Landrum, R.J. Designing for corrosion control.
NACE, 1989.

particle method also before testing. (If a break occurs during pneumatic testing, shattering of the equipment tested can occur.)

6. Whenever possible, to hold down costs, have the equipment made with commercially available materials using standard methods of construction. As an example of when this was not done, some years ago, a bellow-sealed valve was required for an extremely hazardous service. The company involved, now defunct, spent a large amount of the taxpayer's money to design and build a bellow-sealed valve when a satisfactory and better valve had been available all along on the shelf from a major valve manufacturer at a much lower price.
7. Before finalizing a specification, have the specification reviewed by potential fabricators. Many times, a fabricator can suggest ways to save money because he certainly knows best how to build his product. Specify primarily how the equipment should perform rather than detailing how the fabricator should build it.
8. Specifically note the tests required to assure quality.
9. Carefully note in the specification the equipment that is to be inspected during its manufacture so that the fabricator can make provisions for the inspector's visits at the proper time.
10. Do not hesitate to specify a trade name or a catalog number for a product if that product will do the required job. This, of course, precludes that the manufacturer is reliable, competent, and has the reputation of fabricating products of consistent quality at competitive cost.

☐ 5.2 Stainless Steels

Stainless steels are a very important class of alloys that are extensively used in industry. A noncorroding, nonrusting steel was sought for many years. The "discovery" of stainless steel during the period 1900 to 1915 was preceded by more than a century of cumulative effort by many men. The remarkable fact is not that it was discovered in the early 1900s, but that is was not discovered many years before.

In 1790, Vauguelin discovered chromium by reducing it from its ore. Chromium was added experimentally to steels during the 1800s, but by some strange quirk of fate, too little chromium was added to make steels that were corrosion resistant. As a matter of fact, in 1892, Hadfield concluded that chromium *impaired* the corrosion resistance of steel. His alloy contained a maximum of 9% chromium, which is just below the minimum amount required for corrosion resistance. In 1913, Brearly was investigating new alloys for the lining of naval guns. He noticed, during a metallographic study, that the customary etching reagents did not etch steels having high chromium contents. He patented a type of stainless steel in 1916 that is virtually the present day AISI 420 alloy. Almost at the same time, 1909 to 1912, Maurer developed an *austenitic* stainless steel, 18%Cr-8%Ni. From then on, development of stainless alloys was practically continuous, though, at some times, rather hectic. Around 1920, One of history's greatest lawsuits was filed. It was the suit of American Stainless Steel Co. and Electro Metallurgical Co. vs Rustless Iron Corp. of America over who discovered 17% chromium alloys.

Role of Chromium

Chromium is the resistant keystone of all the types of stainless steel. When the amount of chromium is gradually increased in steel, a drastic change in corrosion resistance results. As the chromium content is increased under oxidizing conditions, a surface film attempts to form and then it rather suddenly completes itself when about 12% chromium is present. The oxide layer at that concentration of chromium is tenacious and impenetrable to migrating atoms, either oxygen atoms pressing inward or metallic atoms pressing outward, thus passivating the corrosion action. (Conversely, when the film is destroyed by certain chemical or mechanical action, the steel activates and becomes liable to attack, as discussed previously.) When this strong, continuous film has been formed, the metal is in the *passive* state.

Types of Stainless Steels

Since there are four types of stainless steel to select from, it is important for the designer to understand the differences in corrosion resistance between them. The four general types are austenitic, martensitic, ferritic, and precipitation hardening. Refer to Tables 5.2 through 5.5 for classes, type numbers, and various uses for these types of stainless steels. Comments on the corrosion resistance of various metals and alloys that follow in this section are to highlight certain individual characteristics in widely used services. However, in order to determine the corrosion resistance of various types of stainless steels to contemplated process solutions, the designer should have corrosion tests made following procedures outlined in Chapter 2.

The four classes of stainless steel vary considerably in their chemical composition, corrosion resistance, mechanical properties, and

TABLE 5.2 — Austenitic Stainless Steels

Class	Hardenability	AISI Type	Analysis Compared to Basic Type	Various Uses (Applies to Listed S.S. Types)
Chromium-Nickel	Hardened Only by Cold Work	301	Chromium and nickel lowered for more work hardening	<u>Transportation Industry:</u> Trim, bumpers, wheel, covers for autos, sides for railroad cars.
		302	Basic type 18% chromium, 8% nickel	<u>Food Industry:</u> Tanks, bottles, pasteurizers, buckets, bottling equipment, and vats.
		304	Carbon lower than the basic type	<u>Laundries:</u> Kettles, tables, and driers.
		304L	Carbon below 0.03% to avoid carbide precipitation caused by welding	<u>Dairies:</u> Pasteurizers, separators, tanks, and coolers.
		321 347	These two alloys have been in general replaced by AISI 304L; these alloys are stabilized with titanium (321) and niobium (347) to avoid carbide precipitation caused by welding	<u>Pharmaceutical:</u> Tanks, kettles, and processing equipment. <u>Ships:</u> Hatch covers, doors, and stacks. <u>Building Industry:</u> Architectural trim and paneling. Excellent resistance to the atmosphere. Kitchen sinks, trim, etc. <u>Chemical Industry:</u> Heat exchangers, condensers, tanks, sieve plates, pumps, low-temperature use, dye and bleach equipment for textiles, piping, and tubing. Tanks, tubing, etc., for handling liquid nitrogen and oxygen. Used for storing nitric acid. (Not AISI 301 or 302.)
		303	Sulfur or selenium added for easier machining	For producing nuts, bolts, screws, and shafts where a free-machining steel is required; in certain environments, these materials have limited corrosion resistance.
Chromium-Nickel	Hardened Only by Cold Work	305	Nickel higher for less work hardening	Drawing, cold heating, and spinning applications.
		308	Nickel and chromium higher	Mainly for electrodes or filler metal to weld AISI 304 SS to compensate for any losses of chromium and nickel during welding.
		308L	AISI 308 carbon content reduced	Welding AISI 304L where carbon must be below 0.030%.
		309 310	Chromium and nickel still higher for more corrosion and scaling resistance	Same uses as noted for AISI 304, 304L, etc., for chemical industry, including processing equipment; in addition, these alloys resist oxidation up to 1900 to 2000 F, such as annealing boxes, resistors, retorts, and furnace parts.
		309Cb	Niobium and tantalum added to avoid carbide precipitation	Welding electrodes and filler metal piping and tubing.

TABLE 5.2 — Austenitic Stainless Steels (continued)

Class	Hardenability	AISI Type	Analysis Compared to Basic Type	Various Uses
Chromium-Nickel	Hardened Only by Cold Work	316 317	Molybdenum added for more resistance to pitting and corrosion	<u>Chemical Industry:</u> These types are used where AISI 304 may not have adequate corrosion resistance; can be used for most of the uses listed for AISI 304, 304L, etc., for chemical industry, including towers and screens. Has better resistance to hot organic acid; however, resistance to nitric acid is substantially less. Better resistance to dilute sulfuric acid than AISI 304. Used for handling a wide range of corrodents in piping, tanks, heat exchangers, pumps, etc. <u>Paper Industry:</u> Pumps, evaporators, digesters, piping, and tubing. <u>Soap Manufacturing:</u> Piping and tubing, tanks, towers, heat exchangers.
Chromium-Nickel	Hardened Only by Cold Work	316L	Carbon content limited to 0.30%	Same applications as listed for AISI 316, where protection from carbide precipitation from welding is required.
Chromium-Nickel Manganese	Hardened Only by Cold Work	201[1]	Chromium and nickel lower for more work-hardening	Same uses as for AISI 301.
Chromium-Nickel	Hardened Only by Cold Work	202[1]	Chromium 18% Nickel 5% Manganese 8% basic type	Same uses as for AISI 302.
		204[1]	Carbon somewhat lower	Same uses as for AISI 304.
		204[1]	Carbon below 0.03% to avoid carbon precipitation caused by welding	Same uses as for AISI 304L (can be welded with AISI 308L electrode or filler metal.)

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[1] During a period of nickel shortages, these types were developed to produce basically as much austenite by substituting manganese. They have about the same corrosion resistance as their counterparts in the 300 Series, but have higher strengths.

TABLE 5.3 — Martensitic Stainless Steels

Class	Hardenability	AISI Type	Analysis Compared to Basic Type	Various Uses
Chromium-Iron	Hardenable by Heat Treatment	403	12% chromium with higher mechanical properties	Turbine valves and turbine buckets.
		410	Basic type 12% Chromium	Furnace parts and other heat-resisting uses to 1400 F; trim and seats for steel and cast iron industrial valves; shafts and impellors for pumps; tubing, bubble caps, and petroleum towers; coal screens; bushings and bearings, nuts, and bolts; cutlery, tableware, and kitchen tools.
		414	Nickel added to increase corrosion resistance and and strength	
		416	Sulfur or selenium added for free machinability	Screws, valve stems, nuts, and bolts are made from this metal to save on machining costs. Has reduced corrosion resistance because of the presence of sulfur or selenium.
		420	Carbon higher for greater hardenability	Heat-treated springs and cutlery of all types; heat-treated bushings, bearings, valve seats, and trim; surgical instruments. This alloy is the first SS and was invented by Brearly in 1913.
		431	Higher chromium and nickel for increased corrosion and mechanical properties	Aircraft parts; shafts for ships; milk separators; valves in milk lines; pump parts; wires requiring stiffness and strength.
		440 A, B, and C	Carbon higher to give great hardness	Parts requiring hardness up to 65 Rockwell C; cutlery, valve seats, and trim; heat-treated springs; bushings and bearings; gages of various kinds and surgical instruments.

