chemical wastes. When organophosphorous compounds are incinerated, corrosive phosphorous compounds are produced. Chlorides are also a product of municipal incinerators.

Road traffic and energy production lead to the formation of  $\text{NO}_x$ , which may be oxidized to  $\text{HNO}_3$ . This reaction has a very low rate; therefore, in the vicinity of the emission source the contents of  $\text{HNO}_3$  and nitrates are very low. The antipollution regulations that have been enacted do not prevent the escape into the atmosphere of quantities of these materials sufficient to prevent corrosion problems. The corrosivity of an industrial atmosphere diminishes with increasing distance from the city.

Marine environments are subject to chloride attack resulting from the deposition of fine droplets of crystals formed by evaporation of spray that has been carried by the wind from the sea. The quantity of chloride deposition from marine environments is directly proportional to the distance from the shore. The closer to the shore, the greater the deposition and corrosive effect. The atmospheric test station at Kure Beach, NC, shows that steels exposed 80 feet from the ocean corrode ten to fifteen times faster than steels exposed 800 feet from the ocean.

In addition to these general air contaminants, there may also be specific pollutants found in a localized area. These may be emitted from a manufacturing operation on a continuous or spasmodic basis and can result in a much more serious corrosion problem than that caused by the presence of general atmospheric pollutants.

Because of these varying conditions, a material that is resistant to atmospheric corrosion in one area may not be satisfactory in another. For example, galvanized iron is perfectly suitable for application in rural atmospheres, but it is not suitable when exposed to industrial atmospheres.

### Factors Affecting Atmospheric Corrosion

As previously described, atmospheric corrosion is an electrochemical process and as such depends upon the presence of an electrolyte. The usual electrolyte associated with atmospheric corrosion is water resulting from rain, dew, fog, melting snow, and/or high humidity. Since an electrolyte is not always present, atmospheric corrosion is considered a discontinuous process. Corrosion takes place only during the "time of wetness."

#### *Time of Wetness*

This term refers to the length of time during which the metal surface is covered by a film of water that renders significant atmospheric corrosion possible. The "time of wetness" is dependent upon local climatic conditions such as the frequency of rain, fog, and dew; the temperature of the metal surface; the temperature of the air; the relative humidity of the atmosphere; the wind speed; and the hours of sunshine.

The "time of wetness" can be determined by either meteorological measurements of temperature and relative humidity or by electrochemical cells. The "time of wetness"

determined by meteorological measurements may not necessarily be the same as the actual "time of wetness," because wetness is influenced by the type of metal, pollution of the atmosphere, presence of corrosion products, and degree of coverage against rain. However, the results from these measurements usually show a good correlation with corrosion data from field tests under ordinary outdoor conditions.

### *Adsorption Layers*

The adsorption of water on the metal surface may be the result of the relative humidity of the atmosphere, of the chemical and physical properties of the corrosion products, of the properties of the materials deposited from the air, or of a combination of all three. Industrial atmospheres contain suspended particles of carbon, carbon compounds, metal oxides, sulfuric acid, sodium chloride, and ammonium sulfate. When these substances combine with moisture or when because of their hygroscopic nature they form an electrolyte on the surface, corrosion is initiated.

When hygroscopic salts which are deposited or formed by corrosion absorb moisture from the atmosphere, the metal surface may become wetted. Such absorption occurs above a certain relative humidity, called the critical relative humidity, which corresponds to the vapor pressure above a saturated solution of the salt present. The amount of water on the surface has a direct effect on the corrosion rate. The more water present, the greater the corrosion rate.

### *Phase Layers*

Phase layers are the result of the formation of dew by condensation on a cold metallic surface, or of precipitation in the form of rain or fog, and wet or melting snow. The rate of corrosion will be dependent upon the concentration and nature of the corrodents in the electrolyte, which will vary depending upon the deposition rates, frequency of wetting, drying conditions, and degree of rain protection provided.

If the surface is wetted after a long dry spell during which there has been a large accumulation of surface contamination, the corrosion rate will be greater than for a smaller amount accumulated during a shorter dry period. Corrosion will also be affected by the quantity of electrolyte present.

Dew is an important source of atmospheric corrosion—more so than rain—and particularly under sheltered conditions. Dew forms when the temperature of the metal surface falls below the dew point of the atmosphere. This can occur outdoors during the night when the surface temperature of the metal is lowered as a result of radiant heat transfer between the metal and the sky. It is also quite common for dew to form during the early morning hours when the air temperature rises faster than the metal temperature. Dew may also form when metal products are brought into warm storage after cold shipment.

Under sheltered conditions dew is an important cause of corrosion. The high corrosivity of dew is a result of several factors. Relatively speaking, the concentration of contaminants in dew is higher than in rainwater, which leads to lower pH values. Heavily industrialized areas have reported pH values of dew in the range of 3 and lower.

The washing effect, which occurs with rain, is usually slight or negligible. With little or no runoff, the pollutants remain in the electrolyte and continue their corrosive action. As the dew dries, these contaminants remain on the surface to repeat their corrosive activity with subsequent dew formations.

Depending upon the conditions, rain can either increase or decrease the effects of atmospheric corrosion. Corrosive action is caused by rain when a phase layer of moisture is formed on the metal surface. This activity is increased when the rain washes corrosive promoters such as  $H^+$  and  $SO_4^{2-}$  from the air (acid rain). Rain has the ability to decrease corrosive action on the surface of the metal as a result of washing away the pollutants that have been deposited during the preceding dry spell.

Whether the rain will increase or decrease the corrosive action is dependent upon the ratio of deposition between the dry and wet contaminants. When the dry period deposition of pollutants is greater than the wet period deposition of sulfur compounds, the washing effect of the rain will dominate and the corrosive action will be decreased.

In areas where the air is not as heavily polluted, the corrosive action of the rain will assume much greater importance because it will increase the corrosion rate.

High concentrations of sulfate and nitrate, and high acidity, will be found in areas having an appreciable amount of air pollution. The pH of fog water has been found to be in the range of 2.2 to 4.0 in highly contaminated areas. This leads to increased corrosivity.

### *Dust*

On a weight basis, in many locations, dust is the primary air contaminant. When in contact with metallic surfaces and combined with moisture, this dust can promote corrosion by forming galvanic or differential aeration cells that, because of their hygroscopic nature, form an electrolyte on the surface. This is particularly true if the dust consists of water-soluble particles, or particles on which sulfuric acid is absorbed. Dust-free air therefore is less likely to cause corrosion.

### *Temperature*

During long-term exposure in a temperate climatic zone, temperature appears to have little or no effect on the corrosion rate. The overall effect of temperature on the corrosion rate is complex. As the temperature increases, the rate of corrosive attack is increased as the result of an increase in the rate of electrochemical and chemical reactions as well as the diffusion rate. Consequently, under constant humidity conditions, a temperature increase will promote corrosion.

By the same token, an increase in temperature can cause a decrease in the corrosion rate by causing a more rapid evaporation of the surface moisture film created by rain or dew. This reduces the time of wetness, which in turn reduces the corrosion rate. In addition, as the temperature increases, the solubility of oxygen and other corrosive gases in the electrolyte film is decreased.

When the air temperature falls below 32°F (0°C) the electrolyte film may freeze. When freezing occurs, there is a pronounced decrease in the corrosion rate, which is illustrated by the low corrosion in subarctic or arctic regions.

In general, temperature is a factor influencing corrosion rates, but it is of importance only under extreme conditions.

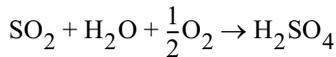
## **Specific Atmospheric Corrodents**

The electrolyte film on the surface will contain various materials deposited from the atmosphere or originating from the corroding metal. The composition of the electrolyte is often the factor that determines the rate of corrosion.

The primary contaminants in the air that lead to atmospheric corrosion are  $\text{SO}_x$ ,  $\text{NO}_x$ , chlorides, and oxygen.

### $\text{SO}_x$

Sulfur dioxide, which results from the burning of fossil fuels (such as coal and oil) and the combustion products from the incineration of organic and hazardous wastes, is the most important corrosive contaminant found in industrial atmospheres. Most of the sulfur derived from the burning of fossil fuels is emitted in the form of gaseous  $\text{SO}_2$ . Once in the atmosphere, their physical and chemical state undergoes change. The sulfur dioxide is oxidized on moist particles or in droplets of water to sulfuric acid:



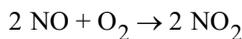
The sulfuric acid can be partially neutralized, particularly with ammonia resulting from the biological decomposition of organic matter. This neutralization forms particles containing  $(\text{NH}_4)_2\text{SO}_4$  and forms of acid ammonium sulfate such as  $\text{NH}_4\text{HSO}_4$  and  $(\text{NH}_4)_3\text{H}(\text{SO}_4)_2$ . Atmospheric corrosion results from the deposition of these various materials on metallic surfaces. Deposition of these sulfur compounds is accomplished by:

1. Dry deposition
  - a. Absorption of sulfur dioxide gas on metal surfaces
  - b. Impaction of sulfate particles
2. Wet deposition
  - a. Removal of gas from the atmosphere by precipitation in the form of rain or fog.