TABLE 5.4 — Ferritic Stainless Steels

Class	Hardenability	AISI Type	Analysis Compared to Basic Type	Various Uses
Chromium-Iron	Non-Hardenable	405	Aluminum added to 12% Chromium to prevent hardening	Boiler tubing and heat exchanger tubing that are welded but not heat treated afterwards.
		430	Chromium 17% — basic type	Heat-resistant parts subject to low stress at temperatures to 1550 F, including furnace and retort parts; heat exchangers, condensers, bubble caps, piping, and tubing; tanks for transportation and storage; automotive trim, and molding.
		431F	Sulfur or selenium added for machinability	Nuts, bolts, screws, and other parts where easy machining is required; has lowered corrosion resistance
		442	Chromium higher to increase scaling resistance	Various equipment to resist temperatures up to 1750 F at low stress, such as furnace parts, soot-blower elements, and heat recuperators; good resistance to high-temperature oxidation and sulfur attack.
		446	Chromium much higher for improved scaling resistance	Stack dampers, burner nozzles, kiln lining, other furnace parts including baffles; also has good resistance to high-temperature oxidation and sulfur attack.

TABLE 5.5 — Precipitation-Hardening Stainless Steels

Class	Hardenability	AISI Type	Analysis Compared to Basic Type	Various Uses
Precipitation Hardening	Hardenable by Heat Treatment	17-4 PH	16% Cr4Ni plus Cu and Ta	High-strength materials, up to around 200,000 psi strengths in the treated condition; useful for missile and aircraft industries where high strength and resistance to mildly corrosion condition is required.
		17-7 PH	A little higher Cr with about double the nickel content plus 1% Al	
		pH 15-7 Mo	Lower Cr with high nickel 7% plus 3.5% Mo at 1% Al	Good resistance to atmospheric conditions.
		Stainless W	17 Cr 7 Ni plus Ti and Al	Used for rubbing parts because of its high hardness including valve seats, valve discs, bushings, and bearings.

hence, uses. Nickel, manganese, carbon, and nitrogen are austenite formers while chromium, molybdenum, and silicon are ferrite formers. The structure of these stainless steels will depend on their chemical composition.

Austenitic stainless steels. The 200 and 300 Series contain nickel as the principal *austenite* former. During World War II, the 200 Series stainless steels were developed because of the shortages of nickel, with manganese substituting in part for the nickel. Both series have about the same corrosion resistance (200 and 300 Series, Table 5.2). The austenitic stainless steels are more corrosion resistant than the straight

chromium grades of stainless steel and generally have the best corrosion resistance of the four types of stainless steels. The 200 and 300 Series stainless steels are hardenable only by cold working. The bulk of the stainless steels used by the process industries are AISI 304, 304L, and 316. The 300 Series stainless steels are probably the most used stainless steels.

Martensitic stainless steels. Martensitic stainless steels (Table 5.3) contain chromium that acts as a *ferrite* former. It is hardenable by heat treatment, the same as carbon steel, because it can form martensite, which is a hard constituent. The corrosion resistance tends to be better in the hardened condition than the annealed condition. The corrosion resistance is generally not as good as austenitic or ferritic stainless steels. The martensitic steels AISI 420, 431, 440A, 440B, and 440C are used when a high hardness coupled with corrosion resistance is required.

Ferritic stainless steels. The ferritic stainless steels (Table 5.4) cannot be hardened by heat treatment because they do not undergo a phase transformation at higher temperatures. These steels are excellent for high temperature service; however, they do not show consistent structural strength at elevated temperatures, so stresses must be kept low. AISI 442 and 446 are generally used in heat treating equipment. AISI 430 was the original material of construction used by the chemical industry for nitric acid service; however, austenitic stainless steels have largely supplanted AISI 430 for this service because of their better fabricability and lower corrosion rates. Ferritic stainless steel alloys have a substantial advantage over austenitic stainless steels because they generally handle stress corrosion cracking better, particularly when chlorides are present.

Precipitation-hardening stainless steel. Precipitation-hardening stainless steel (Table 5.5) hardens by solution-quenching followed by aging, which places precipitates in the slip planes of the alloys rendering these metals hard. None of the precipitation-hardening alloys listed in Table 5.5 have outstanding corrosion resistance. Their corrosion resistance, for instance, is less that of AISI 304 stainless steel. When a very strong, hard alloy is required and only mild corrosion resistance is necessary, these alloys may be ideal. Tensile strengths of 200,000 psi may be obtained. Table 5.6 denotes the chemical composition of wrought stainless alloys, including those discussed above.

Cast stainless alloys. Cast stainless steels do not fall conveniently into any one of the stainless steel types because they vary somewhat from the chemical compositions of wrought alloys, as described before.

TABLE 5.6 — Chemical Composition of Wrought Stainless Steels

AISI Type	C	Mn Maximum	P Maximum	S Maximum	Si Maximum	Cr	Ni	Mo	Other Elements
201	0.15	6.5	0.045	0.030	1.00	17	4.5		N 0.25 maximum
202	0.15	8.0	0.045	0.030	1.00	18	5.0		N 0.25 maximum
204	0.08	8.0	0.045	0.030	1.00	18	5.0		N 0.25 maximum
204L	0.03	8.0	0.045	0.030	1.0	18	5.0		N 0.25 maximum
301	0.15 maximum	2.00	0.045	0.030	1.00	16.00/18.00	6.00/8.00		
302	0.15 maximum	2.00	0.045	0.030	1.00	17.00/19.00	8.00/10.00		
303	0.15 maximum	2.00	0.20	0.15 minimum	1.00	17.00/19.00	8.00/10.00	0.60 maximum	
304	0.08 maximum	2.00	0.045	0.030	1.00	18.00/20.00	8.00/12.00		
304L	0.03 maximum	2.00	0.045	0.030	1.00	18.00/20.00	8.00/12.00		
308	0.08 maximum	2.00	0.045	0.030	1.00	19.00/21.00	10.00/12.00		
309	0.20 maximum	2.00	0.045	0.030	1.00	22.00/24.00	12.00/15.00		
310	0.25 maximum	2.00	0.045	0.030	1.50	24.00/26.00	19.00/22.00		
316	0.08 maximum	2.00	0.045	0.030	1.00	16.00/18.00	10.00/14.00	2.00/3.00	
316L	0.03 maximum	2.00	0.045	0.030	1.00	16.00/18.00	10.00/14.00	2.00/3.00	
317	0.08 maximum	2.00	0.045	0.030	1.00	18.00/20.00	11.00/15.00	3.00/4.00	
321	0.08 maximum	2.00	0.045	0.030	1.00	17.00/19.00	9.00/12.00		Ti 5xC minimum
347	0.08 maximum	2.00	0.045	0.030	1.00	17.00/19.00	9.00/13.00		Cb-Ta 10xC minimum
403	0.15 maximum	1.00	0.040	0.030	0.50	11.50/13.00			
410	0.15 maximum	1.00	0.040	0.030	1.00	11.50/13.00			
405	0.08 maximum	1.00	0.030	0.030	1.00	11.50/14.00			Al 0.10/0.30
414	0.15 maximum	1.00	0.040	0.030	1.00	11.50/13.50	1.25/2.50		
416	0.15 maximum	1.25	0.06	0.15/0.35	1.00	12.00/13.50			
420	over 0.15	1.00	0.040	0.030	1.00	12.00/14.00			
430	0.12 maximum	1.00	0.040	0.030	1.00	14.00/18.00			
431	0.20 maximum	1.00	0.040	0.030	1.00	15.00/17.00	1.25/2.50		
440A	0.60/0.75	1.00	0.040	0.030	1.00	16.00/18.00		0.75 maximum	
440B	0.75/0.95	1.00	0.040	0.030	1.00	16.00/18.00		0.75 maximum	
440C	0.95/1.20	1.00	0.040	0.030				0.75 maximum	
446	0.20 maximum	1.50	0.040	0.030	1.00	23.00/27.00			N 0.25 maximum
17-4 pH						16.5	4		4 Cu; 3Cb + Ta
17-7 pH						17	7		1.1 Al
pH 15-7 Mo						15	7		2.5 Mo, 1.2 Al
Stainless W	0.07					17	7		0.7 Ti, 0.2 Al

The reason for this is that to be castable, an alloy must have a higher silicon content. (Wrought alloys are usually limited to 1% Si.) The additional silicon content is required particularly for thin cast sections. Also, high ferrite content is acceptable in cast products because rolling and forming is not required. Because the ferrite content in an austenite matrix substantially increases strength, such mixed structures of ferrite and austenite would cause great difficulty in rolling and forming if an attempt was made to treat these alloys as wrought alloys, therefore limiting this type of stainless steel to the cast form.

The amount of the ferrite phase in cast alloys is increased by adding or increasing the amounts of ferrite formers, such as chromium and molybdenum, and/or by decreasing the amounts of austenite formers and stabilizers such as nickel, nitrogen, and carbon. Because the cast stainless steel alloys are not limited to chemical composition like wrought alloys, they have unusual properties such as increased yield strengths. Since these alloys can have two distinct microstructures, they are called *duplex* alloys.

Table 5.7 shows some of these cast stainless steels. Note that a designation starting with a "C" indicates that the alloy is used for

TABLE 5.7 — Cast Stainless Steels

Cast Alloy Designation	Wrought Alloy Comparison	% Composition (bal Fe)		
		Cr	Ni	Other Elements
CA-15[1]	410	11.5 to 14	1 maximum	
CA-40[1]	420	11.5 to 14	1 maximum	
CC-50[1]	446	26 to 36	4 maximum	
CF-8[1]	304	18 to 21	8 to 11	
CF-8[1] M	316	18 to 21	9 to 12	Mo 2.2 to 3
CF-20[1]	302	18 to 21	8 to 11	
CF-8[1] C	347	18 to 21	9 to 12	Co (8 x C) minimum (1.0) maximum
CF-16[1] F	303	18 to 21	9 to 12	Mo 1.5 maximum Se 0.20 to 0.35
CD-4 M Cu	—	25 to 27	4.75 to 6	2 Mo, 3 Cu
CH-20[1]	309	22 to 26	12 to 15	
CK-20[1]	310	23 to 27	19 to 22	
CN-7[1] M	Alloy 20	18 to 22	21 to 31	varying amounts of Si, Mo, and copper depending on producer
HC	446	26 to 30	4 maximum	0.50 C
HF	302	19 to 23	9 to 12	0.20 to 0.40 C
HH	309	24 to 28	11 to 14	0.20 to 0.50 C 0.20 maximum N
HK	310	24 to 28	14 to 18	0.20 to 0.60 C

[1] Number refers to "points" of carbon content. For instance, 7 is 0.07%; 20 is 0.20%.

aqueous services and an "H" for heat-resistant services.

The corrosion resistances of cast and wrought stainless steels of similar composition are considered equivalent in most environments. Table 5.7 shows the wrought alloy composition type number it most closely resembles for comparison. "C" alloys contain a number in their designation that signifies the number of points of carbon in the alloy. A point of carbon is 0.01%.

"C" alloys are used for most of the uses noted for wrought alloys. "H" alloys have widespread use in heat-resistant applications, such as castings for turbo superchargers, gas turbines, power plant equipment, and equipment used for the manufacture of glass, cement, synthetic rubber, petroleum products, and chemicals.

Corrosion Resistance of Stainless Steels

Nitric acid. The 300 Series stainless steels are extensively used for handling nitric acid. The most economical choice is generally AISI 304L, which shows good corrosion resistance in the as-welded condition up to about 55 to 60% at 220 F (104 C). The storage of nitric acid at ambient temperatures is handled by AISI 304L up to about 92% acid. (Above that concentration, either AA 3003 or 1100 aluminum has a lower corrosion rate and is generally used.)

AISI 430 stainless steel has been used extensively in the past for shipping and handling nitric acid but has been largely replaced by AISI 304L stainless steel because its resistance covers a broader range of concentrations. AISI 430 is occasionally used when austenitic stainless steels are not satisfactory because of stress corrosion cracking resulting from the presence of chlorides. The major drawback with AISI 430 stainless steels is that they must be heat treated after fabrication. In addition, they are somewhat difficult to weld and must be heat treated after welding or extensive cracking will result. AISI 446 is as resistant to nitric acid as austenitic stainless steels and has the advantage of not being susceptible to chloride stress corrosion cracking. However, it has a great drawback because, for all practical purposes, it is unweldable. Its use for this reason is confined to seamless tubing and pipe not requiring welding.

AISI 316 has been found to be less resistant to nitric acid than other members of the 300 Series. AISI 309 and 310 are not greatly superior in corrosion resistance to AISI 304 in boiling 65% nitric acid. However, a special low carbon version of AISI 310 is extensively used for hot nitric acid.

Hydrochloric acid. Hydrochloric acid rapidly corrodes all four types of stainless steels.

Phosphoric acid. AISI 316L can be used in up to 70 to 80% phosphoric acid if the temperature is below 220 F (104 C). AISI 304L can be used for dilute solutions at ambient temperatures. However, when commercial solutions contain fluoride impurities, the corrosion resistance of austenitic stainless steels will be much lower.

Organic acids. AISI 316L can be used for most organic acids at all concentrations up to the boiling point. Oxalic and formic acids are the exceptions. Oxalic can only be tolerated by AISI 316L at ambient temperatures while formic may be tolerated only up to around 200 F (93 C). At temperatures above the atmospheric boiling point, a more resistant alloy, such as Hastelloy† C-276, should be selected.

Sulfuric acid. As can be seen by consulting the Nelson charts, the 300 Series stainless steels can be used when sulfuric acid is either very dilute or is very strong. In dilute sulfuric acid, the 300 Series stainless steel show borderline passivity where a small change in temperature or concentration can cause very severe corrosion. When reducing agents are present, the protective film may be destroyed causing increased corrosion. Offsetting this, if oxidizing agents are present, the film will be preserved and corrosion resistance will be assured. AISI 316L is much more resistant than AISI 304L to sulfuric acid. AISI 304L is only resistant to cold acid at dilutions below 1%. AISI 316L is satisfactory in cold acid to about 10%, as long as the acid is aerated to preserve the passive state.

□ 5.3 Nickel and Nickel Alloys

Table 5.8 shows the normal composition of nickel and nickel alloys and some uses for these versatile materials. Each of these alloys have excellent corrosion resistance varying in corrosion-resistant properties, as noted below. All of these alloys are more expensive than 300 Series stainless steels and therefore, should not be specified by the designer when stainless steel is suitable.

Corrosion Resistance of Nickel 200

Nickel is a very versatile corrosion-resistant metal. It combines the mechanical properties of the order of mild steel and relatively high corrosion resistance with favorable welding and fabrication qualities. Other characteristics of nickel are that it is:

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† Registered trade name.

TABLE 5.8 — Nominal Composition and Uses of Nickel and Nickel Alloys

Alloy Name	Percent Nominal/Composition							Various Uses
	C	Cr	Ni	Mo	Cu	Fe	Other	
200	0.08		99+					Caustic evaporators and caustic fusion pots; for a variety of chlorination type reactions and for handling chlorine, hydrogen chloride, chlorinated hydrocarbons; heating coils, tanks, tubular condensers, and evaporators.
201	0.01		99+					For use in caustic and other applications involving temperatures above 600 F; the low carbon avoids harmful graphite precipitation.
Monel 400	0.12		67		32	1		Evaporators, piping, reaction vessels; paper mill and oil refinery equipment; storage tanks, food handling equipment, nozzles, bushings, and turbine blading.
Inconel 600	0.08	15	76			8		Process equipment, dairy equipment, manifolds, and food handling equipment; used extensively in oxidizing and carburizing atmospheres at high temperatures.
Inconel 625	0.02	21	61	9		3	4 Co	For process equipment requiring high-strength and high-temperature corrosion resistance.
Incoloy 800	0.05	21	33			46	0.3 Ti 0.3 Al	Pigtails for reformer furnaces and other high-temperature corrosion applications.
Carpenter 20-Cb-3	0.04		34	2.5	3.5	38	0.8 Cb	Heat exchangers and heat exchanger tubes, mixing tanks, process piping, bubble caps, metal cleaning and pickling tanks; pumps, valves, and fittings.
Incoloy 825	0.03	21	42	3	2.3	30	0.9 Ti	Mixing tanks, process piping, valves, and fittings.
Hastelloy B-2	0.01	1	bal	28		2	Co 1 Si 0.1 Mn 1	Process equipment, piping, tubing. Reaction vessels, and heat exchangers.
Hastelloy C-276	0.01	15	bal	16		5.5	Mn 1 Si 0.08 W 4	Tanks, heat exchangers, piping, tubing, and process equipment.
Hastelloy G-3	0.015	22.2	bal	7		19.5	Co 5 W 1.5 Si 0.4 Mn 0.8 Cu 1.8 Cb plus Ta 0.3	Pulp digesters, dissolver vessels and piping, tanks.
Hastelloy G-30	0.03	30	bal	5.0	2	15	Co 5 W 3 Si 8 Mn 1.5 Cb plus Ta 1	Resistant to phosphoric acid and highly oxidizing acids such as nitric/hydrochloric, etc. Useful in pickling acid operations and gold extraction.
Hastelloy C-22	0.01	22	bal	13		3	Co 2.5 W 3 Si 0.08 Mn 0.5 V 0.35	Highly pit resistant. Excellent resistance to oxidizing aqueous media. Resistant to strong oxidizers such as ferric and cupric chlorides.

1. Resistant to neutral or alkaline salts unless they are strongly oxidizing, such as with sodium hypochlorite.
2. With the exception of silver, it has the best resistance to alkalines and is widely used for caustic evaporators and caustic fusion pots.

3. Resistant to anhydrous ammonia but is attacked by ammonium hydroxide solutions.
4. Not susceptible to stress corrosion cracking but, in some applications, is susceptible to pitting under deposits in brackish water.
5. Widely used for many chlorination-type reactions and for handling chlorine, hydrogen chloride, and chlorinated hydrocarbons.
6. Attacked by sodium hypochlorite.
7. Widely used in the food industry.
8. Attacked and embrittled by sulfur-bearing gases at elevated temperatures, as are its alloys. (See Figure 3.77 previously referred to.) Susceptible to both general and intergranular corrosion in sulfur-bearing gases at temperatures above 600 F (315 C).
9. Resistant to steam but may be severely attacked by condensates.
10. Only moderately resistant to some acids but is badly attacked by oxidizing acids, especially nitric acid.
11. Resistant to neutral and slightly acid solutions.

Nickel 201

For caustic or other services involving temperatures above 600 F (315 C), the low carbon grade Nickel 201 should be specified instead of Nickel 200 to avoid harmful graphite precipitation. However, the presence of sulfur in process solutions will cause serious attack on both Nickel 200 and 201.

Alloy 400

Characteristic of Alloy 400 (Monel[†] 400) is that it is:

1. Not very different in corrosion resistance from nickel, but since it is less expensive and appreciably stronger, it is advantageous for the designer to use it instead of nickel when either alloy would be satisfactory.
2. More corrosion resistant than nickel under reducing conditions. In certain environments where reducing compounds are present, or which are nitrogen-blanketed, even strongly acidic solutions can be handled satisfactorily by this alloy.

[†] Registered trade name.

3. Offers some resistance to hydrochloric and sulfuric acids under modest conditions but is seldom used.
4. Used for caustic solutions, because it is not susceptible to SCC.
5. Chloride salts do not cause SCC.
6. Widely used for containing hydrofluoric acid solutions. However, corrosion rates are substantially increased in the presence of air. When used for hydrofluoric acid, this alloy must be stress relieved to obviate stress corrosion cracking.