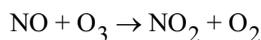
The primary cause of atmospheric corrosion is the dry deposition of sulfur dioxide on metallic surfaces. This type of corrosion is usually confined to areas having a high population, many structures, and severe pollution. Therefore, the atmospheric corrosion caused by sulfur pollutants is usually restricted to the source.

### $\text{NO}_x$

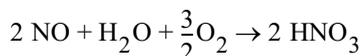
These emissions originate from combustion processes other than those emitting  $\text{SO}_x$ . Road traffic and energy production are the primary sources. Most of the nitrogen oxides are emitted as  $\text{NO}$  in combustion processes. In the atmosphere, oxidation to  $\text{NO}_2$  takes place successfully according to:



As the pollutant moves further from the source it is further oxidized by the influence of ozone:



Near the emission source nitrogen dioxide is considered to be the primary pollutant. The  $\text{NO}_2/\text{NO}$  ratio in the atmosphere varies with time and distance from the source. Allowed enough time, the  $\text{NO}_x$  may be further oxidized according to the reaction:



Since this reaction has a very slow rate, the amounts of  $\text{HNO}_3$  and nitrates in the vicinity of the source are very low.

### *Chlorides*

In marine environments chloride deposition is in the form of droplets or crystals formed by evaporation of spray that has been carried by the wind from the sea. As distance from the shore increases, this deposition decreases as the droplets and crystals are filtered off when the wind passes through vegetation, or when the particles are settled by gravity.

Gaseous HCl is a combustion product derived from the burning of coal and municipal incinerators. This gaseous HCl is very soluble in water and forms hydrochloric acid, which is extremely corrosive.

### *Oxygen*

Oxygen is a natural constituent of air and is readily absorbed from the air into the water film on the metal surface, which may be considered saturated, thus promoting any oxidation reactions.

### *Hydrogen Sulfide*

Trace amounts of hydrogen sulfide are present in some contaminated atmospheres. This can cause the tarnishing of silver and copper by the formation of tarnish films.

## **Effects on Metals Used for Outdoor Applications**

Carbon steel is the most widely used metal for outdoor applications, although large quantities of zinc, aluminum, copper, and nickel-bearing alloys are also used. Metals customarily used for outdoor installations will be discussed.

### *Carbon Steel*

Except in a dry, clean atmosphere, carbon steel does not have the ability to form a protective coating, as some other metals do. In such an atmosphere a thick oxide film will form that prevents further oxidation. Solid particles on the surface are responsible for the start of corrosion. The settled airborne dust promotes corrosion by absorbing  $\text{SO}_2$  and water vapor from the air. Even greater corrosive effects result when particles of hygroscopic salts, such as sulfates or chlorides, settle on the surface and form a corrosive electrolyte.

To protect the surface of unalloyed carbon steel, an additional surface protection must be applied. This protection usually takes the form of an antirust paint or other type of paint formulated for resistance against a specific type of contaminant known to be present in the area. On occasion, plastic or metallic coatings are used.

### *Weathering Steels*

These are steels to which small amounts of copper, chromium, nickel, phosphorus, silicon, manganese, or various combinations thereof have been added. This results in a low-alloy carbon steel that has improved corrosion resistance in rural areas, or in areas exhibiting relatively low pollution levels. Factors that affect the corrosion resistance of these steels are climatic conditions, pollution levels, degree of sheltering from the atmosphere, and specific composition of the steel. Exposure to most atmospheres results in a corrosion rate that becomes stabilized in 3 to 5 years. Over this period of time a protective film, or

patina, dark brown to violet in color, forms. This patina is a tightly adhering rust formation on the surface of the steel that cannot be wiped off. Since the formation of this film is dependent upon the pollution in the air, in rural areas where there may be little or no pollution a longer period of time may be required to form this film. In areas that have a high pollution level of  $\text{SO}_2$ , loose rust particles are formed with a much higher corrosion rate. This film of loose particles offers little or no protection against continued corrosion.

When chlorides are present, such as in a marine environment, the protective film will not be formed. Under these conditions corrosion rates of the weathering steels are equivalent to those of unalloyed carbon steel.

In order to form the patina, periodic flushing followed by a dry period is required. If the steel is installed in such a manner as to be sheltered from the rain, the dark patina will not be formed. Instead, a rust lighter in color forms, which provides the same resistance. The corrosion rate of the weathering steels will be the same as the corrosion rate of unalloyed steel when it is continuously exposed to wetness, such as in water or soil.

Since the patina formed has a pleasant aesthetic appearance, the weathering steels can be used without the application of any protective coating of antirust paint, zinc, or aluminum. This is particularly true in urban and rural areas.

In order to receive the maximum benefit from weathering steels, consideration must be given to the design. The design should eliminate all possible areas where water, dirt, and corrosion products can accumulate. When pockets are present, the time of wetness increases, which leads to the development of corrosive conditions. The design should make maximum use of exposure to the weather. Sheltering from rain should be avoided.

While the protective film is forming, rusting will proceed at a relatively high rate, during which time rusty water is produced. This rusty water may stain masonry, pavements and the like. Consequently, steps should be taken to prevent detrimental staining effects, such as coloring the masonry brown, so that any staining will not be obvious.

### *Zinc*

Galvanized steel (zinc-coated steel) is used primarily in rural or urban atmospheres for protection from atmospheric corrosion. Galvanizing will also resist corrosion in marine atmospheres, provided saltwater spray does not come into direct contact. In areas where  $\text{SO}_2$  is present in any appreciable quantity, galvanized surfaces will be attacked.

### *Aluminum*

Except for those aluminum alloys that contain copper as a major alloying ingredient, aluminum alloys have a high resistance to weathering in most atmospheres. When exposed to air, the surface of the aluminum becomes covered with an amorphous oxide film that provides protection against atmospheric corrosion, particularly  $\text{SO}_2$ .

The shiny metal appearance of aluminum gradually disappears and becomes rough when exposed to  $\text{SO}_2$ . A gray patina of corrosion products forms on the surface. If aesthetics are a consideration, the original surface luster can be retained by anodizing. This anodic oxidation strengthens the oxide coating and improves its protective properties.

It is important that the design utilizing aluminum should eliminate rain-sheltered pockets on which dust and other pollutants may collect. The formation of the protective film will be disturbed and corrosion accelerated by the presence of these pollutants.

### *Copper*

When exposed to the atmosphere over long periods of time, copper will form a coloration on the surface known as patina, which in reality is a corrosion product that acts as a protective film against further corrosion. The length of time required to form the patina depends upon the atmospheres, because the color is due to the formation of copper hydroxide compounds. Initially the patina has a dark color; gradually it turns green. In urban or industrial atmospheres the compound is a mixture of copper/hydroxide/chloride. It takes approximately 7 years for these compounds to form. When exposed to clean or rural atmospheres tens or hundreds of years may be required to form the patina.

The corrosion resistance of copper is the result of the formation of this patina or protective film. Copper roofs are still in existence on many castles and monumental buildings that are centuries old.

### *Nickel 200*

When exposed to the atmosphere a thin corrosion film (usually a sulfate) forms, dulling the surface. The rate of corrosion is extremely slow but increases as the SO<sub>2</sub> content of the atmosphere increases. When exposed to marine or rural atmospheres the corrosion rate is very low.

### *Monel Alloy 400*

The corrosion of monel is negligible in all types of atmospheres. When exposed to rain a thin gray-green patina forms. In sulfurous atmospheres, a smooth brown adherent film forms.

### *Inconel Alloy 600*

In rural atmospheres Inconel alloy 600 will remain bright for many years. When exposed to sulfur-bearing atmospheres a slight tarnish is apt to develop. It is desirable to expose this alloy to atmospheres where the beneficial effects of rain in washing the surface and sun and wind in drying can be utilized. It is not recommended to design on the basis of sheltered exposure.

See [Refs. 6, 11–15](#).

## AUSTENITE

Austenite is a form of carbon steel with a face-centered cubic crystal structure. This form of carbon steel cannot exist below 1333°F (710°C). During heat treatment the holding temperature and time is specified so that the alloy becomes fully austenitic. For common carbon steels the holding temperature is typically specified at 1650°F (900°C). This will make the alloy fully austenitic.

Since austenite has a higher solubility for carbon than the lower-temperature forms of carbon steel, heating the steel to an austenizing temperature causes any carbides that may have formed at the lower temperature to dissolve. Alloys that can form austenite at high temperatures, but transform to other crystal forms at lower temperatures, are capable of being hardened by heat treatment. Martensitic steels are an example.

The austenitic microstructure can be made to be stable at low temperatures by alloying with nickel or manganese. See “[Austenitic Stainless Steels](#).”

## AUSTENITIC DUCTILE CAST IRONS

These cast irons are similar to the austenitic gray cast irons except that they have been treated with magnesium to produce a nodular graphite structure, thereby producing a ductile material. Several different grades are produced, with grade D-2 being the most commonly used grade.

These alloys find use in mildly oxidizing acids, alkalis, salts, seawater, water, foods, plastics, and synthetic fiber manufacturing.

See [Refs. 16](#) and [17](#).