Alloy 600

Characteristics of Alloy 600 (Inconel[†] 600) are that it is:

1. Very resistant to stress corrosion cracking.
2. Resistant to mixtures of steam, CO_2 and air. It does not experience the limitations as does nickel or Monel in this service.
3. Not attacked by ammonium hydroxide solutions as are nickel and Alloy 400.
4. Almost as resistant to alkalis as nickel and is somewhat less vulnerable to the presence of sulfur compounds or sulfur-bearing gases; however, Alloy 600 welded equipment should be stress relieved if it is to be used in strong, hot caustic environments.
5. Only fairly resistant to mineral acids but is used extensively for handling fatty acids at high temperatures.
6. Stronger than nickel or Alloy 400 and is more resistant to oxidation. It is also resistant to chlorine and chlorine-containing compounds at high temperatures. In some cases, it is preferable over nickel because of its higher strength and oxidation resistance.

Alloy 625

Characteristics of Alloy 625 are that it is:

1. Extremely resistant to oxidizing and carburizing atmospheres at high temperatures.
2. Highly corrosion resistant for applications involving halogen compounds.
3. Very corrosion resistant to stress corrosion cracking.

[†] Registered trade name.

Alloy 800

Alloy 800 (Incoloy[†] 800) differs from AISI 310 stainless steel (25% Chromium, 20% Nickel) primarily because of its higher nickel content (33%).

1. The added nickel improves resistance to chloride stress cracking.
2. It reduces the tendency for sigma phase formation. (Sigma phase can cause embrittlement in high-temperature service.)
3. Alloy 800 is susceptible to intergranular attack if used in the as-welded condition in severely corrosive processes.

Carpenter 20 Cb-3

Characteristics of Carpenter 20 Cb-3 are that it is:

1. Similar in nickel content to Alloy 800 but also contains molybdenum, copper, and columbium so it is resistant to a wider range of process conditions. Because it is stabilized, it can be used in the welded condition.
2. Superior to the 300 Series stainless steels in resistance to sulfuric acid and can be used over a considerable range of concentrations and temperatures.
3. Used successfully in many severely corrosive applications. The most frequent services are in hot processes containing sulfuric acid.
4. Used widely for applications where a 300 Series stainless steel would be satisfactory on the process side but would fail by chloride stress corrosion cracking on the cooling water side.
5. Stabilized with columbium.

(Carpenter 20 Cb-3 is sometimes classified as a stainless steel.)

Alloy 825

Characteristics of Alloy 825 are that:

1. Its corrosion resistance is generally about the same as that of Carpenter 20 Cb-3.
2. It is stabilized with titanium and is consequently not susceptible to intergranular attack.
3. It contains more nickel than Carpenter 20 Cb-3. Under certain conditions, therefore, it will show increased corrosion resistance. However, there are other conditions where Carpenter 20-Cb-3 is

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[†] Registered trade name.

superior in corrosion resistance. Tests should be used to determine which alloy to select for a specific environment.

Hastelloy B-2

Characteristics of Hastelloy B-2 are that it is:

1. An improved wrought version of Hastelloy B and has the same corrosion resistance but has improved resistance to knife-line attack.
2. Resistant to intergranular attack, thus making it suitable for most applications in the as-welded condition. It has excellent resistance to pitting and stress corrosion cracking.
3. Resistant to HCl gas, acetic, and phosphoric acids.
4. One of the few metallic materials that can be used for hydrochloric acid service. Alloy B-2 shows good corrosion resistance even to strong hot HCl solutions, as long as there are no strong oxidizing agents present, such as ferric or cupric chloride. Oxidizing ions as low as 50 parts per million can degrade the corrosion resistance of this alloy. (Ferric or cupric salts may develop when HCl comes in contact with iron or copper.)
5. Resistant to boiling sulfuric acid solutions up to about 60% concentration. (In most cases, however, lower cost materials are available for this service.)

Hastelloy C-276

Characteristics of Hastelloy C-276 are that it is:

1. An improved wrought version of Hastelloy C. It has the same corrosion resistance as Hastelloy C with improved fabricability.
2. One of the few materials that will resist the corrosive effects of hypochlorite and chlorine dioxide solutions.
3. Extremely corrosion-resistant to strong oxidizers such as ferric and cupric chlorides or hypochlorites and to wet chlorine gas at room temperature, but attack becomes appreciable in hot solutions, especially in higher concentrations.
4. Resistant to hot contaminated acids, solvents, formic acid, acetic acid, and acetic anhydride.

Hastelloy G-3

Characteristics of Hastelloy G-3 are that it is:

1. An improved wrought version of Hastelloy G. It has the same general corrosion resistance as Hastelloy G with improved resistance to intergranular attack and improved weldability.
2. Very resistant to mixed acids.
3. Very resistant to hot sulfuric and phosphoric acids in the as-welded condition.
4. Tolerant of the corrosive effects of both oxidizing and reducing agents and can handle both acid and alkaline solutions.
5. Applied principally in hot concentrated sulfuric, hydrofluoric, and fluorosilic acids involved in the manufacture of hydrofluoric acid.

Hastelloy G-30

Characteristics of Hastelloy G-30 are that it:

1. Has superior corrosion resistance to phosphoric acid compared to most other nickel and iron-base alloys.
2. Resists highly oxidizing acids such as nitric/hydrochloric, nitric/hydrofluoric, and sulfuric acids.
3. Can be used in the as-welded condition for most process applications.
4. Has been found satisfactory for many applications, including pickling acid operations, petrochemicals, fertilizer manufacturing, pesticide manufacturing, and gold ore extraction.

Hastelloy C-22

Characteristics of Hastelloy C-22 are that it:

1. Is a versatile nickel-chromium-molybdenum alloy claimed to have better overall corrosion resistance than other NiCrMo alloys available today.
2. Has outstanding resistance to pitting, crevice corrosion, and stress corrosion cracking.
3. Has excellent resistance to oxidizing aqueous media, including wet chlorine and mixtures containing nitric acid or oxidizing acids with chloride ions. It is also resistant to reducing aqueous media.
4. Is resistant to strong oxidizers such as ferric and cupric chlorides.
5. Is resistant to chlorine, formic, and acetic acids, and acetic anhydride.
6. Can be used in the as-welded condition without heat treatment.

□ 5.4 Aluminum and Aluminum Alloys

There are many wrought and cast aluminum alloys. The ones most commonly used in corrosive service are shown in Table 5.9. For chemical service, they have the advantage over some other metals by having colorless and nontoxic corrosion products; therefore, fluids and solids handled in aluminum equipment are not discolored by the aluminum. Aluminum alloys do not become brittle at subzero temperatures like various other metals. Aluminum alloys rapidly lose strength at temperatures of 350 F (177 C) or higher.

TABLE 5.9 — Nominal Compositions and Various Uses of Aluminum Alloys

Alloy No.	Mn	Mg	Cr	Cu	Si	Al	Various Uses
1060						99.6%	Railroad tank cars and chemical equipment; premium grade used in special applications, including shipping drums and handling equipment for hydrogen peroxide where impurities catalyze peroxide decomposition.
1100						99.0	Commercial "pure" grade; used for acetic acid service tanks, pumps, and handling equipment.
3003	1.2					bal	About the same corrosion resistance as AA 1100 but with higher mechanical properties; used in tanks, shipping containers, and heat exchangers.
5052		2.5	0.25			bal	Used for equipment requiring higher strengths (28-46 ksi, depending on temper), such as hopper cars, chemical truck bodies, where minimum wall thicknesses are required, and corrosive conditions are mild. Unfired pressure vessels; Alloy 5083 cannot be used in the strain-hardened condition over 150 F, because it will fail by SCC in mildly corrosive environments.
5083	0.7	4.5				bal	
6061	1.0		0.25		0.5	bal	Bars and shapes for structural purposes where corrosion is mild.
355		0.5		1.3	5.0	bal	Cast alloys; these alloys can be heat treated to good mechanical properties (25-39 ksi, depending on temper and alloy); corrosion resistance generally the same as the higher strength wrought aluminum materials; marine hardware, wheels, axle housings.
356		0.3			7.0	bal	

Corrosion Resistance of Aluminum and Aluminum Alloys

Pure aluminum has the greater corrosion resistance when compared to aluminum alloys. As alloying elements are added to pure aluminum, the corrosion resistance is somewhat reduced while the mechanical properties are improved. For this reason, when strength and high corrosion resistance both are required, the designer can specify

Alclad[†] aluminum alloys, which are aluminum structural alloys covered with a thin skin of pure aluminum.

Aluminum and aluminum alloys are corrosion resistant because of their protective oxide film. They are satisfactory materials of construction only in those services where this film can be maintained. *Anodizing* is a treatment which enhances the corrosion resistance and wear resistance of aluminum alloys by greatly increasing the aluminum oxide (Al_2O_3) thickness on the surface. Aluminum is amphoteric and susceptible to attack in strongly alkaline, as well as strongly acidic, solutions. The protective film is only stable in a pH range between 4.5 and 8.5. Corrosion resistance in neutral and many acid conditions is good.

Water. Aluminum is used for handling distilled water and for the distillation of high purity water. Since most plant cooling waters contain impurities, including heavy metal salts that can cause excessive pitting, aluminum and aluminum alloys cannot be used unless the water is inhibited. Copper and mercury salts are particularly dangerous to aluminum, as are other heavy metals. Aluminum and aluminum alloys have excellent resistance to steam and steam condensate, provided there are no entrained alkaline boiler compounds present.

Nitric acid. Aluminum is not sufficiently resistant to mineral acids to allow use except for strong nitric acid, which, at low temperatures, will not break down the protective oxide film and hence good corrosion resistance is permitted. US Interstate Commerce Commission (ICC) regulations allow the shipment of nitric acid in aluminum containers at concentrations above 82%. Nevertheless, care must be exercised by the designer in using aluminum for this service because if concentrations of the nitric acid go below 82%, aluminum will show an increased corrosion rate. Aluminum alloys are very resistant to ammonium nitrate solutions, as long as there are no traces of copper, tin, or lead present. Above 92% nitric acid, the aluminum has greater corrosion resistance than AISI 304L. However, the *welding deposit* must be AA 1100 alloy to resist the corrosion of the acid.