## AUSTENITIC GRAY CAST IRONS

The austenitic gray cast irons are gray irons that have been alloyed with nickel and sometimes copper to produce an austenitic matrix similar to that of the 300 series stainless

## AUSTENITIC STAINLESS STEELS

The austenitic stainless steels are the most widely used family of stainless alloys. They find application in settings ranging from mildly corrosive atmospheres to extremely corrosive environments. This group of alloys are nonmagnetic and are the most important for process industry applications. These stainless steels have a face-centered austenite structure from far below zero up to near melting temperatures as a result of the alloy additions of nickel and manganese. They are not hardenable by heat treatment but can be strain hardened by cold work, which also includes a small amount of ferromagnetism.

To form the austenitic structure it is necessary to add about 8% nickel to the 18% chromium plateau to cause the transition from ferritic to austenitic. Compared with the ferritic structure, the austenitic structure is very tough, formable, and weldable. The nickel addition also improves the corrosion resistance to mild corrosents. This includes resistance to most foods, a wide range of organic chemicals, mild inorganic chemicals, and most natural environments.

To further improve the corrosion resistance, molybdenum is added. This provides excellent corrosion resistance in oxidizing environments, particularly in aqueous solutions. The molybdenum aids in strengthening the passive film which forms on the surface of the stainless steel along with chromium and nickel. The types of stainless steels comprising this group are as follows:

201	304	316L
202	304L	317
22-13-5	305	317L
216L	308	321
301	309	329
302	310	347
303	316	348

Austenitic alloys also make use of the concept of stabilization. Stainless steel types 321 and 347 are stabilized with titanium and niobium, respectively. Another approach is taken to avoid the effects of chromium carbide precipitation. Since the amount of chro-

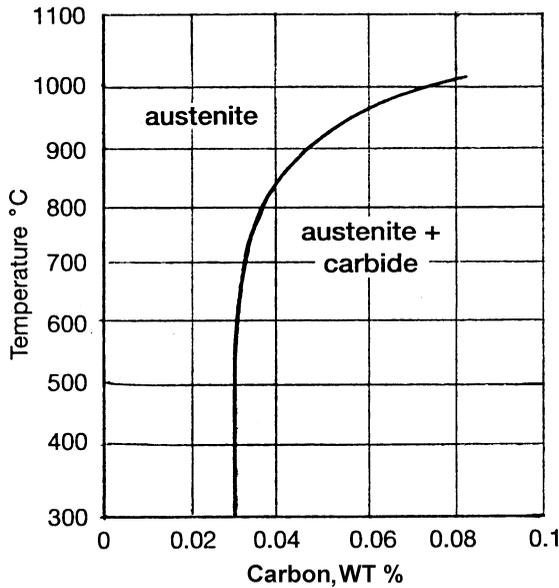


Figure A.7 Solubility of carbon in austenite.

mium that will precipitate is proportional to the amount of carbon present, lowering the carbon content will prevent sensitization.

From an examination of Fig. A.7 it can be seen that by maintaining the carbon content below about 0.035%, versus the usual 0.08% maximum, the harmful effects of chromium carbide precipitation can be avoided. This fact along with improvements in melting technology has resulted in the development of the low-carbon version of many of these alloys.

Various other elements are added to enhance specific properties. The 200 and 300 series of stainless steels both start with the same high-temperature austenite phase that exists in carbon steel, but as mentioned previously retain this structure to below zero. The 200 series of alloys rely mostly on manganese and nitrogen, while the 300 series utilize nickel. Both series of stainless steels have useful levels of ductility and strength. Grades 201 and 301, which are on the lean side of the retention elements, will transform to martensite when formed, but cool to austenite. This results in high-strength parts made by stretching a low-strength starting material. Table A.31 gives the chemical composition of the most commonly used austenitic stainless steels.

As previously mentioned, the corrosion resistance of the austenitic stainless steels is the result of the formation of a passive oxide film on the surface of the metal. Consequently, they perform best under oxidizing conditions, since reducing conditions and chloride ions destroy the film, causing rapid attack. Chloride ions combined with high tensile stresses cause stress corrosion cracking.

### Type 201 (S20100)

This is one of the alloys based on the substitution of manganese for nickel because of the shortage of nickel during and shortly after World War II. It was developed as a substitute

Table A.31 Chemical Composition of Austenitic Stainless Steels

AISI Type	C max.	Mn max.	Si	Cr	Ni	Others <sup>a</sup>
210	0.15	7.5 <sup>b</sup>	1.00	16.00–8.00	3.50–5.50	0.25 max. N
202	0.15	10.00 <sup>c</sup>	1.00	17.00–19.00	4.00–6.00	0.25 max. N
205	0.25	10.50 <sup>d</sup>	0.50	16.50–18.00	1.00–1.75	0.32–0.4 max. N
301	0.15	2.00	1.00	16.00–18.00	6.00–8.00	
302B	0.15	2.00	3.00 <sup>d</sup>	17.00–19.00	8.00–10.00	
303	0.15	2.00	1.00	17.00–19.00	8.00–10.00	0.15 min. S
303 (Se)	0.15	2.00	1.00	17.00–19.00	8.00–10.00	0.15 min. Se
304	0.08	2.00	1.00	18.00–20.00	8.00–12.00	
304L	0.03	2.00	1.00	18.00–20.00	8.00–12.00	
304N	0.08	2.00	1.00	18.00–20.00	8.00–10.50	0.1–0.16 N
305	0.12	2.00	1.00	17.00–19.00	10.00–13.00	
308	0.08	2.00	1.00	19.00–21.00	10.00–12.00	
309	0.20	2.00	1.00	22.00–24.00	12.00–15.00	
309S	0.08	2.00	1.00	22.00–24.00	12.00–15.00	
310	0.25	2.00	1.50	24.00–26.00	19.00–22.00	
310S	0.08	2.00	1.50	24.00–26.00	19.00–22.00	
314	0.25	2.00	3.00 <sup>e</sup>	23.00–26.00	19.00–22.00	
316	0.08	2.00	1.00	16.00–18.00	10.00–14.00	2.00–3.00 Mo
316F	0.08	2.00	1.00	16.00–18.00	10.00–14.00	1.75–2.50 Mo
316L	0.03	2.00	1.00	16.00–18.00	10.00–14.00	2.00–3.00 Mo
316N	0.08	2.00	1.00	16.00–18.00	10.00–14.00	2.00–3.00 Mo
317	0.08	2.00	1.00	18.00–20.00	11.00–15.00	3.00–4.00 Mo
317L	0.03	2.00	1.00	18.00–20.00	11.00–15.00	3.00–4.00 Mo
321	0.08	2.00	1.00	17.00–19.00	9.00–12.00	5 × min. Cb-Ta
330	0.08	2.00	1.50	17.00–20.00	34.00–39.00	0.10 Ta
347	0.08	2.00	1.00	17.00–19.00	9.00–13.00	10 × min. Cb-Ta
348	0.08	2.00	1.00	17.00–19.00	9.00–13.00	10 × min. Cb-Ta, 2.0 Mo, 3.0 Cu

<sup>a</sup>Other elements in addition to those shown are as follows:

Phosphorus is 0.03% max. in type 205; 0.06% max. in type 202 and 205; 0.045% max. in types 301, 302, 302B, 304, 304L, 304N, 305, 308, 309, 310, 310S, 314, 316, 316N, 316L, 317, 317L, 321, 330, 347, and 348; 0.2% max. in types 303, 303 (Se), and 316D. Sulfur is 0.30% max. in types 201, 202, 205, 301, 302, 302B, 304, 304L, 304N, 305, 308, 309, 309S, 310, 310X, 314, 316, 316L, 316N, 317, 317L, 321, 330, 347, and 348; 0.15% min. in type 303; and 0.10% min. in type 316D.

b = Mn range 4.40–7.50%

c = Mn range 7.50–10.00%

d = Mn range 14.00–15.50%

e = Si range 2.00–3.00%

f = Si range 1.500–3.00

for type 304 stainless steel. By adding about 4% manganese and 0.2% nitrogen, the nickel content could be lowered to about 5%. The chemical composition is shown in Table A.31. Although the strength of this alloy is higher than that of type 304, its corrosion resistance is inferior. It does have a corrosion resistance comparable to type 301.

This alloy can be cold worked to high strength levels. It is nonmagnetic as annealed and becomes somewhat magnetic after cold work. Table A.32 shows the mechanical and physical properties of type 201 and 202 stainless steel.

**Table A.32** Mechanical and Physical Properties of Types 201 and 202 Stainless Steel

Property	Type 201	Type 202
Modulus of elasticity $\times 10^6$ (psi)	28.6	28.6
Tensile strength $\times 10^3$ (psi)	95	90
Yield strength 0.2% offset $\times 10^3$ (psi)	45	45
Elongation in 2 in. (%)	40	40
Rockwell hardness	B-90	B-90
Density (lb/in. <sup>3</sup> )	0.28	0.28
Specific gravity	7.7	7.7
Specific heat at 32–212°F (Btu/lb °F)	0.12	0.12
Thermal conductivity at 212°F (Btu/hr ft <sup>2</sup> °F)	9.4	9.4
Izod impact (ft-lb)	115	

**Type 22-13-5 (S20910)**

This is a nitrogen-strengthened stainless alloy having the following composition:

Carbon	0.06%
Manganese	4.00–6.00%
Phosphorous	0.040%
Sulfur	0.030%
Silicon	1.00%
Chromium	20.50–23.50%
Nickel	11.50–13.50%
Molybdenum	1.50–3.00%
Niobium	0.10–0.30%
Vanadium	0.10–0.30%
Nitrogen	0.20–0.40%
Iron	Balance

It is superior in corrosion resistance to type 316 stainless steel with twice the yield strength. It can be welded, machined, and cold worked using the same equipment and methods used for the conventional 300 series stainless steels. It remains nonmagnetic after cold work.

Type 22-13-5 stainless steel has very good corrosion resistance in many reducing and oxidizing acids, chlorides, and pitting environments. It has a pitting resistance equivalent number (PREN) of 45.5. In particular, the alloy provides an excellent level of resistance to pitting and crevice corrosion in seawater. Resistance to intergranular attack in boiling 65% nitric acid and in ferric sulfate–sulfuric acid, is excellent for both the annealed and sensitized conditions. Like other austenitic stainless steels, S20910 under certain conditions may suffer stress corrosion cracking in hot chloride environments. This alloy also exhibits good resistance to sulfide stress cracking at ambient temperatures.

This alloy is sometimes referred to as nitronic 50. Refer to [Table A.33](#) for the mechanical and physical properties of S20910 stainless steel.

**Table A.33** Mechanical and Physical Properties of S20910 Stainless Steel

Property	
Modulus of elasticity $\times 10^6$ (psi)	28
Tensile strength $\times 10^3$ (psi)	210
Yield strength 0.2% offset $\times 10^3$ (psi)	65
Elongation in 2 in. (%)	45
Rockwell hardness	B-96
Density (lb/in. <sup>3</sup> )	0.285
Specific gravity	7.88
Specific heat at 32–212°F (Btu/lb °F)	0.12
Thermal conductivity at 300 °F (Btu/hr ft <sup>2</sup> °F)	108
Thermal expansion coefficient at 32–212°F $\times 10^{-6}$ (in./in. °F)	9.0
Izod impact (ft-lb)	160

**Type 216L (S21603)**

This is a low-carbon alloy in which a portion of the nickel has been replaced by molybdenum. It has the following composition:

Carbon	0.30%
Manganese	7.50–9.00%
Chromium	17.50–22.00%
Molybdenum	2.00–3.00%
Silicon	1.00%
Iron	Balance

This alloy finds application in aircraft, hydraulic lines, heat exchanger tubes, pollution control equipment, and particle accelerator tubes.

**Type 301 (S30100)**

This is a nitrogen-strengthened alloy that has the ability to work harden. As with the 200 series alloys, it forms martensite while deforming but retains the contained strain to higher levels. The chemical composition is shown in [Table A.31](#). Types 301L and 301LN find application in passenger rail cars, buses, and light rail vehicles. The chemical compositions of type 301L (S30103) and type 301LN (S30153) are as follows:

Alloying element	Alloy (%)	
	301L	301LN
Carbon	0.030 max.	0.030 max.
Chromium	16.0–18.0	16.0–18.0
Manganese	2.0 max.	2.0 max.
Nitrogen	0.20 max	0.07–0.20
Nickel	5.0–8.0	5.0–8.0
Phosphorus	0.045 max.	0.045 max.
Sulfur	0.030 max.	0.030 max.
Silicon	1.0 max.	1.0 max.

**Table A.34** Mechanical and Physical Properties of Type 301 Stainless Steel

Property	
Modulus of elasticity $\times 10^6$ (psi)	28
Tensile strength $\times 10^3$ (psi)	110
Yield strength 0.2% offset $\times 10^3$ (psi)	40
Elongation in 2 in. (%)	60
Rockwell hardness	B-95
Density (lb/in. <sup>3</sup> )	0.29
Specific gravity	8.02
Specific heat at 32–212°F (Btu/lb °F)	8.12
Thermal conductivity at 212°F (Btu/hr ft <sup>2</sup> °F)	93
Thermal expansion coefficient at 32–212°F $\times 10^{-6}$ (in./in. °F)	9.4
Izod impact (ft-lb)	

Refer to Table A.34 for the mechanical and physical properties.

### Type 302 (S30200)

Type 302 and type 302B are nonmagnetic, extremely tough and ductile, and two of the most widely used of the chromium-nickel stainless and heat-resisting steels. They are hardenable by heat treating. The chemical composition is shown in Table A.31 and the mechanical and physical properties are shown in Table A.35.

### Type 303 (S30300)

This is a free-machining version of type 304 stainless steel for automatic machining. It is corrosion resistant to atmospheric exposures, sterilizing solutions, most organic and many inorganic chemicals, most dyes, nitric acid, and foods. The chemical composition is given in Table A.31, and the mechanical and physical properties are listed in Table A.36.

### Type 304 (S30400)

Type 304 stainless steels are the most widely used of all stainless steels. Although they have a wide range of corrosion resistance, they are not the most corrosion resistant of

**Table A.35** Mechanical and Physical Properties of Types 302 and 302B Stainless Steel

Property	Type 302	Type 302B
Modulus of elasticity $\times 10^6$ (psi)	28	28
Tensile strength $\times 10^3$ (psi)	90	95
Yield strength 0.2% offset $\times 10^3$ (psi)	40	40
Elongation in 2 in. (%)	50	55
Rockwell hardness	B-85	B-85
Density (lb/in. <sup>3</sup> )	0.29	0.29
Specific gravity	8.02	8.02
Specific heat at 32–212°F (Btu/lb °F)	0.12	0.12
Thermal conductivity at 212°F (Btu/hr ft <sup>2</sup> °F)	9.3	9.3
Thermal expansion coefficient at 32–212°F $\times 10^{-6}$ (in./in. °F)	9.6	9.6
Izod impact (ft-lb)		

**Table A.36** Mechanical and Physical Properties of Types 303 and 303Se Stainless Steel

Property	Type 303	Type 303Se
Modulus of elasticity $\times 10^6$ (psi)	28	28
Tensile strength $\times 10^3$ (psi)	90	90
Yield strength 0.2% offset $\times 10^3$ (psi)	35	35
Elongation in 2 in. (%)	50	50
Rockwell hardness		
Density (lb/in. <sup>3</sup> )	0.29	0.29
Specific gravity	8.027	8.027
Specific heat at 32–212°F (Btu/lb °F)	9.3	9.3
Thermal conductivity at 212°F (Btu/hr ft <sup>2</sup> °F)		
Thermal expansion coefficient at 32–212°F $\times 10^{-6}$ (in./in. °F)		
Izod impact (ft-lb)	120	

the austenitic stainlesses. The chemical composition of various 304 alloys are shown in [Table A.31](#).

Type 304 stainless steel is subject to intergranular corrosion as a result of carbide precipitation. Welding can cause this phenomenon, but competent welders using good welding techniques can control the problem. Depending on the particular corrodent being handled, the effect of carbide precipitation may or may not present a problem. If the corrodent will attack through intergranular corrosion, another alloy should be used.

If the carbon content of the alloy is not allowed to exceed 0.030%, carbide precipitation can be controlled. Type 304L is such an alloy. This alloy can be used for welded sections with no danger of carbide precipitation.

Type 304N has nitrogen added to the alloy, which improves its resistance to pitting and crevice corrosion.

Types 304 and 304L stainless steel exhibit good overall corrosion resistance. They are used extensively in the handling of nitric acid. Refer to [Table A.37](#) for the compatibility of the alloys with selected corrodents and to [Table A.38](#) for the mechanical and physical properties.

### Type 305 (S30500)

Type 305 stainless steel is used extensively for cold heading, severe deep drawing, and spinning operations. The chemical composition is shown in [Table A.31](#). Type 305 stainless steel has the equivalent corrosion resistance of type 304 stainless steel. Refer to [Table A.39](#) for the mechanical and physical properties.