Organic acids and compounds. Aluminum alloys are used throughout industry to handle organic acids including propionic and acetic acids. These acids are regularly shipped in aluminum tank cars. The anhydrides of organic acids are also handled well in aluminum. When using aluminum for these applications, care must be exercised because only small changes in conditions can greatly change performance. For instance, aluminum shows excellent resistance to acetic acid at room temperature at any concentration. Rates are still relatively low up to 120 F (49 C). At the boiling point, it is badly attacked at low

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[†] Registered trade name.

and intermediate concentrations, but corrosion rates decrease rapidly about 90% and resistance to glacial acid is good.

□ 5.5 Carbon and Low Alloy Steels

Many thousands of tons of steel are used every year by the chemical industry and other industries. This may seem paradoxical because of the poor reputation of steel for corrosion resistance since it rusts in water and in the atmosphere. However, because it is relatively inexpensive and easy to weld, carbon and low alloy steels are used widely and successfully for numerous process conditions, alkaline solutions, and for certain acids. There are a few exceptions, but in general, the corrosion resistance of annealed carbon steels are all about the same; however, welding and heat treatment can produce phase changes that can cause changes in the corrosion resistance.

The corrosion resistance of the various alloys listed in Tables 5.10 and 5.11 are predicated more on the condition of the steel as opposed to actual chemical compositions. The quality of the surface, such as rough or smooth, many or few inclusions, the adherence of mill scale, the presence of locked-up stresses, etc., directly affect the steel's resistance to corrosion. Therefore, the specification of a particular carbon steel by the designer will depend more on inherent mechanical properties (either alone or by heat treatment) that the steel possesses rather than for its corrosion resistance. Of course, the quality of the steel must be carefully specified.

TABLE 5.10 — Nominal Compositions and Various Uses of Low Carbon Steel

ANSI/ASTM Specification	Nominal Composition (bal Fe)	Various Uses
A-36	C	Covers structural steel shapes and lists other specifications covering specific mill shapes.
A-283	C	Lowest cost plate material made to ASTM specifications. It is a general purpose steel and used where a minimum amount of quality control testing is acceptable. Its use is limited to a maximum temperature of 650 F for ASME Code vessel use.
A-285	C	Differs from A-283 primarily in the amount of quality control testing that is done. The ASME code permits its use to a maximum temperature of 900 F. Perhaps the most widely used carbon steel for moderate temperature and pressure service.
A-299	C-Mn-Si	Contains 1.25% manganese, which results in the highest strength range of any of the carbon steel plate materials. The addition of manganese does not materially increase corrosion resistance.
A-515	C-Si	This is a lower grade steel than A-516 with an upper temperature limit of 850 F; not used for low-temperature service.
A-516	C-Si	This silicon deoxidized steel plate is designated by ASME to be used at temperatures up to 1000 F; used for low-temperature service down to −20 F because of fine grain size, which imparts excellent low-temperature—impact properties.

TABLE 5.11 — Nominal Composition and Uses of Low-Alloy Steels

ANSI/ASTM Specification	Nominal Composition	Various
A-202B	1/2Cr-1Mn	All the low-alloy steels listed have greater strength than is available in plain low carbon steels. The grades for the various specification numbers differ primarily in the type and amount of alloying elements that are present, which, in turn, provides differences in mechanical properties. These steels are more expensive than carbon steels both in price per pound and cost of fabrication. The cost is 50 to 100% greater than carbon steels. Additionally, if equipment must be fabricated to ASME Code rules, the requirements for stress relief and radiographic examination are more restricted. Used for a myriad of structural applications.
A-204C	C-1/2Mn	
A-302B	Mn-1/2Mo	
A-387B	1Cr-1/2Mo(1)	
A-387D	2 1/4Cr-1Mo(1)	
A-533	1 1/4Cr-1/2Mo(1)	

(1) In addition, CrMo steels are used in applications where more resistance to oxidation from air, oxidation from steam, high temperature hydrogen attack, and graphitization is required.

Alkaline Solutions

Steel is generally resistant to a wide range of alkaline solutions. It is used for the storage and handling of such solutions as anhydrous and aqueous ammonia and sodium hydroxide. Sensitivity to oxygen is practically nonexistent at pH values above 10. Stress corrosion cracking may occur in and adjacent to unstressed relieved welds in carbon steel equipment containing sodium hydroxide solutions if the temperature is well above ambient. See Chapter 3.8, Table 3.4 and Figure 3.55 for detailed information. Inhibitors are frequently used to allow carbon steels to be used in corrosive waters.

Sulfuric Acid

Carbon steel use. Throughout the world, more sulfuric acid (H_2SO_4) is produced than any other inorganic acid. It is generally considered the most important industrial chemical.[42] Carbon steel has long been used as the material of construction for handling and storage of this acid at low temperatures.

Because of the wide variation in the corrosion resistance of carbon steel in sulfuric acid, this section has been purposely expanded so that the designer will understand the factors that control this variation and will know what to do to avoid excessive corrosion.

The wide use of carbon steel in sulfuric acid service is based on its low cost and ease of fabrication coupled with its normally satisfactory corrosion resistance. However, the designer should recognize that acid concentration, temperature, and velocity can have a significant effect on corrosion rates. Before carbon steel is selected as a material of construction, the designer should conduct a thorough study of the actual exposure conditions. In some designs, stainless steels, high-nickel alloys, protective coatings, or anodic protection of carbon steel may be required.

Variables. Carbon steel owes its corrosion resistance to the formation of a film of ferrous sulfate, which is a product of corrosion that forms on the steel. If this protective layer is *not disturbed*, the acid velocity remains low, the acid is *not diluted*, and the *temperature is not raised*, the corrosion rates will be consistently low. The corrosion rates at ambient temperatures from 65 to 96% acid strength are 5 to 20 mils per year and 0 to 5 mils per year from 96 to 110%. (See Figure 3.81.) Reliance on such corrosion rates may prove hazardous for the designer if he does not keep these significant variables in mind. Corrosion penetration rates can be higher than 200 mils per year, depending on these variables.

Acid concentration. The concentration of sulfuric acid is also a dominant factor in the corrosion resistance of carbon steel. Below 65% acid concentration, even at ambient temperatures, carbon steel corrodes, As the concentration decreases to below 50%, the ferrous sulfate corrosion product rapidly goes into solution, thus fostering very high corrosion rates.

Sulfuric acid is hygroscopic and can readily pick up moisture from the air if precautions are not taken. Such dilution of the acid can lower its concentration and lead to aggressive corrosion as mentioned above. An example of this was shown in Chapter 4.4, where a tank bottom corroded through because of acid dilution. Provision must be made by the designer not to allow moisture filled air to be drawn into the sulfuric acid tank during fluctuations in temperature.

Carbon steel should never be used for service in sulfuric acid much under 65% concentration because corrosion rates can be up to 50 mils per year at ambient temperatures and over 200 mils per year at temperatures greater than 175 F (79 C).

Temperature. The effect of temperatures is clear. Carbon steel is not suitable for use at temperatures much over ambient, according to Figure 3.81. Actually, few materials can withstand the 60 to 98% sulfuric acid at temperatures over 250 F (121 C), with the exceptions of tantalum, acid brick-lined steel, platinum, and fluorocarbon plastic.[44]

Ferrous sulfate protective film. When the ferrous sulfate protective film is disturbed by hydrogen bubbles (generated from the corrosive reaction of carbon steel and sulfuric acid), flowing in a steady stream over specific paths, hydrogen grooving can result. (See Chapter 3.13 for further information on hydrogen grooving.)

Velocity. The effect of velocity on the corrosion rates of sulfuric acid on carbon steel are discussed in Chapter 3.4. Several examples are shown where carbon steel tolerated low sulfuric acid velocities, but not higher velocities.

What the Designer Can Do to Reduce Excessive Corrosion of Carbon Steel in Strong Sulfuric Acid

There are several steps a designer can take to reduce excessive corrosion of carbon steel in strong sulfuric acid, including:

Select pipe diameters that will keep the velocity low. When designing pipelines, select pipe diameters that will keep the velocity as low as is economically possible. Try to keep velocities at 8 feet per second or below.

Avoid turbulence whenever possible. Turbulence should be avoided whenever possible because it constitutes local high-velocity acid. Use wide sweep elbows. Where sharp bends must be made, use heavier fittings to afford a greater corrosion allowance.

Specify that outside surfaces of sulfuric acid tanks be painted white. Because acid temperature is critical, the designer should specify that sulfuric acid storage tanks be painted white to reflect the solar rays. Tanks may also be thermally insulated for this purpose.

Obtain an analysis of the sulfuric acid that is to be stored or handled. The designer should obtain an analysis of the sulfuric acid to be stored or handled. If the iron content is below 30 ppm, the acid will tend to pick up more iron. This will increase the corrosion rate. When this is the case, the designer should increase the corrosion allowance.

Require a dryer in conjunction with the vent tube to prevent acid dilution. To keep the acid from being diluted as air in drawn into a tank as the acid is being emptied, a dryer may be required in conjunction with the vent tube. All manway doors and other openings should be closed tightly to exclude air. This should be included in the designer's overall materials guide.

Specify that all welds be of high quality. All welds in sulfuric service should be of high quality, showing full penetration. All butt welds, when size permits, should be double, i.e., welded from both inside and out. Piping with diameters too small to permit double butt welds should be welded using consumable insert rings. (See Chapter 3.1 for further information on rings.) All fillet welds inside tanks must be full penetration, as noted in Chapter 4.1 with the example of barge welds.

Specify multipass welding when using manual arc welding. When manual metal arc welding is to be used, all welding should be specified to be multipass. The reason for this is that in a weld made with a single pass, there is more of a chance that slag will be distributed in a path through the depth of the weld than there would be if more than one pass is made. Sulfuric acid readily attacks such slag leaving voids in the weld deposit causing it to be unsound.