**Table A.37** Compatibility of Types 304, 304L, and 347 Stainless Steel with Selected Corrodents<sup>a</sup>

Chemical	Maximum temp.		Chemical	Maximum temp.	
	°F	°C		°F	°C
Acetaldehyde	200	93	Acetic acid, glacial	210	99
Acetamide	100	38	Acetic anhydride	220	104
Acetic acid 10%	200	93	Acetone	190	88
Acetic acid 50%	170	77	Acetyl chloride	100	38
Acetic acid 80%	170	77	Acrylic acid	130	54

**Table A.37** Compatibility of Types 304, 304L, and 347 Stainless Steel with Selected Corrodents<sup>a</sup> (Continued)

Chemical	Maximum temp.		Chemical	Maximum temp.	
	°F	°C		°F	°C
Acrylonitrile	210	99	Bromine gas, moist	x	x
Adipic acid	210	99	Bromine liquid	x	x
Allyl alcohol	220	104	Butadiene	180	82
Allyl chloride	120	49	Butyl acetate	80	27
Alum	x	x	Butyl alcohol	200	93
Aluminum acetate	210	99	Butyl phthalate	210	99
Aluminum chloride, aqueous	x	x	Butyric acid	180	82
Aluminum chloride, dry	150	66	Calcium bisulfite <sup>d</sup>	300	149
Aluminum fluoride	x	x	Calcium carbonate	210	99
Aluminum hydroxide	80	27	Calcium chlorate 10%	210	99
Aluminum nitrate	80	27	Calcium chloride <sup>b,c</sup>	80	27
Aluminum sulfate <sup>b</sup>	210	99	Calcium hydroxide 10%	210	99
Ammonia gas	90	32	Calcium hydroxide, sat.	200	93
Ammonium carbonate	200	93	Calcium hypochlorite	x	x
Ammonium chloride 10%	230	110	Calcium nitrate	90	32
Ammonium chloride 50%	x	x	Calcium oxide	90	32
Ammonium chloride, sat.	x	x	Calcium sulfate	210	99
Ammonium fluoride 10%	x	x	Caprylic acid <sup>a</sup>	210	99
Ammonium fluoride 25%	x	x	Carbon bisulfide	210	99
Ammonium hydroxide 25%	230	110	Carbon dioxide, dry	210	99
Ammonium hydroxide, sat.	210	99	Carbon dioxide, wet	200	93
Ammonium nitrate <sup>c</sup>	210	99	Carbon disulfide	210	99
Ammonium persulfate	x	x	Carbon monoxide	570	299
Ammonium phosphate 40%	130	54	Carbon tetrachloride	210	99
Ammonium sulfate 10–40%	x	x	Carbonic acid	210	99
Ammonium sulfide	210	99	Cellosolve	210	99
Ammonium sulfite	210	99	Chloroacetic acid, 50% water	x	x
Amyl acetate	300	149	Chloroacetic acid	x	x
Amyl alcohol	80	27	Chlorine gas, dry	x	x
Amyl chloride	150	66	Chlorine gas, wet	x	x
Aniline	500	260	Chlorine, liquid <sup>b</sup>	110	43
Antimony trichloride	x	x	Chlorobenzene	210	99
Aqua regia 3:1	x	x	Chloroform <sup>c</sup>	210	99
Barium carbonate	80	27	Chlorosulfonic acid	x	x
Barium chloride	x	x	Chromic acid 10%	200	93
Barium hydroxide	230	110	Chromic acid 50%	90	32
Barium sulfate	210	99	Chromyl chloride	210	99
Barium sulfide	210	99	Citric acid 15%	210	99
Benzaldehyde	210	99	Citric acid, concentrated	80	27
Benzene	230	110	Copper acetate	210	99
Benzene sulfonic acid 10%	210	99	Copper carbonate 10%	80	27
Benzoic acid	400	204	Copper chloride	x	x
Benzyl alcohol	90	32	Copper cyanide	210	99
Benzyl chloride	210	99	Copper sulfate <sup>d</sup>	210	99
Borax	150	66	Cresol	160	71
Boric acid <sup>b</sup>	400	204	Cupric chloride 5%	x	x
Bromine gas, dry	x	x	Cupric chloride 50%	x	x

**Table A.37** Compatibility of Types 304, 304L, and 347 Stainless Steel with Selected Corrodents<sup>a</sup> (Continued)

Chemical	Maximum temp.		Chemical	Maximum temp.	
	°F	°C		°F	°C
Cyclohexane	100	38	Nitric acid, anhydrous	80	27
Cyclohexanol	80	27	Nitrous acid, concentrated	80	27
Dichloroethane (ethylene dichloride)	210	99	Oleum	100	38
Ethylene glycol	210	99	Perchloric acid 10%	x	x
Ferric chloride	x	x	Perchloric acid 70%	x	x
Ferric chloride 50% in water	x	x	Phenol <sup>b</sup>	560	293
Ferric nitrate 10–50%	210	99	Phosphoric acid 50-80% <sup>d</sup>	120	49
Ferrous chloride	x	x	Picric acid <sup>b</sup>	300	149
Fluorine gas, dry	470	243	Potassium bromide 30%	210	99
Fluorine gas, moist	x	x	Salicylic acid	210	99
Hydrobromic acid, dilute	x	x	Silver bromide 10%	x	x
Hydrobromic acid 20%	x	x	Sodium carbonate 30%	210	99
Hydrobromic acid 50%	x	x	Sodium chloride to 30% <sup>b</sup>	210	99
Hydrochloric acid 20%	x	x	Sodium hydroxide 10%	210	99
Hydrochloric acid 38%	x	x	Sodium hydroxide 50%	210	99
Hydrocyanic acid 10%	210	99	Sodium hydroxide, concentrated	90	32
Hydrofluoric acid 30%	x	x	Sodium hypochlorite 20%	x	x
Hydrofluoric acid 70%	x	x	Sodium hypochlorite, concentrated	x	x
Hydrofluoric acid 100%	x	x	Sodium sulfide to 50% <sup>b</sup>	210	99
Hypochlorous acid	x	x	Stannic chloride	x	x
Iodine solution 10%	x	x	Stannous chloride	x	x
Ketones, general	200	93	Sulfuric acid 10%	x	x
Lactic acid 25% <sup>b,d</sup>	120	49	Sulfuric acid 50%	x	x
Lactic acid, concentrated <sup>b,d</sup>	80	27	Sulfuric acid 70%	x	x
Magnesium chloride	x	x	Sulfuric acid 90% <sup>d</sup>	80	27
Malic acid 50%	120	49	Sulfuric acid 98% <sup>d</sup>	80	27
Manganese chloride	x	x	Sulfuric acid 100% <sup>d</sup>	80	27
Methyl chloride <sup>b</sup>	210	99	Sulfuric acid, fuming	90	32
Methyl ethyl ketone	200	93	Sulfurous acid	x	x
Methyl isobutyl ketone	200	93	Thionyl chloride	x	x
Muriatic acid	x	x	Toluene	210	99
Nitric acid 5%	210	99	Trichloroacetic acid	x	x
Nitric acid 20%	190	88	White liquor	100	38
Nitric acid 70%	170	77	Zinc chloride	x	x

<sup>a</sup>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.

<sup>b</sup>Subject to pitting.

<sup>c</sup>Subject to stress cracking.

<sup>d</sup>Subject to intergranular attack (type 304).

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

**Table A.38** Mechanical and Physical Properties of Types 304 and 304L Stainless Steel

Property	Type of alloy	
	304	304L
Modulus of elasticity $\times 10^6$ psi	28.0	28.0
Tensile strength $\times 10^3$ psi	85	80
Yield strength 0.2% offset $\times 10^3$ psi	35	30
Elongation in 2 in., %	55	55
Hardness, Rockwell	B-80	B-80
Density, lb/in. <sup>3</sup>	0.29	0.29
Specific gravity	8.02	8.02
Specific heat (32–212°F), Btu/lb °F	0.12	0.12
Thermal conductivity, Btu/h ft <sup>2</sup> °F at 212°F	9.4	9.4
Thermal expansion coefficient (32–212°F) $\times 10^{-6}$ in./in. °F	9.6	9.6
Izod impact, ft-lb	110	110

**Table A.39** Mechanical and Physical Properties of Alloy Type 305 Stainless Steel

Property	
Modulus of elasticity $\times 10^6$ (psi)	28
Tensile strength $\times 10^3$ (psi)	85
Yield strength 0.2% offset $\times 10^3$ (psi)	35
Elongation in 2 in. (%)	50
Rockwell hardness	B-80
Density (lb/in. <sup>3</sup> )	0.29
Specific gravity	8.027

**Table A.40** Mechanical and Physical Properties of Alloy Type 308 Stainless Steel

Property	
Modulus of elasticity $\times 10^6$ (psi)	28
Tensile strength $\times 10^3$ (psi)	115
Yield strength 0.2% offset $\times 10^3$ (psi)	80
Elongation in 2 in. (%)	40
Rockwell hardness	B-80

**Type 308 (S30800)**

The chemical composition of type 308 stainless steel is given in [table A.31](#). Note that this alloy has an increased chromium and nickel content over that of type 304 stainless steel. In the annealed condition, type 308 exhibits greater yield and tensile strength than annealed type 304. The corrosion resistance of type 308 is slightly better than that of 304 stainless. Refer to Table A.40 for the mechanical and physical properties.

**Table A.41** Mechanical and Physical Properties of Types 309 and 309S Stainless Steel

Property	Type 309	Type 309S
Modulus of elasticity $\times 10^6$ (psi)	29	29
Tensile strength $\times 10^3$ (psi)	90	90
Yield strength 0.2% offset $\times 10^3$ (psi)	45	45
Elongation in 2 in. (%)	45	45
Rockwell hardness	B-85	B-85
Density (lb/in. <sup>3</sup> )	0	0.29
Specific gravity	8.02	8.02
Specific heat at 32–212°F (Btu/lb °F)	0.12	0.12
Thermal conductivity at 212°F (Btu/hr ft <sup>2</sup> °F)	8	8
Thermal expansion coefficient at 32–212°F $\times 10^{-6}$ (in./in. °F)	8.3	8.3

### Type 309 (S30900)

Types 309 and 309S are superior heat-resisting stainless alloys. They are applicable for continuous exposure to 2000°F (1093°C) and for intermittent exposure to 1800°F (982°C). The chemical composition is shown in [Table A.31](#).

Types 309 and 309S have slightly better corrosion resistance to the corrosive action of high-sulfur gases, provided they are oxidizing, but poor resistance to reducing gases like hydrogen sulfide. These alloys are excellent in resisting sulfite liquors, nitric acid, nitric-sulfuric acid mixtures, and acetic and lactic acids. Type 309S, with a maximum of 0.08% carbon, resists corrosion in welded parts. These alloys may be susceptible to chloride stress corrosion cracking. The mechanical and physical properties are shown in [Table A.41](#).

### Type 310 (S31000)

This is an alloy for high temperatures. It is an improvement over types 309 and 309S. The 310 and 310S alloys have a maximum allowable temperature of 2100°F (1149°C) at continuous operation and 1900°F (1037°C) for intermittent service. Chemical compositions are shown in [Table A.31](#).

These alloys have better general corrosion resistance than type 304 and type 309. They have excellent high-temperature oxidation resistance and good resistance to both carburizing and reducing environments. Chloride stress corrosion cracking may cause a problem under the right conditions. Type 310S, with 0.08% maximum carbon, offers improved resistance in welded components. Refer to [Table A.42](#) for the mechanical and physical properties.

### Type 316 (S31600)

These chromium-nickel grades of stainless steel have molybdenum added in the range of 2–3%. The molybdenum substantially increases resistance to pitting and crevice corrosion in systems containing chlorides and improves overall resistance to most types of corrosion in chemical-reducing neutral solutions.

In general, these alloys are more corrosion resistant than type 304 stainless steels. With the exception of oxidizing acids, such as nitric, the type 316 alloys will provide satisfactory resistance to corrodents handled by type 304 with the added ability to handle some corrodents that type 304 alloy cannot handle.

Type 316L stainless steel is the low-carbon version of type 316 and offers the additional feature of preventing excessive intergranular precipitation of chromium carbides

**Table A.42** Mechanical and Physical Properties of Type 310 and Type 310S Stainless Steel

Property	Type 310	Type 310S
Modulus of elasticity $\times 10^6$ (psi)	29	29
Tensile strength $\times 10^3$ (psi)	95	95
Yield strength 0.2% offset $\times 10^3$ (psi)	45	45
Elongation in 2 in. (%)	45	45
Rockwell hardness	B-85	B-85
Density (lb/in. <sup>3</sup> )	0.28	0.28
Specific gravity	7.7	7.7
Thermal conductivity (Btu/ft hr °F)		
at 70°F		8.0
at 1500°F		10.8

during welding and stress relieving. Table A.43 shows the compatibility of types 316 and 316L stainless steel with selected corrodents. The chemical composition of types 316 and 316L stainless steel are shown in Table A.31. The mechanical and physical properties of type 316 and 316L stainless steel are shown in Table A.44.

**Table A.43** Compatibility of Types 316, 316L Stainless Steels with Selected Corrodents<sup>a</sup>

Chemical	Maximum temp.		Chemical	Maximum temp.	
	°F	°C		°F	°C
Acetaldehyde	210	99	Ammonium carbonate	400	204
Acetamide	340	171	Ammonium chloride 10%	230	110
Acetic acid 10%	420	216	Ammonium chloride 50%	x	x
Acetic acid 50%	400	204	Ammonium chloride, sat.	x	x
Acetic acid 80%	230	110	Ammonium fluoride 10%	90	32
Acetic acid, glacial	400	204	Ammonium fluoride 25%	x	x
Acetic anhydride	380	193	Ammonium hydroxide 25%	230	110
Acetone	400	204	Ammonium hydroxide, sat.	210	99
Acetyl chloride	400	204	Ammonium nitrate <sup>b</sup>	300	149
Acrylic acid	120	49	Ammonium persulfate 10%	360	182
Acrylonitrile	210	99	Ammonium phosphate 40%	130	54
Adipic acid	210	99	Ammonium sulfate 10–40%	400	204
Allyl alcohol	400	204	Ammonium sulfide	390	171
Allyl chloride	100	38	Ammonium sulfite	210	99
Alum	200	93	Amyl acetate	300	149
Aluminum acetate	200	93	Amyl alcohol	400	204
Aluminum chloride, aqueous	x	x	Amyl chloride	150	56
Aluminum chloride, dry	150	66	Aniline	500	260
Aluminum fluoride	90	32	Antimony trichloride	x	x
Aluminum hydroxide	400	204	Aqua regia 3:1	x	x
Aluminum nitrate	200	93	Barium carbonate	80	27
Aluminum sulfate <sup>b</sup>	210	99	Barium chloride <sup>c</sup>	210	99
Ammonia gas	90	32	Barium hydroxide	400	204
Ammonium bifluoride 10%	90	32	Barium sulfate	210	99

Table A.43 Compatibility of Types 316, 316L Stainless Steels with Selected Corrodents<sup>a</sup> (Continued)

Chemical	Maximum temp.		Chemical	Maximum temp.	
	°F	°C		°F	°C
Barium sulfide	210	99	Citric acid 15%	200	93
Benzaldehyde	400	204	Citric acid, concentrated <sup>c</sup>	380	193
Benzene	400	204	Copper acetate	210	99
Benzene sulfonic acid 10%	210	99	Copper carbonate 10%	80	27
Benzoic acid	400	204	Copper chloride	x	x
Benzyl alcohol	400	204	Copper cyanide	210	99
Benzyl chloride	210	99	Copper sulfate	400	204
Borax	400	204	Cresol	100	38
Boric acid	400	204	Cupric chloride 5%	x	x
Bromine gas, dry	x	x	Cupric chloride 50%	x	x
Bromine gas, moist	x	x	Cyclohexane	400	204
Bromine liquid	x	x	Cyclohexanol	80	27
Butadiene	400	204	Dichloroethane (ethylene dichloride)	400	204
Butyl acetate	380	193	Ethylene glycol	340	171
Butyl alcohol	400	204	Ferric chloride	x	x
<i>n</i> -Butylamine	400	204	Ferric chloride 50% in water	x	x
Butyl phthalate	210	99	Ferric nitrate 10–50%	350	177
Butyric acid	400	204	Ferrous chloride	x	x
Calcium bisulfide	60	16	Fluorine gas, dry	420	216
Calcium bisulfite	350	177	Fluorine gas, moist	x	x
Calcium carbonate	205	96	Hydrobromic acid, dilute	x	x
Calcium chloride <sup>b</sup>	210	99	Hydrobromic acid 20%	x	x
Calcium hydroxide 10%	210	99	Hydrobromic acid 50%	x	x
Calcium hypochlorite	80	27	Hydrochloric acid 20%	x	x
Calcium nitrate	350	177	Hydrochloric acid 38%	x	x
Calcium oxide	80	27	Hydrocyanic acid 10%	210	99
Calcium sulfate	210	99	Hydrofluoric acid 30%	x	x
Caprylic acid	400	204	Hydrofluoric acid 70%	x	x
Carbon bisulfide	400	204	Hydrofluoric acid 100%	80	27
Carbon dioxide, dry	570	299	Hypochlorous acid	x	x
Carbon dioxide, wet	200	93	Iodine solution 10%	x	x
Carbon disulfide	400	204	Ketones, general	250	121
Carbon monoxide	570	299	Lactic acid 25%	210	99
Carbon tetrachloride <sup>b,c</sup>	400	204	Lactic acid, concentrated <sup>c,e</sup>	300	149
Carbonic acid	350	177	Magnesium chloride 50% <sup>b,c</sup>	210	99
Cellosolve	400	204	Malic acid	250	121
Chloroacetic acid, 50% water	x	x	Manganese chloride 30%	210	99
Chloroacetic acid	x	x	Methyl chloride, dry	350	177
Chlorine gas, dry	400	204	Methyl ethyl ketone	330	166
Chlorine gas, wet	x	x	Methyl isobutyl ketone	350	177
Chlorine, liquid dry	120	49	Muriatic acid	x	x
Chlorobenzene, ELC only	260	127	Nitric acid 5% <sup>e</sup>	210	99
Chloroform <sup>b</sup>	210	99	Nitric acid 20% <sup>e</sup>	270	132
Chlorosulfonic acid	x	x	Nitric acid 70% <sup>e</sup>	400	204
Chromic acid 10% <sup>d</sup>	400	204	Nitric acid, anhydrous <sup>e</sup>	110	43
Chromic acid 50% <sup>d</sup>	150	49	Nitrous acid, concentrated	80	27
Chromyl chloride	210	99	Oleum	80	27

**Table A.43** Compatibility of Types 316, 316L Stainless Steels with Selected Corrodents<sup>a</sup> (Continued)

Chemical	Maximum temp.		Chemical	Maximum temp.	
	°F	°C		°F	°C
Perchloric acid 10%	x	x	Stannic chloride	x	x
Perchloric acid 70%	x	x	Stannous chloride 10%	210	99
Phenol	570	299	Sulfuric acid 10%	x	x
Phosphoric acid 50–80% <sup>c</sup>	400	204	Sulfuric acid 50%	x	x
Picric acid	400	204	Sulfuric acid 70%	x	x
Potassium bromide 30% <sup>c</sup>	350	177	Sulfuric acid 90% <sup>c</sup>	80	27
Salicylic acid	350	177	Sulfuric acid 98% <sup>e</sup>	210	99
Silver bromide 10%	x	x	Sulfuric acid 100% <sup>c</sup>	210	99
Sodium carbonate	350	177	Sulfuric acid, fuming	210	99
Sodium chloride to 30% <sup>b</sup>	350	177	Sulfurous acid <sup>e</sup>	150	66
Sodium hydroxide 10%	350	177	Thionyl chloride	x	x
Sodium hydroxide 50% <sup>a</sup>	350	177	Toulene	350	177
Sodium hydroxide, concentrated	350	177	Trichloroacetic acid	x	x
Sodium hypochlorite 20%	x	x	White liquor	100	38
Sodium hypochlorite, concentrated	x	x	Zinc chloride	200	93
Sodium sulfide to 50%	190	88			

<sup>a</sup>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.