Example – The inside of a carbon steel horizontal tank was inspected that had held 66 degree Baume (93%) sulfuric acid for many years. The shell weld seams had been properly designed using double butt welds. However, it was reported that the welding had been accomplished by using 1/4-in. (7-mm) electrodes (AWS E-7010). The butt weld had filled the welding groove in one pass. The inside weld was found to be riddled with holes, some to the bottom of the weld pass. Pieces of the weld could be literally lifted out of the weld groove. To make repairs, the inside weld was completely ground out and welded in three passes with a 5/32-in. (4-mm)-diameter electrode (AWS E-6010). No further weld corrosion was reported.

Specify the removal of the mill scale from the sheet or plate ordered. In the purchase order for steel, the designer should specify that the mill scale must be removed from the sheet or plate ordered. Mill scale is readily consumed by sulfuric acid, leaving pock marks that can become sites for localized corrosion.

Make sure weld surfaces are smooth. Welds with rough surfaces should be lightly ground or sandblasted to obtain a smooth surface. It is not necessary to grind flush. The welds should be smooth enough so that acid cannot be retained on the surface after the acid is emptied.

Use standards for guidelines. As a guideline, the designer can use a corrosion allowance of 1/4 in. (7 mm) for storing 70 to 100.5% sulfuric acid and 1/8 in. (3 mm) for 100.5 to 110% acid, providing the temperature is ambient. Use API Standard 650 (1980) as a guide when designing sulfuric acid tanks. Generally, ASTM Standard A-516 Grade 70 or A-662 Grade B steel will satisfy the requirements as long as the notch toughness properties are met.

Consider anodic protection for critical applications. For critical applications of carbon steel tanks in sulfuric acid service, the designer has the option of specifying anodic protection. (Refer to Chapter 6.4.) Anodic protection[42] can lower mild steel corrosion rates to 1 to 2 mils per year, which is considerably lower than corrosion rates would be without such protection. Anodic systems have been satisfactory for controlling corrosion in many sulfuric acid tanks and other process equipment.

Other Acids

Carbon steel has very poor resistance to hydrochloric, nitric, phosphoric, and acetic acids and should not be used. However, there are mixed acids for which carbon steel is a permissible material of construction. For example, certain mixtures of sulfuric acid, nitric acid, and water can be contained in steel.

Atmosphere

In all atmospheres (except perhaps under very dry conditions), steel surfaces must be painted for protection. (See Chapter 6.6.) Industrial and marine atmospheres are the most aggressive to steel. Low alloy steels containing small amounts of copper (1/4%), such as Corten[†] steel, may show better resistance than plain carbon steel. This is attributed to the formation of a more adherent rust or oxide film that minimizes further rusting. It is difficult to predict the corrosion resistance of carbon and low allow steels because the atmospheric conditions in various locations vary greatly.

Water

The corrosion resistance of steel in various waters depends on many factors, such as pH, amount of dissolved solids, amount of dissolved oxygen, temperature, and velocity. Hydrogen evolution from carbon steel in water can occur at pH values as high as 4.5 and tends to decrease as the pH value is increased. However, even at pH levels of 7 to 10, care must be exercised to obviate hydrogen embrittlement.

[†] Registered trade name.

The protective films formed at lower pH values are often discontinuous and hence not very protective. At pH values of 10 or above, a tightly adherent film that is very resistant to corrosion forms. Inhibitors are frequently used to allow carbon steels to be used in corrosive waters.

Steam Generation

Carbon steel is used universally for steam generating equipment, pipelines, and other handling equipment. Excellent service life is obtained if the boiler water is properly deaerated and/or chemically treated. Sulfites, hydrazine, and other chemicals are used to scavenge the oxygen in the water; otherwise, the dissolved oxygen would cause aggressive attack on the steel.

Inorganic Salt Solutions

Solutions of acidic salts, such as NH_4Cl and $AlCl_3$, are very corrosive to steel. Alkaline salts, such as Na_2CO_3, however, are generally noncorrosive except for strongly oxidizing salts like sodium hypochlorite. When brines are handled in steel, they should be kept at pH levels above 7 and should be inhibited or deaerated.

High-Temperature Corrosion

The oxide coating that forms on steel is protective up to about 1,000 F (593 C). High-temperature hydrogen attack increases with temperature and the hydrogen partial pressure. Alloying ingredients in steel significantly increase resistance to high-temperature corrosion. Alloying elements, such as chromium and molybdenum, are used.

Gases

Alloy steels are used to handle gases containing carbon monoxide and in ammonia mixtures, they are used for nitriding steel.

☐ 5.6 Copper and Copper Alloys

Copper and copper-base alloys have been extensively used throughout industry for corrosion resistance. Table 5.12 shows 15 copper alloys that are generally most used for this purpose. The wrought alloys are very easily formed because of their excellent ductility. The cast alloys have excellent castability. The welding of some alloys is complicated by high thermal conductivity; however, the exception is high silicon Bronze A, which has a much lower thermal conductivity and can consequently be welded with the insert gas process, almost as easily as stainless steel.

TABLE 5.12 — Nominal Compositions and Various Uses of Copper-Base Alloys

Copper Development Association No.	Name	Cu (%)	Zn (%)	Sn (%)	Ni (%)	Others (%)	Various Uses
122	Phosphorous Deoxidized Copper	99.9 minimum				P-0.015 to 0.040	Plumbing and gas lines; gasoline and water lines; heat exchanger tubes.
230	Red Brass	85	15				Heat exchanger tubes, flexible hose.
270	Yellow Brass	65	35				Springs, plumbing accessories.
443	Admiralty Brass	71	28	1			Condenser, heat exchangers, evaporator tubes, condenser tube sheets, distillation tubes, ferrules.
465	Naval Brass	60	39	1			Marine hardware, nuts, valve stems, condenser plates, bolts.
687	Aluminum Brass	77	21			Al-2	Heat exchanger, evaporator and condenser tubing, distillation tubes.
521	Phosphor Bronze B	92		8		P-0.25	Textile machinery, bridge bearing plates, chemical hardware, bellows, springs.
614	Aluminum Bronze D	91				Al-7 Fe-2	Marine sheeting, tanks, nuts, bolts, condenser tubes.
655	High Silicon Bronze A	94	1		0.5	Si-3 Mn-1 Fe-0.5	Seamless tubes, heat exchangers, welded hot water storage heaters, fasteners.
706	90-10 Cupro-Nickel	88			10		Salt water piping, evaporator tubes, chemical process equipment, distillation tubes, condenser tubes and tube sheets, heat exchanger tubes.
710	80-20 Cupro-Nickel	78			20		
715	70-30 Cupro-Nickel	69			30		
905	Tin Bronze Casting	88	2	10			Steam fittings, pump impellers, pump bodies, valves, bushings, bearings, piston rings.
836	Leaded Red Brass Casting	85	5	5		Pb-5	Pipe fittings, plumbing goods, low-pressure valve bodies.

Corrosion Resistance of Copper and Copper Alloys

Referring to Table 5.12, phosphorous deoxidized copper is the first material listed and is universally used as tubing. The next five alloys, mainly comprising copper and zinc, are members of the *brass* family. These alloys are used widely in industry for tubing and process equipment. As described in Chapter 3.12, these alloys are susceptible to selective leaching or dezincification called *dealloying*, especially in hot, polluted, or mildly acid solutions. The corrosion resistance can be increased by adding inhibiting elements, such as phosphorus, antimony, or arsenic to the copper melt. These alloys are also susceptible to stress corrosion cracking, as noted in Chapter 3.8. The addition of inhibiting elements does not reduce the stress corrosion cracking tendency. The alloys listed as *bronzes* in Table 5.12 are essentially composed of copper and tin and have a corrosion resistance much greater than the brasses. They are not susceptible to dealloying and have increased corrosion resistance, but they do not have immunity to stress corrosion cracking. They are also more expensive than the brasses. The three *cupro-nickels* listed have outstanding corrosion resistance and are widely used for salt water service. The last two alloys listed are *copper alloy castings*. They are very useful in industry for intricate parts such as valve bodies and pipe fittings.

Basic solutions. Solutions of ammonium hydroxide are very corrosive to copper and its alloys because of the formation of a soluble complex copper-ammonia compound. Hot dilute caustic solutions are only mildly corrosive to the bronzes.

Mercury. Mercury and mercury compounds will rapidly crack stressed copper alloy parts; in fact, the mercurous nitrate test is a regularly used laboratory test to detect residual stresses in copper alloys. Mercury will even crack elemental copper.

Neutral and alkaline salts. Copper and its alloys are generally resistant to neutral or alkaline salts solutions; however, there should be definite assurance that there is no acid involved.

Oxidizing salts. Solutions of oxidizing salts, such as hypochlorite, are damaging to copper and copper alloys. Acid salts and oxidizing acid salts, such as ferric chlorides, are also very corrosive as are all oxidizing acids.

Organic compounds. Many organic compounds, such as esters, alcohols, ketones, etc., are handled in copper equipment. Deaeration is not required unless appreciable acidity is developed.

Non-oxidizing acids. Copper and copper-base alloys are quite resistant to dilute solutions of most non-oxidizing acids, either hot or cold, and also cold concentrated solutions, provided that the oxygen is completely excluded by nitrogen blanketing or assurance of reducing conditions. Copper and copper-base alloys, in direct contrast to austenitic stainless steels, thrive on reducing conditions but fail in oxidizing conditions. Copper is actually a noble material and consequently, hydrogen does not generally evolve during corrosion. For this reason, it is not attacked by acids unless oxygen or oxidizing agents are present. In such cases, the corrosion mechanism involves the reduction of oxygen at the cathode. In some applications in industry where stainless steels would not be satisfactory and when only very expensive high alloys would be satisfactory, the cupro-nickels and aluminum bronzes protected from oxygen by nitrogen blankets have given satisfactory service with great monetary savings.

Nitric acid. Nitric acid, which is an oxidizing acid, rapidly attacks copper and copper-base alloys.

Acetylene. In some cases, the mild corrosion of copper and copper alloys releases undesirable corrosion products. The copper salts formed may discolor the finished product or act as a catalyst for undesirable side reactions. For example, acetylene forms a very explosive compound with silver and copper alloys when moisture and alloys containing more than 65% copper interact. This interaction may cause an explosion. Therefore, wet acetylene under pressure should never contact even one copper-base fitting or part (or silver-soldered part).