<sup>b</sup>Subject to stress cracking.

<sup>c</sup>Subject to pitting

<sup>d</sup>Subject to crevice attack.

<sup>e</sup>Subject to intergranular corrosion.

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

**Table A.44** Mechanical and Physical Properties of Type 316 and 316L Stainless Steels

Property	Alloy type	
	316	316L
Modulus of elasticity $\times 10^6$ , psi	28	28
Tensile strength $\times 10^3$ psi	75	70
Yield strength 0.2% offset $\times 10^3$ psi	30	25
Elongation in 2 in., %	50	50
Hardness, Rockwell	B-80	B-80
Density, lb/in. <sup>3</sup>	0.286	0.286
Specific gravity	7.95	7.95
Specific heat (32–212°F Btu/lb °F)	0.12	0.12
Thermal conductivity, Btu/h ft <sup>2</sup> °F		
at 70°F	9.3	9.3
at 1500°F	12.4	12.4
Thermal expansion coefficient (32–212°F) $\times 10^{-6}$ in./in. °F	8.9	8.9
Izod impact, ft-lb	110	110

Type 316H stainless steel has a higher carbon content for better high-temperature creep properties and to meet requirements of ASME Section VIII, Table UHA-21, Footnote 8. This alloy is used in temperatures over 1832°F (1000°C). It has the following chemical composition:

Chromium	16.0–18.0%
Nickel	10.0–14.0%
Molybdenum	2.0–3.0%
Carbon	0.04–0.10%
Iron	Balance

The corrosion resistance of type 316H stainless steel is the same as that of type 316 stainless except after long exposure to elevated temperatures, where intergranular corrosion may be more severe. It may also be susceptible to chloride stress cracking.

Type 316N is a high-nitrogen type 316 stainless steel. The chemical composition is shown in Table A.31. It has a higher strength than type 316 and greater ASME Section VIII allowables. Corrosion resistance is the same as for type 316, and it may be susceptible to chloride stress cracking.

Type 316LN stainless steel is a low-carbon, high-nitrogen type 316 stainless with the following composition:

Chromium	16.0–18.0%
Nickel	10.0–15.0%
Molybdenum	2.0–3.0%
Carbon	0.035%
Nitrogen	0.10–0.16%
Iron	Balance

Type 316LN stainless has the same high-temperature strength and ASME allowables as type 316, but the weldability of type 316L. The corrosion resistance is the same as that of type 316 stainless, and there may be susceptibility to chloride stress corrosion cracking.

### **Type 317 (S317000)**

Type 317 stainless steel contains greater amounts of molybdenum, chromium, and nickel than type 316. The chemical composition is shown in Table A.31. As a result of the increased alloying elements, these alloys offer higher resistance to pitting and crevice corrosion than type 316 in various process environments encountered in the process industry. However, they may still be subject to chloride stress corrosion cracking.

Type 317L is a low-carbon version of the basic alloy that offers the additional advantage of preventing inter-granular precipitation of chromium carbide during welding and stress relieving. The chemical composition is shown in Table A.31.

Type 317L has improved pitting resistance over type 316L, but still may be subject to chloride stress corrosion cracking. The compatibility of type 317 and type 317L stainless steel with selected corrodents is shown in Table A.45. Refer to Table A.46 for the mechanical and physical properties of type 317 and 317L stainless steel.

Table A.45 Compatibility of Types 317 and 317L Stainless Steel with Selected Corrodents<sup>a</sup>

Chemical	Maximum	Chemical	Maximum
	temp.		temp.
	°F/°C		°F/°C
Acetaldehyde	150/66	Copper sulfate	70/21
Acetic acid 10%	232/111	Ferric chloride	70/21
Acetic acid 50%	232/111	Hydrochloric acid 20%	x
Acetic acid 80%	240/116	Hydrochloric acid 38%	x
Acetic acid, glacial	240/116	Hydrofluoric acid 30%	x
Acetic anhydride	70/21	Hydrofluoric acid 70%	x
Acetone	70/21	Hydrofluoric acid 100%	x
Aluminum chloride, aqueous	x	Iodine solution 10%	70/21
Aluminum chloride, dry	x	Lactic acid 25%	70/21
Aluminum sulfate 50–55%	225/107	Lactic acid, concentrated	330/166
Ammonium nitrate 66%	70/21	Magnesium chloride	70/21
Ammonium phosphate	80/27	Nitric acid 5%	70/21
Ammonium sulfate 10–40%	100/38	Nitric acid 20%	210/99
Benzene	100/38	Nitric acid 70%	210/99
Boric acid	210/99	Phenol	70/21
Bromine gas, dry	x	Phosphoric acid 50–80%	140/60
Bromine gas, moist	x	Sodium carbonate	210/99
Bromine liquid	x	Sodium chloride	x
Butyl alcohol 5%	195/91	Sodium hydroxide 10%	210/99
Calcium chloride	210/99	Sodium hydroxide 50%	70/21
Calcium hypochlorite	70/21	Sodium hydrochlorite 20%	70/21
Carbon tetrachloride	70/21	Sodium hypochlorite, concentrated	70/21
Carbonic acid	70/21	Sodium sulfate to 50%	210/99
Chloroacetic acid 78%	122/50	Sulfuric acid 10%	120/49
Chlorine, liquid	x	Sulfuric acid 50%	x
Chlorobenzene	265/129	Sulfuric acid 70%	x
Chromic acid 10%	x	Sulfuric acid 90%	x
Chromic acid 50%	x	Sulfuric acid 98%	x
Citric acid 15%	210/99	Sulfuric acid 100%	x
Citric acid, concentrated	210/99	Sulfurous acid	x

<sup>a</sup>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.

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

Type 317LM stainless steel is a low-carbon, high-molybdenum form of type 317. It has better corrosion resistance than types 317L, 316L, and 304L and the best chloride resistance of the 300 series stainless steels. It may be susceptible to chloride stress corrosion cracking. The chemical composition of type 317LM is as follows:

Chromium	18.0–20.0%
Nickel	13.0–17.0%
Molybdenum	4.0–5.0%
Nitrogen	0.1% max.
Carbon	0.03% max.
Nickel	Balance

**Table A.46** Mechanical and Physical Properties of Type 317 and 317L Stainless Steels

Property	Alloy type	
	317	317L
Modulus of elasticity $\times 10^6$ , psi	28.0	28.0
Tensile strength $\times 10^3$ , psi	75	75
Yield strength 0.2% offset $\times 10^3$ , psi	30	30
Elongation in 2 in., %	35	35
Hardness, Rockwell	B-85	B-85
Density, lb/in. <sup>3</sup>	0.286	0.286
Specific gravity		
Specific heat (32–212°F) Btu/lb°F	0.12	0.12
Thermal conductivity, Btu/h ft <sup>2</sup> °F		
at 70°F	9.3	9.3
at 1500°F	12.4	12.4
Thermal expansion coefficient (32–212°F) $\times 10^{-6}$ , in./in. °F	9.2	9.2
Izod impact, ft-lb	110	110

Type 317LMN is a low-carbon, high-molybdenum, high-nitrogen type 317 stainless steel with the following chemical composition:

Chromium	17.0–20.0%
Nickel	13.0–17.0%
Molybdenum	4.0–5.0%
Nitrogen	0.1–0.2%
Carbon	0.03% max.
Nickel	Balance

The corrosion resistance of this alloy is the same as for type 317LM with the added advantage of preventing chromium carbide precipitation during welding or stress relieving.

### Type 321 (S32100)

By alloying austenitic stainless steels with a small amount of an element having a higher affinity for carbon than does chromium, carbon is restrained from diffusing to the grain boundaries, and any carbon that reaches the boundary reacts with the element instead of the chromium. These are known as stabilized grades. Type 321 is such an alloy which is stabilized by the addition of titanium. Its chemical composition is shown in [Table A.31](#). The mechanical and physical properties are shown in [Table A.47](#).