Marine use. Copper compounds are highly toxic to most organisms. For instance, copper was once used extensively for sheathing the bottom of wooden ships to prevent fouling caused by the buildup of marine organisms. Copper in paints can prevent or slow down the buildup of marine organisms that can cause localized corrosion on steel ship bottoms. Brass, aluminum bronze, cupro-nickels, tin-bronze castings, and other copper-base alloys are used extensively for hardware and sheathing for use in ships and other marine environments.

□ 5.7 Titanium and Titanium Alloys

There are four grades of titanium and titanium alloys that are used extensively in industry. (See Table 5.13.) These alloys are corrosion resistant because of their protective oxide films and are best under oxidizing conditions similar to austenitic stainless steels. The strength to weight ratio of titanium is very high. Titanium is easily welded, but the

TABLE 5.13 — Nominal Compositions and Various Uses of Titanium and Titanium Alloys

ASTM B-265 (Grade)	C (maximum)	Fe (maximum)	Al	O	V	N	Pd	Minimum Tensile (Strength/ksi)	Various Uses
2	0.10	0.30				0.03		50	Uses include parts requiring excellent corrosion resistance, high formability, good strength to weight ratio, and good weldability; plate, sheet, strip, and tubing available; marine hardware aircraft parts, ordinance parts, parts and hardware for the space industry and tubing parts, vessels, heat exchangers, etc. for the chemical industry. The latter uses are based primarily on resistance to chloride stress corrosion cracking, for which the additional cost can be justified.
3	0.10	0.30				0.05		65	
5	0.20	0.40	6		4			130	
7	0.10	0.30		0.25		0.03	0.12 to 0.15	50	

molten metal must be completely shielded from the oxygen and nitrogen of the air. (See AWS specification D10k, "Practices and Procedures for Welding Titanium Pipe and Tubing" for further details on welding.) The use of titanium in industry is limited to a maximum temperature of 600 F (315 C). Commercially pure titanium is available in several grades. Grade 2 is most commonly used for industrial equipment, since it is approved by the ASME Code for Unfired Pressure Vessels. Grade 7, containing small amounts of palladium, offers enhanced corrosion resistance in certain environments. Grades 3 and 5 are used where increased tensile strength is required (65,000 and 130,000 psi/min, respectively).

Corrosion Resistance of Titanium and Titanium Alloys

Depending on the environment, titanium and its alloys have varied degrees of corrosion resistance.

Brackish water and seawater. Titanium has excellent resistance to corrosive attack by seawater and most chloride salt solutions. It is not susceptible to stress corrosion cracking in plant cooling waters or chloride solutions like austenitic stainless steel.

Titanium is susceptible to crevice corrosion in solutions that the metal would ordinarily be resistant to. Of the four titanium grades listed in Table 5.13, Grade 7 is much more resistant to this form of attack and yet is not entirely immune.

Hydrochloric and sulfuric acids. Titanium has poor resistance to reducing mineral acids, such as sulfuric and hydrochloric. However, if strong oxidizing agents are present, such as ferric or cupric salts, titanium can be used with fairly low corrosion rates. Grade 7 has substantially better resistance under non-oxidizing or slight reducing conditions than Grades 2 or 3.

Hydrofluoric acid. Titanium is vigorously attacked by hydrofluoric acid and by any solution that contains more than 5 to 50 ppm of fluoride ions.

Organic acids. This material is very resistant to some organic acids. It is resistant to acetic acid as long as there is around 0.2% water present. Oxalic, trichloroacetic, and formic acids corrode titanium.

Nitric acid. Titanium has good resistance to nitric acid under certain conditions. It is very resistant to dilute and concentrated nitric acid. At temperatures above atmospheric boiling, it has much greater corrosion resistance than austenitic stainless steels.

Oxidizing salts. Titanium and titanium alloys have excellent resistance to oxidizing salts such as hypochlorites, cupric, and ferric chlorides. These salts tend to pit most other metal but actually inhibit corrosion in titanium.

Wet chlorine. Titanium has excellent resistance to wet chlorine, except where there are crevices which will cause rapid failure. Dry chlorine can cause a violent exothermic reaction. At least 1% water must be present to prevent this reaction.

Red fuming nitric acid. Titanium is catastrophically attacked in red fuming nitric acid with high NO_2 content and low water content.

Galvanic corrosion effects. Because titanium has the ability to easily and immediately passivate, it is seldom affected by galvanic corrosion.

□ 5.8 Unified Numbering System (UNS)

During this century, there has developed a bewildering array of metals and alloys, each with its own designation or number. Because there was not a central organization established at that time, these designations have come from trade names, trade associations, and technical organizations; consequently, there was confusion regarding metal and alloy identities. The composition of type 304 stainless steel, for instance, was different in ASTM, SAE, and AISI standards. The differences were small, but there were discrepancies. There were also instances when the same number was assigned to two entirely different alloys and other cases when there was more than one identification number for the same material. Starting in 1969, SAE and ASTM conducted a study for the Army Materials and Mechanics Research Center, Watertown, Massachusetts, to determine the feasibility of developing a new consistent numbering system for metals and alloys.

Out of the SAE/ASTM study evolved the Unified Numbering System (UNS), which has eliminated the confusion in numbering metals and alloys. The designer is cautioned that a UNS number by itself is not a specification. It is a number carefully controlled by SAE and ASTM in conjunction with various technical societies to indicate established specifications published elsewhere, which limits the form, condition, quality, chemical analysis, etc., of various metals and alloys.

Whenever practical, the original number designation of a specific metal or alloy is incorporated in the UNS number. For instance, AISI 304 stainless steel is UNS S 30400; Nickel Alloy 600 is UNS N 06600; and Aluminum Alloy 6061 is UNS A 96061.

The primary series of UNS numbers are shown in Table 5.14. The UNS numbers corresponding to all the metals and alloys shown in Tables 5.2 through 5.13 are shown in Table 5.15. As mentioned before, the designer should become familiar with this system because it will be used more and more and should help the designer in assuring that he actually receives the corrosion-resistant materials that he requires. The designer should refer to "Unified System for Metals and Alloys," SAE Standard HS1086a and ASTM Standard DS-56A for a compilation of all UNS numbers assigned so far.

TABLE 5.14 — Primary Series of UNS Numbers[1]

UNS Series	Metal
Nonferrous metals and alloys	
A00001-A99999	Aluminum and aluminum alloys
C00001-C99999	Copper and copper alloys
N00001-N99999	Nickel and nickel alloys
R00001-R99999	Reactive and refractory metals and alloys
Ferrous metals and alloys	
J00001-J99999	Cast steels
K00001-K99999	Miscellaneous steels and ferrous alloys
S00001-S99999	Heat and corrosion resistant (stainless) steels

[1] Abbreviated table from SAE HS1086a and ASTM DS-56A.

□ 5.9 Overall Materials Guide (OMG)

The proper selection of materials of construction is very important, as emphasized before. If the optimum material is not determined, either the equipment may fail or the cost of the equipment will be higher than necessary. Past experience shows that after a plant has been operating, it is sometimes difficult to determine what materials of construction were used for a piece of equipment without laboriously studying blue print files, specifications, and purchase orders. In addition, the reasons why certain materials were selected are often obscure or unknown. The purpose of an Overall Materials Guide (OMG) is to list in one document the materials of construction for each piece of equipment in a specific plant, and the reasons why these specific materials of construction were chosen.

TABLE 5.15 — Unified Numbering System

Refer to Table No.	Type of Metal or Alloy	Designation No.	UNS No.
5.2	Austenitic Stainless Steel	AISI 301	S30100
		AISI 302	S30200
		AISI 304	S30400
		AISI 304L	S30403
		AISI 321	S32100
		AISI 347	S34700
		AISI 303	S30300
		AISI 305	S30500
		AISI 308	S30800
		AISI 308L	S30803
		AISI 309	S30900
		AISI 310	S31000
		AISI 309Cb	S30904
		AISI 316	S31600
		AISI 317	S31700
		AISI 316L	S31603
		AISI 201	S20100
		AISI 202	S20200
		AISI 204	S20400
		AISI 204L	S20403
5.3	Martensitic Stainless Steel	AISI 403	S40300
		AISI 410	S41000
		AISI 414	S41400
		AISI 416	S41600
		AISI 420	S42000
		AISI 431	S43100
		AISI 440A	S44002
		AISI 440B	S44003
		AISI 440C	S44004
5.4	Ferritic Stainless Steel	AISI 405	S40500
		AISI 431	S43100
		AISI 442	S44200
		AISI 446	S44600
5.5	Precipitation-Hardening Stainless Steel	17 to 4 PH	S17400
		17 to 7 PH	S17700
		PH15-17Mo	S15700
		Stainless W	S17600
5.7	Cast Stainless Steel	CA-15	J91150
		CA-40	J91153
		CA-50	J92615
		CF-8	J92600
		CF-8M	J92900
		CF-20	J92602
		CF-8c	J93400
		CF-16f	J92701
		CD-4MCu	J93402
		CH-20	J93402
		CK-20	J94202
		CN-7M	J95150
		HC	J92605
		HF	J92603
		HH	J93503
		HK	J94224
5.8	Nickel and Nickel Alloys	200	N02200
		201	N02201
		400	N04400
		600	N06600
		625	N06625
		800	N8800
		20 Cb-3	N8020
		825	N8825

TABLE 5.15 — Unified Numbering System (continued)

Refer to Table No.	Type of Metal or Alloy	Designation No.(1)	UNS No.
		Hastelloy B-2	N10665
		Hastelloy C-276	N10276
		Hastelloy G-3	N06007
5.9	Aluminum and Aluminum Alloys	AA 1060	A91060
		AA 1100	A91100
		AA 3003	A93003
		AA 5052	A95052
		AA 5083	A95083
		AA 6061	A96061
		AA 355	A33550
		AA 356	A13560
5.10	Low Carbon Steel	ASTM A-36 (Shapes)	K02600
		ASTM A-283	K02800
		ASTM A-285 (c)	K02801
		ASTM A-299	K02803
		ASTM A-515(65)	K02800
		ASTM A-516(70)	K02700
5.11	Low-Alloy Steels	ASTM A-202B	K12542
		ASTM A-204C	K12320
		ASTM A-302B	K12022
		ASTM A-387B	K12143
		ASTM A-398D	K41545
		ASTM A-533(B)	K12539
5.12	Copper and Copper-Base Alloys	CDA 122	C12200
		CDA 230	C23000
		CDA 270	C27000
		CDA 443	C44300
		CDA 465	C46500
		CDA 687	C68700
		CDA 521	C52100
		CDA 614	C61400
		CDA 655	C65500
		CDA 706	C70600
		CDA 710	C71000
		CDA 715	C71500
		CDA 905	C90500
		CDA 836	C83600
5.13	Titanium and Titanium Alloys	ASTM B-265 Grade 2	R50400
		ASTM B-265 Grade 3	R50550
		ASTM B-265 Grade 5	R56401
		ASTM B-265 Grade 7	R52400

Additional Purposes of the Overall Materials Guide

The OMG serves the following additional purposes:

1. If a materials selection was based on past experience, the OMG will state where that experience was gained (such as at another operating plant.)
2. In a critical piece of equipment, the source and content of the corrosion data backing up the materials choice can be stated.

3. Special precautions can be listed to avoid mistakes during startup. Many corrosion problems can arise because process conditions, such as higher temperatures, can be far different during startup than during subsequent plant operations.
4. The OMG can be turned over to plant operations personnel when the plant goes on stream. Any knowledge of process limitations or precautions regarding corrosion resistance can be noted.
5. The OMG can be invaluable in later years when the plant is contemplating for one reason or another, the substitution of another material of construction for a specific piece of equipment or process.

Overall Materials Guide Example

Table 5.16 shows a complete OMG compiled for a simulated plant. It should be emphasized that an OMG is not intended to supplant the normal materials specifications, purchase orders, equipment lists, or operating procedures.

TABLE 5.16 — Overall Materials Specification (OMG) of a Typical Plant Installation

Equipment Name	Materials of Construction	Reasons for Selection
Special Gas Heater	Tubes: SA213 AISI 304L(1) Shell and Tube Sheets: SA240 AISI 304L(1)	Gases on both sides. Process gas, tube side in at 544 F (284 C) and exits at 346 F (174 C). Other gas, shell side entrance is 212 F (100 C) and exit is 468 F (242 C). These temperatures are well within temperature limitation for AISI 304L, and this alloy will withstand the corrosion of condensate formed during shutdown.
Secondary Condenser	Tubes: Unalloyed titanium SB338 welded Tube Sheets: Detaclad SB265 Grade 1 or 2 titanium on SA516 Grade 70 carbon steel Channel: SA240 AISI 304L(1) Shell: SA516 Grade 70 carbon steel	Process gas enters tubes at 362 F (183 C) and exits at 98 F (37 C). Cold water is on the shell side. Water is 102 F (39 C), out at 147 F (64 C). The temperature is too high for AISI 304L in the presence of chloride bearing water; therefore, titanium tubes must be used. The channel can be AISI 304L stainless steel because the water does not contact it. The tubes are very long, therefore, since the expansion of titanium is less than carbon steel; an expansion joint has been included.
Crossover Body Flange	SA516 Grade 70 (per UG-15 ASME Section VIII) (Originally was SA105) with weld overlay of AISI 309L stainless steel deposit	Flange could be solid AISI 304L but would be too expensive. Use standard forged flange made of 70M T/S steel protected with 1/2-in. (12.7-mm) stainless steel overlay. Sample was submitted that showed carbon content to be below 0.03% carbon on surface. Stainless steel required to protect at startup and to assure no iron oxide being formed. Temperature 520 F (271 C) Corrosion resistance of materials of construction based on experience at Plant No. 21.
Acid Storage	AISI 304L stainless steel(1)	Stainless steel required for 57% maximum acid. The extra low carbon grade specified so tanks can be used in the as-welded condition at ambient temperature. Install corrosion coupons or corrosion probe before startup. Observe at 3-month intervals.
Demineralized Water Storage Tank	AA 3003 Aluminum	Aluminum required for water purity. Watch that no heavy elements contact inside or outside.
Ammonia Primary Evaporator	Shell: SA516 Grade 70 carbon steel Tubes: Incoloy 800	Carbon steel would be satisfactory for this application, however, there can be a fluctuating level that could cause accelerated corrosion; therefore, Incoloy 800 is specified.
Special Condenser	Tubes: 90/10 Cu/Ni Tube Sheets: carbon steel (ASTM A-285, Grade C). Water boxes: carbon steel. Shell and tube support plates: carbon steel ASTM A-285, Grade C.	AISI 304L stainless steel tubes could be used; but, because of lower heat transfer coefficient, they would require more area and cost more. Steam in and out at 147 F (64 C). River water in at 93 F (34 C) ant out at 111 F (44 C). Because river water is used at a high temperature, stainless steel tubes might fail by chloride stress corrosion cracking; therefore, cupro-nickel, which is immune to this type of attack, is used. Install corrosion coupons or probe on river water side.
Double Heater	SA213 AISI 304L stainless steel(1) tubes and tube sheet; SA516 Grade 70 carbon steel shell.	Gas enters at 122 F (50 C) and leaves at 212 F (100 C) on the tube side. High pressure steam is on shell side which condenses. Steam in at 370 F (188 C), out at 367 F (186 C). Since H.P. steam will carry no chlorides, AISI 304L tubes may be used. Care must be exercised during startup so that no chlorides are introduced.
Acid Sump Tank	AISI 304L stainless steel(1)	Stainless steel required because of presence of

TABLE 5.16 — Overall Materials Specification (OMG) of a Typical Plant Installation (continued)

Equipment Name	Materials of Construction	Reasons for Selection
		acid. Standard sump tank. Since the tank is underground, 2 shop coats of bitumastic No. 50 on all external surfaces are required.
Reactor Heater	Tubes: AISI 321H(1) Tube Sheets & Shell: AISI 321(1) Ferrules and Heat Shield: Inconel 600 Expansion Joint Bellows: Incoloy 800	Process gas on tube side at 944 F (507 C) entrance and 734 F (390 C) exit. Both conditions demand excellent high temperature and corrosion resistance. Design pressure 160 psi, design temperature 914 F (490 C). AISI 304L stainless steel limited by Code to maximum of 800 F (427 C). AISI 321 is allowed by the Code to be used at 932 F (499 C) temperature. This alloy is stabilized with titanium and, therefore, can be used in the as-welded condition. Gas enters shell at 460 F (238 C) and exits at 745 F (396 C).
Steam Separator	Shell: SA204 Grade A	Steam inlet temperature 766 F (408 C). Corrosion allowance 1/8 in. (3.2 mm). Design temperature was 800 F (427 C); therefore, carbon steel over the long term might not hold up. A carbon-molybdenum steel was therefore used.
Acid Cooler	AISI 304L stainless steel(1)	Cooling acid from 136 F (58 C) to 116 F (47 C). Water 122 F (48 C) from 88 F (31 C). AISI 304L stainless steel required for corrosion resistance. Install corrosion coupons or corroaison probe observed at 3-month intervals.
Heat Exchanger	Tubes: SA213 AISI 304L(1) Tube Sheets: Detaclad SA240 AISI 304L on SA105 carbon steel Channel: SA240 AISI 304L(1) Shell: SA516 Grade 70	Process gas enters at 406 F (208 C) and exits at 276 F (136 C) on the tube side. On the shell side is boiler feed water condensate. Water in at 212 F (100 C) and out at 347 F (175 C). Such water should have practically no chlorides. The required makeup water (probably 10%) is reported to have less than 1 ppm chlorides. Exchanger designed to operate completely full of water. Under these conditions, AISI 304L stainless steel may be used. Carefully check makeup water for chlorides before addition. Do not add if over 2 ppm.
Condensate Drum	Carbon Steel: SA516 Grade 70	Carbon steel satisfactory as long as there is a corrosion allowance of 1/8 in. (3.2 mm). Place corrosion coupons or probe in drum to ascertain if any pitting develops. Install before startup. Observe at 3-month intervals.
Expansion Joint	Incoloy 800	This material has shown good heat, corrosion, and fatigue resistance in plant operations. Incoloy 800 also has good resistance to corrosion by acid. Temperature 1558 F (848 C). Care must be exercised during startup that 1600 F (871 C) temperature limit is not exceeded.

(1) Should be corrosion evaluated per ASTM Standard A-262 C.

■ 6 — CONTROL TECHNIQUES

□ 6.1 Quality Control

Questions the Designer Should Ask to Control Quality

A designer who is concerned about corrosion resistance must have some way to control quality; otherwise, he may not receive from the manufacturer the corrosion performance he expects from the equipment he has designed. His quality control program should be outlined in the purchase order. Remember that quality can and should be controlled by the designer.

There are many inspection methods available to the designer, but before he specifies one or more of these methods, he should answer the following crucial questions:

1. How corrosive are the process conditions?
2. How toxic are the process conditions?
3. How susceptible is the material of construction to a specific corrosion form, such as crevice corrosion or stress corrosion cracking?
4. How sensitive is the corrosion resistance of the material of construction to shifts in chemical composition?
5. What joining method is to be used? How sensitive is the corrosion resistance of the material of construction to the method of joining, such as welding?
6. How competent is the fabricator? What reputation does he have for self inspection? Does he use Code qualified welders?
7. Is heat treatment required (either for equipment stability or corrosion resistance)?
8. If heat treatment is required, how sensitive are the materials of construction to the heat treatment?
9. How sensitive was the material of construction to mill operations when it was originally produced?
10. If welding is to be the joining method, how important is the filler metal to corrosion performance?