Type 321 stainless steel can be used wherever type 316 is suitable, with improved corrosion resistance, particularly in the presence of nitric acid. This alloy is particularly useful in high-temperature service in the carbide precipitation range and for parts heated intermittently between 800 and 1650°F (427–899°C). Even with the improved overall corrosion resistance it still may be susceptible to chloride stress corrosion cracking. [Table A.48](#) provides the compatibility of type 321 with selected corrodents.

**Table A.47** Mechanical and Physical Properties of Type 321 Stainless Steel

Property	
Modulus of elasticity $\times 10^6$ , psi	29
Tensile strength $\times 10^3$ , psi	75
Yield strength 0.2% offset $\times 10^3$ , psi	30
Elongation in 2 in., %	35
Hardness, Rockwell	B-85
Density, lb/in. <sup>3</sup>	0.286
Specific gravity	7.92
Specific heat (32–212°F) Btu/lb°F	0.12
Thermal conductivity, Btu/h ft <sup>2</sup> °F	
at 70°F	9.3
at 1500°F	12.8
Thermal expansion coefficient (312–212°F) $\times 10^{-6}$ , in./in. °F	9.3
Izod impact, ft-lb	110

**Table A.48** Compatibility of Type 321 Stainless Steel with Selected Components<sup>a</sup>

Chemical	Maximum	Chemical	Maximum
	temp.		temp.
	°F/°C		°F/°C
Acetic acid 10%	x	Copper sulfate	70/21
Acetic acid 50%	x	Ferric chloride	x
Acetic acid 80%	x	Hydrochloric acid 20%	x
Acetic acid, glacial	x	Hydrochloric acid 38%	x
Acetic anhydride	70/21	Hydrofluoric acid 30%	x
Alum	x	Hydrofluoric acid 70%	x
Aluminum chloride, aqueous	x	Hydrofluoric acid 100%	x
Aluminum chloride, dry	x	Iodine solution 10%	x
Aluminum sulfate	70/21	Lactic acid 25%	70/21
Ammonium phosphate	70/21	Lactic acid, concentrated	70/21
Ammonium sulfate 10–40%	70/21	Magnesium chloride	x
Benzene	100/38	Nitric acid 5%	70/21
Boric acid	210/99	Nitric acid 20%	210/99
Bromine gas, dry	x	Nitric acid 70%	210/99
Bromine gas, moist	x	Phenol	x
Bromine liquid	x	Phosphoric acid 50–80%	70/21
Calcium chloride	x	Sodium carbonate	70/21
Calcium hypochlorite	x	Sodium chloride	x
Carbon tetrachloride	x	Sodium hydroxide 10%	70/21
Carbonic acid	70/21	Sodium hydroxide 50%	70/21
Chloroacetic acid	x	Sodium hydrochlorite 20%	x
Chlorine, liquid	x	Sodium hypochlorite, concentrated	x
Chromic acid 10%	x	Sodium sulfate to 50%	70/21
Chromic acid 50%	x	Sulfuric acid 98%	x
Citric acid 15%	70/21	Sulfuric acid 100%	x
Citric acid, concentrated	70/21	Sulfurous acid	x

<sup>a</sup>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.

Type 321H is a high-carbon type 321 stainless steel with better high-temperature creep properties, and it meets the requirements of ASME Section VIII, Table UHA.21, Footnote 8.

The corrosion resistance of type 321H is the same as the corrosion resistance of type 321, and it may be susceptible to chloride stress corrosion cracking. It has the following chemical composition:

Chromium	17.0–20.0%
Nickel	9.0–13.0%
Carbon	0.04–0.10%
Titanium	4× carbon min., 0.60% max.
Iron	Balance

Type 321H stainless steel is used in applications where temperatures exceed 1000°F/538°C.

### Type 329 (S32900)

Type 329 stainless steel is listed under the austenitic stainless steels but in actuality is the basic material of duplex stainless steels. It has the following chemical composition:

Chromium	26.5%
Nickel	4.5%
Molybdenum	1.5%
Carbon	0.05%
Iron	Balance

The general corrosion resistance of type 329 stainless steel is slightly above that of type 316 stainless steel in most media. In addition, since the nickel content is low, it has good resistance to chloride stress corrosion cracking.

The mechanical and physical properties are shown in [Table A.49](#).

### Type 347 (S34700)

Type 347 stainless steel is a niobium-stabilized alloy. Its chemical composition can be found in [Table A.31](#). Being stabilized, it will resist carbide precipitation during welding and intermittent heating to 800–1650°F (427–899°C), and it has good high-temperature scale resistance. Basically, this alloy is equivalent to type 304 stainless steel with the added protection against carbide precipitation. Type 304L offers this protection but is limited to a maximum operating temperature of 800°F (427°C), while type 347 can be operated to 1000°F (538°C).

In general, the corrosion resistance of type 347 is equivalent to that of type 304 stainless steel, and it may be susceptible to chloride stress corrosion cracking. [Table A.36](#) shows the compatibility of type 347 stainless with selected corrodents. [Table A.50](#) shows the mechanical and physical properties of type 347 stainless steel.

**Table A.49** Mechanical and Physical Properties of Types 329 and 330 Stainless Steel

Property	Type 329	Type 330
Modulus of elasticity $\times 10^6$ , psi		28.5
Tensile strength $\times 10^3$ , psi	105	80
Yield strength 0.2% offset $\times 10^3$ , psi	80	38
Elongation in 2 in., %	25	40
Hardness, Rockwell	Brinell 230	Rockwell B-80
Density, lb/inc <sup>3</sup>	0.280	0.289
Specific gravity	7.7	8.01
Specific heat (32–212°F) Btu/lb°F		8.0
Thermal conductivity at 70°F (Btu/h ft <sup>2</sup> °F)		
Thermal expansion coefficient at 32–212°F $\times 10^{-6}$ , (in./in. °F)		
Izod impact, (ft-lb)	90	

**Table A.50** Mechanical and Physical Properties of Type 347 Stainless Steel

Property	
Modulus of elasticity $\times 10^6$ , psi	29.0
Tensile strength $\times 10^3$ , psi	75
Yield strength 0.2% offset $\times 10^3$ , psi	30
Elongation in 2 in., %	35
Hardness, Rockwell	B-85
Density, lb/inc <sup>3</sup>	0.285
Specific gravity	7.92
Specific heat (32–212°F) Btu/lb°F	
Thermal conductivity, Btu/h ft <sup>2</sup> °F	
at 70–212°F	9.3
at 1500°F	12.8
Thermal expansion coefficient (32–212°F) $\times 10^{-6}$ , (in./in. °F)	9.3
Izod impact, (ft-lb)	110

Type 347H stainless steel is a high-carbon type 347 to provide better high-temperature creep properties and to meet requirements of ASME Section VIII, Table UHA21, Footnote 8. The chemical composition is as follows:

Chromium	17–20%
Nickel	9–13%
Carbon	0.04–0.10%
Niobium + Tantalum	8 $\times$ carbon min., 1.0% max.
Iron	Balance

Type 347H has the same corrosion resistance as type 347 and may be susceptible to chloride stress corrosion cracking. It is used in applications where temperatures can exceed 1000°F/538°C. Refer to [Table A.51](#) for the mechanical and physical properties.

**Table A.51** Mechanical and Physical Properties of Type 347H Stainless Steel

Property	
Modulus of elasticity $\times 10^6$ , psi	29
Tensile strength $\times 10^3$ , psi	75
Yield strength 0.2% offset $\times 10^3$ , psi	30
Elongation in 2 in., %	35
Hardness, Rockwell	B-90
Density, lb/in. <sup>3</sup>	0.285
Specific gravity	7.88
Thermal conductivity, Btu/h ft <sup>2</sup> °F	
at 70–212°F	9.3
at 1500°F	12.8

**Type 348 (S34800)**

Type 348 stainless steel is the same as type 347 except that the tantalum content is restricted to a maximum of 0.10%. The chemical composition is as follows:

Chromium	17.0–20.0%
Nickel	9.0–13.0%
Carbon	0.08% max.
Niobium + Tantalum	10 $\times$ Carbon min. 1.0% max. (0.01% max. Tantalum)
Iron	Balance

In general, the corrosion resistance is the same as that of type 347 stainless, and it may be subject to chloride stress corrosion cracking. This alloy is used in nuclear applications where tantalum is undesirable because of high neutron cross-section. Table A.52 shows the mechanical and physical properties of type 348 stainless steel.

**Table A.52** Mechanical and Physical Properties of Type 348 Stainless Steel

Property	
Modulus of elasticity $\times 10^6$ , psi	29.0
Tensile strength $\times 10^3$ , psi	95
Yield strength 0.2% offset $\times 10^3$ , psi	40
Elongation in 2 in., %	45
Hardness, Rockwell	B-85
Density, lb/in. <sup>3</sup>	0.285
Specific gravity	7.88
Thermal conductivity at 212°F (Btu/h ft <sup>2</sup> °F)	9.3

Type 348H stainless steel is a high carbon version of type 348 designed to provide better high-temperature creep properties and to meet the requirements of ASME Section VIII, Table UHA-21, Footnote 8. It finds application in nuclear environments, at temperatures over 1000°F (538°C).

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